BEFORE THE ENVIRONMENTAL PROTECTION AGENCY

PETITION FOR RULEMAKING PURSUANT TO SECTION 21 OF THE TOXIC SUBSTANCES CONTROL ACT, 15 U.S.C. § 2620, CONCERNING THE REGULATION OF CARBON DIOXIDE

Credit: NOAA

CENTER FOR BIOLOGICAL DIVERSITY

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PETITIONERS

June 30, 2015

NOTICE OF PETITION

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The Center for Biological Diversity ("Center") is a non-profit, public interest environmental organization dedicated to the protection of native species and their habitats through science, policy and environmental law. The Center has over 800,000 members and online activists throughout the United States and around the world. The Center's Oceans Program and its supporters are specifically concerned with the conservation of marine species, the preservation of ocean ecosystems and the effective implementation of U.S. environmental laws, including the Toxic Substances Control Act. The Center submits this petition on its own behalf and on behalf of its members and staff with an interest in protecting the marine environment.

Donn J. Viviani, PhD, is a retired U.S. Environmental Protection Agency scientist. He was the Director of the Climate Policy Assessment Division in the Office of Policy, Economics and Innovation. He also served as Chairman of the Great Lakes Water Board's Toxic Substances Committee and as a member of the Science Coordinating Committee for the International Joint Commission for the Great Lakes. Dr. Viviani enjoys the ocean and submits this petition, in part, so his grandchildren will be able to enjoy it as well. Dr. Viviani also submits a supplement to the petition, under his signature only, and respectively requests that it be considered.

ACTION REQUESTED

Pursuant to section 21 of the Toxic Substances Control Act ("TSCA" or the "Act"), 15 U.S.C. § 2620, and section 553(e) of the Administrative Procedure Act ("APA"), 5 U.S.C. § 553(e), the Center for Biological Diversity and Donn J. Viviani (collectively, "Petitioners") hereby petition the Administrator of the U.S. Environmental Protection Agency ("EPA") to promulgate regulations protecting public health and the environment from the serious harms associated with anthropogenic emissions of carbon dioxide, including ocean acidification. Specifically, Petitioners request that EPA adopt a rule under section 6 of the Act, 15 U.S.C. § 2605, requiring manufacturers and processors to mitigate these emissions.

This petition sets in motion a specific process, placing definite response requirements on EPA. Specifically, TSCA stipulates that the agency "*shall* either grant or deny the petition" within 90 days following its receipt, "promptly commenc[ing] an appropriate [rulemaking]

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proceeding" if such action is warranted. 15 U.S.C. § 2620(b)(3) (emphasis added). Conversely, should EPA deny this petition, the agency must publish the reasons for denial in the Federal Register. 15 U.S.C. § 2620(b)(3); *see also* 5 U.S.C. § 555(e) ("Prompt notice shall be given of the denial in whole or in part of a written application, petition, or other request of an interested person made in connection with any agency proceeding."). Pursuant to 15 U.S.C. § 2620(b)(4), petitioners may file suit in federal district court to challenge an adverse or untimely determination. *See also* 5 U.S.C. §§ 702, 706.

As described in this petition, anthropogenic emissions of carbon dioxide satisfy the standard for regulation set forth at 15 U.S.C. § 2605. For example, EPA has acknowledged that these emissions have the potential to alter ocean chemistry, thus imperiling important marine ecosystems and presenting an unreasonable risk of injury to the environment. Accordingly, the agency must promptly commence the proposed rulemaking to reduce and mitigate these harms. In the event that EPA concludes that there are insufficient data and experience upon which to determine or predict the effects of carbon dioxide emissions, we alternatively request that the agency adopt a rule under section 4 of the Act, 15 U.S.C. § 2603, requiring manufacturers and processors responsible for the generation of carbon dioxide to undertake testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Dated this 30th day of June 2015.

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INTRODUCTION

Ocean acidification — caused by carbon dioxide ("CO_2") emissions — is a severe threat to the marine environment and the health of people who depend on oceans and coasts. Because of the unreasonable risk that CO_2 poses to the environment and human health, this petition seeks rulemaking under the Toxic Substances Control Act ("TSCA") to regulate CO_2 from cradle to grave.

About 28% of CO_2 emissions from power generation, cement production, industry, and other sources are absorbed by the ocean. These CO_2 emissions cause seawater to become more acidic and corrosive to sea life. Anthropogenic CO_2 emissions have increased the acidity of the oceans on average by 30%, and by the end of the century scientists predict that the oceans will become 150-170% more acidic.

While the most dangerous consequences of CO_2 on our oceans are still to come, harmful impacts on the environment are already well-documented.

- Billions of oyster larvae have perished in the Pacific Northwest due to ocean acidification;
- 53% of pteropods, plankton that form the base of the marine food web, along the West Coast have severely dissolved shells because of the corrosive nearshore conditions; and
- Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%.

These are just some of the harmful environmental impacts of ocean acidification caused by CO_2 emissions. Anthropogenic CO_2 emissions are contributing to increasingly corrosive conditions for marine animals, and will continue to grow more severe absent actions to promptly reduce CO_2 pollution in the atmosphere.

TSCA was enacted in part to address the threat of ozone depletion caused by chlorofuorocarbon (CFC) emissions. And here again TSCA regulation is needed where airborne emissions are causing damage to our environment — this time threatening ocean ecosystems, fish and shellfish industries, and communities that depend on oceans and coral reefs.

Petitioners specifically request that EPA take the following actions:

1. **Make a determination under TSCA § 6 that CO_2 presents an unreasonable risk of injury to health or the environment; and**
2. **Initiate rulemaking to control CO_2; or**
3. **If EPA finds data inadequate to make a §6 determination then EPA must initiate rulemaking for testing under TSCA § 4.**

This petition presents scientific evidence that establishes that CO_2 presents an unreasonable risk of injury to the environment, and therefore EPA must take action under TSCA section 6.

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I. The Toxic Substances Control Act

Congress enacted TSCA, 15 U.S.C. §§ 2601 *et seq.*, "to assure that … innovation and commerce in … chemical substances and mixtures do not present an unreasonable risk of injury to health or the environment."[1] Accordingly, lawmakers required those responsible for the manufacture and processing of these compounds to develop "adequate data" describing their effects, and authorized EPA to devise and implement reasonable controls to prevent the risk of injury to health or the environment.[2]

Section 6 of TSCA mandates that EPA "shall" regulate a chemical substance for which

> there is a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance or mixture, or that any combination of such activities, presents or will present an unreasonable risk of injury to health or the environment.[3]

Permissible regulations include requirements prohibiting or "limiting the amount of such substance … which may be manufactured, processed, or distributed in commerce."[4] EPA can also require processors "to give public notice of such risk [of injury], and . . . to replace or repurchase such substance . . . to adequately protect health or the environment."[5] In assessing risk, EPA must consider:

> (A) the effects of such substance or mixture on health and the magnitude of the exposure of human beings to such substance or mixture,
> (B) the effects of such substance or mixture on the environment and the magnitude of the exposure of the environment to such substance or mixture,
> (C) the benefits of such substance or mixture for various uses and the availability of substitutes for such uses, and
> (D) the reasonably ascertainable economic consequences of the rule, after consideration of the effect on the national economy, small business, technological innovation, the environment, and public health.[6]

Thus, if there is a reasonable basis to conclude that a proposed rule is necessary to protect the environment, then EPA must grant a petition for rulemaking and initiate rulemaking procedures. Factual certainty is not required; instead, the agency may "base its action on scientific theories, consideration of projections from available data, modeling using reasonable assumptions, and extrapolations from limited data."[7] Even if EPA determines that another federal law "could

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[1] 15 U.S.C. § 2601(b)(3) (2012). Within the meaning of TSCA, the term "chemical substance" includes "any organic or inorganic substance of a particular molecular identity." *Id.* § 2602(2).
[2] *Id.* § 2601(b)(1) & (2).
[3] *Id.* § 2605(a) (emphasis added).
[4] *Id.* § 2605(a)(1)(B).
[5] *Id.* § 2605(b)(2)(B).
[6] *Id.* § 2605(c)(1). E.
[7] Lead Fishing Sinkers; Response to Citizens' Petition and Proposed Ban, 59 Fed. Reg. 11,122, 11,138 (Mar. 9, 1994) (*citing* H.R. Rep. No. 1341, 9th Cong., 2d Sess. 32 (1976)).

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[sufficiently] eliminate[] or reduce[]" the risk associated with a particular chemical substance, the agency may elect to regulate the substance under TSCA, provided that a "comparison of the estimated costs" and "relative efficiency" reveals that such action promotes the public interest.[8]

In the event that EPA lacks adequate data and experience upon which to determine the health and environmental risks associated with a particular chemical substance, the agency "*shall* by rule require that testing be conducted on such substance."[9] Specifically, Section 4 of the Act authorizes EPA to compel manufacturers and processors to evaluate the safety of substances that "may present an unreasonable risk of injury to health or the environment" or that "[are] or will be produced in substantial quantities" and, thus, "may reasonably be anticipated to enter the environment in substantial quantities" or result in "significant or substantial human exposure."[10] TSCA provides for testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Over forty years ago, the Council on Environmental Quality warned of the "high priority need" for a new legal authority capable of ensuring the safe use of toxic chemicals.[11] Despite TSCA's powerful potential, however, EPA has accomplished very little under the Act. This petition presents substantial scientific evidence demonstrating that anthropogenic emissions of CO_2 pose an unreasonable risk to human and environmental health. Indeed, studies show that significant and potentially irreversible harm has already occurred. As the Council recognized decades ago, "[w]e should no longer be limited to repairing [this] damage after it has been done; nor should we continue to allow the entire population or the entire environment to be used as a laboratory." Instead, EPA must take prompt action to reduce and mitigate the anthropogenic production of CO_2.

II. EPA Must Issue a Rule to Regulate or Require Tests for CO_2 Causing Ocean Acidification

CO_2 presents an unreasonable risk of injury to the environment because its exposure to the ocean changes seawater chemistry with harmful impacts on marine life and ecosystems. Substantial evidence supports this conclusion and is discussed in this petition. Accordingly, this petition seeks a rulemaking to regulate CO_2 under TSCA.

This petition requires EPA to make a determination under TSCA section 6 if the injury to the environment and health from CO_2 is unreasonable. Alternately, if the Agency demonstrates that the existing science is insufficient to make a determination under TSCA section 6, EPA must initiate test rules under TSCA section 4 to develop the missing information needed to determine if the TSCA section 6 trigger is met and how best to mitigate the harm.

A. TSCA Authorizes EPA to Act on CO_2

To enable the achievement of TSCA's ambitious objectives, Congress broadly defined EPA's jurisdiction under the Act. As described above, TSCA explicitly directs EPA to initiate

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[8] *Id.*
[9] *Id.* § 2603 (emphasis added).
[10] *Id.*
[11] Council on Envtl. Quality, Toxic Substances at v (April 1971).

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rulemaking upon finding that "the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance" threatens public health or the environment.[12] TSCA then authorizes the regulation of "chemical substances" that are "in commerce," a test met by CO_2. Indeed, CO_2 is already on the TSCA inventory as a "chemical in commerce."[13] CO_2 necessarily qualifies as a "chemical substance," a category that includes "any organic or inorganic substance of a particular molecular identity."[14] Moreover, the anthropogenic emissions at issue are in commerce; federal courts have previously concluded that air emissions[15] and "incidental byproducts of industrial chemical processes" are within the scope of EPA's authority under the Act.[16] Existing scientific evidence demonstrates that the anthropogenic production of CO_2 has already damaged marine ecosystems and endangered vulnerable portions of the human population. For the reasons described below, EPA must promptly reduce and mitigate these harms.

1. CO_2 Is a Chemical Substance

First, carbon dioxide is a "chemical substance" falling within the scope of the Act. The Act defines "chemical substance" as "any organic or inorganic substance of a particular molecular identity, including any combination of such substances occurring in whole or in part as a result of a chemical reaction or occurring in nature and (ii) any element or uncombined radical."[17]. CO_2 meets this definition. CO_2 is a chemical substance that occurs both in nature and as a result of a chemical reaction. It consists of a carbon atom bonded to two oxygen atoms:

$$O=C=O$$

It is identified by molecular formula CO_2 and by CAS number 124-38-9.

2. CO_2 Is in Commerce

Second, CO_2 is in commerce, and it is already on the TSCA inventory (CAS 124-38-9) with "chemical in commerce" as the stated reason for regulation.[18] Under TSCA's statutory text, "commerce" is defined as "trade, traffic, transportation, or other commerce . . . between a place in a State and any place outside of such state, or . . . which affects trade, traffic, transportation, or commerce."[19] CO_2 is primarily produced as a byproduct from the combustion of fossil fuels; according to the EPA, CO_2 emissions account for 77% of greenhouse gas emissions worldwide.[20]

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[12] *Id.* §§ 2605(a), 2603(a)(1)(A)(i), 2506(a). Although TSCA does not define "disposal," other federal environmental laws explain that this term encompasses "the discharge, deposit, injection, dumping, spilling, leaking, or placing of any solid waste or hazardous waste into or on any land or water so that such solid waste or hazardous waste or any constituent thereof may enter the environment or be emitted into the air or discharged into any waters, including ground waters." 42 U.S.C. §§ 6903(3), 9601(29).
[13] EPA, Substance Registry at http://1.usa.gov/1IBS1w6 (last accessed June 28, 2015).
[14] 15 U.S.C. § 2602(2). This definition excludes specific compounds already subject to federal control, such as pesticides, tobacco products, nuclear materials and food, drugs and cosmetics. *Id.* § 2602(2)(B).
[15] *Citizens for a Better Env't v. Thomas*, 704 F. Supp. 149, 152 (E.D. Ill. 1989).
[16] *Envtl. Def. Fund v. Envtl. Prot. Agency*, 636 F.2d 1267, 1271 (D.C. Cir. 1980).
[17] 15 U.S.C. § 2602(2)(A).
[18] EPA, Substance Registry at http://1.usa.gov/1IBS1w6.
[19] 15 U.S.C. § 2602(3).
[20] EPA, Global Greenhouse Gas Emissions Data, http://www.epa.gov/climatechange/ghgemissions/global.html (last updated June 21, 2013; last accessed June 28, 2015).

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The most voluminous sources of greenhouse gas emissions are energy suppliers,[21] industry,[22] land use and forestry,[23] agriculture,[24] transportation,[25] commercial and residential buildings,[26] and waste and wastewater.[27] All of these emitters produce CO_2 as a byproduct of their ordinary processes.

TSCA's statutory and regulatory text support the proposition that CO_2 emitted as a byproduct of industrial processes can be regulated under TSCA because CO_2 in this context is manufactured, meaning "produce[d] . . . with the purpose of obtaining an immediate or eventual commercial advantage."[28] All of the industries listed above which emit CO_2 are performed to obtain an immediate or eventual commercial advantage, as all of these industries are commercial and part of a competitive market. Therefore, incidental production of CO_2 is manufactured or produced "for a commercial purpose," and is found "in commerce" pursuant to TSCA regulations.

Accordingly, CO_2 emissions fit the regulatory definition of a chemical substance produced for a commercial purpose. This is bolstered by the broad definition of "commerce" in the TSCA statute; at the very least, CO_2 emissions "affect" trade, traffic, transportation, and commerce.

TSCA's purpose and regulatory text support the regulation of chemical substances that are an incidental byproduct, and indeed EPA has regulated chemical byproducts under TSCA before. For example, PCBs are regulated under TSCA even when they are only incidentally produced as a byproduct of industrial processes.[29] EPA regulates PCB "byproducts" for which there are no separate commercial intents, and TSCA regulates inadvertently vented PCB emissions.[30] Moreover, EPA's authority under TSCA broadly defines what it regulates under "disposal" of PCBs to include intentional and accidental disposal.[31] EPA has also previously prohibited wastes from chemical manufacturing under TSCA.[32]

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[21] Which emit greenhouse gases through "[t]he burning of coal, natural gas, and oil for electricity and heat." *Id.*

[22] Which emit greenhouse gases through "fossil fuels burned on-site at facilities for energy" and "chemical, metallurgical, and mineral transformation processes not associated with energy consumption." *Id.*

[23] Which emit "carbon dioxide . . . from deforestation, land clearing for agriculture, and fires or decay of peat soils." *Id.*

[24] "Greenhouse emissions from agriculture mostly come from the management of agricultural soils, livestock, rice production, and biomass burning." *Id.*

[25] Which emit greenhouse gases through "fossil fuels burned for road, rail, air, and marine transportation." *Id.*

[26] Which emit greenhouse gases from "on-site energy generation and burning fuels or heat in buildings or cooking in homes." *Id.*

[27] Which emit carbon dioxide through the "incineration of some waste products that were made with fossil fuels, such as plastics and synthetic textiles." *Id.*

[28] 40 C.F.R. § 710.3; 40 C.F.R. § 704.3 ("Manufacture for commercial purposes also applies to substances that are produced coincidentally during the manufacture, processing, use, or disposal of another substance or mixture, including both byproducts that are separated from that other substance or mixture and impurities that remain in that substance or mixture. Such byproducts and impurities may, or may not, in themselves have commercial value. They are nonetheless produced for the purpose of obtaining a commercial advantage since they are part of the manufacture of a chemical product for a commercial purpose.").

[29] 44 Fed. Reg. 31525 (May 31, 1979); 40 C.F.R. § 761.

[30] *See, e.g.,* 40 C.F.R. Part 761.

[31] 40 C.F.R. § 761.3.

[32] 45 Fed. Reg. 592 (March 11, 1980);40 C.F.R. § 775 (1980) (prohibiting disposal of 2,3,7,8-tetracholorodibenzo-p-dioxin (TCDD) a manufacturing waste).

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Further, CO_2 emissions are in commerce as they are traded, bought, and sold as carbon offsets. CO_2 is also produced for commerical purposes including for uses in fertilizer, beverage carbonation, dry ice, refrigeration, pressurization, fire extinguishment, and packaging.

B. EPA Should Initiate Rulemaking to Control CO_2 under TSCA

Petitioners request that EPA make finding that CO_2 presents or will present an unreasonable risk of injury to the environment or health. TSCA requires that EPA "shall" initiate rulemaking upon finding "a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use or disposal of a chemical substance of mixture … presents or will present an unreasonable risk of injury to health or the environment."[33]

The information and supporting documents provided in this petition indicate that CO_2 is already causing injury to the environment due to ocean acidification. The scientific evidence further supports that the injury to the environment and health will grow more severe as CO_2 pollution continues. EPA cannot deny that CO_2 is harming the environment. Indeed, EPA acknowledges that ocean acidification poses risk:

> Ocean acidification, like Climate change is primarily caused by increasing carbon dioxide (CO_2) concentrations in the atmosphere. As a result of absorbing large quantities of human made CO_2 emissions the ocean chemistry is changing, which is likely to negatively affect important marine ecosystems and species including coral reefs, shellfish, and fisheries.

(Environmental Protection Agency 2010).

EPA must find that such injury is an unreasonable risk.[34] While Congress did not define the phrase "unreasonable risk," EPA has interpreted relevant legislative history to require that the agency:

> balance the benefits derived from risk reduction against the social and economic costs incurred, taking into account such factors as the extent and magnitude of risk posed; the societal consequences of removing or restricting use of products; availability and potential hazards of substitutes; and impacts on industry, employment, and international trade.[35]

No specific factual determination is necessary to establish "unreasonable risk." For example, even under the stricter standard of 15 U.S.C. § 2606, EPA need not present evidence of actual injury before obtaining emergency injunctive relief to control "immanently hazardous chemical substance[s] or mixture[s]."[36] For the reasons discussed below, application of the agency's balancing test supports the additional regulation of CO_2.

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[33] 15 U.S.C. § 2605(a).
[34] *Id.*
[35] EPA, Guidance for Petitioning the Environmental Protection Agency Under Section 21 of the Toxic Substances Control Act, 50 Fed. Reg. 46,825 (Nov. 13, 1985).
[36] *See* H.R. Conf. Rep. No. 94-1679 78 (1976).

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According to scientific experts: "Reducing CO_2 emissions is the only way to minimise [sic] long-term, large-scale risks" (IBGP et al. 2013).

1. CO_2 Pollution Presents an Unreasonable Risk of Injury to the Environment

There is clear consensus among leading national and international scientific bodies that anthropogenic CO_2 causes changes in ocean chemistry that harm the marine environment. The Intergovernmental Panel on Climate Change ("IPCC") determined that human sources of CO_2 have caused a significant decline in surface ocean pH (Rhein et al. 2013), and over 90 national academies of sciences, including the United States', have signed a statement that ocean acidification will "cause grave harm to important marine ecosystems as CO_2 concentrations reach 450 ppm and above" (Interacademy Panel 2009). The Interacademy Panel concluded that CO_2 has increased ocean acidity with "potentially profound consequences for marine plants and animals" including severe threats to coral reefs, polar ecosystems, and a likely reduction in marine food supplies (*Id.*). The National Research Council also acknowledges that "existing data support a growing consensus in the research community that most documented responses to acidification reflect impairment of physiological capacity or performance" for marine life with likely substantial socioeconomic impacts (National Research Council 2013). The U.S. National Climate Assessment concluded that ocean acidification will alter marine ecosystems in dramatic ways including threatening coral reef habitats and causing reduced growth and survival of shellfish in all regions (Doney et al. 2014).

EPA acknowledges that "ocean acidification presents a suite of environmental changes that would likely negatively affect ocean ecosystems, fisheries, and other marine resources." 75 Fed. Reg. 13538 (Mar. 22, 2010). EPA previously concluded that greenhouse gases, including CO_2, endanger public health and the environment in part because of ocean acidification.[37]

There is no doubt that CO_2 pollution is changing ocean chemistry and harming the marine environment. Unabated, there will be severe and detrimental impacts on marine ecosystems, the economy, and public health. Accordingly, EPA must find that CO_2 poses an unreasonable risk to the environment and health.

a. CO_2 Causes Irreversible Ocean Acidification

Ocean acidification is a major threat to the marine environment. The oceans have absorbed CO_2 emitted into the atmosphere from power plants, manufacturing, cement production, and land use changes. Between 1750 and 2011, human activities have released 375 gigatons of carbon into the atmosphere, and approximately half of that has been absorbed by the oceans (Rhein et al. 2013). Each day about 22 million metric tons of CO_2 is taken up by the oceans (Feely et al. 2008). This uptake of CO_2 is changing ocean chemistry, causing the oceans to become more acidic. Since the industrial revolution surface ocean pH has declined by 0.11 units on average, corresponding with

[37] EPA, Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act 80 (Dec. 7, 2009).

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a 30% increase in acidity (Orr et al. 2005; Caldeira & Wickett 2005).[38] If emissions continue unabated, ocean acidity will increase up to 170% by the end of the century (IBGP et al. 2013).

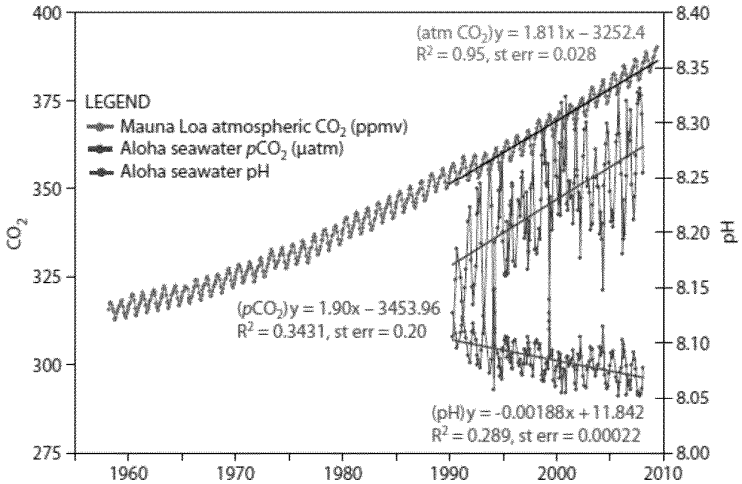

Figure 1. Time series of atmospheric CO 2 at Mauna Loa (ppmv) and surface ocean pH and pCO2 (µatm) at Ocean Station Aloha in the subtropical North Pacific Ocean (see inset map). Note that the increase in oceanic CO 2 over the period of observations is consistent with the atmospheric increase within the statistical limits of the measurements. (Feely et al. 2009).

Anthropogenic ocean acidification exceeds the trend in natural variability significantly, up to 30 times in some regions (Friedrich et al. 2012). The rate of change in ocean acidity is unprecedented in the past 300 million years, a period that includes four mass extinctions (Honisch et al. 2012; Zeebe 2012). The seawater chemistry change is an order of magnitude faster than what occurred 55 million years ago during Paleocene-Eocene Thermal Maximum, which is considered to be the closest analogue to the present, and during that period 96% of marine species went extinct (*Id.*). The current changes in seawater chemistry are irreversible on human timescales (Royal Society 2005).

CO_2's impact on ocean chemistry is fundamentally altering the marine environment with negative impacts on marine species, habitats and ecosystems.

i. What Is Ocean Acidification

When the ocean absorbs CO_2 from the atmosphere it changes ocean chemistry. CO_2 that is absorbed by seawater reacts to form carbonic acid, which dissociates to form bicarbonate and releases hydrogen ions. This reaction reduces the amount of carbonate ions and decreases pH. The oceans store a significant amount of the CO_2 pollution from human activities (Royal Society 2005). While this has provided society with an important service of buffering against climate change impacts, it comes at a cost to the marine environment.

[38] Because the pH scale is logarithmic a small decrease is a significant change in acidity; for example, a decrease of 0.1 pH is an approximate 30 percent increase in acidity.

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Globally, surface water pH has declined 0.11 units on average between 1750 and 1994 (Sabine et al. 2004). Long-term monitoring has documented the impact of increasing atmospheric CO_2 on declining seawater pH in the Pacific and Atlantic Oceans (*see* Figure 2). Results from time-series stations in the North Atlantic and North Pacific show a decrease of about 0.002 pH per year (Rhein et al. 2013).

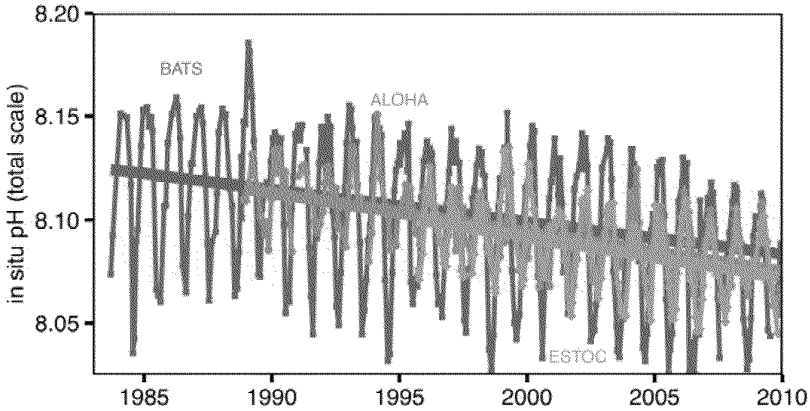

Figure 2. Long-term trends of surface seawater pH at three subtropical ocean time series in the North Atlantic and North Pacific Oceans, including (a) Bermuda Atlantic Time-series Study (BATS, 31°40'N, 64°10'W; green) and Hydrostation S (32°10', 64°30'W) from 1983 to present (updated from Bates, 2007); (b) Hawaii Ocean Time-series (HOT) at Station ALOHA (A Long-term Oligotrophic Habitat Assessment; 22°45'N, 158°00'W; orange) from 1988 to present (updated from Dore et al., 2009) and (c) European Station for Time series in the Ocean (ESTOC, 29°10'N, 15°30'W; blue) from 1994 to present (updated from González-Dávila et al., 2010). Atmospheric pCO2 (black) from the Mauna Loa Observatory Hawaii is shown in the top panel. Lines show linear fits to the data, whereas Table 3.2 give results for harmonic fits to the data (updated from Orr, 2011).(Rhein et al. 2013)

Ocean acidification not only makes the oceans more acidic, but it also reduces the amount of carbonate ions available for animals to build the shells and skeletons they need to survive. Carbonate is an important constituent of seawater because many organisms form their shells and skeletons by complexing calcium and carbonate. Waters that are supersaturated with aragonite are generally good for shell-building, while undersaturated waters (<1.0 Ω_{ar}) are corrosive to some marine animals. Corals require supersaturated waters above 3.3 Ω_{ar} (Meissner et al. 2012). Globally, there has been a decrease of about -0.4 Ω_{ar} (Gruber et al. 2012). The aragonite saturation state has declined 16% since the Industrial Revolution due, in large part, to anthropogenic CO_2 (Feely et al. 2012a; Ishii et al. 2011). Modeling of the oceans' aragonite saturation predicts that by the end of the century up to 75% of ocean volume could be undersaturated with respect to aragonite (Joos et al. 2011).

ii. Observed and Predicted Acidification

CO_2 has already had measurable impacts on seawater chemistry. Some regions, such as those with upwelling systems or high latitudes, are especially vulnerable to ocean acidification.

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1. Pacific Coast

The West Coast is already experiencing adverse impacts of ocean acidification. As early as 2008, a survey off the coasts of Washington, Oregon, and California revealed that this region is already experiencing corrosive waters not expected until mid-century (See figure 3) (Feely 2008). Researchers found seawater undersaturated with respect to aragonite upwelling onto large portions of the continental shelf, reaching shallow depths of 40 to 120 meters (*Id.*). According to the study, the waters were last at the surface approximately 50 years ago when atmospheric CO_2 concentrations were much lower (Feely et al. 2008). Feely et al. report that in the Pacific Ocean there has been a decrease of the saturation state of surface seawater with respect to aragonite and calcite as well as an upward shoaling of the saturation horizon by about 1-2 meters per year on average, due in large part to anthropogenic CO_2 (R. A. Feely, Sabine, et al. 2012). As a result, marine organisms in surface waters, in the water column, and on the sea floor along the West Coast of the United States are already being exposed to corrosive water during the upwelling season.

Modeling of the California Current System demonstrates that the area is rapidly approaching year-round undersaturation with respect to aragonite and it is departing significantly from natural variability (Hauri et al. 2013). Time series monitoring shows that the aragonite saturation state along the California coast is much lower than would be expected in the North Pacific (Harris, DeGrandpre et al. 2013). Surface Ω_{ar} values ranged between 0.66 and 3.9 compared to an estimated pre-industrial range of 1.0 to 4.7. While some areas, like Puget Sound, already exhibit undersaturated conditions every year (Feely, Klinger, et al. 2012; Reum et al. 2014), scientists predict that most shallow shelf areas along the West Coast will become undersaturated with respect to aragonite within the next 20-30 years (Capone & Hutchins 2013; Gruber et al. 2012).

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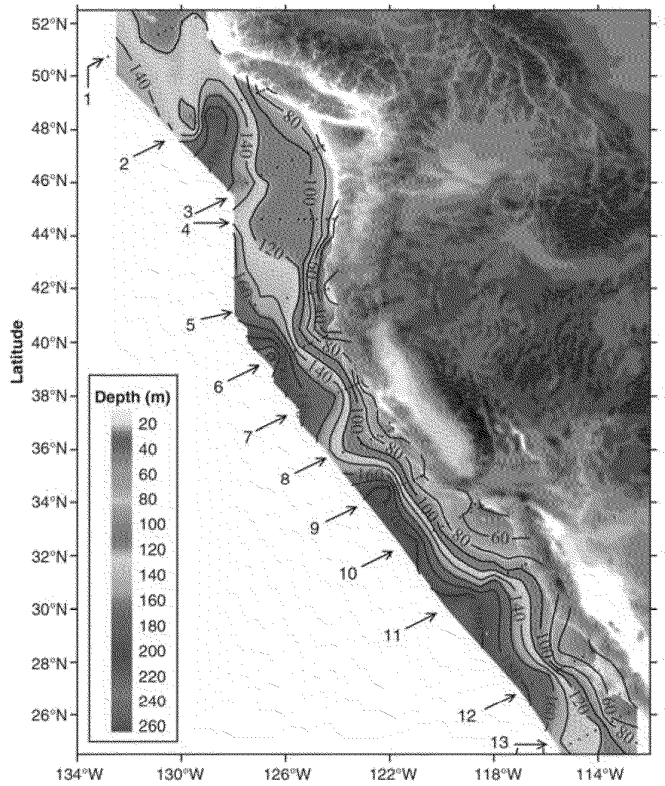

Figure 3. Distribution of the depths of the undersaturated water (aragonite saturation < 1.0; pH < 7.75) on the continental shelf of western North America from Queen Charlotte Sound, Canada, to San Gregorio Baja California Sur,Mexico. On transect line 5, the corrosive water reaches all the way to the surface in the inshore waters near the coast. The black dots represent station locations (Feely et al. 2008).

2. *Alaskan Waters*

High latitude waters are the "bellwether" of ocean acidification because these will be the first ocean regions to become persistently undersaturated with respect to aragonite as a result of greenhouse gas pollution (Fabry et al. 2009; Steinacher et al. 2009). High-latitude waters have naturally lower carbonate ion concentrations and saturation states due to a combination of cold temperatures which increase the solubility of CO_2 and ocean mixing patterns (Fabry et al. 2009; Mathis et al. 2011a). As early as 2016, 10% of Arctic surface waters are expected to be undersaturated with respect to aragonite for at least one month per year (Steinacher et al. 2009).

Recent observations of calcium carbonate saturation states in the North Pacific and Bering Sea have found that full water column undersaturation of calcium carbonate due to ocean acidification is already prevalent. Mathis et al. (2011a) reported that extensive areas of bottom waters over the Bering Sea shelf are becoming undersaturated with respect to aragonite for at least several months (July to September), and some areas of bottom water were already observed to be undersaturated with respect to calcite (Fabry et al. 2009, Mathis et al. 2011a).

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Scientists predict that polar waters will be corrosive to shellbuilding animals within decades (IBGP et al. 2013). A 2015 study of observations in the Chukchi and Beaufort Seas in the Arctic indicates that within 15 years waters will become so corrosive that it will be difficult for marine animals to build and maintain their shells (Mathis et al. 2015). The highly productive fisheries of Alaska are in some of the most rapidly changing seawater conditions (Mathis et al. 2014).

3. Sub-tropical Waters

Subtropical waters have experienced declining saturation states due to ocean acidification. Within decades, scientists believe that ocean acidification will impair coral growth (IBGP et al. 2013). Models show that by the end of the century, most coral reef areas will no longer have aragonite saturation states that are optimal for coral growth. A 10-year study of the Caribbean region found a strong regional decrease in aragonite saturation state between 1996-2006, from 4.05 to 3.9, resulting from CO_2 (Gledhill et al. 2008). Modeling predicts that under various emissions scenarios the coral reefs in the Caribbean will be thermally and chemically stressed between now and 2030 (Meissner et al. 2012). Even under the most optimistic scenario, 98% of reefs will be stressed by 2050 (*Id.*). In the Pacific subtropical ocean near Hawaii, there are nearly 20 years of time-series measurements of significant decreasing seawater pH that match the ocean's uptake of atmospheric CO_2 (Dore et al. 2009)

4. Atlantic Coast

Even ocean waters not at high latitude, in upwelling systems, or containing coral reefs ecosystems are, or will soon be, exhibiting signs of ocean acidification. Observations of East Coast waters during all seasons show that while they remain supersaturated with respect to aragonite, by the end of this century, saturation states of aragonite and calcite will decrease by 20–40%, with the lowest Ωar dropping to 1.3 in some seasons (Jiang et al. 2010). A survey of the Atlantic Coast showed that waters in the Northeast and particularly the Gulf of Maine are the most susceptible to ocean acidification (Wang 2013).

iii. CO_2 Kills and Injures Marine Life

High-CO_2 waters seriously harm marine wildlife and the entire ocean ecosystem. When CO_2 concentrations in seawater increase, the availability of carbonate ions decreases, making it more difficult for marine organisms to form, build, and maintain the calcium carbonate shells and skeletons required for their survival. As seawater becomes more corrosive, it can kill fish eggs and inhibit the development of, and essentially dissolve, the shells of small crustaceans, baby shellfish, and other tiny creatures at the base of the food web (Fabry 2008). Ocean acidification also harms and stresses fish, squid, and other animals that do not build shells (*Id.*). Not only does ocean acidification directly threaten various types of marine animals, it also has implications for the broader marine environment and food web.

The harmful effects of ocean acidification have already begun to occur. For example, ocean acidification has caused:

- A massive die-off of oysters in the Pacific Northwest (Barton et al. 2012; R. a. Feely, Sabine, et al. 2012; Washington State Blue Ribbon Panel 2012);

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- Declines in abundance and size of the California mussel, blue mussel and goose barnacle in tidepools correlated with a severely declining pH (Wootton et al. 2008);
- Sluggish growth of corals in the Caribbean and Great Barrier Reef (De'ath et al. 2009; De'ath et al. 2012; Gledhill et al. 2008); and
- Shells of plankton to dissolve off the California Coast and thinner and weaker shells of plankton in the Southern Ocean (Bednarsek 2014; Moy et al. 2009).

In a meta-analysis of over 400 experiments examining the impacts of ocean acidification on marine organisms, Kroeker et al. (2013) found the biological effects to be generally large and negative. This analysis was restricted to experiments with pH manipulations of less than 0.5 units, in order to reflect the predicted level of ocean acidification by the end of the century (IPCC 2007). By limiting the analysis to small variations in pH, this study shows that within the foreseeable future ocean acidification will have "profound repercussions for marine organisms" (Kroeker et al. 2010). While the negative effect of ocean acidification was most pronounced for calcification and survival (27% reductions in both responses), the study also revealed significant negative effects on growth and reproduction (11 to 19%, respectively). In addition, abundance was reduced by 15%. The strength of this analysis suggests that the patterns highlighted in this study are a robust representation of the current literature on ocean acidification.

While most of the worst consequences of ocean acidification are predicted for the future, scientists have already observed damage from CO_2 in the oceans. Additionally, the impacts of ocean acidification can affect the entire marine food web by altering habitat, prey availability, and species interactions.

b. High-CO_2 Waters Injure the Growth, Survival, Fitness, and Reproduction of Marine Animals

The primary known harm of CO_2 in the oceans is that it impairs the growth and survival of animals that build shells. Because ocean acidification reduces the availability of carbonate ions that marine animals use to calcify their shells and skeletons, CO_2 reduces the ability of these animals to build their protective structures (Doney et al. 2009). Acidified waters can also damage and dissolve shells.

These negative effects have been observed in the ocean as well as documented in laboratory studies. Corals, coralline algae, plankton, mollusks, and other shellfish exposed to future levels of ocean acidification have all experienced problems (Kleypas & Yates 2009; Kuffner et al. 2007; Barton et al. 2012; Talmage & Gobler 2011; Talmage & Gobler 2009; Orr et al. 2005; Riebesell et al. 2000).

i. Molluscs, Echinoderms, and Crustaceans

High CO_2 waters are lethal to shellfish. Since 2005, waters off the coast of Washington and Oregon have been killing oysters and other molluscs. Shellfish hatcheries in Washington and Oregon reported massive mortalities of oyster larvae (Washington State Blue Ribbon Panel 2012).Wild oysters also failed to reproduce in Willapa Bay, Washington (*Id.*). Scientists have definitively linked oyster production failures to high-CO_2 ocean waters that were used to raise larvae (Barton et al. 2012).

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In response to reported shellfish hatchery problems in Oregon, Barton et al. reported the results of their observations from the Whiskey Creek Hatchery on Netarts Bay in the summer of 2009 (Barton et al. 2012). Unlike previous laboratory experiments, this study analyzed calcifying organism responses in the ambient-water CO_2 chemistry of Oregon's coastal waters. Larval production and mid-stage growth (~120 um to ~150 um) of the oyster, *Crassostrea gigas*, were both significantly negatively correlated with the chemistry of waters in which larval oysters were spawned and reared for the first 48 hours of life. Although the impact of the exposure was not immediate, the delayed reaction caused a significant decline in growth for mid-sized oyster larvae and reduced overall production. The findings corroborate other laboratory studies that show that many marine species, especially at the larval stage, are adversely affected by ocean acidification.

Scientific studies have demonstrated that even modest pH declines affect the sensitive and vulnerable early developmental stages of organisms because these life histories have specific environmental needs (Kurihara 2008) (*see* Figure 10, below, showing negative effects from low pH treatments). A number of studies have found a delay in development or less development, degraded shells, decreased rate of metamorphosis, shell thickness, and loss of hinge integrity (Ross et al. 2011a). The resulting reduced larval size can reduce the feeding efficiency of larvae, and smaller larvae are more susceptible to starvation because they encounter comparatively less food (Kurihara & Shirayama 2004). Sub-lethal effects of elevated acidity can severely alter the composition and fitness of larvae, and given the high mortality rates of larvae in the water column and during the transition to benthic settler, small perturbations to larvae potentially may have large alterations to settlement dynamics, post-settlement mortality, recruitment, and ultimately adult populations (Ross et al. 2011).

Watson et al. (2009) exposed one day-old oyster larvae to a range of pH conditions, from 7.6 to 8.1, for 10 days and showed significant decline in the survival and growth of young larvae at lower pH. Waldbusser et al. (2010), in a study on the Chesapeake Bay, showed that even modest changes in pH present conditions that are corrosive to shells and have physiological impacts on adult and larval oysters. Biocalcification declined significantly with a reduction of 0.2 pH units, making juvenile bivalves more susceptible to predation and other mortality factors (*Id.*).

Negative effects have been seen on the metamorphosis, size, and survival of larval hard clams (*Mercenaria mercenaria*), bay scallops (*Argopecten irradians*), and Eastern oysters (*Crassostrea virginica*) at levels of CO_2 predicted to occur in the 21st century (Talmage & Gobler 2011). At 650 ppm, or an approximate drop of 0.3-0.4 from pre-industrial values, both *M. mercenaria* and *A. irrandians* larvae exhibited dramatic declines (over 50%) in survivorship as well as significantly delayed matamorphosis and significantly smaller size. *C. virginica* also experienced lowered growth and delayed metamorphosis at this level, an indicator that current and future increases in CO_2 populations may deplete or alter the composition of shellfish populations in coastal ecosystems (*Id.*).

The Olympia oyster, *Ostrea lurida*, a foundation species in estuaries along the Pacific coast, exhibits clear decline in larval growth and settlement as levels of CO_2 affect seawater pH. (Hettinger et al. 2012). Oysters in this experiment were raised at three levels of seawater pH,

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including a control (8.0) and two additional levels (7.9 and 7.8). Larvae reared under pH 7.8 exhibited a 15% decrease in larval shell growth rate, and a 7% decrease in shell area at settlement, compared to larvae reared under control conditions. Impacts were even more pronounced a week after settlement, with juveniles that had been reared as larvae under reduced pH exhibiting a 41% decrease in shell growth rate.

Oysters on the Atlantic coast also experience the ill effects of ocean acidification. Dickinson et al. (2012) found negative effects on juvenile eastern oysters after exposure to water with a 0.2 pH change. Exposure of the oysters to elevated acidity led to a significant increase in mortality, reduction of tissue energy stores and negative soft tissue growth, indicating energy deficiency. Under ocean acidification conditions, thermal tolerance is impaired in oyster larvae, leading to reduced development, size and increased abnormality (Ross et al. 2011; Parker et al. 2010). Similar results have been found in red abalone, with thermal tolerance impaired at pH 7.87 compared to control (pH 8.05) (Zippay and Hoffman 2010).

In studies with edible mussel (*Mytilus edulis*) and Pacific oyster (*Crassostrea gigas*) researchers found a strong decline of calcification under ocean acidification conditions (Gazeau et al. 2007). Based upon these results, researchers concluded that mussel and oyster calcification may decrease by 25% and 10%, respectively, by the end of the century." (*Id.*). Oysters and mussels also exhibit development abnormalities when exposed to acidification (Kurihara 2008). When oyster eggs were reared under pH 7.8, they showed malformations of their shell, and when reared under pH 7.4, more than 70% of the larvae were either completely non-shelled, or only partially shelled, and only 4% of CO_2 treated embryos developed into normal larvae by 48 hours after fertilization, in contrast to about 70% successful development in control embryos.

The shrimp *Palaemon pacificus* displayed variable responses at different developmental stages, pH and length of exposure (Kurihara 2008). Following long term (30 weeks) exposure of adults to pH 7.89 and 7.64, survival and egg production in early developmental stages decreased in both treatments. Findlay et al. (2010) found a slower rate of development of embryos in the common intertidal northern hemisphere barnacle *Semibalanus balanoides* with an estimated 19 days delay in reaching 50% hatching stage at pH 7.7. Other amphipods have exhibited metabolic changes in response to acidification levels greater than what is allowed under the federal criterion (Hauton et al. 2009).

Echinoderms exhibit delayed and asymmetrical development when exposed to acidified conditions. In the absence of adequate adaptation or acclimation, lowered pH levels will have a range of sub-lethal effects on sea urchins, brittlestar and seastar larvae from a range of geographical regions (Ross et al. 2011). Larvae of the ecological keystone brittlestar, *Ophiothrix fragilis*, either were abnormal, had altered skeletal proportions, or asymmetry during skeletogenesis, and there was a delay in development at pH levels of 7.9, or approximately 0.3 units below current surface levels (Gutowska et al. 2009). Other experiments on brittlestar in low pH waters resulted in dramatic results; acidification of 0.2 units induced 100% larval mortality within an eight day period. Control larvae showed 70% survival over the same period. Because the calcite skeleton of the larval brittlestar aids key functions such as feeding and vertical migration, and defense against predators, abnormal development of the skeleton will have drastic consequences for fitness. The developmental abnormalities may be exacerbated by temperature

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increases predicted for the end of the century; some scientists suggest that this may result in the disappearance of echinoderms from the surface oceans within the next 50-100 years (Ross et al. 2011a).

Reproductive success is compromised by ocean acidification. The fertilization rate of sea urchins decreases with increasing CO_2 concentrations (8.1 to 6.8 pH) (Kurihara 2008). In another sea urchin experiment utilizing six CO_2 concentrations, with a pH between 8.01 (control) and 6.83, cleavage rate, developmental speed, and larval morphology all declined with increased CO_2 concentration (Kurihara & Shirayama 2004). At a 0.2 change from control, effects could be seen on the morphology and development of the larvae, and these effects became more pronounced with greater pH changes (*Id.*) (*see* Figure 4, below). The authors concluded that "all the effects of raised CO_2 concentration observed in this study would have a negative impact on the survival of sea urchin embryos in their early life history." A recent study showed that sea urchin sperm flagellar motility was significantly reduced when seawater pH decreased by .3 units, from 8.0 to 7.7 (Suwa et al. 2010). As discussed above, decreased flagellar motility has severe consequences for fertilization and subsequent population dynamics; if sperm lose their ability to find eggs, the population size will necessarily diminish.

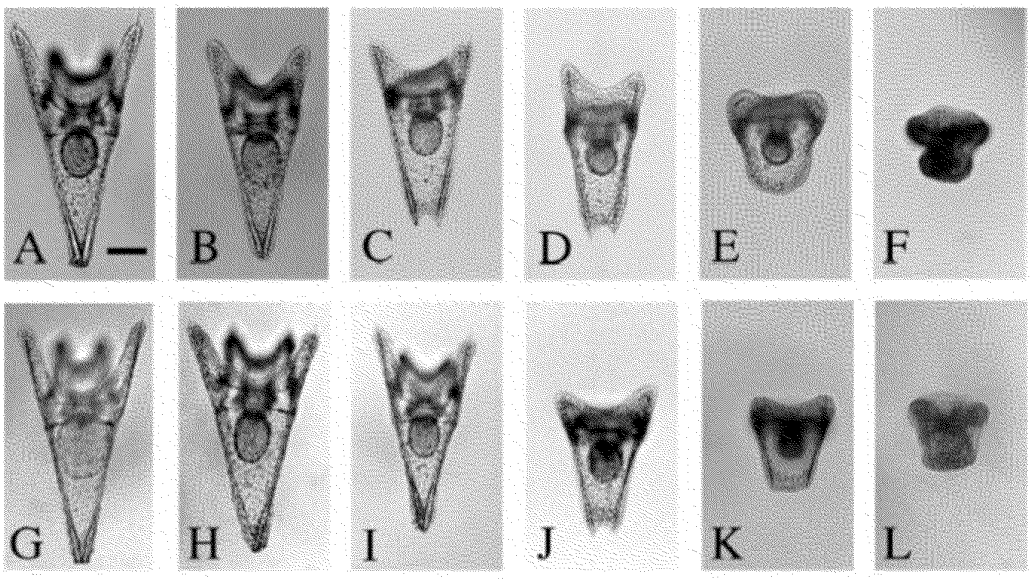

Fig. 6. *Hemicentrotus pulcherrimus*. Morphology of 4-armed pluteus larvae cultured for 3 d in (A–F) CO_2-seawater and (G–L) HCl-seawater. (A & G) control (pH 8.0); (B & H) +500 ppm (pH 7.8); (C & I) +1000 ppm (pH 7.6); (D & J) +2000 ppm (pH 7.4); (E & K) +5000 ppm (pH 7.0); (F & L) +10 000 ppm (pH 6.8). Scale bar = 50 µm

Figure 4. Declining development of sea urchin larvae exposed to acidified waters (Kurihara & Shirayama 2004).

Even moderate increases in atmospheric CO_2 and ensuing acidification adversely affect the growth of both gastropods and sea urchins (Shirayama & Thornton 2005). Before the end of this century, atmospheric CO_2 is likely to increase by more than 200 ppm, decreasing the pH of the ocean by approximately 0.3 units from pre-industrial levels. Two species of sea urchin as well as the gastropod *Strombus luhanus* were exposed for six months to waters with this level of elevated CO_2, and all three species exhibited similar consequences. Increased CO_2 negatively affected growth rate, calcification, shell height and body mass, and metabolic activity

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(Shirayama & Thornton 2005). The developing embryos of the gastropod and intertidal snail *Littorina obtusata* also demonstrate slower overall development time, altered embryonic movement, and modification of shell shape in hatchlings while exposed to acidified waters (pH 7.6) (Ellis et al. 2009).

Arnold et al. (2009) investigated the effect of ocean acidification on lobsters and found that indirect disruption of calcification and carapace mass may adversely affect the competitive fitness and recruitment success of larval lobsters with serious consequences for population dynamics and marine ecosystem function

Reduced metabolism is expected to impair predator-prey interactions, as well as have consequences for growth, reproduction, and survival. Metabolic suppression has previously been reported to occur in a variety of adult marine invertebrates, including crabs, squid, worms, bivalves, pteropods and amphipods (Albright 2011). Slowed metabolism is generally achieved by halting energy-expensive processes, such as protein synthesis, and therefore may lead to reductions in growth and reproductive potential (*Id.*). The blue mussel *Mytilus edulis* has strong physiological mechanisms by which it is able to protect body tissues against short-term exposure to acidified seawater, but these come at an energetic cost, and will result in reduced growth during long term exposures (Bibby et al. 2008). Consequently, the predicted long-term changes to sea water are likely to have a significant effect on the health and survival of blue mussel populations (*Id.*). Mussel beds are a dominant coastal habitat and provide food and structure for a diverse array of species in an otherwise physically stressful environment; any decline in their population structure will lead to a reduction in appropriate habitat for a myriad of other species.

In summary, acidified waters impact the development, growth, and reproductive success of a suite of echinoderms, crustaceans, and molluscs. A growing body of information is becoming available on the effecting of declining pH on these organisms and their ecosystems. The results of these studies are clear; as pH falls even 0.2 units from pre-industrial values, these organisms will struggle to survive in their increasingly acidic environment.

ii. Corals

Coral reef ecosystems, which are estimated to harbor one-third of marine species and which support the livelihoods of a half billion people, are particularly threatened by ocean acidification. Some corals are already experiencing reduced calcification (De'ath et al. 2009; Cooper et al. 2008; Bates et al. 2010; Gledhill et al. 2008). Due to the ocean acidification and warming, reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations of 450 ppm (Veron et al. 2009; Bijma et al. 2013). Prominent coral scientists have called for reducing atmospheric CO_2 to less than 350 ppm to protect coral reefs from collapse (Veron et al. 2009, Frieler et al. 2012). Coral reefs cannot exist below 7.8 pH units (Fabricius et al. 2011), and the threshold for coral growth is 3.3 Ω_{ar} (Meissner et al. 2012).

Ricke et al. (2013) analyzed aragonite saturation state (Ω_{ar}) surrounding reefs in CMIP5 simulations under several representative concentration pathway (RCP) scenarios (Ricke et al. 2013). The study found that in preindustrial times, 99.9% of reefs adjacent to open ocean in the CMIP5 ensemble were located in regions with $\Omega a > 3.5$. Accordingly, the study used $\Omega a = 3.5$ as

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an upper bound viability threshold for corals, while also examining thresholds of $\Omega a = 3.25$ and 3. Under a business-as-usual scenario (RCP 8.5), every coral reef considered was projected to be surrounded by water with $\Omega_{ar} < 3$ by the end of the 21st century and the reefs' long-term fate was independent of their specific saturation threshold. Under scenarios with significant CO_2 emissions abatement, the Ω_{ar} threshold for reefs was critical to projecting their fate. The study concluded that the "results indicate that to maintain a majority of reefs surrounded by waters with $\Omega_{ar} > 3{:}5$ to the end of the century, very aggressive reductions in emissions are required."

Corals are among the ecosystems most threatened by ocean acidification. To date, most scientific investigations into the effects of ocean acidification on coral reefs have been related to the reefs' unique ability to produce voluminous amounts of calcium carbonate (Kleypas & Yates 2009). The persistence of carbonate structures on coral reefs is essential in providing habitats for a large number of species and maintaining the extraordinary biodiversity associated with these ecosystems. As a consequence of ocean acidification, the ability of marine calcifiers to produce calcium carbonate will decrease, resulting in a transition from a condition of net accretion to one of net erosion, with drastic consequences for the role and function of these ecosystems (Kleypas & Yates 2009).

Coral reefs are predicted to drastically lower their calcification rates in the near future, and historical records show that calcification rates have already fallen relative to pre-industrial values. According to scientists, the main reef building organisms will calcify up to 50% less relative to pre-industrial rates by the middle of this century (*Id.*). A drop of approximately 60% coral reef calcification is projected for the end of the century, when pH is predicted to fall 0.5 units below pre-industrial values (Caldeira & Archer 2007). Many studies suggest calcification rates could be reduced between 20-60% at 560ppm, or 7.9 pH, and that a reduction of this magnitude would fundamentally alter reef structure and function (Convention on Biological Diversity 2009). According to the model of Silverman et al. (2009), developed from field observations from more than 9,000 reef locations, all coral reefs are expected to reduce calcification by more than 80% relative to their pre-industrial rate at 560 ppm (0.3 pH change), and at this point "all coral reefs will cease to grow and start to dissolve." The Interacademy Panel on International Issues concurs; "at current emission rates models suggest that all coral reefs and polar ecosystems will be severely affected by 2050 or potentially even earlier."

In a meta-analysis on coral calcification responses to ocean acidification, the coral calcification declined by a mean of 15% per unit decrease in aragonite saturation state ($2 < \Omega < 4$) (Chan and Connolly 2013). On current emission trends, calcification will decline 22% on average for corals by the end of the century (*Id.*). This falls to the lower range of responses that have been predicted by ocean acidification researchers and described above, which the authors believe reflects variation in the calcification responses of different corals.

Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%, (Caldeira & Archer 2007), and data from the Great Barrier Reef indicates a 14% decline in calcification rates between 1990 and 2005 (De'ath et al. 2009). Other studies in the Great Barrier reef indicate a decline of approximately 21%, and analysis of coral growth records confirm that this decline is unprecedented in recent centuries (Cooper et al. 2008). A model based on field samples shows that calcification of coral reefs in French

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Polynesia declined 15% between the pre-industrial period and 1992, and that rates will decline 40% by 2050, when CO_2 levels reach 560 ppm (pH 7.9) (Anthony et al. 2011). Near Bermuda, historical records show that coral skeletal density has decreased 33%, and coral calcification rates have declined by 52% as a result of changes in seawater carbonate chemistry (Bates et al. 2010). These observed changes have occurred even before a 0.2 unit decline in ocean pH; as atmospheric CO_2 continues to rise and lower pH values, calcification rates will maintain their precipitous decline.

Ocean acidification acts in concert with ocean warming and coral bleaching in furthering coral reef decline (Anlauf et al. 2011) (observing a 3% reduction in acidification with a 0.2 decline in pH, and a 30% decline when acidification is coupled with 1° C warming). While natural variability in the annual cycle and interannual variability may account for some of the observed change in coral growth rates, scientists are "virtually certain" that anthropogenic trends already exceed natural variability (Friedrich et al. 2012). Studies projecting the combined impacts of ocean acidification and ocean warming on corals predict that coral erosion will exceed calcification rates at atmospheric CO_2 concentrations of 450 to 500 ppm, (Hoegh-Guldberg et al. 2007), and all coral reefs will begin dissolve at CO_2 concentrations of 560 ppm (Silverman et al. 2009). These figures correspond to a 0.2 and 0.3 unit drop in pH, respectively, as compared to pre-industrial values. Van Hooidonk et al. (2014) presented updated global projections for threats to coral reefs from ocean warming and ocean acidification based on ensembles of IPCC AR5 climate models using the Representative Concentration Pathways (RCPs). For all tropical reef locations, the study projected absolute and percentage changes in aragonite saturation state (Ω_{ar}) for the period between 2006 and the onset of annual severe bleaching.

In the Caribbean, a recent study concluded that "coral reef communities are likely to be essentially gone from substantial parts of the Southeast Caribbean by the year 2035" (Buddemeier et al. 2011). The Great Barrier Reef has lost 50% of its coral cover since 1985 as a result of the combined effects of ocean acidification, global warming, coral bleaching, coral predation by starfish, and cyclone damage (De'ath et al. 2012). In short, due to the synergistic impacts of ocean acidification, mass bleaching, and local impacts, coral reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations 450 ppm, or pH 8.0, a level that is expected before mid-century (Veron et al. 2009).

Many experimental studies show declining calcification rates and other ill effects when corals are exposed to acidified waters. Decreases in calcification rates across a suite of benthic species and calcifying systems range from 3 to 60% for a doubling in pCO_2, which corresponds to a 0.3 reduction in pH (Abbasi & Abbasi 2011). The average response of corals is a 30% decline in calcification in response to a doubling in pCO_2 (*Id.*). In a study of an assemblage of corals exposed to conditions designed to mimic the change that may be experienced in the next 50-100 years (pH decline of 0.22 to 0.28 units), calcification rates declined between 44% and 80%.

The coral *Acropora palmata* (listed as threatened under the Endangered Species Act), once the dominant reef building coral in the Caribbean, experiences impaired fertilization, settlement, and growth with increasing pCO_2 (Albright et al. 2010). The cumulative impact of ocean acidification on fertilization and settlement success is an estimated 52% and 73% reduction in the number of larval settlers on the reef under pCO_2 conditions projected for the middle and end

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of this century, respectively (0.2 and 0.5 decline in pH) (*Id.*). After only 8 days of high CO_2 conditions (pH 7.75), *Acropora* experiences a statistically significant (18%) reduction in calcification rate (Murubini et al. 2003). Furthermore, there 22 coral species listed as threatened under the Endangered Species Act primarily because of threats from ocean warming, acidification and disease. The rule proposing listing for the corals found that ocean acidification was one of the highest priority threats for corals:

> Ocean acidification has the potential to cause substantial reduction in coral calcification and reef cementation. Further, ocean acidification adversely affects adult growth rates and fecundity, fertilization, pelagic planula settlement, polyp development, and juvenile growth.

77 Fed. Reg. at 73230 (Dec. 7, 2012). In other words, ocean acidification is driving the extinction of corals and the destruction of coral reef ecosystems.

Experimental studies evaluating the effects of ocean acidification on early life history stages of corals generally conclude that primary polyp growth is hindered by increasing acidity (Albright et al. 2010, Cohen & Holcomb 2009). Renegar and Riegl (2005) showed a significant decrease in the growth rate of *Acropora cervicornis* larvae at pH levels 0.3-0.5 units below control. Larvae of the common Atlantic golf ball coral, *Favia fragum*, shows significant delays in both the initiation of calcification and subsequent growth of the primary corallite in acidic waters (8.17 – 7.54 pH) (Cohen & Holcomb 2009). Visible changes in the skeletal development were observed in all non-control treatments, and in the most acidic waters skeletal development was 75% less than the control.

Acidification also affects cold water corals. Cold water corals have a worldwide but patchy distribution, and are often found in areas with highly productive fisheries (De Mol et al. 2002; Kenyon et al. 2003). Overall, more than two-thirds of all known coral species are cold water corals (Roberts & Hirshfield 2012; Cairns 2007). Recent exploration and research that has begun to search for, map, and observe cold water corals has found that these organisms are fragile, long-lived, slow-growing, very sensitive to physical or environmental disturbance and adapted for a specific environmental niche (McDonough & Puglise 2003). Alaskan waters are already showing widespread evidence of ocean acidification as a result of greenhouse gas emissions (Mathis et al. 2011a). By 2100, 70% of cold-water corals will be exposed to corrosive waters (Convention on Biological Diversity 2009). Conditions in waters typically inhabited by cold-water corals are even less favorable for calcification than those experienced by warm water corals; this may cause cold-water corals to be affected earlier and more strongly by CO_2-related ocean acidification than their warm water counterparts (Abbasi & Abbasi 2011).

The vulnerable early developmental and reproductive stages of cold water corals may be especially strongly impacted (Kurihara 2008; Dupont & Thorndyke 2009; Kroeker et al. 2010). In an experiment on the cold-water coral *Lophelia pertusa*, lowering the pH by 0.3 units relative to the ambient level resulted in calcification being reduced by 56% (Maier et al. 2009). Lower pH reduced calcification more in fast growing, young polyps (59% reduction) than in older polyps (40% reduction). Thus, corals' larvae and young corals are significantly more susceptible to ocean acidification than adults, and will likely show a higher degree of reduced calcification

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and growth with reduced pH, making young and larval corals less likely to survive to maturity as the ocean continues to absorb anthropogenic CO_2 and as climate change progresses.

In addition to reduced calcification rates, the strength of cementation may also be reduced in waters with a lower pH, promoting higher rates of physical and bio-erosion (Manzello et al. 2008). Once coral reefs experience lowered calcification and poor cementation, erosion and reef flattening can result, which severely reduced the structural heterogeneity of reefs and lowers its potential to support biodiversity. An important new study of reef bioerosion determined that the combined effects of lower calcification with increased bioerosion can significantly degrade coral reefs (Wissshak et al. 2012). In the study, a common bioeroding sponge in the Great Barrier Reef was observed on massive Porites. The sponge was more effective at bioerosion of the corals at high CO_2, ranging from 17% increase from present day levels to 61% increase at the highest CO_2 treatment. The researchers describe the important role of balancing the antagonistic processes of calcification and bioerosion in a reef for a healthy coral ecosystem, and predict detrimental consequences under ocean acidification as calcification declines and bioerosion increases.

Bioerosion may result in a loss of change in fish assemblages, lower densities of commercially important species, and lower rates of larval fish recruitment (Feary et al. 2007). Weaker reef calcification and cementation also increases the potential for reef damage as storm frequency and intensity increases with continued global warning, leading to further reef degradation (*Id.*). In a study looking at the impacts of storm damage and ocean acidification, researchers concluded that table coral populations are vulnerable to collapse (Madin et al. 2012). In the Indo-Pacific, table corals provide an important role in the reef ecosystem by creating reef structure and sheltering other reef species. They are also particularly vulnerable to ocean acidification, thermal stress, bleaching, disease and stress from storm waves. The table corals will become more vulnerable to storm waves as ocean acidification reduces calcification and increases bioerosion, therefore weakening their cementation and structure. Madin et al. (2012) found that a coral colony was four times more likely to be dislodged by a storm wave by the end of the century ocean acidification levels. Because of this vulnerability, the results showed that table corals are prone to large and rapid declines in coral cover.

Numerous biological responses independent of calcification are also negatively impacted by ocean acidification. Corals in acidifying waters are likely to be in a nutritionally or energetically stressed state and thus less likely to initiate reproduction, or successfully reproduce, due to negative impacts of ocean acidification on all stages of the reproductive cycle (Maier et al. 2009; McCulloch et al. 2012). Sperm flagellar motility also declines in response to decreasing pH. If sperm lose their ability to find eggs in the vast extent of the sea, the life of marine organisms is potentially limited. Sperm flagellar motility, which is indispensable for fertilization, is regulated by an elevation of intracellular sperm pH (Morita et al. 2010). While 69% of *Acropora* sperm were motile at pH 8.0, 46% were motile at pH 7.8, and fewer than 20% at pH 7.7 (*Id.*). Additionally, the physiological costs associated with reproduction are more likely to result in the demise of the organism due to the compounding stressors from ocean acidification and climate change (Wood et al. 2008, Cohen & Holcomb 2009). Significant reductions in metabolism have been observed for coral larvae following exposure to waters with a 0.2 decline in pH, levels projected to occur by the middle of this century (Albright & Langdon 2011).

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Albright et al. (2010) concluded that with increased CO_2 concentrations to those projected to occur in this century (560 atm to 800 atm, or a 0.3 to 0.5 decline in pH from pre-industrial values), the fertilization success of the tropical reef-building coral *Acropora palmata* decreased by 12-13%, settlement success reduced 45-69%, and linear extension was significantly reduced. The compounding effect of these impacts translated to 52-73% reduction in the number of larval settlers on the reef. Albright et al. (2010) predicted that the net impact on recruitment would actually be greater than that given that the depressed post-settlement growth is likely to result in elevated rates of post-settlement mortality. This corroborates other studies showing negative impacts on early-stage tropical corals.

Albright and Langdon (2011) tested the effects of ocean acidification on sexual recruitment of tropical corals. Larval metabolism was depressed by 27% at acidification levels expected by mid-century (0.3 pH reduction) and 63% at end-of-century acidification levels (0.4-0.5 pH reduction). Settlement was also reduced 42-45% and 55-60% at the mid and end-of-century levels respectively, relative to controls (Albright & Langdon 2011). Another study of larvae of tropical corals showed that short-term or long term exposure of larvae to ocean acidification decreased their metamorphosis (Suwa et al. 2010). This means that even when larval survivorship is unchanged, the success of recruiting new corals could be inhibited by ocean acidification (*Id.*).

Additionally, under conditions of acidification planktonic larvae lose their preference for settlement on the optimal crustose coralline algae communities (Doropoulos et al. 2012). Crustose coralline algae in turn, will experience a lower recruitment rate as marine waters become more acidic. Crustose coralline algae, a red calcifying algae, is of key importance in coral reef ecosystems, stabilizing reef structures and providing an important food source for benthic organisms (Convention on Biological Diversity 2009). Crustose coralline algae form a major calcifying component of the marine benthos from polar to tropical regions and are considered to influence the settlement of coral recruits. With a mean pH change of 0.26 between control and treatment, Kuffner et al. (2007) found that crustose coralline algae growth rates declined by 40%, and recruitment rate and percentage cover decreased by 78% and 92%, respectively.

In sum, reproduction is critical to maintaining a healthy coral reef population, and the long-term impacts of ocean acidification on reproduction, especially on larval settlement and growth, may significantly reduce the corals' ability to recover or maintain a population in the face of human caused disturbances and anthropogenic CO_2 emissions. This would result in a lack of reproductive capacity, genetic bottlenecks, and population collapse (Dupont et al. 2010; Ross et al. 2011).

As the world's oceans become more acidic and less saturated with carbonate minerals, corals are expected to build weaker skeletons and experience slower growth rates, which will make it more difficult for corals to retain competitive advantage over other marine organisms (Guinotte et al. 2006). As coral skeletons weaken, they will become increasingly at risk of storm damage and bioerosion, which will reduce the structural complexity of the reef system, reducing habitat quality and diversity alongside the loss of coastal protection functions (Hoegh-Guldberg et al. 2007). At greater than 550 ppm, coral reef ecosystems will be reduced to "crumbling

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frameworks." (*Id.*). Extensive studies have demonstrated that small changes in ocean chemistry will cause a suite of negative impacts, from reduced calcification rates to lowered reproductive success.

iii. Plankton

Plankton, which comprise the basis of the marine food web, are among the calcifying organisms adversely affected by ocean acidification. Changes to calcifying zooplankton, such as pteropods and foraminfera, have the potential to affect the ecological and tropic dynamics which govern the exchange of energy and cycling of nutrients throughout the marine food web (Gattuso & Hansson 2011). For example, the shelled pteropod, *Limacina helicina*, an Arctic pelagic mollusc, is a food source for higher predators such as fishes, whales and birds that are particularly important in high latitude areas. *L. helicina* makes up about 60 percent of the pink salmon diet (Comeau et al. 2012). A decline of pteropod population would likely cause dramatic changes to various pelagic ecosystems, and impact the commercially important salmon fishery; a 10% decrease in pteropods can lead to a 20% reduction in pink salmon body weight (Aydin 2005).

Pteropods form integral components of food webs, and are considered an overall indicator of ecosystem health (Orr et al. 2005). Studies have shown that pteropods exposed to a pH value predicted for the end of this century exhibited a 28% decrease in calcification (Comeau et al. 2009). Experiments on *L. helicina* showed that changes from 8.05 pH to 7.89 pH (Δ -0.16 units) cased shell dissolution and cracks appeared at 7.76pH, and linear extension of the shell decreased as a function of declining pH (Comeau et al. 2012). Samples show dissolution already happening in areas that have low aragonite saturation states. A sampling study off the coasts of California, Oregon, and Washington showed average to severe dissolution of *L. helicina* for 53% of onshore individuals and 24% of offshore individuals (Bednarsek 2014). A sampling study in 2008 of the Southern Ocean found severe dissolution of *L. helicina* in Ω_{ara} 1.0 (Bednarsek 2012). Another study found shell weights of one form of Antarctic species declined 35% from 1997-2006 (Roberts unpublished).

Ample studies corroborate that high CO_2 waters dissolve the shells of *L. helicina* and reduce calcification rates. Comeau et al. (2010) noted decreased calcification for *L. helicina* with decrease in aragonite saturation. Lishka (2012) looked at overwintering *L. helicina* and L. retroversa in the Arctic and noted that they do not calcify in the winter, and they are subject to dissolution under high CO_2 conditions. Bednarsek (2012) looked at *L. helicina* and *Clio pyramidata* from the Southern Ocean under different aragonite saturation states and recorded dissolution stages.

Modeling by Comeau et al. (2012) shows that by the end of the century *Limacina helicina* will not be able to calcify over much of the Arctic because of aragonite undersaturation—prediction may be conservative because it did not account for shell dissolution. Commentary suggests that as waters warm these pteropods will be trapped in acidified conditions and will "disappear entirely by the end of the century." Modeling suggests that waters in the California Current will be undersaturated year-round by 2050 (Gruber 2012). Modeling of the Arctic suggests that by mid-century the Bering Sea will be persistently undersaturated with respect to aragonite (Mathis 2011). An analysis of survey measurements in 2005-2006 and 1991-1992 demonstrated a

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shoaling of the aragonite saturation state in waters off Alaska (Feely et al. 2012). In the North Pacific the aragonite saturation state shoaled to depths less than 200 m between 40˚N and 50˚N (*Id.*). On average, the calcite saturation horizon in the Pacific shoaled about 1 m/yr from 1991 to 2006 (*Id.*).

Other species of plankton are also harmed by CO_2. Another pteropod, *Clio pyramidata,* kept in aragonite undersaturated waters began to dissolve within two days (Orr et al. 2005). Some coccolithophorids are also susceptible to ocean acidification. Studies showed that CO_2 related changes to seawater caused reduced calcification, resulting in malformed and incomplete shells. Calcification of cocolithophorids declined 15-44%, and their shells were malformed as pH changed up to about 0.3 units (Riebesell et al. 2000). Coccolithophorids are globally distributed and bloom in massive areas affecting the optical properties of the ocean, reflecting light from the earth, and play a major role in the ocean carbon cycle. Elevated CO_2 concentrations also reduce the shell mass of foraminifera (Kleypas et al. 2006). Modern shell weights of foraminifera in the Southern Ocean are 30–35% lower than those from preindustrial sediments, which is consistent with reduced calcification induced by ocean acidification (Moy et al. 2009).

iv. Cephlopods and Fish

The negative physiological effects of ocean acidification are not confined to invertebrates. For example, the gametes, embryos, and larvae of vertebrates such as fish are vulnerable to changes in ocean chemistry and have shown impairments in their homing and predator/prey detection capabilities.

Changes in the ocean's CO_2 concentration result in accumulation of CO_2 in the tissues and fluids of fish and other marine animals, called hypercapnia, and increased acidity in the body fluids, called acidosis. These impacts can cause a variety of problems for marine animals, including difficulties with acid-base regulation, calcification, growth, respiration, energy turnover, predation response, and mode of metabolism (Pörtner et al. 2005; Pörtner et al. 2004). Studies have shown adverse impacts in squid and fish, among other animals (Rosa & Seibel 2008; Ishimatsu et al. 2004; Pörtner et al. 2004). For example, when exposed to acidification, orange clownfish suffer a type of brain malfunction that interferes with their homing abilities and makes them 5-9 times more likely to swim toward a predator (Munday et al. 2009; Simpson et al. 2011; Ferrari et al. 2011).

Laboratory experiments have shown that ocean acidification at levels expected to occur within this century impairs larval orange clownfish and damselfish sensory abilities and behavior, making it more difficult for them to locate suitable settlement sites on reef habitat and avoid predators. Specifically, ocean acidification disrupts smell, hearing, and behavior of larval orange clownfish, (Munday et al. 2009; Nilsson et al. 2012), making larval clownfish attracted to odors from predators and unfavorable habitat (Munday et al. 2010; Dickson et al. 2010). Olfactory cues that prompted avoidance or neutral behavior in controls (pH 8.15) stimulated strong preference behavior in larvae raised at pH 7.8, in addition to significant reduction in response to usually positive preferences. Ocean acidification also impairs the hearing capacity of larval clownfish, which is predicted to have negative effects on settlement success and survival (Simpson et al. 2011).

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Similarly, research on six damselfish species found that ocean acidification impairs larval damselfish smell, vision, learning, behavior, and brain function, leading to higher risk of mortality. For example, in acidified waters, larval damselfish (1) become attracted to predator odors and display much riskier behaviors, making them more prone to predation; two species suffered a five-fold to nine-fold increase in predation rate at CO_2 levels of 700 to 850 ppm, or 0.3 pH units below control (Munday et al. 2009; Ferrari et al. 2011); (2) cannot discriminate between habitat olfactory cues, making it more difficult to locate appropriate settlement habitat (Devine et al. 2011); (3) settle on the reef during dangerous times—the full moon rather than new moon—when they are more vulnerable to predation (Devine et al. 2011); (4) fail to visually recognize or evade important predator species; (5) cannot learn to respond appropriately to a common predator by watching other fish react or by smelling injured fish, unlike fish under normal conditions (*Id.*); and (6) suffer disruption of an important neurotransmitter which is thought to result in the sensory and behavioral impairment observed in acidified conditions (Nilsson et al. 2012).

An animal's ability to transport oxygen is reduced by pH changes (Pörtner 2005). Water breathing animals have a limited capacity to compensate for changes in the acidity (Haugan 2006). For example, fish that take up oxygen and respire CO_2 through their gills are vulnerable because decreased pH can affect the respiratory gas exchange (Royal Society 2005). Changes in metabolic rate are caused by the changes in pH, carbonates, and CO_2 in marine animals (Haugan 2006).

Squid, for example, show a very high sensitivity to pH because of their energy intensive manner of swimming (Royal Society 2005). Because of their energy demand, even under a moderate 0.15 pH change squid have reduced capacity to carry oxygen and higher CO_2 pressures are likely to be lethal (Pörtner 2004). Even species more tolerant to pH changes experience decreased metabolism from increased CO_2 in the water (Pörtner 2004). For example, as much as 50% mortality was observed in copepods after only six days of exposure to waters with a pH level 0.2 units below the control (Pörtner 2005). Reducing pH by 0.3 pH cased a 31% decline in metabolic rate and a 45% decrease in activity level for the jumbo squid, an important predator in the Easter Pacific (Rosa & Seibel 2008).

In fish, pH also affects circulation. Fishexposed to high concentrations of CO_2 in seawater experience cardiac failure and increased mortality (Ishimatsu 2004). At lower concentrations sublethal effects can be expected that can seriously compromise the fitness of fish. Juvenile and larval stages of fish were found to be even more vulnerable (Ishimatsu 2004).

In sum, ocean acidification can have many adverse effects on marine animals that can reduce their fitness and survival (Royal Society 2005). Many marine animals have low thresholds for long-term CO_2 exposure (Pörtner 2005).

c. Other Environmental Impacts of Ocean Acidification

i. Increased Toxicity of Harmful Algal Blooms and Sediments

Ocean acidification may already be increasing the toxicity of harmful algal blooms known as "red tides." These toxic red tides poison shellfish, marine mammals, fish, and even cause

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paralytic shellfish poisoning in people. High CO_2 levels in seawater magnify the toxins of harmful algae. (Fu et al. 2012; Avery O Tatters et al. 2013; Tatters et al. 2012; Avery O. Tatters et al. 2013). Studies of the genus *Pseudo-nitzscia* show that the toxicity of diatoms which produce a neurotoxin increases significantly under ocean acidification conditions. A -0.5pH change caused toxin production in the diatoms to increase 4.2-fold and a -0.3pH unit change increased the toxicity 2.5-fold (Tatters et al. 2012). Many studies on the effects of ocean acidification and algal blooms have been conducted at CO_2 levels that are already occurring in California, and the increase in the toxicity of harmful algal blooms in Southern California (and resulting mass mortalities of fish and marine mammals) may be due, in part, to acidified waters (*Id.*) However, these studies suggest that the damage will become much worse.

Additionally, research shows that under conditions of ocean acidification sediments become more toxic (Roberts, Birchenough et al. 2013). Ocean acidification makes sediment-bound metals more available and thus more toxic for aquatic life (*Id.*) For example, ocean acidification increases the toxicity of copper (Campbell & Mangan 2014).

ii. Noise Pollution Increases in Low pH Waters

Ocean acidification can also decrease the sound absorption of seawater, causing sounds to travel further with potential impacts on marine mammals and other marine life sensitive to the sounds of vessel traffic, seismic surveys, and other noise pollution (Hester et al. 2008). Sound travels 10-15 percent further with a change of 0.1 pH, and it is predicted to increase about 40 percent by mid-century (Hester et al. 2008). Additionally, a decline of 0.3 pH units causes a 40 percent decrease in the sound absorption of surface seawater and sound may travel 70 percent farther, further affecting sensitive marine mammals (Brewer et al. 2009).

d. Ocean Acidification's Ecosystem Impacts

While the full implications of elevated CO_2 on marine ecosystems are not well-documented, there is high confidence that there will be negative ecosystem consequences from ocean acidification. The exact changes are difficult to predict, but some of the anticipated impacts include loss of diversity, loss of abundance of calcifying species, shifting prey and predator interactions, and loss of suitable habitat.

New mesocosm studies have sought to understand some of the potential ecosystem impacts of CO_2. Studies of biodiversity near underwater volcanic vents demonstrate reduced richness in high-CO_2 waters. For example, coral species diversity declined by about 39% between low and high-CO_2 sites, with the reefs shifting from complex communities to a coral reef dominated by massive Porites. Most importantly, the researchers found that coral reef development ceases at 7.7 pH, and they concluded that a pH decline below 7.8 would be "catastrophic for coral reefs" (Fabricius et al. 2011). Scientists also observed that in high-CO_2 waters the loss of complex coral reef habitat resulted in a loss of diversity of reef-associated species such as crustaceans and crinoids (Fabricius et al. 2014). Looking at the macroinvertebrates, the density declined 48% between control and high-CO_2 areas and taxa diversity declined by 77% (*Id.*).

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Loss of species diversity associated with ocean acidification can also result from changes in competitive interactions. A study of a rocky reef near volcanic vents documented that macro algae outcompeted calcareous species in low-pH waters (Kroeker et al. 2012). The researchers explained that under the high-CO_2 conditions the calcifying species grew more slowly while the seaweed took hold and that grazing of seaweed was depressed (*Id.*). In another study, while the areas near volcanic vents lacked scleractinian corals and had low abundance of sea urchins and coralline algae, invasive algal species benefited from the acidified conditions (Hall-Spencer et al. 2008).

Research on the diversity the intertidal community in the Pacific Northwest documented a shift from a ecosystem dominated by calcifying animals to one with non-calcifying organisms as pH declined. Researchers documented declines in abundance and size of the California mussel, blue mussel, and goose barnacle in tidepools on the Olympic Coast in Washington (Wootton et al. 2008). They found that in years with low pH waters the calcifying animals were replaced by non-calcifying organisms (*Id.*).

The synergistic impacts of ocean acidification and warming are also potentially severe. Ocean acidification may induce a negative climate feedback that may increase temperature rise. Mesocosm studies found that ocean acidification may amplify global warming through decreasing biogenic production of the marine sulfur component dimethylsulphide which can impact cloud albedo (Six 2013). Ocean acidification therefore may also contribute to climate change impacts on the environment.

2. Risk Reduction Costs and Benefits

EPA must make a determination whether the risk of ocean acidification is unreasonable and this constitutes a balancing of costs and benefits. While it is EPA's burden to conduct this analysis, petitioners present some limited data on (1) the socio-economic costs of CO_2 pollution in light of ocean acidification, (2) the feasibility of controls on CO_2 pollution, and (3) the social cost of carbon including the costs of delaying action to reduce and mitigate CO_2 pollution.

a. Socioeconomic Costs of Ocean Acidification

The release of CO_2 into the environment is already having social and economic impact, and these impacts are predicted to become even more concerning. Primary economic concerns are from the loss of fisheries and coral reefs. Ocean acidification also poses food security and nutrition risks.

U.N. Convention on Biological Diversity estimated costs on the predicted damage of ocean acidification and predicts that the oceans will lose more than $1 trillion in value annually from ocean acidification (Convention on Biological Diversity 2014). CO_2 related ocean warming and acidification will threaten marine food resources by disrupting marine communities, promoting harmful algal blooms and the spread of some diseases, and increasing contaminants in fish and shellfish (Tirado et al. 2010).

The United Nations Environment Programme reported that ocean acidification's impact on marine organisms is a threat to food security (UNEP 2010). The report documents that ocean

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acidification is measurable and increasing, which poses a threat to fisheries resources and the billions of people that have a marine-based diet (United Nations Environment Programme 2010). Seafood has been shown to prevent hundreds of thousands of premature deaths, as well as significantly reduce infant morbidity; a decline of seafood availability will decrease these benefits. Some populations, including subsistence fishing populations and poor communities, depend on seafood and mortality and morbidity can result from the loss of these food sources (Mozaffarian 2006). For example, 95% of Alaskan households do some sort of subsistence fishing, and 17% of the state's population, 120,000 people, depend on subsistence fishing (Mathis et al. 2014). Many subsistence fishers also have cultural ties threatened by ocean acidification. Accordingly, CO_2 can result in social and environmental justice concerns that must also be assessed and weighed (Convention on Biological Diversity 2014).

Not only will ocean acidification affect global food webs and ecosystems, it will have a direct effect on the global economy. The U.S. economy is very dependent on the health of the ocean. In 2009, the ocean economy contributed over $223 billion annually to the U.S. gross domestic product and provided more than 2.6 million jobs (NOAA, http://oceanservice.noaa.gov/facts/oceaneconomy.html). Cooley and Doney (2009) estimate that if just a 10-25% decrease in United States mollusk harvests from 2007 were to occur today, $75-187 million in direct revenue would be lost each year henceforth, with a net loss of $1.7-10 billion through mid-century, when pH levels are approximately 0.3 units below pre-industrial values. In Washington State alone, the seafood industry generates $1.7 billion for gross state product and employs 42,000 people (Washington State Blue Ribbon Panel 2012). Already, shellfish hatchery failures in Washington have caused an economic stir and caused some hatcheries to relocate. Alaska's commercial fishing industry is valued at over $4 billion a year, and supports 90,000 jobs—recreational fishing and fishing tourism add even more value. Meanwhile, Alaska is ranked among the most vulnerable areas to acidification.

Tropical coral reefs provide ecosystem services, such as habitat and nursery functions for commercial and recreational fisheries and coastal protection. As reefs decline in acidified waters, there will be an ecological shift to a new ecosystem state dominated by less commercially valuable species. In 2009, Brander et al. estimated the annual economic damage of ocean acidification-induced coral reef loss to escalate rapidly over time, reaching $870 billion by 2100 (Brander et al. 2009a). In 2014, Brander et al. increased the anticipated loss of ecosystem services from corals to be $1000 billion (UNEP 2014). Shoreline protection offered by coral reefs and the services it provides by preventing loss of life, property damage and erosion are also reduced by CO_2 emissions.

Lane et al. (2014) modeled three major U.S. locations for shallow water reefs -- South Florida, Puerto Rico, and Hawaii – to project future reef cover and the economic values generated by coral reefs for a greenhouse gas emissions mitigation scenario that represents international implementation of policies to reduce global emissions (resulting in a CO_2 concentration of 427 ppm in 2100), compared to a business as usual greenhouse gas emissions scenario resulting in a CO_2 concentration of 785 ppm in 2100. The study estimated that reducing emissions would result in an "avoided loss" in Hawaii of approximately $10.6 billion in recreational use values compared to business as usual. Reducing emissions was projected to provide fewer economic benefits in Puerto Rico and South Florida, where sea-surface temperatures are already close to

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bleaching thresholds and coral cover is projected to drop well below 5% cover under both scenarios by 2050, and below 1% cover under both scenarios by 2100 (Lane et al. 2014).

As discussed previously, the toxicity of harmful algal blooms increases under conditions of ocean acidification. These toxins not only poison marine mammals, but also cause paralytic shellfish poisoning in people. Scientists hypothesize that some of the increases red tides off the coast of Southern California may be related to ocean acidification, though this has yet to be confirmed. In turn, harmful algal blooms cost the United States approximately $82 million each year from impacts to fisheries, public health, management, and lost recreational opportunities (Hoagland and Scatasta 2006).

A recent study estimated that the damage our oceans will face from emissions-related problems will amount to $428 billion a year by 2050 and nearly $2 trillion per year by the century's end (Noone et al. 2012).

> Acidification impacts processes so fundamental to the overall structure and function of marine ecosystems that any significant changes could have far-reaching consequences for the oceans of the future and the millions of people that depend on its food and other resources for their livelihoods.

(Doney et al. 2009). There is also a significant cost to delaying action. According to a recent report by the Council of Economic Advisers, delaying the implementation of policies to mitigate climate change could significantly increase economic damages, in addition to worsening environmental harm.[39]

While there are still large unknowns on the biological consequences of ocean acidification, the science we have is clear: from shellfish to corals, and from pteropods to fish, our marine resources are threatened by the acidification of our ocean waters.

b. Risk Reduction Methods

There are several ways to reduce risk from CO_2. EPA should use a suite of tools to reduce emissions, sequester CO_2, mitigate harms, and promote alternatives. Under TSCA EPA has authority to:[40]

- prohibit or limit the amount of production or distribution of a substance in commerce;
- prohibit or limit the production or distribution of a substance for a particular use;
- limit the volume or concentration of the chemical produced;
- prohibit or regulate the manner or method of commercial use;
- require warning labels and/or instructions on containers or products;
- require notification of the risk of injury to distributors and, to the extent possible, consumers;

[39] Executive Office of the President of the United States, The Cost of Delaying Action to Stem Climate Change at 1 (July 2014).
[40] 15 U.S.C. § 260.

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- require record-keeping by producers;
- specify disposal methods; and
- require replacement or repurchase of products already distributed.

EPA also may impose any of these requirements in combination or for a specific geographical region. [41] Specifically, the agency must impose controls sufficient "to protect adequately against such risk using the least burdensome requirement."[42]

There is evidence that many industries could employ existing technology to achieve meaningful emissions reductions affordably. EPA's own data demonstrate that lower pollution rates are readily achievable for many industrial sources of CO_2. For example, the agency has identified dozens of "control measures and energy efficiency options that are currently available for pulp and paper mill processes," ranging from technological upgrades to improved equipment maintenance.[43] Similarly, EPA has compiled more than a decade of reports on "cost-effective" control strategies and other approaches available to reduce cement plant CO_2 emissions, "includ[ing], for example, energy efficiency measures, reductions in cement clinker content, and raw materials substitution."[44]

Although cost-effective strategies to reduce CO_2 emissions are available, existing controls have not reduced CO_2 emissions sufficiently to protect against environmental harm. For example, most natural gas power plants have *never* exceeded the agency's recently proposed emissions limit, thus indicating that existing and newly constructed facilities could easily satisfy a more stringent standard.[45] Because energy-related CO_2 pollution accounts for more than eighty percent of U.S. greenhouse gas production, readily achievable reductions in this sector would significantly benefit the environment.[46] Similarly, the pulp and paper industry ranks among the largest consumers of energy,[47] and emitted nearly 58 million metric tons of CO_2 equivalent gases in 2004.[48] Moreover, market incentives and regulatory controls are effective in increasing the rate of innovation for technologies that can reduce CO_2 emissions.

If a chemical presenting an unreasonable risk to health and the environment has already been distributed, EPA may prescribe procedures by which relevant manufacturers and purchasers must replace or repurchase that chemical.[49] In the present situation, we urge the agency to exercise its

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[41] *Id.*
[42] 15 U.S.C. § 2605(a).
[43] *See* EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 11 (2010).
[44] EPA, National Emission Standards for Hazardous Air Pollutants From the Portland Cement Manufacturing Industry and Standards of Performance for Portland Cement Plants, 75 Fed. Reg. 54,970, 54,997 (Sep. 9, 2010).
[45] Ctr. for Biological Diversity, Comments on Standards of Performance for Greenhouse Gas Emissions from New Stationary Sources: Electric Utility Generating Units (Proposed Rule) Docket No. EPA-HQ-OAR-2013-0495 at 13-14 (May 9, 2014).
[46] U.S. Dept. of State, U.S. Climate Action Report at 16 (2010).
[47] *See* U.S. Energy Information Administration, First Use of Energy for All Purposes (Fuel and Nonfuel), 2010 (Mar. 2013), http://www.eia.gov/consumption/manufacturing/data/2010/#r1.
[48] EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 7 (2010).
[49] 15 U.S.C. § 2605(a)(7)(C).

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authority to remediate existing harm by requiring that responsible parties mitigate past CO_2 emissions.

There are numerous approaches to mitigating and sequestering CO_2 emissions that EPA must evaluate. Effective land use and agricultural practices can significantly reduce carbon emissions and sequester CO_2. Federal programs aimed at consumers can reduce CO_2 emissions. For example, EPA's Energy Star program has prevented 1.8 billion tons of greenhouse gas emissions by providing information that helps customers select energy efficient devices. Sequestration of CO_2 in products, infrastructure, and waste management are among numerous methods that could be cost-effective to mitigate CO_2 pollution.

c. Social Costs of Carbon

In any analysis of the cost and benefits of reducing CO_2 pollution, the costs of failing to address the problem of global warming should be included. Most efforts to quantify the social costs of carbon underestimate the real-world costs of CO_2 pollution. Nevertheless, EPA may not ignore these costs.

Global emissions must be less than 1000 Gt of CO_2 between 2000 and 2050 to avoid dangerous climate change, which scientists have recommended that this means maintaining temperature change below 2° C.[50] This means keeping atmospheric CO_2 to 450 ppm, a threshold below which experts also use for ocean acidification (Veron et al. 2009; Silverman et al. 2009; Interacademy Panel 2009; McNeil & Matear 2008; Sea et al. 2007). For example, coral scientists predict that at 450 ppm, reef-building will be severely diminished or will cease altogether (Veron et al. 2009). But the global community has already used a substantial portion of this CO_2 budget, emitting 305 Gt of CO_2 between 2000 and 2008 alone.[51] As a result, the years between now and 2020 have been dubbed the "critical decade."[52] Because carbon emissions must peak soon and decline thereafter, the sooner emissions peak, the less severe the subsequent annual reductions will need to be;[53] correspondingly, if emissions are not sufficiently curbed in this decade, avoiding catastrophic damages will require much more drastic, disruptive and costly measures and may no longer be possible at all. Nonetheless, if action is taken immediately, it is both technologically and economically feasible to reduce emissions by 2020 and lay the groundwork for future emissions reductions.[54]

Every year that the world delays its efforts to reach sustainable levels of greenhouse gas emissions represents a lost opportunity of tremendous economic significance. McKinsey & Company estimated in 2009 that for every year of delay, 1.8 Gt of potential CO_2 abatement is foregone.[55] This delay, and the accompanying Gts of lost CO_2 abatement, has a price tag, as the

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[50] Australia Department of Climate Change and Energy Efficiency, The Critical Decade: Climate Science, Risks and Responses at 53 (May 2011), *available at* http://www.scribd.com/doc/56043375/The-Critical-Decade-Climate-Change-Commision-Report.
[51] *Id.*
[52] *Id.*
[53] UNEP, The Emissions Gap Report at 14 (Nov. 2010), *available at* http://www.unep.org/publications/ebooks/emissionsgapreport/; for a discussion of economic implications of these facts, *see infra.*
[54] *Id.* at 23.
[55] McKinsey & Company, Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve at 16 (2009), *available at* www.worldwildlife.org/climate/WWWFBinaryitem11334.pdf.

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damage caused by CO_2 emissions accelerate while the cumulative amount of greenhouse gases in the atmosphere rises, both because of the increasingly dire damages wrought by rising temperatures and other greenhouse gas effects, *and* because of the delay factor itself. If governments delay mitigation in the present, the emissions reduction curve in future years necessarily becomes much steeper, requiring much more drastic and costly emission reduction mechanisms with tremendous economy-wide disruptions, just to "catch up" with the lost opportunities from prior years to reach a sustainable emissions trajectory—or risk undergoing unsustainable climatic extremes.

Economists have sought to quantify the costs of waiting to embark upon an emissions reduction path. In 2007, researchers used the DICE model[56] to estimate the cost of delaying mitigation for a given period of time and then switching to an optimal abatement trajectory. According to their findings, the global cost of ten years of delay, relative to starting on an optimal trajectory in the present, ranges from hundreds of billions to several trillion dollars.[57] For instance, this study estimates that it would cost somewhere between $200 and $400 billion dollars to delay action for ten years and then embark upon a mitigation strategy that would result in stabilization at 3 °C (a level now universally understood to far exceed the dangerous). The cost of delaying mitigation soars into the trillions of dollars as the delay continues, until it ultimately becomes impossible to achieve a certain level of temperature stabilization. According to this study, more than thirty years' delay of changing the current course would make it impossible – no matter what the expense – to stabilize temperature rises at 2° C above pre-industrial levels.

EPA and other federal agencies have been using the social cost of carbon to estimate the climate benefits of rulemakings since it was first developed by a dozen agencies (including USDA, CEQ and EPA) and published by the Interagency Working Group in 2010.[58] The social cost of carbon, usually expressed as a dollar-per-ton figure, provides an estimate of the economic damages associated with an increase in CO_2 emissions, conventionally one metric ton, in a given year. The dollar figure can also represent the value of damages avoided for emission reductions achieved by federal rulemakings. The social cost of carbon is designed to provide a comprehensive estimate of climate change damages, including, but not limited to, changes in net agricultural productivity, human health, and property damages from increased flood risk. However, given current modeling and data limitations, even EPA has conceded that that the social cost of carbon protocol is likely a conservative estimate because it does not yet account for all important damages.[59] Nevertheless, the protocol is designed for use in regulatory processes like this one. In 2013 the Federal Interagency Working Group increased its estimates of the social cost of carbon, using the same 3% annual discount rate, by 50%.[60] The 2013 estimates are 50% higher for emissions in 2010, with greater percentage increases in subsequent years. Yet, even these social

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[56] DICE stands for the Dynamic Integrated Climate and Economy model developed by William Nordhaus in 1990.
[57] Keller, K. et al., The Regrets of Procrastination in Climate Policy, Environmental Research Letters (2007), *available at* iopscience.iop.org/1748-9326/2/2/024004/.
[58] EPA, The Social Cost of Carbon, http://www.epa.gov/climatechange/EPAactivities/economics/scc.html (last accessed June 28, 2015).
[59] *Id.*
[60] Interagency Working Group on Social Cost of Carbon, United States Government, Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 (Nov. 2013) at 3, available at http://www.whitehouse.gov/sites/default/files/omb/assets/inforeg/technical-updatesocial-cost-of-carbon-for-regulator-impact-analysis.pdf.

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cost of carbon figures significantly underestimate the true social cost of carbon, possibly by several orders of magnitude.

Economists have noted that the social cost of carbon is far greater than the $21 per ton of CO_2 assumed by interagency protocol in 2010 and greater than the 2013 revision.[61] There are several inadequacies that make the values too conservative. Foremost, the models fail to evaluate ocean acidification—to the contrary the models consider the ocean a sink for CO_2. The FUND model used in the Working Group's analysis wholly excludes consideration of climate-induced catastrophic events. But the Working Group weighs the values generated by each of the three models equally, even though the FUND model's values is significantly lower[62] than the others, and consequently pulls down the final value of the social cost of carbon. The potential for catastrophic climate events, and the increasing likelihood that tipping points will be reached even sooner than anticipated, are increasingly serious risks, however, and, despite the associated uncertainties, must be fully represented in any evaluation of the social cost of carbon. Instead, the Working Group employed a risk-neutral approach, clearly inappropriate in light of the vast majority of scientific studies. Also, the models used fail to account fully or even partially for certain highly complex aspects of climate change, including the possibility of interrelations between different sectors and accelerating damage feedback loops, non-CO_2 emissions,[63] and social and political instability. Moreover, the valuation techniques and discount rates used to reach these values are inherently problematic and fail to represent the full value of all losses from climate change, in significant part because some cannot be reduced to monetary terms.

Other evaluations of the social cost of carbon attempt to account for these omitted factors. The Stern Review, in particular, reaches a SCC of $85/ton of CO_2 (in 2000 dollars).[64] For comparison purposes with a Working Group value of $21 in 2005 dollars, this amount is equivalent to

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[61] F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon (2010) (the social cost of carbon could be over $800 per ton of CO2 equivalent; F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon, in Economics, vol. 6 (Apr. 4, 2012) (reaching similar conclusions), available online at http://www.economics-ejournal.org/economics/journalarticles/2012-10 (last visited June 27, 2014); P. Epstein et al., Full cost accounting for the life cycle of coal, Ann. N.Y. Acad. Sci. (2011) (estimating the social cost of coal at between $10 and $100 per ton of CO2 equivalent); L. Johnson & C. Hope, The social cost of carbon in U.S. regulatory impact analyses: an introduction and critique, J. Envtl. Stud. & Sci. (Sept. 9, 2012) (finding a social cost of a ton of CO2 emissions to be 2.6 to over 12 times larger than the Interagency Working Group's central estimate of $21 per ton of CO2) available online athttp://link.springer.com/article/10.1007%2Fs13412-012-0087-7 (last visited June 27, 2014) E. Stanton et al., Comments on the 2013 Technical Update of the Social Cost of Carbon, January 27, 2014.

[62] Interagency Working Group on the Social Cost of Carbon, Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, at 16-A-11, Fig. 16-A-4.2, *available at* http://www.rff.org/Publications/WPC/Pages/Estimating-the-Social-Cost-of-Carbon-for-Regulatory-Impact-Analysis.aspx.

[63] For instance, the estimated social cost of methane and SF_6, are, respectively, $105/tonne and $200,000/tonne. *See* Intergovernmental Panel on Climate Change, Climate Change 2007 Synthesis Report 822, *available at* http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html. For a critical analysis of the Working Group's assumptions, *see also* Ackerman, F. and Stanton, E. A., The Social Cost of Carbon A Report for the Economics for Equity and the Environment Network (April 1, 2010), *available at* http://www.e3network.org/papers/SocialCostOfCarbon_SEI_20100401.pdf.

[64] Nicholas Stern, Stern Review on the Economics of Climate Change Part III: The Economics of Stabilisation at 287 (2006), *available at* http://webarchive.nationalarchives.gov.uk/+/http:/www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm.

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$96.25/ton in 2005. The Stern Review uses the PAGE model, which explicitly models for the risk of catastrophic climate change.[65] In contrast with the Working Group, the Stern Review uses a mean temperature increase of 3.9 °C for its baseline scenario (consistent with the Third IPCC Report) and a 4.3 °C increase for its higher climate scenario. The resulting higher value of the social cost of carbon is thus very likely to be a closer approximation of the real cost of CO_2.

Meanwhile, the costs of reducing CO_2 emissions are well worth taking prompt action. The "central estimates of the annual costs of achieving stabilisation between 500 and 550ppm CO_2 are around 1% of global GDP, if we start to take strong action now. [...] It would already be very difficult and costly to aim to stabilise at 450ppm CO_2e. If we delay, the opportunity to stabilise at 500-550ppm CO_2e may slip away.'"(Stern 2006). Likewise, the benefits of addressing CO_2 for ocean acidification also have the ancillary effect of slowing global warming and preventing costs associated with climate change.

The recently proposed rule to reducing power plant CO_2 emissions calculates both costs and benefits—notably the benefits far exceed the costs. The recently proposed rules for reducing power plant carbon emissions, calculates both costs and benefits for a more modest reduction. EPA projects that the annual compliance cost will be $4.3 to $5.5 billion (in 2011 dollars, depending on discount rate) in 2020 and $5.5 billion (for a 5% discount rate) in 2030.[66] The total combined climate benefits and health co-benefits are estimated to be $15.6 to $88 billion in 2020 and $32.3 to $151 billion in 2030 (depending on discount rate and the options chosen).[67] The insurance industry also is well aware of the potential costs of failing to address CO2 emissions and its associated effects, including: "[h]urricanes and other flooding events … [h]ealth issues associated with heat waves… more airborne allergens, rising temperatures, greater humidity, more wildfires, and more dust and particulate pollution may considerably exacerbate upper respiratory disease (rhinitis, conjunctivitis, sinusitis, asthma) and cardiovascular disease."[68] A European insurance company estimates losses from extreme climate change events of 37% within a decade, over $1 trillion under bad circumstances.[69] The increasing frequency and severity of storms in the U.S. has caused damages to increase 60-fold from 1950s to the 1990s.[70]

Petitioners ask that action to mitigate ocean acidification under TSCA be initiated, either through TSCA section 6 (e.g., requiring "repurchasing" relief using sequestration, emission reductions, etc.), or through section 4 in order to determine the need for action under section 6 and the most effective mitigation strategies. In any case, petitioners suggest that costs be apportioned among

[65] According to the Working Group itself, DICE "offers the best insight into the SCC if the world were to experience catastrophic climate change." *See* Working Group, *supra* note 62, at 16-A-35.
[66] EPA, Regulatory Impact Analysis Technical Document EPA-452/R-14-002 (June 2014).
[67] *Id.*
[68] National Association of Insurance Commissioners, The Potential Impact of Climate Change on Insurance Regulation at 10 (2008).
[69] See e.g. Allianz, Climate Change and the Financial Sector: An Action Plan; Evan Mills, Responding to Climate Change: The Insurance Industry Perspective.
[70] Mills, E. Insurance in a Climate of Change, Science 308: 1040 (2005).

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CO_2 emission contributors according to the cumulative CO_2 emission inventory information EPA has collected.[71]

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In summary, the weight of the scientific information on ocean acidification is sufficient to make a determination that CO_2 poses an unreasonable risk, to the extent that EPA declines to find the data adequate, then EPA must develop a test rule under TSCA section 4 as described below.

C. Alternatively, EPA Must Require Testing to Develop Adequate Data

EPA must make a determination as to whether adequate data exist to evaluate the environmental and health effects of CO_2. There is well-established scientific information on the risk of CO_2 on the environment, but if EPA determines that the data are insufficient then it must develop a testing rule.

In enacting TSCA, Congress declared that "adequate data should be developed with respect to the effect of chemical substances and mixtures on health and the environment and that the development of such data should be the responsibility of those who manufacture and those who process such chemical substances and mixtures."[72] Accordingly, section 4 directs EPA to require additional testing upon determining that "the manufacture, distribution in commerce, processing, use, or disposal of chemical substance or mixture … may present an unreasonable risk of injury to health or the environment," or if the chemical is produced in substantial quantities and there is a potential for a substantial quality to be released into the environment.[73]

1. CO_2 May Present an Unreasonable Risk

As described in depth in this petition, CO_2 may present an unreasonable risk to the environment. EPA interprets this to mean that there is a "substantial (i.e., more than theoretical) probability" of unreasonable risk to the environment or health.[74] The information in this petition meets the threshold for a testing rule and establishes a substantial probability that CO_2 poses an unreasonable risk to the environment, but EPA need not even make such a determination because CO_2 is produced in such large volumes that it clearly meets the criterion of exposure of substantial quantities being released into the environment.

2. Substantial Quantities of CO_2 Are Released into the Environment

It is undeniable that substantial qualities of CO_2 are released into the environment. EPA established a threshold value of one million pounds for a release of a chemical to be substantial. *TSCA Section 4(a)(1)(B) Final Statement of Policy; Criteria for Evaluating Substantial*

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[71] This could be structured similar to the sponsorship format used in TSCA's High Production Volume (HPV) Program.
[72] 15 U.S.C. § 2601(b)(1).
[73] 15 U.S.C. § 2603 (a)(1)(A), (B)(i).
[74] *Chemical Mfrs. Ass'n v. EPA*, 859 F.2d 977, 988 (D.C. Cir. 1988).

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Production, Substantial Release, and Substantial or Significant Human Exposure, 58 Fed. Reg. 28736, 28746 (May 14, 1993). According to the IPCC:

> From 1750 to 2011, CO_2 emissions from fossil fuel combustion and cement production have released 375 [345 to 405] GtC to the atmosphere, while deforestation and other land use change are estimated to have released 180 [100 to 260] GtC. This results in cumulative anthropogenic emissions of 555 [470 to 640] GtC.

(IPCC 2013, Summary for Policymakers).

In 2012, a total of 9.7 gigatonnes of CO_2 were released into the atmosphere from fossil fuel combustion and cement production (Global Carbon Project 2013). These emissions are expected to increase to 9.9 gigatonnes in 2013 (*Id.*). The United States contributed 14% of CO_2 emissions to the atmosphere (*Id.*). Models estimate that between 2003 and 2012, the oceans absorbed 27% of CO_2 from the atmosphere (*Id.*). Over the next millennium, the oceans will absorb 90% of anthropogenic CO_2 (Kleypas et al. 2006).

Therefore, the threshold of substantial release is exceeded by more than a million times over.

3. Recommendations for Testing

EPA should consider a test rule to fill the information gaps needed to make a determination of whether CO_2 presents an unreasonable risk of injury to the environment. Some recommendations for consideration include:

- Testing CO_2 reduction strategies. For example, research and development for emissions reduction strategies that include alternative practices, conservation, alternative fuels. Testing CO_2 sequestration and capture approaches, and assessing attainable CO_2 emissions reductions for industries with significant CO_2 emissions.
- Conducting a vulnerability assessment for marine and coastal species and ecosystems. Determining atmospheric CO_2 levels necessary to conserve marine ecosystems from dangerous ocean acidification. Emissions scenarios are important for informing policy approaches to acidification.
- Forecasting species' responses to ocean acidification using modeling tools to predict range shifts, demographic and population trends, and physiological responses across taxonomic groups using a range of climate models, emissions scenarios, and management timelines (25, 50, 100 years). Identify wildlife species and ecosystems imperiled by ocean acidification by evaluating range shift models and population viability models run under future ocean acidification levels. Recommend conservation actions, including protected status, for species that are most at risk. Protect species across their range since populations are likely to have different adaptations to local oceanic conditions.
- Determining the economic values of ecosystems that are at risk from ocean acidification and the costs of reducing CO_2 emissions to preserve those ecosystems.

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Additionally, EPA can use guidance on research needs based on existing research plans. There are a number of sources recommending research and data needs (National Research Council 2013; Washington State Blue Ribbon Panel 2012; National Research Council 2010).

According to TSCA, developing the data is "the responsibility of those who manufacture and those who process such chemical substances and mixtures."[75] For example, responsibility could be apportioned based on the historical carbon emissions from the EPA Greenhouse Gas Emission Inventory together with current emissions. Typically for test rules with multiple responsible parties consortiums are set up to comply.[76] Here, for example, utilities, cement and lime manufacturers, waste incinerators, and other large producers of CO_2 should be responsible for developing unbiased, independent data.

While this may seem like a complicated undertaking, EPA has successfully completed more complex test rules. For example, from 1998 through the present, the agency used three sets of regulatory test rules under TSCA to collect chemical data for almost 3,000 high production volume (HPV) chemicals, including over 10,000 individual studies with data from domestic and foreign producers.[77]

EPA must develop test rules under TSCA section 4 for research and data development focused on information essential for making a definitive TSCA section 6 finding. These would include risk, benefit and cost information.

D. Inadequacy of Existing CO_2 Reduction Strategies

Petitioners are aware that the Agency has recently planned and initiated several emission reduction actions aimed at slowing the rate at which carbon emissions are increasing. However, these actions by themselves, while laudable, will not stabilize atmospheric CO_2 at a level which will prevent widespread harm from ocean acidification.

1. Global Greenhouse Gas Emissions Are Increasing Substantially

The atmospheric concentration of CO_2 reached 400 parts per million (ppm) for the first time in human history in May, 2013, compared to the pre-industrial concentration of ~280 ppm (Scripps Institution of Oceanography 2013). The current CO_2 concentration has not been exceeded during the past 800,000 years and likely not during the past 15 to 20 million years (Denman et al. 2007; Tripati et al. 2009). Atmospheric CO_2 emissions have risen particularly rapidly since the 2000s (Raupach et al. 2007; Friedlingstein et al. 2010). The global fossil fuel CO_2 emissions growth rate was 1.0% per year in the 1990s compared with 3.1% per year since 2000, and this growth rate has largely tracked or exceeded the most fossil-fuel-intensive emissions scenarios projected by the IPCC (A1FI and RCP 8.5) since 2000 (Raupach et al. 2007, Peters et al. 2012). The CO_2 emissions growth rate fell slightly in 2009 due largely to the global financial and economic

[75] 15 U.S.C. § 2601
[76] 15 U.S.C. § 2602 (b)(3)(A)
[77] EPA, High Production Volume (HPV) Challenge; http://www.epa.gov/chemrtk/index.htm (last accessed June 28, 2015).

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crisis; however, the decrease was less than half of what was expected and was short-lived (Fiedlingstein et al. 2010). In 2014 and 2015, global CO_2 concentrations exceeded 400ppm.[78]

2. U.S. Measures to Reduce Greenhouse Gas Emissions Are Insufficient

EPA has taken some initial steps toward curbing greenhouse pollution under the Act. In 2009, the agency issued a formal finding that greenhouse pollution endangers public health and welfare and moved to limit emissions from passenger cars and trucks. The EPA also acknowledged that major new or modified "stationary" sources of greenhouse pollution, like power plants and factories, must obtain permits and control their emissions before beginning construction. However, it narrowed the scope of this requirement considerably under its so-called "tailoring rule," which initially limits the permitting program to only a few hundred very large sources of greenhouse gases, letting a huge number of smaller — but still significant — sources off the hook.

While existing domestic laws including the Clean Air Act, Energy Policy and Conservation Act, Clean Water Act, Endangered Species Act and others provide authority to executive branch agencies to require greenhouse gas emissions reductions from virtually all major sources in the United States, these agencies are either failing to implement or only partially implementing these laws for greenhouse gases. The landmark 2014 pact with China to reduce greenhouse gas emissions is significant, but there is little to ensure it is enforced and implemented. According to the plan, United States will reduce CO_2 emissions 26 to 28% below 2005 levels by 2025.

Proposed power plant rules also fail to do enough to cut CO_2 pollution. Using the Clean Air Act, the president aims to reduce existing power plant emissions 30 percent below 2005 levels (or about 7.7 percent below 1990 levels, the base year for the international climate treaty) by 2030. But international scientists warned years ago that developed countries like the United States must reduce their emissions 25 percent to 40 percent below 1990 levels by 2020 to avoid tipping the scales further toward a climate catastrophe. Likewise, the recently announced plans to limit power plant emissions (Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units) focuses on emission reduction. Power plants are responsible for about a third of our carbon emissions, and the rule is designed to reduce those emissions by almost a third by 2030. This would result in a 10% decrease in 15 years. Stabilizing atmospheric concentration to prevent further acidification of the oceans would require about an 80% decrease in all emissions. Clearly this is a good first step, but by itself inadequate to address acidification.

EPA has issued a rulemaking regulating greenhouse gas emissions from automobiles that will reduce greenhouse emissions emitted per vehicle mile traveled by passenger vehicles in the future. But because the improvements are modest and more vehicles are projected to drive more miles in the future, the rule will not reduce emissions from this sector overall but will only slow the rate of increase.[79] Meanwhile, even the government concedes that "these reductions in emissions are not sufficient by themselves to reduce total HD vehicle emissions below their 2005

[78] NOAA, Trends in Atmospheric Carbon Dioxide, http://www.esrl.noaa.gov/gmd/ccgg/trends/
[79] EPA, Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule, 75 Fed. Reg. 25324 (May 7, 2010).

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levels by 2020."[80] This means that the vehicle rule is far from achieving emissions goals agreed to by the U.S. in the Copenhagen Accord, which aim to keep global warming below 2˚C.

The EPA has also to date issued only a single proposed rule under the new source pollution standard program for stationary sources of pollution, for electric generating units (power plants). While there is enormous potential to reduce emissions through this program overall and through the power plants rule in particular, the EPA has instead proposed a weak and flawed rule that it admits will not reduce emissions from these sources between now and 2020 compared to what would be expected without the rule.[81] Indeed, in the rulemaking the EPA conceded that new power plant rule on greenhouse gas emissions "will not have direct impact on U.S. emissions of greenhouse gases under expected economic conditions."[82]

While full implementation of our flagship environmental laws, particularly the Clean Air Act, would provide an effective and comprehensive greenhouse gas reduction strategy, due to their non-implementation, existing domestic regulatory mechanisms must be considered inadequate to protect marine species from climate change and ocean acidification.

3. International Measures to Reduce Greenhouse Gas Emissions Are Inadequate

International initiatives are also currently inadequate to effectively address climate change. The United Nations Framework Convention on Climate Change, negotiated in 1992 at Rio de Janeiro, Brazil, provides the forum for the international negotiations. In the Framework Convention, signed and ratified by the United States, the world agreed to take the actions necessary to avoid dangerous climate change. Parties to the Convention also agreed as a matter of fairness that the world's rich, developed countries, having caused the vast majority of emissions responsible for the problem, would take the lead in solving it. It was not until the 1997 meeting in Kyoto, Japan, that the first concrete, legally binding agreement for reducing emissions was signed: the Kyoto Protocol. The Protocol requires the world's richest countries to reduce emissions an average of 5 percent below 1990 levels by 2012, while developing nations also take steps to reduce emissions without being subject to binding emissions targets as they continue to raise their standard of living. The United States has been a major barrier to progress in the international negotiations. After the Clinton administration extracted many concessions from the rest of the world in exchange for the United States signing on in Kyoto, the Senate rejected the equity principles behind the Convention, saying the United States should not agree to reduce its own emissions unless all other countries — regardless of their responsibility or ability — were similarly bound. Citing the same excuses, President George W. Bush repudiated the Kyoto Protocol entirely. Thus the United States is the only industrialized country in the world that has yet to ratify the Kyoto Protocol. The United States negotiating team under both the George W. Bush and the Obama administrations has pursued two primary objectives in the international talks: to refuse any legally binding emissions reduction commitments until all other

[80] NHTSA, Medium- and Heavy-Duty Fuel Efficiency Improvement Program – Final Environmental Impact Statement (June 2011).
[81] EPA, Standards of Performance for Greenhouse Gas Emissions for New Stationary Sources: Electric Utility Generating Units, 77 Fed. Reg. 22392, 22430-33 (April 13, 2012).
[82] *Id.* at 22401.

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countries— but particularly China and India — do so, and to push back the date for a new agreement. Not surprisingly, the United States had failed to meet its (never ratified) Kyoto pledge to reduce emissions to 7.2% below 1990 levels by 2012; to the contrary, U.S. emissions have increased by 10.5% since 1990 (EPA 2012).

Moreover, the Kyoto Protocol's first commitment period only sets targets for action through 2012, and there is still no binding international agreement governing greenhouse gas emissions in the years beyond 2012. While the 2009 U.N. Climate Change Conference in Copenhagen called on countries to hold the increase in global temperature below 2□C (an inadequate target for avoiding dangerous climate change), the non-binding "Copenhagen Accord" that emerged from the conference, and the subsequent "Cancún Accords" of 2010 and "Durban Platform" of 2011 failed to enact binding regulations that limit emissions to reach this goal.[83] Even if countries were to meet their Copenhagen and Cancún pledges, analyses have found that collective national pledges to cut greenhouse gas emissions are inadequate to achieve the 2°C target, and instead suggest emission scenarios leading to 2.5□C to 5□C warming (Rogelj et al. 2010; UNEP 2011; UNEP 2010). As of July 2013, many governments were not implementing the policies needed to meet their inadequate 2020 emission reduction pledges, making it more difficult to keep global temperature rise to 2□C and likely leading to a temperature rise of at least 3.5□C (USGCRP 2013). As noted in the NMFS Management Report, the U.S. has yet to issue regulations to limit greenhouse gas emissions in accordance with its pledge under the Copenhagen Accord (NMFS 2012).

CONCLUSION

In conclusion, this petition requires EPA to make a determination whether CO_2 poses an unreasonable risk to the environment therefore requiring regulation under section 6 of TSCA. In an extensive review of the literature on the impact of ocean acidification on marine fauna and ecosystem processes, the authors found that while additional research is called for, sufficient information exists to state with certainty that deleterious impacts on some marine species are unavoidable, and that substantial alteration of marine ecosystems is likely over the next century. (Fabry et al. 2008). If, nonetheless, EPA determines that the information is insufficient to make such a finding it must develop testing rules pursuant to TSCA section 4.

[83] The non-legally binding Copenhagen Accord of 2009 and Cancún Accords of 2010 recognize the objective of limiting warming to 2°C above pre-industrial temperatures, but do not enact binding regulations to achieve this goal (http://cancun.unfccc.int/cancun-agreements/main-objectives-of-the-agreements/#c33; unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf). According to the Durban Platform, developed and developing nations agreed to a process to develop a "new protocol, another legal instrument, or agreed outcome with legal force that will be applicable to all Parties to the UN climate convention"; this legal instrument must be developed as of 2015 and will not take effect until 2020 (unfccc.int/resource/docs/2011/cop17/eng/l10.pdf).

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BEFORE THE ENVIRONMENTAL PROTECTION AGENCY

PETITION FOR RULEMAKING PURSUANT TO SECTION 21 OF THE TOXIC SUBSTANCES CONTROL ACT, 15 U.S.C. § 2620, CONCERNING THE REGULATION OF CARBON DIOXIDE

Credit: NOAA

CENTER FOR BIOLOGICAL DIVERSITY

DONN J. VIVIANI, PhD

PETITIONERS

June 30, 2015

NOTICE OF PETITION

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The Center for Biological Diversity ("Center") is a non-profit, public interest environmental organization dedicated to the protection of native species and their habitats through science, policy and environmental law. The Center has over 800,000 members and online activists throughout the United States and around the world. The Center's Oceans Program and its supporters are specifically concerned with the conservation of marine species, the preservation of ocean ecosystems and the effective implementation of U.S. environmental laws, including the Toxic Substances Control Act. The Center submits this petition on its own behalf and on behalf of its members and staff with an interest in protecting the marine environment.

Donn J. Viviani, PhD, is a retired U.S. Environmental Protection Agency scientist. He was the Director of the Climate Policy Assessment Division in the Office of Policy, Economics and Innovation. He also served as Chairman of the Great Lakes Water Board's Toxic Substances Committee and as a member of the Science Coordinating Committee for the International Joint Commission for the Great Lakes. Dr. Viviani enjoys the ocean and submits this petition, in part, so his grandchildren will be able to enjoy it as well. Dr. Viviani also submits a supplement to the petition, under his signature only, and respectively requests that it be considered.

ACTION REQUESTED

Pursuant to section 21 of the Toxic Substances Control Act ("TSCA" or the "Act"), 15 U.S.C. § 2620, and section 553(e) of the Administrative Procedure Act ("APA"), 5 U.S.C. § 553(e), the Center for Biological Diversity and Donn J. Viviani (collectively, "Petitioners") hereby petition the Administrator of the U.S. Environmental Protection Agency ("EPA") to promulgate regulations protecting public health and the environment from the serious harms associated with anthropogenic emissions of carbon dioxide, including ocean acidification. Specifically, Petitioners request that EPA adopt a rule under section 6 of the Act, 15 U.S.C. § 2605, requiring manufacturers and processors to mitigate these emissions.

This petition sets in motion a specific process, placing definite response requirements on EPA. Specifically, TSCA stipulates that the agency "*shall* either grant or deny the petition" within 90 days following its receipt, "promptly commenc[ing] an appropriate [rulemaking]

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proceeding" if such action is warranted. 15 U.S.C. § 2620(b)(3) (emphasis added). Conversely, should EPA deny this petition, the agency must publish the reasons for denial in the Federal Register. 15 U.S.C. § 2620(b)(3); *see also* 5 U.S.C. § 555(e) ("Prompt notice shall be given of the denial in whole or in part of a written application, petition, or other request of an interested person made in connection with any agency proceeding."). Pursuant to 15 U.S.C. § 2620(b)(4), petitioners may file suit in federal district court to challenge an adverse or untimely determination. *See also* 5 U.S.C. §§ 702, 706.

As described in this petition, anthropogenic emissions of carbon dioxide satisfy the standard for regulation set forth at 15 U.S.C. § 2605. For example, EPA has acknowledged that these emissions have the potential to alter ocean chemistry, thus imperiling important marine ecosystems and presenting an unreasonable risk of injury to the environment. Accordingly, the agency must promptly commence the proposed rulemaking to reduce and mitigate these harms. In the event that EPA concludes that there are insufficient data and experience upon which to determine or predict the effects of carbon dioxide emissions, we alternatively request that the agency adopt a rule under section 4 of the Act, 15 U.S.C. § 2603, requiring manufacturers and processors responsible for the generation of carbon dioxide to undertake testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Dated this 30th day of June 2015.

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INTRODUCTION

Ocean acidification — caused by carbon dioxide ("CO_2") emissions — is a severe threat to the marine environment and the health of people who depend on oceans and coasts. Because of the unreasonable risk that CO_2 poses to the environment and human health, this petition seeks rulemaking under the Toxic Substances Control Act ("TSCA") to regulate CO_2 from cradle to grave.

About 28% of CO_2 emissions from power generation, cement production, industry, and other sources are absorbed by the ocean. These CO_2 emissions cause seawater to become more acidic and corrosive to sea life. Anthropogenic CO_2 emissions have increased the acidity of the oceans on average by 30%, and by the end of the century scientists predict that the oceans will become 150-170% more acidic.

While the most dangerous consequences of CO_2 on our oceans are still to come, harmful impacts on the environment are already well-documented.

- Billions of oyster larvae have perished in the Pacific Northwest due to ocean acidification;
- 53% of pteropods, plankton that form the base of the marine food web, along the West Coast have severely dissolved shells because of the corrosive nearshore conditions; and
- Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%.

These are just some of the harmful environmental impacts of ocean acidification caused by CO_2 emissions. Anthropogenic CO_2 emissions are contributing to increasingly corrosive conditions for marine animals, and will continue to grow more severe absent actions to promptly reduce CO_2 pollution in the atmosphere.

TSCA was enacted in part to address the threat of ozone depletion caused by chlorofuorocarbon (CFC) emissions. And here again TSCA regulation is needed where airborne emissions are causing damage to our environment — this time threatening ocean ecosystems, fish and shellfish industries, and communities that depend on oceans and coral reefs.

Petitioners specifically request that EPA take the following actions:

1. **Make a determination under TSCA § 6 that CO_2 presents an unreasonable risk of injury to health or the environment; and**
2. **Initiate rulemaking to control CO_2; or**
3. **If EPA finds data inadequate to make a §6 determination then EPA must initiate rulemaking for testing under TSCA § 4.**

This petition presents scientific evidence that establishes that CO_2 presents an unreasonable risk of injury to the environment, and therefore EPA must take action under TSCA section 6.

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I. The Toxic Substances Control Act

Congress enacted TSCA, 15 U.S.C. §§ 2601 *et seq.*, "to assure that … innovation and commerce in … chemical substances and mixtures do not present an unreasonable risk of injury to health or the environment."[1] Accordingly, lawmakers required those responsible for the manufacture and processing of these compounds to develop "adequate data" describing their effects, and authorized EPA to devise and implement reasonable controls to prevent the risk of injury to health or the environment.[2]

Section 6 of TSCA mandates that EPA "shall" regulate a chemical substance for which

> there is a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance or mixture, or that any combination of such activities, presents or will present an unreasonable risk of injury to health or the environment.[3]

Permissible regulations include requirements prohibiting or "limiting the amount of such substance … which may be manufactured, processed, or distributed in commerce."[4] EPA can also require processors "to give public notice of such risk [of injury], and . . . to replace or repurchase such substance . . . to adequately protect health or the environment."[5] In assessing risk, EPA must consider:

> (A) the effects of such substance or mixture on health and the magnitude of the exposure of human beings to such substance or mixture,
> (B) the effects of such substance or mixture on the environment and the magnitude of the exposure of the environment to such substance or mixture,
> (C) the benefits of such substance or mixture for various uses and the availability of substitutes for such uses, and
> (D) the reasonably ascertainable economic consequences of the rule, after consideration of the effect on the national economy, small business, technological innovation, the environment, and public health.[6]

Thus, if there is a reasonable basis to conclude that a proposed rule is necessary to protect the environment, then EPA must grant a petition for rulemaking and initiate rulemaking procedures. Factual certainty is not required; instead, the agency may "base its action on scientific theories, consideration of projections from available data, modeling using reasonable assumptions, and extrapolations from limited data."[7] Even if EPA determines that another federal law "could

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[1] 15 U.S.C. § 2601(b)(3) (2012). Within the meaning of TSCA, the term "chemical substance" includes "any organic or inorganic substance of a particular molecular identity." *Id.* § 2602(2).
[2] *Id.* § 2601(b)(1) & (2).
[3] *Id.* § 2605(a) (emphasis added).
[4] *Id.* § 2605(a)(1)(B).
[5] *Id.* § 2605(b)(2)(B).
[6] *Id.* § 2605(c)(1). E.
[7] Lead Fishing Sinkers; Response to Citizens' Petition and Proposed Ban, 59 Fed. Reg. 11,122, 11,138 (Mar. 9, 1994) (*citing* H.R. Rep. No. 1341, 9th Cong., 2d Sess. 32 (1976)).

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[sufficiently] eliminate[] or reduce[]" the risk associated with a particular chemical substance, the agency may elect to regulate the substance under TSCA, provided that a "comparison of the estimated costs" and "relative efficiency" reveals that such action promotes the public interest.[8]

In the event that EPA lacks adequate data and experience upon which to determine the health and environmental risks associated with a particular chemical substance, the agency "*shall* by rule require that testing be conducted on such substance."[9] Specifically, Section 4 of the Act authorizes EPA to compel manufacturers and processors to evaluate the safety of substances that "may present an unreasonable risk of injury to health or the environment" or that "[are] or will be produced in substantial quantities" and, thus, "may reasonably be anticipated to enter the environment in substantial quantities" or result in "significant or substantial human exposure."[10] TSCA provides for testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Over forty years ago, the Council on Environmental Quality warned of the "high priority need" for a new legal authority capable of ensuring the safe use of toxic chemicals.[11] Despite TSCA's powerful potential, however, EPA has accomplished very little under the Act. This petition presents substantial scientific evidence demonstrating that anthropogenic emissions of CO_2 pose an unreasonable risk to human and environmental health. Indeed, studies show that significant and potentially irreversible harm has already occurred. As the Council recognized decades ago, "[w]e should no longer be limited to repairing [this] damage after it has been done; nor should we continue to allow the entire population or the entire environment to be used as a laboratory." Instead, EPA must take prompt action to reduce and mitigate the anthropogenic production of CO_2.

II. EPA Must Issue a Rule to Regulate or Require Tests for CO_2 Causing Ocean Acidification

CO_2 presents an unreasonable risk of injury to the environment because its exposure to the ocean changes seawater chemistry with harmful impacts on marine life and ecosystems. Substantial evidence supports this conclusion and is discussed in this petition. Accordingly, this petition seeks a rulemaking to regulate CO_2 under TSCA.

This petition requires EPA to make a determination under TSCA section 6 if the injury to the environment and health from CO_2 is unreasonable. Alternately, if the Agency demonstrates that the existing science is insufficient to make a determination under TSCA section 6, EPA must initiate test rules under TSCA section 4 to develop the missing information needed to determine if the TSCA section 6 trigger is met and how best to mitigate the harm.

A. TSCA Authorizes EPA to Act on CO_2

To enable the achievement of TSCA's ambitious objectives, Congress broadly defined EPA's jurisdiction under the Act. As described above, TSCA explicitly directs EPA to initiate

[8] *Id.*
[9] *Id.* § 2603 (emphasis added).
[10] *Id.*
[11] Council on Envtl. Quality, Toxic Substances at v (April 1971).

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rulemaking upon finding that "the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance" threatens public health or the environment.[12] TSCA then authorizes the regulation of "chemical substances" that are "in commerce," a test met by CO_2. Indeed, CO_2 is already on the TSCA inventory as a "chemical in commerce."[13] CO_2 necessarily qualifies as a "chemical substance," a category that includes "any organic or inorganic substance of a particular molecular identity."[14] Moreover, the anthropogenic emissions at issue are in commerce; federal courts have previously concluded that air emissions[15] and "incidental byproducts of industrial chemical processes" are within the scope of EPA's authority under the Act.[16] Existing scientific evidence demonstrates that the anthropogenic production of CO_2 has already damaged marine ecosystems and endangered vulnerable portions of the human population. For the reasons described below, EPA must promptly reduce and mitigate these harms.

1. CO_2 Is a Chemical Substance

First, carbon dioxide is a "chemical substance" falling within the scope of the Act. The Act defines "chemical substance" as "any organic or inorganic substance of a particular molecular identity, including any combination of such substances occurring in whole or in part as a result of a chemical reaction or occurring in nature and (ii) any element or uncombined radical."[17]. CO_2 meets this definition. CO_2 is a chemical substance that occurs both in nature and as a result of a chemical reaction. It consists of a carbon atom bonded to two oxygen atoms:

$$O=C=O$$

It is identified by molecular formula CO_2 and by CAS number 124-38-9.

2. CO_2 Is in Commerce

Second, CO_2 is in commerce, and it is already on the TSCA inventory (CAS 124-38-9) with "chemical in commerce" as the stated reason for regulation.[18] Under TSCA's statutory text, "commerce" is defined as "trade, traffic, transportation, or other commerce . . . between a place in a State and any place outside of such state, or . . . which affects trade, traffic, transportation, or commerce."[19] CO_2 is primarily produced as a byproduct from the combustion of fossil fuels; according to the EPA, CO_2 emissions account for 77% of greenhouse gas emissions worldwide.[20]

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[12] *Id.* §§ 2605(a), 2603(a)(1)(A)(i), 2506(a). Although TSCA does not define "disposal," other federal environmental laws explain that this term encompasses "the discharge, deposit, injection, dumping, spilling, leaking, or placing of any solid waste or hazardous waste into or on any land or water so that such solid waste or hazardous waste or any constituent thereof may enter the environment or be emitted into the air or discharged into any waters, including ground waters." 42 U.S.C. §§ 6903(3), 9601(29).
[13] EPA, Substance Registry at http://1.usa.gov/1IBS1w6 (last accessed June 28, 2015).
[14] 15 U.S.C. § 2602(2). This definition excludes specific compounds already subject to federal control, such as pesticides, tobacco products, nuclear materials and food, drugs and cosmetics. *Id.* § 2602(2)(B).
[15] *Citizens for a Better Env't v. Thomas*, 704 F. Supp. 149, 152 (E.D. Ill. 1989).
[16] *Envtl. Def. Fund v. Envtl. Prot. Agency*, 636 F.2d 1267, 1271 (D.C. Cir. 1980).
[17] 15 U.S.C. § 2602(2)(A).
[18] EPA, Substance Registry at http://1.usa.gov/1IBS1w6.
[19] 15 U.S.C. § 2602(3).
[20] EPA, Global Greenhouse Gas Emissions Data, http://www.epa.gov/climatechange/ghgemissions/global.html (last updated June 21, 2013; last accessed June 28, 2015).

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The most voluminous sources of greenhouse gas emissions are energy suppliers,[21] industry,[22] land use and forestry,[23] agriculture,[24] transportation,[25] commercial and residential buildings,[26] and waste and wastewater.[27] All of these emitters produce CO_2 as a byproduct of their ordinary processes.

TSCA's statutory and regulatory text support the proposition that CO_2 emitted as a byproduct of industrial processes can be regulated under TSCA because CO_2 in this context is manufactured, meaning "produce[d] . . . with the purpose of obtaining an immediate or eventual commercial advantage."[28] All of the industries listed above which emit CO_2 are performed to obtain an immediate or eventual commercial advantage, as all of these industries are commercial and part of a competitive market. Therefore, incidental production of CO_2 is manufactured or produced "for a commercial purpose," and is found "in commerce" pursuant to TSCA regulations.

Accordingly, CO_2 emissions fit the regulatory definition of a chemical substance produced for a commercial purpose. This is bolstered by the broad definition of "commerce" in the TSCA statute; at the very least, CO_2 emissions "affect" trade, traffic, transportation, and commerce.

TSCA's purpose and regulatory text support the regulation of chemical substances that are an incidental byproduct, and indeed EPA has regulated chemical byproducts under TSCA before. For example, PCBs are regulated under TSCA even when they are only incidentally produced as a byproduct of industrial processes.[29] EPA regulates PCB "byproducts" for which there are no separate commercial intents, and TSCA regulates inadvertently vented PCB emissions.[30] Moreover, EPA's authority under TSCA broadly defines what it regulates under "disposal" of PCBs to include intentional and accidental disposal.[31] EPA has also previously prohibited wastes from chemical manufacturing under TSCA.[32]

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[21] Which emit greenhouse gases through "[t]he burning of coal, natural gas, and oil for electricity and heat." *Id.*

[22] Which emit greenhouse gases through "fossil fuels burned on-site at facilities for energy" and "chemical, metallurgical, and mineral transformation processes not associated with energy consumption." *Id.*

[23] Which emit "carbon dioxide . . . from deforestation, land clearing for agriculture, and fires or decay of peat soils." *Id.*

[24] "Greenhouse emissions from agriculture mostly come from the management of agricultural soils, livestock, rice production, and biomass burning." *Id.*

[25] Which emit greenhouse gases through "fossil fuels burned for road, rail, air, and marine transportation." *Id.*

[26] Which emit greenhouse gases from "on-site energy generation and burning fuels or heat in buildings or cooking in homes." *Id.*

[27] Which emit carbon dioxide through the "incineration of some waste products that were made with fossil fuels, such as plastics and synthetic textiles." *Id.*

[28] 40 C.F.R. § 710.3; 40 C.F.R. § 704.3 ("Manufacture for commercial purposes also applies to substances that are produced coincidentally during the manufacture, processing, use, or disposal of another substance or mixture, including both byproducts that are separated from that other substance or mixture and impurities that remain in that substance or mixture. Such byproducts and impurities may, or may not, in themselves have commercial value. They are nonetheless produced for the purpose of obtaining a commercial advantage since they are part of the manufacture of a chemical product for a commercial purpose.").

[29] 44 Fed. Reg. 31525 (May 31, 1979); 40 C.F.R. § 761.

[30] *See, e.g.,* 40 C.F.R. Part 761.

[31] 40 C.F.R. § 761.3.

[32] 45 Fed. Reg. 592 (March 11, 1980);40 C.F.R. § 775 (1980) (prohibiting disposal of 2,3,7,8-tetracholorodibenzo-p-dioxin (TCDD) a manufacturing waste).

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Further, CO_2 emissions are in commerce as they are traded, bought, and sold as carbon offsets. CO_2 is also produced for commerical purposes including for uses in fertilizer, beverage carbonation, dry ice, refrigeration, pressurization, fire extinguishment, and packaging.

B. EPA Should Initiate Rulemaking to Control CO_2 under TSCA

Petitioners request that EPA make finding that CO_2 presents or will present an unreasonable risk of injury to the environment or health. TSCA requires that EPA "shall" initiate rulemaking upon finding "a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use or disposal of a chemical substance of mixture … presents or will present an unreasonable risk of injury to health or the environment."[33]

The information and supporting documents provided in this petition indicate that CO_2 is already causing injury to the environment due to ocean acidification. The scientific evidence further supports that the injury to the environment and health will grow more severe as CO_2 pollution continues. EPA cannot deny that CO_2 is harming the environment. Indeed, EPA acknowledges that ocean acidification poses risk:

> Ocean acidification, like Climate change is primarily caused by increasing carbon dioxide (CO_2) concentrations in the atmosphere. As a result of absorbing large quantities of human made CO_2 emissions the ocean chemistry is changing, which is likely to negatively affect important marine ecosystems and species including coral reefs, shellfish, and fisheries.

(Environmental Protection Agency 2010).

EPA must find that such injury is an unreasonable risk.[34] While Congress did not define the phrase "unreasonable risk," EPA has interpreted relevant legislative history to require that the agency:

> balance the benefits derived from risk reduction against the social and economic costs incurred, taking into account such factors as the extent and magnitude of risk posed; the societal consequences of removing or restricting use of products; availability and potential hazards of substitutes; and impacts on industry, employment, and international trade.[35]

No specific factual determination is necessary to establish "unreasonable risk." For example, even under the stricter standard of 15 U.S.C. § 2606, EPA need not present evidence of actual injury before obtaining emergency injunctive relief to control "immanently hazardous chemical substance[s] or mixture[s]."[36] For the reasons discussed below, application of the agency's balancing test supports the additional regulation of CO_2.

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[33] 15 U.S.C. § 2605(a).
[34] *Id.*
[35] EPA, Guidance for Petitioning the Environmental Protection Agency Under Section 21 of the Toxic Substances Control Act, 50 Fed. Reg. 46,825 (Nov. 13, 1985).
[36] *See* H.R. Conf. Rep. No. 94-1679 78 (1976).

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According to scientific experts: "Reducing CO_2 emissions is the only way to minimise [sic] long-term, large-scale risks" (IBGP et al. 2013).

1. CO_2 Pollution Presents an Unreasonable Risk of Injury to the Environment

There is clear consensus among leading national and international scientific bodies that anthropogenic CO_2 causes changes in ocean chemistry that harm the marine environment. The Intergovernmental Panel on Climate Change ("IPCC") determined that human sources of CO_2 have caused a significant decline in surface ocean pH (Rhein et al. 2013), and over 90 national academies of sciences, including the United States', have signed a statement that ocean acidification will "cause grave harm to important marine ecosystems as CO_2 concentrations reach 450 ppm and above" (Interacademy Panel 2009). The Interacademy Panel concluded that CO_2 has increased ocean acidity with "potentially profound consequences for marine plants and animals" including severe threats to coral reefs, polar ecosystems, and a likely reduction in marine food supplies (*Id.*). The National Research Council also acknowledges that "existing data support a growing consensus in the research community that most documented responses to acidification reflect impairment of physiological capacity or performance" for marine life with likely substantial socioeconomic impacts (National Research Council 2013). The U.S. National Climate Assessment concluded that ocean acidification will alter marine ecosystems in dramatic ways including threatening coral reef habitats and causing reduced growth and survival of shellfish in all regions (Doney et al. 2014).

EPA acknowledges that "ocean acidification presents a suite of environmental changes that would likely negatively affect ocean ecosystems, fisheries, and other marine resources." 75 Fed. Reg. 13538 (Mar. 22, 2010). EPA previously concluded that greenhouse gases, including CO_2, endanger public health and the environment in part because of ocean acidification.[37]

There is no doubt that CO_2 pollution is changing ocean chemistry and harming the marine environment. Unabated, there will be severe and detrimental impacts on marine ecosystems, the economy, and public health. Accordingly, EPA must find that CO_2 poses an unreasonable risk to the environment and health.

a. CO_2 Causes Irreversible Ocean Acidification

Ocean acidification is a major threat to the marine environment. The oceans have absorbed CO_2 emitted into the atmosphere from power plants, manufacturing, cement production, and land use changes. Between 1750 and 2011, human activities have released 375 gigatons of carbon into the atmosphere, and approximately half of that has been absorbed by the oceans (Rhein et al. 2013). Each day about 22 million metric tons of CO_2 is taken up by the oceans (Feely et al. 2008). This uptake of CO_2 is changing ocean chemistry, causing the oceans to become more acidic. Since the industrial revolution surface ocean pH has declined by 0.11 units on average, corresponding with

[37] EPA, Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act 80 (Dec. 7, 2009).

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a 30% increase in acidity (Orr et al. 2005; Caldeira & Wickett 2005).[38] If emissions continue unabated, ocean acidity will increase up to 170% by the end of the century (IBGP et al. 2013).

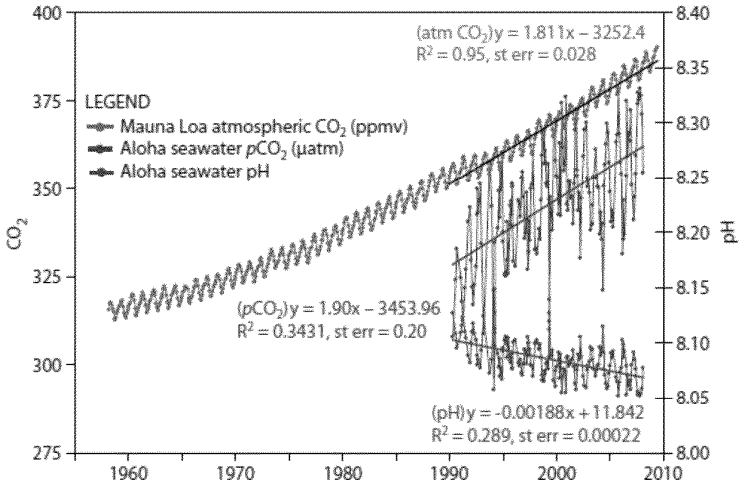

Figure 1. Time series of atmospheric CO 2 at Mauna Loa (ppmv) and surface ocean pH and pCO2 (µatm) at Ocean Station Aloha in the subtropical North Pacific Ocean (see inset map). Note that the increase in oceanic CO 2 over the period of observations is consistent with the atmospheric increase within the statistical limits of the measurements. (Feely et al. 2009).

Anthropogenic ocean acidification exceeds the trend in natural variability significantly, up to 30 times in some regions (Friedrich et al. 2012). The rate of change in ocean acidity is unprecedented in the past 300 million years, a period that includes four mass extinctions (Honisch et al. 2012; Zeebe 2012). The seawater chemistry change is an order of magnitude faster than what occurred 55 million years ago during Paleocene-Eocene Thermal Maximum, which is considered to be the closest analogue to the present, and during that period 96% of marine species went extinct (*Id.*). The current changes in seawater chemistry are irreversible on human timescales (Royal Society 2005).

CO_2's impact on ocean chemistry is fundamentally altering the marine environment with negative impacts on marine species, habitats and ecosystems.

i. What Is Ocean Acidification

When the ocean absorbs CO_2 from the atmosphere it changes ocean chemistry. CO_2 that is absorbed by seawater reacts to form carbonic acid, which dissociates to form bicarbonate and releases hydrogen ions. This reaction reduces the amount of carbonate ions and decreases pH. The oceans store a significant amount of the CO_2 pollution from human activities (Royal Society 2005). While this has provided society with an important service of buffering against climate change impacts, it comes at a cost to the marine environment.

[38] Because the pH scale is logarithmic a small decrease is a significant change in acidity; for example, a decrease of 0.1 pH is an approximate 30 percent increase in acidity.

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Globally, surface water pH has declined 0.11 units on average between 1750 and 1994 (Sabine et al. 2004). Long-term monitoring has documented the impact of increasing atmospheric CO_2 on declining seawater pH in the Pacific and Atlantic Oceans (*see* Figure 2). Results from time-series stations in the North Atlantic and North Pacific show a decrease of about 0.002 pH per year (Rhein et al. 2013).

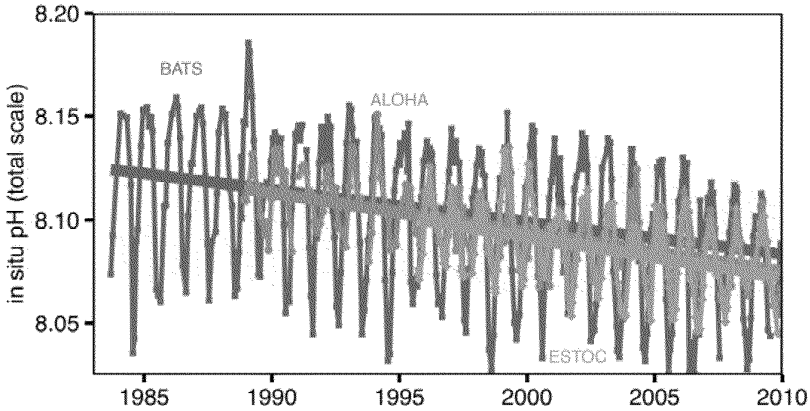

Figure 2. Long-term trends of surface seawater pH at three subtropical ocean time series in the North Atlantic and North Pacific Oceans, including (a) Bermuda Atlantic Time-series Study (BATS, 31°40'N, 64°10'W; green) and Hydrostation S (32°10', 64°30'W) from 1983 to present (updated from Bates, 2007); (b) Hawaii Ocean Time-series (HOT) at Station ALOHA (A Long-term Oligotrophic Habitat Assessment; 22°45'N, 158°00'W; orange) from 1988 to present (updated from Dore et al., 2009) and (c) European Station for Time series in the Ocean (ESTOC, 29°10'N, 15°30'W; blue) from 1994 to present (updated from González-Dávila et al., 2010). Atmospheric pCO2 (black) from the Mauna Loa Observatory Hawaii is shown in the top panel. Lines show linear fits to the data, whereas Table 3.2 give results for harmonic fits to the data (updated from Orr, 2011).(Rhein et al. 2013)

Ocean acidification not only makes the oceans more acidic, but it also reduces the amount of carbonate ions available for animals to build the shells and skeletons they need to survive. Carbonate is an important constituent of seawater because many organisms form their shells and skeletons by complexing calcium and carbonate. Waters that are supersaturated with aragonite are generally good for shell-building, while undersaturated waters (<1.0 Ω_{ar}) are corrosive to some marine animals. Corals require supersaturated waters above 3.3 Ω_{ar} (Meissner et al. 2012). Globally, there has been a decrease of about -0.4 Ω_{ar} (Gruber et al. 2012). The aragonite saturation state has declined 16% since the Industrial Revolution due, in large part, to anthropogenic CO_2 (Feely et al. 2012a; Ishii et al. 2011). Modeling of the oceans' aragonite saturation predicts that by the end of the century up to 75% of ocean volume could be undersaturated with respect to aragonite (Joos et al. 2011).

ii. Observed and Predicted Acidification

CO_2 has already had measurable impacts on seawater chemistry. Some regions, such as those with upwelling systems or high latitudes, are especially vulnerable to ocean acidification.

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1. Pacific Coast

The West Coast is already experiencing adverse impacts of ocean acidification. As early as 2008, a survey off the coasts of Washington, Oregon, and California revealed that this region is already experiencing corrosive waters not expected until mid-century (See figure 3) (Feely 2008). Researchers found seawater undersaturated with respect to aragonite upwelling onto large portions of the continental shelf, reaching shallow depths of 40 to 120 meters (*Id.*). According to the study, the waters were last at the surface approximately 50 years ago when atmospheric CO_2 concentrations were much lower (Feely et al. 2008). Feely et al. report that in the Pacific Ocean there has been a decrease of the saturation state of surface seawater with respect to aragonite and calcite as well as an upward shoaling of the saturation horizon by about 1-2 meters per year on average, due in large part to anthropogenic CO_2 (R. A. Feely, Sabine, et al. 2012). As a result, marine organisms in surface waters, in the water column, and on the sea floor along the West Coast of the United States are already being exposed to corrosive water during the upwelling season.

Modeling of the California Current System demonstrates that the area is rapidly approaching year-round undersaturation with respect to aragonite and it is departing significantly from natural variability (Hauri et al. 2013). Time series monitoring shows that the aragonite saturation state along the California coast is much lower than would be expected in the North Pacific (Harris, DeGrandpre et al. 2013). Surface Ω_{ar} values ranged between 0.66 and 3.9 compared to an estimated pre-industrial range of 1.0 to 4.7. While some areas, like Puget Sound, already exhibit undersaturated conditions every year (Feely, Klinger, et al. 2012; Reum et al. 2014), scientists predict that most shallow shelf areas along the West Coast will become undersaturated with respect to aragonite within the next 20-30 years (Capone & Hutchins 2013; Gruber et al. 2012).

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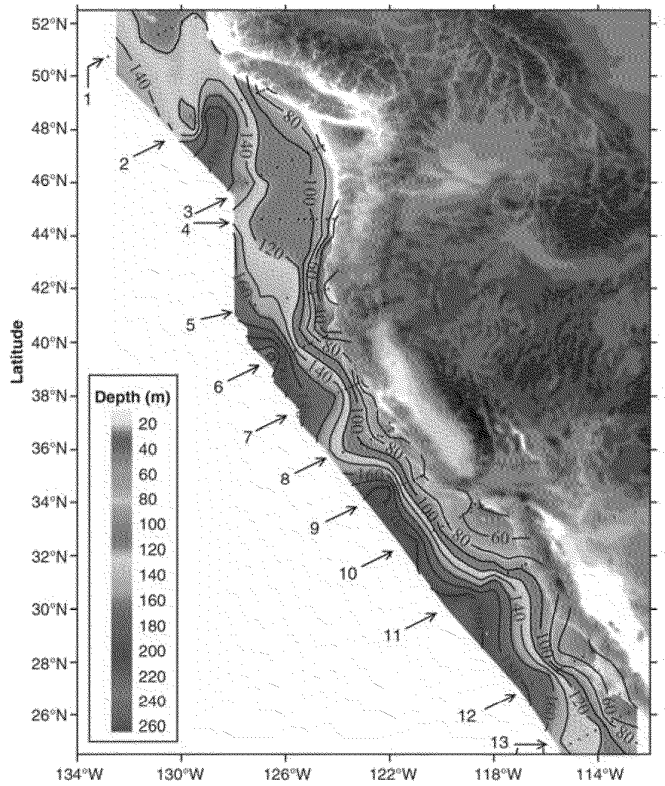

Figure 3. Distribution of the depths of the undersaturated water (aragonite saturation < 1.0; pH < 7.75) on the continental shelf of western North America from Queen Charlotte Sound, Canada, to San Gregorio Baja California Sur,Mexico. On transect line 5, the corrosive water reaches all the way to the surface in the inshore waters near the coast. The black dots represent station locations (Feely et al. 2008).

2. *Alaskan Waters*

High latitude waters are the "bellwether" of ocean acidification because these will be the first ocean regions to become persistently undersaturated with respect to aragonite as a result of greenhouse gas pollution (Fabry et al. 2009; Steinacher et al. 2009). High-latitude waters have naturally lower carbonate ion concentrations and saturation states due to a combination of cold temperatures which increase the solubility of CO_2 and ocean mixing patterns (Fabry et al. 2009; Mathis et al. 2011a). As early as 2016, 10% of Arctic surface waters are expected to be undersaturated with respect to aragonite for at least one month per year (Steinacher et al. 2009).

Recent observations of calcium carbonate saturation states in the North Pacific and Bering Sea have found that full water column undersaturation of calcium carbonate due to ocean acidification is already prevalent. Mathis et al. (2011a) reported that extensive areas of bottom waters over the Bering Sea shelf are becoming undersaturated with respect to aragonite for at least several months (July to September), and some areas of bottom water were already observed to be undersaturated with respect to calcite (Fabry et al. 2009, Mathis et al. 2011a).

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Scientists predict that polar waters will be corrosive to shellbuilding animals within decades (IBGP et al. 2013). A 2015 study of observations in the Chukchi and Beaufort Seas in the Arctic indicates that within 15 years waters will become so corrosive that it will be difficult for marine animals to build and maintain their shells (Mathis et al. 2015). The highly productive fisheries of Alaska are in some of the most rapidly changing seawater conditions (Mathis et al. 2014).

3. Sub-tropical Waters

Subtropical waters have experienced declining saturation states due to ocean acidification. Within decades, scientists believe that ocean acidification will impair coral growth (IBGP et al. 2013). Models show that by the end of the century, most coral reef areas will no longer have aragonite saturation states that are optimal for coral growth. A 10-year study of the Caribbean region found a strong regional decrease in aragonite saturation state between 1996-2006, from 4.05 to 3.9, resulting from CO_2 (Gledhill et al. 2008). Modeling predicts that under various emissions scenarios the coral reefs in the Caribbean will be thermally and chemically stressed between now and 2030 (Meissner et al. 2012). Even under the most optimistic scenario, 98% of reefs will be stressed by 2050 (*Id.*). In the Pacific subtropical ocean near Hawaii, there are nearly 20 years of time-series measurements of significant decreasing seawater pH that match the ocean's uptake of atmospheric CO_2 (Dore et al. 2009)

4. Atlantic Coast

Even ocean waters not at high latitude, in upwelling systems, or containing coral reefs ecosystems are, or will soon be, exhibiting signs of ocean acidification. Observations of East Coast waters during all seasons show that while they remain supersaturated with respect to aragonite, by the end of this century, saturation states of aragonite and calcite will decrease by 20–40%, with the lowest Ωar dropping to 1.3 in some seasons (Jiang et al. 2010). A survey of the Atlantic Coast showed that waters in the Northeast and particularly the Gulf of Maine are the most susceptible to ocean acidification (Wang 2013).

iii. CO_2 Kills and Injures Marine Life

High-CO_2 waters seriously harm marine wildlife and the entire ocean ecosystem. When CO_2 concentrations in seawater increase, the availability of carbonate ions decreases, making it more difficult for marine organisms to form, build, and maintain the calcium carbonate shells and skeletons required for their survival. As seawater becomes more corrosive, it can kill fish eggs and inhibit the development of, and essentially dissolve, the shells of small crustaceans, baby shellfish, and other tiny creatures at the base of the food web (Fabry 2008). Ocean acidification also harms and stresses fish, squid, and other animals that do not build shells (*Id.*). Not only does ocean acidification directly threaten various types of marine animals, it also has implications for the broader marine environment and food web.

The harmful effects of ocean acidification have already begun to occur. For example, ocean acidification has caused:

- A massive die-off of oysters in the Pacific Northwest (Barton et al. 2012; R. a. Feely, Sabine, et al. 2012; Washington State Blue Ribbon Panel 2012);

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- Declines in abundance and size of the California mussel, blue mussel and goose barnacle in tidepools correlated with a severely declining pH (Wootton et al. 2008);
- Sluggish growth of corals in the Caribbean and Great Barrier Reef (De'ath et al. 2009; De'ath et al. 2012; Gledhill et al. 2008); and
- Shells of plankton to dissolve off the California Coast and thinner and weaker shells of plankton in the Southern Ocean (Bednarsek 2014; Moy et al. 2009).

In a meta-analysis of over 400 experiments examining the impacts of ocean acidification on marine organisms, Kroeker et al. (2013) found the biological effects to be generally large and negative. This analysis was restricted to experiments with pH manipulations of less than 0.5 units, in order to reflect the predicted level of ocean acidification by the end of the century (IPCC 2007). By limiting the analysis to small variations in pH, this study shows that within the foreseeable future ocean acidification will have "profound repercussions for marine organisms" (Kroeker et al. 2010). While the negative effect of ocean acidification was most pronounced for calcification and survival (27% reductions in both responses), the study also revealed significant negative effects on growth and reproduction (11 to 19%, respectively). In addition, abundance was reduced by 15%. The strength of this analysis suggests that the patterns highlighted in this study are a robust representation of the current literature on ocean acidification.

While most of the worst consequences of ocean acidification are predicted for the future, scientists have already observed damage from CO_2 in the oceans. Additionally, the impacts of ocean acidification can affect the entire marine food web by altering habitat, prey availability, and species interactions.

b. High-CO_2 Waters Injure the Growth, Survival, Fitness, and Reproduction of Marine Animals

The primary known harm of CO_2 in the oceans is that it impairs the growth and survival of animals that build shells. Because ocean acidification reduces the availability of carbonate ions that marine animals use to calcify their shells and skeletons, CO_2 reduces the ability of these animals to build their protective structures (Doney et al. 2009). Acidified waters can also damage and dissolve shells.

These negative effects have been observed in the ocean as well as documented in laboratory studies. Corals, coralline algae, plankton, mollusks, and other shellfish exposed to future levels of ocean acidification have all experienced problems (Kleypas & Yates 2009; Kuffner et al. 2007; Barton et al. 2012; Talmage & Gobler 2011; Talmage & Gobler 2009; Orr et al. 2005; Riebesell et al. 2000).

i. Molluscs, Echinoderms, and Crustaceans

High CO_2 waters are lethal to shellfish. Since 2005, waters off the coast of Washington and Oregon have been killing oysters and other molluscs. Shellfish hatcheries in Washington and Oregon reported massive mortalities of oyster larvae (Washington State Blue Ribbon Panel 2012).Wild oysters also failed to reproduce in Willapa Bay, Washington (*Id.*). Scientists have definitively linked oyster production failures to high-CO_2 ocean waters that were used to raise larvae (Barton et al. 2012).

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In response to reported shellfish hatchery problems in Oregon, Barton et al. reported the results of their observations from the Whiskey Creek Hatchery on Netarts Bay in the summer of 2009 (Barton et al. 2012). Unlike previous laboratory experiments, this study analyzed calcifying organism responses in the ambient-water CO_2 chemistry of Oregon's coastal waters. Larval production and mid-stage growth (~120 um to ~150 um) of the oyster, *Crassostrea gigas*, were both significantly negatively correlated with the chemistry of waters in which larval oysters were spawned and reared for the first 48 hours of life. Although the impact of the exposure was not immediate, the delayed reaction caused a significant decline in growth for mid-sized oyster larvae and reduced overall production. The findings corroborate other laboratory studies that show that many marine species, especially at the larval stage, are adversely affected by ocean acidification.

Scientific studies have demonstrated that even modest pH declines affect the sensitive and vulnerable early developmental stages of organisms because these life histories have specific environmental needs (Kurihara 2008) (*see* Figure 10, below, showing negative effects from low pH treatments). A number of studies have found a delay in development or less development, degraded shells, decreased rate of metamorphosis, shell thickness, and loss of hinge integrity (Ross et al. 2011a). The resulting reduced larval size can reduce the feeding efficiency of larvae, and smaller larvae are more susceptible to starvation because they encounter comparatively less food (Kurihara & Shirayama 2004). Sub-lethal effects of elevated acidity can severely alter the composition and fitness of larvae, and given the high mortality rates of larvae in the water column and during the transition to benthic settler, small perturbations to larvae potentially may have large alterations to settlement dynamics, post-settlement mortality, recruitment, and ultimately adult populations (Ross et al. 2011).

Watson et al. (2009) exposed one day-old oyster larvae to a range of pH conditions, from 7.6 to 8.1, for 10 days and showed significant decline in the survival and growth of young larvae at lower pH. Waldbusser et al. (2010), in a study on the Chesapeake Bay, showed that even modest changes in pH present conditions that are corrosive to shells and have physiological impacts on adult and larval oysters. Biocalcification declined significantly with a reduction of 0.2 pH units, making juvenile bivalves more susceptible to predation and other mortality factors (*Id.*).

Negative effects have been seen on the metamorphosis, size, and survival of larval hard clams (*Mercenaria mercenaria*), bay scallops (*Argopecten irradians*), and Eastern oysters (*Crassostrea virginica*) at levels of CO_2 predicted to occur in the 21st century (Talmage & Gobler 2011). At 650 ppm, or an approximate drop of 0.3-0.4 from pre-industrial values, both *M. mercenaria* and *A. irrandians* larvae exhibited dramatic declines (over 50%) in survivorship as well as significantly delayed matamorphosis and significantly smaller size. *C. virginica* also experienced lowered growth and delayed metamorphosis at this level, an indicator that current and future increases in CO_2 populations may deplete or alter the composition of shellfish populations in coastal ecosystems (*Id.*).

The Olympia oyster, *Ostrea lurida*, a foundation species in estuaries along the Pacific coast, exhibits clear decline in larval growth and settlement as levels of CO_2 affect seawater pH. (Hettinger et al. 2012). Oysters in this experiment were raised at three levels of seawater pH,

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including a control (8.0) and two additional levels (7.9 and 7.8). Larvae reared under pH 7.8 exhibited a 15% decrease in larval shell growth rate, and a 7% decrease in shell area at settlement, compared to larvae reared under control conditions. Impacts were even more pronounced a week after settlement, with juveniles that had been reared as larvae under reduced pH exhibiting a 41% decrease in shell growth rate.

Oysters on the Atlantic coast also experience the ill effects of ocean acidification. Dickinson et al. (2012) found negative effects on juvenile eastern oysters after exposure to water with a 0.2 pH change. Exposure of the oysters to elevated acidity led to a significant increase in mortality, reduction of tissue energy stores and negative soft tissue growth, indicating energy deficiency. Under ocean acidification conditions, thermal tolerance is impaired in oyster larvae, leading to reduced development, size and increased abnormality (Ross et al. 2011; Parker et al. 2010). Similar results have been found in red abalone, with thermal tolerance impaired at pH 7.87 compared to control (pH 8.05) (Zippay and Hoffman 2010).

In studies with edible mussel (*Mytilus edulis*) and Pacific oyster (*Crassostrea gigas*) researchers found a strong decline of calcification under ocean acidification conditions (Gazeau et al. 2007). Based upon these results, researchers concluded that mussel and oyster calcification may decrease by 25% and 10%, respectively, by the end of the century." (*Id.*). Oysters and mussels also exhibit development abnormalities when exposed to acidification (Kurihara 2008). When oyster eggs were reared under pH 7.8, they showed malformations of their shell, and when reared under pH 7.4, more than 70% of the larvae were either completely non-shelled, or only partially shelled, and only 4% of CO_2 treated embryos developed into normal larvae by 48 hours after fertilization, in contrast to about 70% successful development in control embryos.

The shrimp *Palaemon pacificus* displayed variable responses at different developmental stages, pH and length of exposure (Kurihara 2008). Following long term (30 weeks) exposure of adults to pH 7.89 and 7.64, survival and egg production in early developmental stages decreased in both treatments. Findlay et al. (2010) found a slower rate of development of embryos in the common intertidal northern hemisphere barnacle *Semibalanus balanoides* with an estimated 19 days delay in reaching 50% hatching stage at pH 7.7. Other amphipods have exhibited metabolic changes in response to acidification levels greater than what is allowed under the federal criterion (Hauton et al. 2009).

Echinoderms exhibit delayed and asymmetrical development when exposed to acidified conditions. In the absence of adequate adaptation or acclimation, lowered pH levels will have a range of sub-lethal effects on sea urchins, brittlestar and seastar larvae from a range of geographical regions (Ross et al. 2011). Larvae of the ecological keystone brittlestar, *Ophiothrix fragilis*, either were abnormal, had altered skeletal proportions, or asymmetry during skeletogenesis, and there was a delay in development at pH levels of 7.9, or approximately 0.3 units below current surface levels (Gutowska et al. 2009). Other experiments on brittlestar in low pH waters resulted in dramatic results; acidification of 0.2 units induced 100% larval mortality within an eight day period. Control larvae showed 70% survival over the same period. Because the calcite skeleton of the larval brittlestar aids key functions such as feeding and vertical migration, and defense against predators, abnormal development of the skeleton will have drastic consequences for fitness. The developmental abnormalities may be exacerbated by temperature

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increases predicted for the end of the century; some scientists suggest that this may result in the disappearance of echinoderms from the surface oceans within the next 50-100 years (Ross et al. 2011a).

Reproductive success is compromised by ocean acidification. The fertilization rate of sea urchins decreases with increasing CO_2 concentrations (8.1 to 6.8 pH) (Kurihara 2008). In another sea urchin experiment utilizing six CO_2 concentrations, with a pH between 8.01 (control) and 6.83, cleavage rate, developmental speed, and larval morphology all declined with increased CO_2 concentration (Kurihara & Shirayama 2004). At a 0.2 change from control, effects could be seen on the morphology and development of the larvae, and these effects became more pronounced with greater pH changes (*Id.*) (*see* Figure 4, below). The authors concluded that "all the effects of raised CO_2 concentration observed in this study would have a negative impact on the survival of sea urchin embryos in their early life history." A recent study showed that sea urchin sperm flagellar motility was significantly reduced when seawater pH decreased by .3 units, from 8.0 to 7.7 (Suwa et al. 2010). As discussed above, decreased flagellar motility has severe consequences for fertilization and subsequent population dynamics; if sperm lose their ability to find eggs, the population size will necessarily diminish.

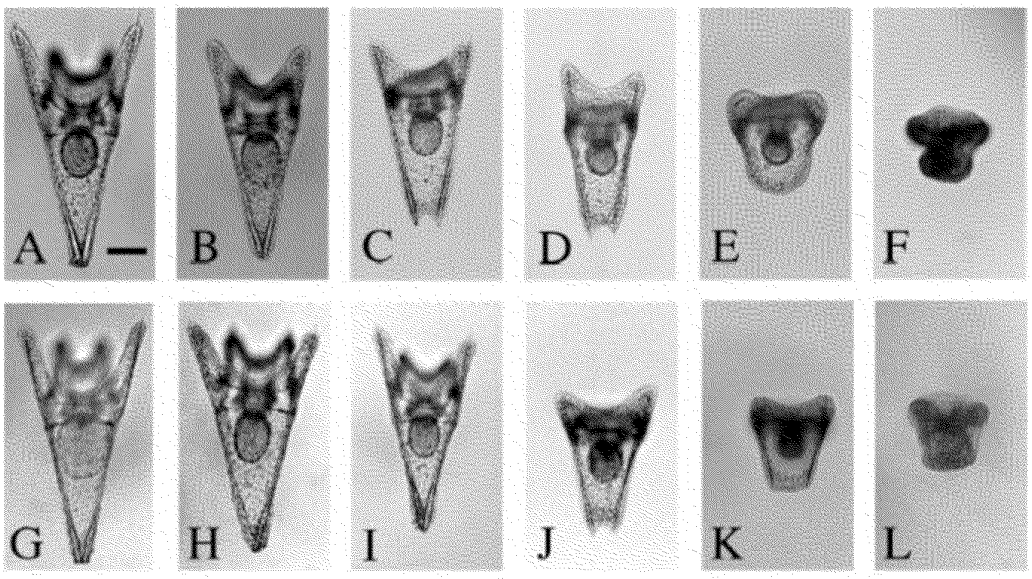

Fig. 6. *Hemicentrotus pulcherrimus*. Morphology of 4-armed pluteus larvae cultured for 3 d in (A–F) CO_2-seawater and (G–L) HCl-seawater. (A & G) control (pH 8.0); (B & H) +500 ppm (pH 7.8); (C & I) +1000 ppm (pH 7.6); (D & J) +2000 ppm (pH 7.4); (E & K) +5000 ppm (pH 7.0); (F & L) +10 000 ppm (pH 6.8). Scale bar = 50 µm

Figure 4. Declining development of sea urchin larvae exposed to acidified waters (Kurihara & Shirayama 2004).

Even moderate increases in atmospheric CO_2 and ensuing acidification adversely affect the growth of both gastropods and sea urchins (Shirayama & Thornton 2005). Before the end of this century, atmospheric CO_2 is likely to increase by more than 200 ppm, decreasing the pH of the ocean by approximately 0.3 units from pre-industrial levels. Two species of sea urchin as well as the gastropod *Strombus luhanus* were exposed for six months to waters with this level of elevated CO_2, and all three species exhibited similar consequences. Increased CO_2 negatively affected growth rate, calcification, shell height and body mass, and metabolic activity

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(Shirayama & Thornton 2005). The developing embryos of the gastropod and intertidal snail *Littorina obtusata* also demonstrate slower overall development time, altered embryonic movement, and modification of shell shape in hatchlings while exposed to acidified waters (pH 7.6) (Ellis et al. 2009).

Arnold et al. (2009) investigated the effect of ocean acidification on lobsters and found that indirect disruption of calcification and carapace mass may adversely affect the competitive fitness and recruitment success of larval lobsters with serious consequences for population dynamics and marine ecosystem function

Reduced metabolism is expected to impair predator-prey interactions, as well as have consequences for growth, reproduction, and survival. Metabolic suppression has previously been reported to occur in a variety of adult marine invertebrates, including crabs, squid, worms, bivalves, pteropods and amphipods (Albright 2011). Slowed metabolism is generally achieved by halting energy-expensive processes, such as protein synthesis, and therefore may lead to reductions in growth and reproductive potential (*Id.*). The blue mussel *Mytilus edulis* has strong physiological mechanisms by which it is able to protect body tissues against short-term exposure to acidified seawater, but these come at an energetic cost, and will result in reduced growth during long term exposures (Bibby et al. 2008). Consequently, the predicted long-term changes to sea water are likely to have a significant effect on the health and survival of blue mussel populations (*Id.*). Mussel beds are a dominant coastal habitat and provide food and structure for a diverse array of species in an otherwise physically stressful environment; any decline in their population structure will lead to a reduction in appropriate habitat for a myriad of other species.

In summary, acidified waters impact the development, growth, and reproductive success of a suite of echinoderms, crustaceans, and molluscs. A growing body of information is becoming available on the effecting of declining pH on these organisms and their ecosystems. The results of these studies are clear; as pH falls even 0.2 units from pre-industrial values, these organisms will struggle to survive in their increasingly acidic environment.

ii. Corals

Coral reef ecosystems, which are estimated to harbor one-third of marine species and which support the livelihoods of a half billion people, are particularly threatened by ocean acidification. Some corals are already experiencing reduced calcification (De'ath et al. 2009; Cooper et al. 2008; Bates et al. 2010; Gledhill et al. 2008). Due to the ocean acidification and warming, reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations of 450 ppm (Veron et al. 2009; Bijma et al. 2013). Prominent coral scientists have called for reducing atmospheric CO_2 to less than 350 ppm to protect coral reefs from collapse (Veron et al. 2009, Frieler et al. 2012). Coral reefs cannot exist below 7.8 pH units (Fabricius et al. 2011), and the threshold for coral growth is 3.3 Ω_{ar} (Meissner et al. 2012).

Ricke et al. (2013) analyzed aragonite saturation state (Ω_{ar}) surrounding reefs in CMIP5 simulations under several representative concentration pathway (RCP) scenarios (Ricke et al. 2013). The study found that in preindustrial times, 99.9% of reefs adjacent to open ocean in the CMIP5 ensemble were located in regions with $\Omega a > 3.5$. Accordingly, the study used $\Omega a = 3.5$ as

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an upper bound viability threshold for corals, while also examining thresholds of $\Omega a = 3.25$ and 3. Under a business-as-usual scenario (RCP 8.5), every coral reef considered was projected to be surrounded by water with $\Omega_{ar} < 3$ by the end of the 21st century and the reefs' long-term fate was independent of their specific saturation threshold. Under scenarios with significant CO_2 emissions abatement, the Ω_{ar} threshold for reefs was critical to projecting their fate. The study concluded that the "results indicate that to maintain a majority of reefs surrounded by waters with $\Omega_{ar} > 3:5$ to the end of the century, very aggressive reductions in emissions are required."

Corals are among the ecosystems most threatened by ocean acidification. To date, most scientific investigations into the effects of ocean acidification on coral reefs have been related to the reefs' unique ability to produce voluminous amounts of calcium carbonate (Kleypas & Yates 2009). The persistence of carbonate structures on coral reefs is essential in providing habitats for a large number of species and maintaining the extraordinary biodiversity associated with these ecosystems. As a consequence of ocean acidification, the ability of marine calcifiers to produce calcium carbonate will decrease, resulting in a transition from a condition of net accretion to one of net erosion, with drastic consequences for the role and function of these ecosystems (Kleypas & Yates 2009).

Coral reefs are predicted to drastically lower their calcification rates in the near future, and historical records show that calcification rates have already fallen relative to pre-industrial values. According to scientists, the main reef building organisms will calcify up to 50% less relative to pre-industrial rates by the middle of this century (*Id.*). A drop of approximately 60% coral reef calcification is projected for the end of the century, when pH is predicted to fall 0.5 units below pre-industrial values (Caldeira & Archer 2007). Many studies suggest calcification rates could be reduced between 20-60% at 560ppm, or 7.9 pH, and that a reduction of this magnitude would fundamentally alter reef structure and function (Convention on Biological Diversity 2009). According to the model of Silverman et al. (2009), developed from field observations from more than 9,000 reef locations, all coral reefs are expected to reduce calcification by more than 80% relative to their pre-industrial rate at 560 ppm (0.3 pH change), and at this point "all coral reefs will cease to grow and start to dissolve." The Interacademy Panel on International Issues concurs; "at current emission rates models suggest that all coral reefs and polar ecosystems will be severely affected by 2050 or potentially even earlier."

In a meta-analysis on coral calcification responses to ocean acidification, the coral calcification declined by a mean of 15% per unit decrease in aragonite saturation state ($2 < \Omega < 4$) (Chan and Connolly 2013). On current emission trends, calcification will decline 22% on average for corals by the end of the century (*Id.*). This falls to the lower range of responses that have been predicted by ocean acidification researchers and described above, which the authors believe reflects variation in the calcification responses of different corals.

Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%, (Caldeira & Archer 2007), and data from the Great Barrier Reef indicates a 14% decline in calcification rates between 1990 and 2005 (De'ath et al. 2009). Other studies in the Great Barrier reef indicate a decline of approximately 21%, and analysis of coral growth records confirm that this decline is unprecedented in recent centuries (Cooper et al. 2008). A model based on field samples shows that calcification of coral reefs in French

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Polynesia declined 15% between the pre-industrial period and 1992, and that rates will decline 40% by 2050, when CO_2 levels reach 560 ppm (pH 7.9) (Anthony et al. 2011). Near Bermuda, historical records show that coral skeletal density has decreased 33%, and coral calcification rates have declined by 52% as a result of changes in seawater carbonate chemistry (Bates et al. 2010). These observed changes have occurred even before a 0.2 unit decline in ocean pH; as atmospheric CO_2 continues to rise and lower pH values, calcification rates will maintain their precipitous decline.

Ocean acidification acts in concert with ocean warming and coral bleaching in furthering coral reef decline (Anlauf et al. 2011) (observing a 3% reduction in acidification with a 0.2 decline in pH, and a 30% decline when acidification is coupled with 1° C warming). While natural variability in the annual cycle and interannual variability may account for some of the observed change in coral growth rates, scientists are "virtually certain" that anthropogenic trends already exceed natural variability (Friedrich et al. 2012). Studies projecting the combined impacts of ocean acidification and ocean warming on corals predict that coral erosion will exceed calcification rates at atmospheric CO_2 concentrations of 450 to 500 ppm, (Hoegh-Guldberg et al. 2007), and all coral reefs will begin dissolve at CO_2 concentrations of 560 ppm (Silverman et al. 2009). These figures correspond to a 0.2 and 0.3 unit drop in pH, respectively, as compared to pre-industrial values. Van Hooidonk et al. (2014) presented updated global projections for threats to coral reefs from ocean warming and ocean acidification based on ensembles of IPCC AR5 climate models using the Representative Concentration Pathways (RCPs). For all tropical reef locations, the study projected absolute and percentage changes in aragonite saturation state (Ω_{ar}) for the period between 2006 and the onset of annual severe bleaching.

In the Caribbean, a recent study concluded that "coral reef communities are likely to be essentially gone from substantial parts of the Southeast Caribbean by the year 2035" (Buddemeier et al. 2011). The Great Barrier Reef has lost 50% of its coral cover since 1985 as a result of the combined effects of ocean acidification, global warming, coral bleaching, coral predation by starfish, and cyclone damage (De'ath et al. 2012). In short, due to the synergistic impacts of ocean acidification, mass bleaching, and local impacts, coral reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations 450 ppm, or pH 8.0, a level that is expected before mid-century (Veron et al. 2009).

Many experimental studies show declining calcification rates and other ill effects when corals are exposed to acidified waters. Decreases in calcification rates across a suite of benthic species and calcifying systems range from 3 to 60% for a doubling in pCO_2, which corresponds to a 0.3 reduction in pH (Abbasi & Abbasi 2011). The average response of corals is a 30% decline in calcification in response to a doubling in pCO_2 (*Id.*). In a study of an assemblage of corals exposed to conditions designed to mimic the change that may be experienced in the next 50-100 years (pH decline of 0.22 to 0.28 units), calcification rates declined between 44% and 80%.

The coral *Acropora palmata* (listed as threatened under the Endangered Species Act), once the dominant reef building coral in the Caribbean, experiences impaired fertilization, settlement, and growth with increasing pCO_2 (Albright et al. 2010). The cumulative impact of ocean acidification on fertilization and settlement success is an estimated 52% and 73% reduction in the number of larval settlers on the reef under pCO_2 conditions projected for the middle and end

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of this century, respectively (0.2 and 0.5 decline in pH) (*Id.*). After only 8 days of high CO_2 conditions (pH 7.75), *Acropora* experiences a statistically significant (18%) reduction in calcification rate (Murubini et al. 2003). Furthermore, there 22 coral species listed as threatened under the Endangered Species Act primarily because of threats from ocean warming, acidification and disease. The rule proposing listing for the corals found that ocean acidification was one of the highest priority threats for corals:

> Ocean acidification has the potential to cause substantial reduction in coral calcification and reef cementation. Further, ocean acidification adversely affects adult growth rates and fecundity, fertilization, pelagic planula settlement, polyp development, and juvenile growth.

77 Fed. Reg. at 73230 (Dec. 7, 2012). In other words, ocean acidification is driving the extinction of corals and the destruction of coral reef ecosystems.

Experimental studies evaluating the effects of ocean acidification on early life history stages of corals generally conclude that primary polyp growth is hindered by increasing acidity (Albright et al. 2010, Cohen & Holcomb 2009). Renegar and Riegl (2005) showed a significant decrease in the growth rate of *Acropora cervicornis* larvae at pH levels 0.3-0.5 units below control. Larvae of the common Atlantic golf ball coral, *Favia fragum*, shows significant delays in both the initiation of calcification and subsequent growth of the primary corallite in acidic waters (8.17 – 7.54 pH) (Cohen & Holcomb 2009). Visible changes in the skeletal development were observed in all non-control treatments, and in the most acidic waters skeletal development was 75% less than the control.

Acidification also affects cold water corals. Cold water corals have a worldwide but patchy distribution, and are often found in areas with highly productive fisheries (De Mol et al. 2002; Kenyon et al. 2003). Overall, more than two-thirds of all known coral species are cold water corals (Roberts & Hirshfield 2012; Cairns 2007). Recent exploration and research that has begun to search for, map, and observe cold water corals has found that these organisms are fragile, long-lived, slow-growing, very sensitive to physical or environmental disturbance and adapted for a specific environmental niche (McDonough & Puglise 2003). Alaskan waters are already showing widespread evidence of ocean acidification as a result of greenhouse gas emissions (Mathis et al. 2011a). By 2100, 70% of cold-water corals will be exposed to corrosive waters (Convention on Biological Diversity 2009). Conditions in waters typically inhabited by cold-water corals are even less favorable for calcification than those experienced by warm water corals; this may cause cold-water corals to be affected earlier and more strongly by CO_2-related ocean acidification than their warm water counterparts (Abbasi & Abbasi 2011).

The vulnerable early developmental and reproductive stages of cold water corals may be especially strongly impacted (Kurihara 2008; Dupont & Thorndyke 2009; Kroeker et al. 2010). In an experiment on the cold-water coral *Lophelia pertusa*, lowering the pH by 0.3 units relative to the ambient level resulted in calcification being reduced by 56% (Maier et al. 2009). Lower pH reduced calcification more in fast growing, young polyps (59% reduction) than in older polyps (40% reduction). Thus, corals' larvae and young corals are significantly more susceptible to ocean acidification than adults, and will likely show a higher degree of reduced calcification

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and growth with reduced pH, making young and larval corals less likely to survive to maturity as the ocean continues to absorb anthropogenic CO_2 and as climate change progresses.

In addition to reduced calcification rates, the strength of cementation may also be reduced in waters with a lower pH, promoting higher rates of physical and bio-erosion (Manzello et al. 2008). Once coral reefs experience lowered calcification and poor cementation, erosion and reef flattening can result, which severely reduced the structural heterogeneity of reefs and lowers its potential to support biodiversity. An important new study of reef bioerosion determined that the combined effects of lower calcification with increased bioerosion can significantly degrade coral reefs (Wissshak et al. 2012). In the study, a common bioeroding sponge in the Great Barrier Reef was observed on massive Porites. The sponge was more effective at bioerosion of the corals at high CO_2, ranging from 17% increase from present day levels to 61% increase at the highest CO_2 treatment. The researchers describe the important role of balancing the antagonistic processes of calcification and bioerosion in a reef for a healthy coral ecosystem, and predict detrimental consequences under ocean acidification as calcification declines and bioerosion increases.

Bioerosion may result in a loss of change in fish assemblages, lower densities of commercially important species, and lower rates of larval fish recruitment (Feary et al. 2007). Weaker reef calcification and cementation also increases the potential for reef damage as storm frequency and intensity increases with continued global warning, leading to further reef degradation (*Id.*). In a study looking at the impacts of storm damage and ocean acidification, researchers concluded that table coral populations are vulnerable to collapse (Madin et al. 2012). In the Indo-Pacific, table corals provide an important role in the reef ecosystem by creating reef structure and sheltering other reef species. They are also particularly vulnerable to ocean acidification, thermal stress, bleaching, disease and stress from storm waves. The table corals will become more vulnerable to storm waves as ocean acidification reduces calcification and increases bioerosion, therefore weakening their cementation and structure. Madin et al. (2012) found that a coral colony was four times more likely to be dislodged by a storm wave by the end of the century ocean acidification levels. Because of this vulnerability, the results showed that table corals are prone to large and rapid declines in coral cover.

Numerous biological responses independent of calcification are also negatively impacted by ocean acidification. Corals in acidifying waters are likely to be in a nutritionally or energetically stressed state and thus less likely to initiate reproduction, or successfully reproduce, due to negative impacts of ocean acidification on all stages of the reproductive cycle (Maier et al. 2009; McCulloch et al. 2012). Sperm flagellar motility also declines in response to decreasing pH. If sperm lose their ability to find eggs in the vast extent of the sea, the life of marine organisms is potentially limited. Sperm flagellar motility, which is indispensable for fertilization, is regulated by an elevation of intracellular sperm pH (Morita et al. 2010). While 69% of *Acropora* sperm were motile at pH 8.0, 46% were motile at pH 7.8, and fewer than 20% at pH 7.7 (*Id.*). Additionally, the physiological costs associated with reproduction are more likely to result in the demise of the organism due to the compounding stressors from ocean acidification and climate change (Wood et al. 2008, Cohen & Holcomb 2009). Significant reductions in metabolism have been observed for coral larvae following exposure to waters with a 0.2 decline in pH, levels projected to occur by the middle of this century (Albright & Langdon 2011).

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Albright et al. (2010) concluded that with increased CO_2 concentrations to those projected to occur in this century (560 atm to 800 atm, or a 0.3 to 0.5 decline in pH from pre-industrial values), the fertilization success of the tropical reef-building coral *Acropora palmata* decreased by 12-13%, settlement success reduced 45-69%, and linear extension was significantly reduced. The compounding effect of these impacts translated to 52-73% reduction in the number of larval settlers on the reef. Albright et al. (2010) predicted that the net impact on recruitment would actually be greater than that given that the depressed post-settlement growth is likely to result in elevated rates of post-settlement mortality. This corroborates other studies showing negative impacts on early-stage tropical corals.

Albright and Langdon (2011) tested the effects of ocean acidification on sexual recruitment of tropical corals. Larval metabolism was depressed by 27% at acidification levels expected by mid-century (0.3 pH reduction) and 63% at end-of-century acidification levels (0.4-0.5 pH reduction). Settlement was also reduced 42-45% and 55-60% at the mid and end-of-century levels respectively, relative to controls (Albright & Langdon 2011). Another study of larvae of tropical corals showed that short-term or long term exposure of larvae to ocean acidification decreased their metamorphosis (Suwa et al. 2010). This means that even when larval survivorship is unchanged, the success of recruiting new corals could be inhibited by ocean acidification (*Id.*).

Additionally, under conditions of acidification planktonic larvae lose their preference for settlement on the optimal crustose coralline algae communities (Doropoulos et al. 2012). Crustose coralline algae in turn, will experience a lower recruitment rate as marine waters become more acidic. Crustose coralline algae, a red calcifying algae, is of key importance in coral reef ecosystems, stabilizing reef structures and providing an important food source for benthic organisms (Convention on Biological Diversity 2009). Crustose coralline algae form a major calcifying component of the marine benthos from polar to tropical regions and are considered to influence the settlement of coral recruits. With a mean pH change of 0.26 between control and treatment, Kuffner et al. (2007) found that crustose coralline algae growth rates declined by 40%, and recruitment rate and percentage cover decreased by 78% and 92%, respectively.

In sum, reproduction is critical to maintaining a healthy coral reef population, and the long-term impacts of ocean acidification on reproduction, especially on larval settlement and growth, may significantly reduce the corals' ability to recover or maintain a population in the face of human caused disturbances and anthropogenic CO_2 emissions. This would result in a lack of reproductive capacity, genetic bottlenecks, and population collapse (Dupont et al. 2010; Ross et al. 2011).

As the world's oceans become more acidic and less saturated with carbonate minerals, corals are expected to build weaker skeletons and experience slower growth rates, which will make it more difficult for corals to retain competitive advantage over other marine organisms (Guinotte et al. 2006). As coral skeletons weaken, they will become increasingly at risk of storm damage and bioerosion, which will reduce the structural complexity of the reef system, reducing habitat quality and diversity alongside the loss of coastal protection functions (Hoegh-Guldberg et al. 2007). At greater than 550 ppm, coral reef ecosystems will be reduced to "crumbling

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frameworks." (*Id.*). Extensive studies have demonstrated that small changes in ocean chemistry will cause a suite of negative impacts, from reduced calcification rates to lowered reproductive success.

iii. Plankton

Plankton, which comprise the basis of the marine food web, are among the calcifying organisms adversely affected by ocean acidification. Changes to calcifying zooplankton, such as pteropods and foraminfera, have the potential to affect the ecological and tropic dynamics which govern the exchange of energy and cycling of nutrients throughout the marine food web (Gattuso & Hansson 2011). For example, the shelled pteropod, *Limacina helicina*, an Arctic pelagic mollusc, is a food source for higher predators such as fishes, whales and birds that are particularly important in high latitude areas. *L. helicina* makes up about 60 percent of the pink salmon diet (Comeau et al. 2012). A decline of pteropod population would likely cause dramatic changes to various pelagic ecosystems, and impact the commercially important salmon fishery; a 10% decrease in pteropods can lead to a 20% reduction in pink salmon body weight (Aydin 2005).

Pteropods form integral components of food webs, and are considered an overall indicator of ecosystem health (Orr et al. 2005). Studies have shown that pteropods exposed to a pH value predicted for the end of this century exhibited a 28% decrease in calcification (Comeau et al. 2009). Experiments on *L. helicina* showed that changes from 8.05 pH to 7.89 pH (Δ -0.16 units) cased shell dissolution and cracks appeared at 7.76pH, and linear extension of the shell decreased as a function of declining pH (Comeau et al. 2012). Samples show dissolution already happening in areas that have low aragonite saturation states. A sampling study off the coasts of California, Oregon, and Washington showed average to severe dissolution of *L. helicina* for 53% of onshore individuals and 24% of offshore individuals (Bednarsek 2014). A sampling study in 2008 of the Southern Ocean found severe dissolution of *L. helicina* in Ω_{ara} 1.0 (Bednarsek 2012). Another study found shell weights of one form of Antarctic species declined 35% from 1997-2006 (Roberts unpublished).

Ample studies corroborate that high CO_2 waters dissolve the shells of *L. helicina* and reduce calcification rates. Comeau et al. (2010) noted decreased calcification for *L. helicina* with decrease in aragonite saturation. Lishka (2012) looked at overwintering *L. helicina* and L. retroversa in the Arctic and noted that they do not calcify in the winter, and they are subject to dissolution under high CO_2 conditions. Bednarsek (2012) looked at *L. helicina* and *Clio pyramidata* from the Southern Ocean under different aragonite saturation states and recorded dissolution stages.

Modeling by Comeau et al. (2012) shows that by the end of the century *Limacina helicina* will not be able to calcify over much of the Arctic because of aragonite undersaturation—prediction may be conservative because it did not account for shell dissolution. Commentary suggests that as waters warm these pteropods will be trapped in acidified conditions and will "disappear entirely by the end of the century." Modeling suggests that waters in the California Current will be undersaturated year-round by 2050 (Gruber 2012). Modeling of the Arctic suggests that by mid-century the Bering Sea will be persistently undersaturated with respect to aragonite (Mathis 2011). An analysis of survey measurements in 2005-2006 and 1991-1992 demonstrated a

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shoaling of the aragonite saturation state in waters off Alaska (Feely et al. 2012). In the North Pacific the aragonite saturation state shoaled to depths less than 200 m between 40˚N and 50˚N (*Id.*). On average, the calcite saturation horizon in the Pacific shoaled about 1 m/yr from 1991 to 2006 (*Id.*).

Other species of plankton are also harmed by CO_2. Another pteropod, *Clio pyramidata,* kept in aragonite undersaturated waters began to dissolve within two days (Orr et al. 2005). Some coccolithophorids are also susceptible to ocean acidification. Studies showed that CO_2 related changes to seawater caused reduced calcification, resulting in malformed and incomplete shells. Calcification of cocolithophorids declined 15-44%, and their shells were malformed as pH changed up to about 0.3 units (Riebesell et al. 2000). Coccolithophorids are globally distributed and bloom in massive areas affecting the optical properties of the ocean, reflecting light from the earth, and play a major role in the ocean carbon cycle. Elevated CO_2 concentrations also reduce the shell mass of foraminifera (Kleypas et al. 2006). Modern shell weights of foraminifera in the Southern Ocean are 30–35% lower than those from preindustrial sediments, which is consistent with reduced calcification induced by ocean acidification (Moy et al. 2009).

iv. Cephlopods and Fish

The negative physiological effects of ocean acidification are not confined to invertebrates. For example, the gametes, embryos, and larvae of vertebrates such as fish are vulnerable to changes in ocean chemistry and have shown impairments in their homing and predator/prey detection capabilities.

Changes in the ocean's CO_2 concentration result in accumulation of CO_2 in the tissues and fluids of fish and other marine animals, called hypercapnia, and increased acidity in the body fluids, called acidosis. These impacts can cause a variety of problems for marine animals, including difficulties with acid-base regulation, calcification, growth, respiration, energy turnover, predation response, and mode of metabolism (Pörtner et al. 2005; Pörtner et al. 2004). Studies have shown adverse impacts in squid and fish, among other animals (Rosa & Seibel 2008; Ishimatsu et al. 2004; Pörtner et al. 2004). For example, when exposed to acidification, orange clownfish suffer a type of brain malfunction that interferes with their homing abilities and makes them 5-9 times more likely to swim toward a predator (Munday et al. 2009; Simpson et al. 2011; Ferrari et al. 2011).

Laboratory experiments have shown that ocean acidification at levels expected to occur within this century impairs larval orange clownfish and damselfish sensory abilities and behavior, making it more difficult for them to locate suitable settlement sites on reef habitat and avoid predators. Specifically, ocean acidification disrupts smell, hearing, and behavior of larval orange clownfish, (Munday et al. 2009; Nilsson et al. 2012), making larval clownfish attracted to odors from predators and unfavorable habitat (Munday et al. 2010; Dickson et al. 2010). Olfactory cues that prompted avoidance or neutral behavior in controls (pH 8.15) stimulated strong preference behavior in larvae raised at pH 7.8, in addition to significant reduction in response to usually positive preferences. Ocean acidification also impairs the hearing capacity of larval clownfish, which is predicted to have negative effects on settlement success and survival (Simpson et al. 2011).

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Similarly, research on six damselfish species found that ocean acidification impairs larval damselfish smell, vision, learning, behavior, and brain function, leading to higher risk of mortality. For example, in acidified waters, larval damselfish (1) become attracted to predator odors and display much riskier behaviors, making them more prone to predation; two species suffered a five-fold to nine-fold increase in predation rate at CO_2 levels of 700 to 850 ppm, or 0.3 pH units below control (Munday et al. 2009; Ferrari et al. 2011); (2) cannot discriminate between habitat olfactory cues, making it more difficult to locate appropriate settlement habitat (Devine et al. 2011); (3) settle on the reef during dangerous times—the full moon rather than new moon—when they are more vulnerable to predation (Devine et al. 2011); (4) fail to visually recognize or evade important predator species; (5) cannot learn to respond appropriately to a common predator by watching other fish react or by smelling injured fish, unlike fish under normal conditions (*Id.*); and (6) suffer disruption of an important neurotransmitter which is thought to result in the sensory and behavioral impairment observed in acidified conditions (Nilsson et al. 2012).

An animal's ability to transport oxygen is reduced by pH changes (Pörtner 2005). Water breathing animals have a limited capacity to compensate for changes in the acidity (Haugan 2006). For example, fish that take up oxygen and respire CO_2 through their gills are vulnerable because decreased pH can affect the respiratory gas exchange (Royal Society 2005). Changes in metabolic rate are caused by the changes in pH, carbonates, and CO_2 in marine animals (Haugan 2006).

Squid, for example, show a very high sensitivity to pH because of their energy intensive manner of swimming (Royal Society 2005). Because of their energy demand, even under a moderate 0.15 pH change squid have reduced capacity to carry oxygen and higher CO_2 pressures are likely to be lethal (Pörtner 2004). Even species more tolerant to pH changes experience decreased metabolism from increased CO_2 in the water (Pörtner 2004). For example, as much as 50% mortality was observed in copepods after only six days of exposure to waters with a pH level 0.2 units below the control (Pörtner 2005). Reducing pH by 0.3 pH cased a 31% decline in metabolic rate and a 45% decrease in activity level for the jumbo squid, an important predator in the Easter Pacific (Rosa & Seibel 2008).

In fish, pH also affects circulation. Fishexposed to high concentrations of CO_2 in seawater experience cardiac failure and increased mortality (Ishimatsu 2004). At lower concentrations sublethal effects can be expected that can seriously compromise the fitness of fish. Juvenile and larval stages of fish were found to be even more vulnerable (Ishimatsu 2004).

In sum, ocean acidification can have many adverse effects on marine animals that can reduce their fitness and survival (Royal Society 2005). Many marine animals have low thresholds for long-term CO_2 exposure (Pörtner 2005).

c. Other Environmental Impacts of Ocean Acidification

i. Increased Toxicity of Harmful Algal Blooms and Sediments

Ocean acidification may already be increasing the toxicity of harmful algal blooms known as "red tides." These toxic red tides poison shellfish, marine mammals, fish, and even cause

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paralytic shellfish poisoning in people. High CO_2 levels in seawater magnify the toxins of harmful algae. (Fu et al. 2012; Avery O Tatters et al. 2013; Tatters et al. 2012; Avery O. Tatters et al. 2013). Studies of the genus *Pseudo-nitzscia* show that the toxicity of diatoms which produce a neurotoxin increases significantly under ocean acidification conditions. A -0.5pH change caused toxin production in the diatoms to increase 4.2-fold and a -0.3pH unit change increased the toxicity 2.5-fold (Tatters et al. 2012). Many studies on the effects of ocean acidification and algal blooms have been conducted at CO_2 levels that are already occurring in California, and the increase in the toxicity of harmful algal blooms in Southern California (and resulting mass mortalities of fish and marine mammals) may be due, in part, to acidified waters (*Id.*) However, these studies suggest that the damage will become much worse.

Additionally, research shows that under conditions of ocean acidification sediments become more toxic (Roberts, Birchenough et al. 2013). Ocean acidification makes sediment-bound metals more available and thus more toxic for aquatic life (*Id.*) For example, ocean acidification increases the toxicity of copper (Campbell & Mangan 2014).

ii. Noise Pollution Increases in Low pH Waters

Ocean acidification can also decrease the sound absorption of seawater, causing sounds to travel further with potential impacts on marine mammals and other marine life sensitive to the sounds of vessel traffic, seismic surveys, and other noise pollution (Hester et al. 2008). Sound travels 10-15 percent further with a change of 0.1 pH, and it is predicted to increase about 40 percent by mid-century (Hester et al. 2008). Additionally, a decline of 0.3 pH units causes a 40 percent decrease in the sound absorption of surface seawater and sound may travel 70 percent farther, further affecting sensitive marine mammals (Brewer et al. 2009).

d. Ocean Acidification's Ecosystem Impacts

While the full implications of elevated CO_2 on marine ecosystems are not well-documented, there is high confidence that there will be negative ecosystem consequences from ocean acidification. The exact changes are difficult to predict, but some of the anticipated impacts include loss of diversity, loss of abundance of calcifying species, shifting prey and predator interactions, and loss of suitable habitat.

New mesocosm studies have sought to understand some of the potential ecosystem impacts of CO_2. Studies of biodiversity near underwater volcanic vents demonstrate reduced richness in high-CO_2 waters. For example, coral species diversity declined by about 39% between low and high-CO_2 sites, with the reefs shifting from complex communities to a coral reef dominated by massive Porites. Most importantly, the researchers found that coral reef development ceases at 7.7 pH, and they concluded that a pH decline below 7.8 would be "catastrophic for coral reefs" (Fabricius et al. 2011). Scientists also observed that in high-CO_2 waters the loss of complex coral reef habitat resulted in a loss of diversity of reef-associated species such as crustaceans and crinoids (Fabricius et al. 2014). Looking at the macroinvertebrates, the density declined 48% between control and high-CO_2 areas and taxa diversity declined by 77% (*Id.*).

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Loss of species diversity associated with ocean acidification can also result from changes in competitive interactions. A study of a rocky reef near volcanic vents documented that macro algae outcompeted calcareous species in low-pH waters (Kroeker et al. 2012). The researchers explained that under the high-CO_2 conditions the calcifying species grew more slowly while the seaweed took hold and that grazing of seaweed was depressed (*Id.*). In another study, while the areas near volcanic vents lacked scleractinian corals and had low abundance of sea urchins and coralline algae, invasive algal species benefited from the acidified conditions (Hall-Spencer et al. 2008).

Research on the diversity the intertidal community in the Pacific Northwest documented a shift from a ecosystem dominated by calcifying animals to one with non-calcifying organisms as pH declined. Researchers documented declines in abundance and size of the California mussel, blue mussel, and goose barnacle in tidepools on the Olympic Coast in Washington (Wootton et al. 2008). They found that in years with low pH waters the calcifying animals were replaced by non-calcifying organisms (*Id.*).

The synergistic impacts of ocean acidification and warming are also potentially severe. Ocean acidification may induce a negative climate feedback that may increase temperature rise. Mesocosm studies found that ocean acidification may amplify global warming through decreasing biogenic production of the marine sulfur component dimethylsulphide which can impact cloud albedo (Six 2013). Ocean acidification therefore may also contribute to climate change impacts on the environment.

2. Risk Reduction Costs and Benefits

EPA must make a determination whether the risk of ocean acidification is unreasonable and this constitutes a balancing of costs and benefits. While it is EPA's burden to conduct this analysis, petitioners present some limited data on (1) the socio-economic costs of CO_2 pollution in light of ocean acidification, (2) the feasibility of controls on CO_2 pollution, and (3) the social cost of carbon including the costs of delaying action to reduce and mitigate CO_2 pollution.

a. Socioeconomic Costs of Ocean Acidification

The release of CO_2 into the environment is already having social and economic impact, and these impacts are predicted to become even more concerning. Primary economic concerns are from the loss of fisheries and coral reefs. Ocean acidification also poses food security and nutrition risks.

U.N. Convention on Biological Diversity estimated costs on the predicted damage of ocean acidification and predicts that the oceans will lose more than $1 trillion in value annually from ocean acidification (Convention on Biological Diversity 2014). CO_2 related ocean warming and acidification will threaten marine food resources by disrupting marine communities, promoting harmful algal blooms and the spread of some diseases, and increasing contaminants in fish and shellfish (Tirado et al. 2010).

The United Nations Environment Programme reported that ocean acidification's impact on marine organisms is a threat to food security (UNEP 2010). The report documents that ocean

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acidification is measurable and increasing, which poses a threat to fisheries resources and the billions of people that have a marine-based diet (United Nations Environment Programme 2010). Seafood has been shown to prevent hundreds of thousands of premature deaths, as well as significantly reduce infant morbidity; a decline of seafood availability will decrease these benefits. Some populations, including subsistence fishing populations and poor communities, depend on seafood and mortality and morbidity can result from the loss of these food sources (Mozaffarian 2006). For example, 95% of Alaskan households do some sort of subsistence fishing, and 17% of the state's population, 120,000 people, depend on subsistence fishing (Mathis et al. 2014). Many subsistence fishers also have cultural ties threatened by ocean acidification. Accordingly, CO_2 can result in social and environmental justice concerns that must also be assessed and weighed (Convention on Biological Diversity 2014).

Not only will ocean acidification affect global food webs and ecosystems, it will have a direct effect on the global economy. The U.S. economy is very dependent on the health of the ocean. In 2009, the ocean economy contributed over $223 billion annually to the U.S. gross domestic product and provided more than 2.6 million jobs (NOAA, http://oceanservice.noaa.gov/facts/oceaneconomy.html). Cooley and Doney (2009) estimate that if just a 10-25% decrease in United States mollusk harvests from 2007 were to occur today, $75-187 million in direct revenue would be lost each year henceforth, with a net loss of $1.7-10 billion through mid-century, when pH levels are approximately 0.3 units below pre-industrial values. In Washington State alone, the seafood industry generates $1.7 billion for gross state product and employs 42,000 people (Washington State Blue Ribbon Panel 2012). Already, shellfish hatchery failures in Washington have caused an economic stir and caused some hatcheries to relocate. Alaska's commercial fishing industry is valued at over $4 billion a year, and supports 90,000 jobs—recreational fishing and fishing tourism add even more value. Meanwhile, Alaska is ranked among the most vulnerable areas to acidification.

Tropical coral reefs provide ecosystem services, such as habitat and nursery functions for commercial and recreational fisheries and coastal protection. As reefs decline in acidified waters, there will be an ecological shift to a new ecosystem state dominated by less commercially valuable species. In 2009, Brander et al. estimated the annual economic damage of ocean acidification-induced coral reef loss to escalate rapidly over time, reaching $870 billion by 2100 (Brander et al. 2009a). In 2014, Brander et al. increased the anticipated loss of ecosystem services from corals to be $1000 billion (UNEP 2014). Shoreline protection offered by coral reefs and the services it provides by preventing loss of life, property damage and erosion are also reduced by CO_2 emissions.

Lane et al. (2014) modeled three major U.S. locations for shallow water reefs -- South Florida, Puerto Rico, and Hawaii – to project future reef cover and the economic values generated by coral reefs for a greenhouse gas emissions mitigation scenario that represents international implementation of policies to reduce global emissions (resulting in a CO_2 concentration of 427 ppm in 2100), compared to a business as usual greenhouse gas emissions scenario resulting in a CO_2 concentration of 785 ppm in 2100. The study estimated that reducing emissions would result in an "avoided loss" in Hawaii of approximately $10.6 billion in recreational use values compared to business as usual. Reducing emissions was projected to provide fewer economic benefits in Puerto Rico and South Florida, where sea-surface temperatures are already close to

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bleaching thresholds and coral cover is projected to drop well below 5% cover under both scenarios by 2050, and below 1% cover under both scenarios by 2100 (Lane et al. 2014).

As discussed previously, the toxicity of harmful algal blooms increases under conditions of ocean acidification. These toxins not only poison marine mammals, but also cause paralytic shellfish poisoning in people. Scientists hypothesize that some of the increases red tides off the coast of Southern California may be related to ocean acidification, though this has yet to be confirmed. In turn, harmful algal blooms cost the United States approximately $82 million each year from impacts to fisheries, public health, management, and lost recreational opportunities (Hoagland and Scatasta 2006).

A recent study estimated that the damage our oceans will face from emissions-related problems will amount to $428 billion a year by 2050 and nearly $2 trillion per year by the century's end (Noone et al. 2012).

> Acidification impacts processes so fundamental to the overall structure and function of marine ecosystems that any significant changes could have far-reaching consequences for the oceans of the future and the millions of people that depend on its food and other resources for their livelihoods.

(Doney et al. 2009). There is also a significant cost to delaying action. According to a recent report by the Council of Economic Advisers, delaying the implementation of policies to mitigate climate change could significantly increase economic damages, in addition to worsening environmental harm.[39]

While there are still large unknowns on the biological consequences of ocean acidification, the science we have is clear: from shellfish to corals, and from pteropods to fish, our marine resources are threatened by the acidification of our ocean waters.

b. Risk Reduction Methods

There are several ways to reduce risk from CO_2. EPA should use a suite of tools to reduce emissions, sequester CO_2, mitigate harms, and promote alternatives. Under TSCA EPA has authority to:[40]

- prohibit or limit the amount of production or distribution of a substance in commerce;
- prohibit or limit the production or distribution of a substance for a particular use;
- limit the volume or concentration of the chemical produced;
- prohibit or regulate the manner or method of commercial use;
- require warning labels and/or instructions on containers or products;
- require notification of the risk of injury to distributors and, to the extent possible, consumers;

[39] Executive Office of the President of the United States, The Cost of Delaying Action to Stem Climate Change at 1 (July 2014).
[40] 15 U.S.C. § 260.

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- require record-keeping by producers;
- specify disposal methods; and
- require replacement or repurchase of products already distributed.

EPA also may impose any of these requirements in combination or for a specific geographical region. [41] Specifically, the agency must impose controls sufficient "to protect adequately against such risk using the least burdensome requirement."[42]

There is evidence that many industries could employ existing technology to achieve meaningful emissions reductions affordably. EPA's own data demonstrate that lower pollution rates are readily achievable for many industrial sources of CO_2. For example, the agency has identified dozens of "control measures and energy efficiency options that are currently available for pulp and paper mill processes," ranging from technological upgrades to improved equipment maintenance.[43] Similarly, EPA has compiled more than a decade of reports on "cost-effective" control strategies and other approaches available to reduce cement plant CO_2 emissions, "includ[ing], for example, energy efficiency measures, reductions in cement clinker content, and raw materials substitution."[44]

Although cost-effective strategies to reduce CO_2 emissions are available, existing controls have not reduced CO_2 emissions sufficiently to protect against environmental harm. For example, most natural gas power plants have *never* exceeded the agency's recently proposed emissions limit, thus indicating that existing and newly constructed facilities could easily satisfy a more stringent standard.[45] Because energy-related CO_2 pollution accounts for more than eighty percent of U.S. greenhouse gas production, readily achievable reductions in this sector would significantly benefit the environment.[46] Similarly, the pulp and paper industry ranks among the largest consumers of energy,[47] and emitted nearly 58 million metric tons of CO_2 equivalent gases in 2004.[48] Moreover, market incentives and regulatory controls are effective in increasing the rate of innovation for technologies that can reduce CO_2 emissions.

If a chemical presenting an unreasonable risk to health and the environment has already been distributed, EPA may prescribe procedures by which relevant manufacturers and purchasers must replace or repurchase that chemical.[49] In the present situation, we urge the agency to exercise its

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[41] *Id.*
[42] 15 U.S.C. § 2605(a).
[43] *See* EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 11 (2010).
[44] EPA, National Emission Standards for Hazardous Air Pollutants From the Portland Cement Manufacturing Industry and Standards of Performance for Portland Cement Plants, 75 Fed. Reg. 54,970, 54,997 (Sep. 9, 2010).
[45] Ctr. for Biological Diversity, Comments on Standards of Performance for Greenhouse Gas Emissions from New Stationary Sources: Electric Utility Generating Units (Proposed Rule) Docket No. EPA-HQ-OAR-2013-0495 at 13-14 (May 9, 2014).
[46] U.S. Dept. of State, U.S. Climate Action Report at 16 (2010).
[47] *See* U.S. Energy Information Administration, First Use of Energy for All Purposes (Fuel and Nonfuel), 2010 (Mar. 2013), http://www.eia.gov/consumption/manufacturing/data/2010/#r1.
[48] EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 7 (2010).
[49] 15 U.S.C. § 2605(a)(7)(C).

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authority to remediate existing harm by requiring that responsible parties mitigate past CO_2 emissions.

There are numerous approaches to mitigating and sequestering CO_2 emissions that EPA must evaluate. Effective land use and agricultural practices can significantly reduce carbon emissions and sequester CO_2. Federal programs aimed at consumers can reduce CO_2 emissions. For example, EPA's Energy Star program has prevented 1.8 billion tons of greenhouse gas emissions by providing information that helps customers select energy efficient devices. Sequestration of CO_2 in products, infrastructure, and waste management are among numerous methods that could be cost-effective to mitigate CO_2 pollution.

c. Social Costs of Carbon

In any analysis of the cost and benefits of reducing CO_2 pollution, the costs of failing to address the problem of global warming should be included. Most efforts to quantify the social costs of carbon underestimate the real-world costs of CO_2 pollution. Nevertheless, EPA may not ignore these costs.

Global emissions must be less than 1000 Gt of CO_2 between 2000 and 2050 to avoid dangerous climate change, which scientists have recommended that this means maintaining temperature change below 2° C.[50] This means keeping atmospheric CO_2 to 450 ppm, a threshold below which experts also use for ocean acidification (Veron et al. 2009; Silverman et al. 2009; Interacademy Panel 2009; McNeil & Matear 2008; Sea et al. 2007). For example, coral scientists predict that at 450 ppm, reef-building will be severely diminished or will cease altogether (Veron et al. 2009). But the global community has already used a substantial portion of this CO_2 budget, emitting 305 Gt of CO_2 between 2000 and 2008 alone.[51] As a result, the years between now and 2020 have been dubbed the "critical decade."[52] Because carbon emissions must peak soon and decline thereafter, the sooner emissions peak, the less severe the subsequent annual reductions will need to be;[53] correspondingly, if emissions are not sufficiently curbed in this decade, avoiding catastrophic damages will require much more drastic, disruptive and costly measures and may no longer be possible at all. Nonetheless, if action is taken immediately, it is both technologically and economically feasible to reduce emissions by 2020 and lay the groundwork for future emissions reductions.[54]

Every year that the world delays its efforts to reach sustainable levels of greenhouse gas emissions represents a lost opportunity of tremendous economic significance. McKinsey & Company estimated in 2009 that for every year of delay, 1.8 Gt of potential CO_2 abatement is foregone.[55] This delay, and the accompanying Gts of lost CO_2 abatement, has a price tag, as the

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[50] Australia Department of Climate Change and Energy Efficiency, The Critical Decade: Climate Science, Risks and Responses at 53 (May 2011), *available at* http://www.scribd.com/doc/56043375/The-Critical-Decade-Climate-Change-Commision-Report.
[51] *Id.*
[52] *Id.*
[53] UNEP, The Emissions Gap Report at 14 (Nov. 2010), *available at* http://www.unep.org/publications/ebooks/emissionsgapreport/; for a discussion of economic implications of these facts, *see infra.*
[54] *Id.* at 23.
[55] McKinsey & Company, Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve at 16 (2009), *available at* www.worldwildlife.org/climate/WWWFBinaryitem11334.pdf.

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damage caused by CO_2 emissions accelerate while the cumulative amount of greenhouse gases in the atmosphere rises, both because of the increasingly dire damages wrought by rising temperatures and other greenhouse gas effects, *and* because of the delay factor itself. If governments delay mitigation in the present, the emissions reduction curve in future years necessarily becomes much steeper, requiring much more drastic and costly emission reduction mechanisms with tremendous economy-wide disruptions, just to "catch up" with the lost opportunities from prior years to reach a sustainable emissions trajectory—or risk undergoing unsustainable climatic extremes.

Economists have sought to quantify the costs of waiting to embark upon an emissions reduction path. In 2007, researchers used the DICE model[56] to estimate the cost of delaying mitigation for a given period of time and then switching to an optimal abatement trajectory. According to their findings, the global cost of ten years of delay, relative to starting on an optimal trajectory in the present, ranges from hundreds of billions to several trillion dollars.[57] For instance, this study estimates that it would cost somewhere between $200 and $400 billion dollars to delay action for ten years and then embark upon a mitigation strategy that would result in stabilization at 3 °C (a level now universally understood to far exceed the dangerous). The cost of delaying mitigation soars into the trillions of dollars as the delay continues, until it ultimately becomes impossible to achieve a certain level of temperature stabilization. According to this study, more than thirty years' delay of changing the current course would make it impossible – no matter what the expense – to stabilize temperature rises at 2° C above pre-industrial levels.

EPA and other federal agencies have been using the social cost of carbon to estimate the climate benefits of rulemakings since it was first developed by a dozen agencies (including USDA, CEQ and EPA) and published by the Interagency Working Group in 2010.[58] The social cost of carbon, usually expressed as a dollar-per-ton figure, provides an estimate of the economic damages associated with an increase in CO_2 emissions, conventionally one metric ton, in a given year. The dollar figure can also represent the value of damages avoided for emission reductions achieved by federal rulemakings. The social cost of carbon is designed to provide a comprehensive estimate of climate change damages, including, but not limited to, changes in net agricultural productivity, human health, and property damages from increased flood risk. However, given current modeling and data limitations, even EPA has conceded that that the social cost of carbon protocol is likely a conservative estimate because it does not yet account for all important damages.[59] Nevertheless, the protocol is designed for use in regulatory processes like this one. In 2013 the Federal Interagency Working Group increased its estimates of the social cost of carbon, using the same 3% annual discount rate, by 50%.[60] The 2013 estimates are 50% higher for emissions in 2010, with greater percentage increases in subsequent years. Yet, even these social

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[56] DICE stands for the Dynamic Integrated Climate and Economy model developed by William Nordhaus in 1990.
[57] Keller, K. et al., The Regrets of Procrastination in Climate Policy, Environmental Research Letters (2007), *available at* iopscience.iop.org/1748-9326/2/2/024004/.
[58] EPA, The Social Cost of Carbon, http://www.epa.gov/climatechange/EPAactivities/economics/scc.html (last accessed June 28, 2015).
[59] *Id.*
[60] Interagency Working Group on Social Cost of Carbon, United States Government, Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 (Nov. 2013) at 3, available at http://www.whitehouse.gov/sites/default/files/omb/assets/inforeg/technical-updatesocial-cost-of-carbon-for-regulator-impact-analysis.pdf.

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cost of carbon figures significantly underestimate the true social cost of carbon, possibly by several orders of magnitude.

Economists have noted that the social cost of carbon is far greater than the $21 per ton of CO_2 assumed by interagency protocol in 2010 and greater than the 2013 revision.[61] There are several inadequacies that make the values too conservative. Foremost, the models fail to evaluate ocean acidification—to the contrary the models consider the ocean a sink for CO_2. The FUND model used in the Working Group's analysis wholly excludes consideration of climate-induced catastrophic events. But the Working Group weighs the values generated by each of the three models equally, even though the FUND model's values is significantly lower[62] than the others, and consequently pulls down the final value of the social cost of carbon. The potential for catastrophic climate events, and the increasing likelihood that tipping points will be reached even sooner than anticipated, are increasingly serious risks, however, and, despite the associated uncertainties, must be fully represented in any evaluation of the social cost of carbon. Instead, the Working Group employed a risk-neutral approach, clearly inappropriate in light of the vast majority of scientific studies. Also, the models used fail to account fully or even partially for certain highly complex aspects of climate change, including the possibility of interrelations between different sectors and accelerating damage feedback loops, non-CO_2 emissions,[63] and social and political instability. Moreover, the valuation techniques and discount rates used to reach these values are inherently problematic and fail to represent the full value of all losses from climate change, in significant part because some cannot be reduced to monetary terms.

Other evaluations of the social cost of carbon attempt to account for these omitted factors. The Stern Review, in particular, reaches a SCC of $85/ton of CO_2 (in 2000 dollars).[64] For comparison purposes with a Working Group value of $21 in 2005 dollars, this amount is equivalent to

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[61] F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon (2010) (the social cost of carbon could be over $800 per ton of CO2 equivalent; F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon, in Economics, vol. 6 (Apr. 4, 2012) (reaching similar conclusions), available online at http://www.economics-ejournal.org/economics/journalarticles/2012-10 (last visited June 27, 2014); P. Epstein et al., Full cost accounting for the life cycle of coal, Ann. N.Y. Acad. Sci. (2011) (estimating the social cost of coal at between $10 and $100 per ton of CO2 equivalent); L. Johnson & C. Hope, The social cost of carbon in U.S. regulatory impact analyses: an introduction and critique, J. Envtl. Stud. & Sci. (Sept. 9, 2012) (finding a social cost of a ton of CO2 emissions to be 2.6 to over 12 times larger than the Interagency Working Group's central estimate of $21 per ton of CO2) available online athttp://link.springer.com/article/10.1007%2Fs13412-012-0087-7 (last visited June 27, 2014) E. Stanton et al., Comments on the 2013 Technical Update of the Social Cost of Carbon, January 27, 2014.

[62] Interagency Working Group on the Social Cost of Carbon, Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, at 16-A-11, Fig. 16-A-4.2, *available at* http://www.rff.org/Publications/WPC/Pages/Estimating-the-Social-Cost-of-Carbon-for-Regulatory-Impact-Analysis.aspx.

[63] For instance, the estimated social cost of methane and SF_6, are, respectively, $105/tonne and $200,000/tonne. *See* Intergovernmental Panel on Climate Change, Climate Change 2007 Synthesis Report 822, *available at* http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html. For a critical analysis of the Working Group's assumptions, *see also* Ackerman, F. and Stanton, E. A., The Social Cost of Carbon A Report for the Economics for Equity and the Environment Network (April 1, 2010), *available at* http://www.e3network.org/papers/SocialCostOfCarbon_SEI_20100401.pdf.

[64] Nicholas Stern, Stern Review on the Economics of Climate Change Part III: The Economics of Stabilisation at 287 (2006), *available at* http://webarchive.nationalarchives.gov.uk/+/http:/www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm.

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$96.25/ton in 2005. The Stern Review uses the PAGE model, which explicitly models for the risk of catastrophic climate change.[65] In contrast with the Working Group, the Stern Review uses a mean temperature increase of 3.9 °C for its baseline scenario (consistent with the Third IPCC Report) and a 4.3 °C increase for its higher climate scenario. The resulting higher value of the social cost of carbon is thus very likely to be a closer approximation of the real cost of CO_2.

Meanwhile, the costs of reducing CO_2 emissions are well worth taking prompt action. The "central estimates of the annual costs of achieving stabilisation between 500 and 550ppm CO_2 are around 1% of global GDP, if we start to take strong action now. [...] It would already be very difficult and costly to aim to stabilise at 450ppm CO_2e. If we delay, the opportunity to stabilise at 500-550ppm CO_2e may slip away.'"(Stern 2006). Likewise, the benefits of addressing CO_2 for ocean acidification also have the ancillary effect of slowing global warming and preventing costs associated with climate change.

The recently proposed rule to reducing power plant CO_2 emissions calculates both costs and benefits—notably the benefits far exceed the costs. The recently proposed rules for reducing power plant carbon emissions, calculates both costs and benefits for a more modest reduction. EPA projects that the annual compliance cost will be $4.3 to $5.5 billion (in 2011 dollars, depending on discount rate) in 2020 and $5.5 billion (for a 5% discount rate) in 2030.[66] The total combined climate benefits and health co-benefits are estimated to be $15.6 to $88 billion in 2020 and $32.3 to $151 billion in 2030 (depending on discount rate and the options chosen).[67] The insurance industry also is well aware of the potential costs of failing to address CO2 emissions and its associated effects, including: "[h]urricanes and other flooding events … [h]ealth issues associated with heat waves… more airborne allergens, rising temperatures, greater humidity, more wildfires, and more dust and particulate pollution may considerably exacerbate upper respiratory disease (rhinitis, conjunctivitis, sinusitis, asthma) and cardiovascular disease."[68] A European insurance company estimates losses from extreme climate change events of 37% within a decade, over $1 trillion under bad circumstances.[69] The increasing frequency and severity of storms in the U.S. has caused damages to increase 60-fold from 1950s to the 1990s.[70]

Petitioners ask that action to mitigate ocean acidification under TSCA be initiated, either through TSCA section 6 (e.g., requiring "repurchasing" relief using sequestration, emission reductions, etc.), or through section 4 in order to determine the need for action under section 6 and the most effective mitigation strategies. In any case, petitioners suggest that costs be apportioned among

[65] According to the Working Group itself, DICE "offers the best insight into the SCC if the world were to experience catastrophic climate change." *See* Working Group, *supra* note 62, at 16-A-35.
[66] EPA, Regulatory Impact Analysis Technical Document EPA-452/R-14-002 (June 2014).
[67] *Id.*
[68] National Association of Insurance Commissioners, The Potential Impact of Climate Change on Insurance Regulation at 10 (2008).
[69] See e.g. Allianz, Climate Change and the Financial Sector: An Action Plan; Evan Mills, Responding to Climate Change: The Insurance Industry Perspective.
[70] Mills, E. Insurance in a Climate of Change, Science 308: 1040 (2005).

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CO_2 emission contributors according to the cumulative CO_2 emission inventory information EPA has collected.[71]

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In summary, the weight of the scientific information on ocean acidification is sufficient to make a determination that CO_2 poses an unreasonable risk, to the extent that EPA declines to find the data adequate, then EPA must develop a test rule under TSCA section 4 as described below.

C. Alternatively, EPA Must Require Testing to Develop Adequate Data

EPA must make a determination as to whether adequate data exist to evaluate the environmental and health effects of CO_2. There is well-established scientific information on the risk of CO_2 on the environment, but if EPA determines that the data are insufficient then it must develop a testing rule.

In enacting TSCA, Congress declared that "adequate data should be developed with respect to the effect of chemical substances and mixtures on health and the environment and that the development of such data should be the responsibility of those who manufacture and those who process such chemical substances and mixtures."[72] Accordingly, section 4 directs EPA to require additional testing upon determining that "the manufacture, distribution in commerce, processing, use, or disposal of chemical substance or mixture … may present an unreasonable risk of injury to health or the environment," or if the chemical is produced in substantial quantities and there is a potential for a substantial quality to be released into the environment.[73]

1. CO_2 May Present an Unreasonable Risk

As described in depth in this petition, CO_2 may present an unreasonable risk to the environment. EPA interprets this to mean that there is a "substantial (i.e., more than theoretical) probability" of unreasonable risk to the environment or health.[74] The information in this petition meets the threshold for a testing rule and establishes a substantial probability that CO_2 poses an unreasonable risk to the environment, but EPA need not even make such a determination because CO_2 is produced in such large volumes that it clearly meets the criterion of exposure of substantial quantities being released into the environment.

2. Substantial Quantities of CO_2 Are Released into the Environment

It is undeniable that substantial qualities of CO_2 are released into the environment. EPA established a threshold value of one million pounds for a release of a chemical to be substantial. *TSCA Section 4(a)(1)(B) Final Statement of Policy; Criteria for Evaluating Substantial*

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[71] This could be structured similar to the sponsorship format used in TSCA's High Production Volume (HPV) Program.
[72] 15 U.S.C. § 2601(b)(1).
[73] 15 U.S.C. § 2603 (a)(1)(A), (B)(i).
[74] *Chemical Mfrs. Ass'n v. EPA*, 859 F.2d 977, 988 (D.C. Cir. 1988).

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Production, Substantial Release, and Substantial or Significant Human Exposure, 58 Fed. Reg. 28736, 28746 (May 14, 1993). According to the IPCC:

> From 1750 to 2011, CO_2 emissions from fossil fuel combustion and cement production have released 375 [345 to 405] GtC to the atmosphere, while deforestation and other land use change are estimated to have released 180 [100 to 260] GtC. This results in cumulative anthropogenic emissions of 555 [470 to 640] GtC.

(IPCC 2013, Summary for Policymakers).

In 2012, a total of 9.7 gigatonnes of CO_2 were released into the atmosphere from fossil fuel combustion and cement production (Global Carbon Project 2013). These emissions are expected to increase to 9.9 gigatonnes in 2013 (*Id.*). The United States contributed 14% of CO_2 emissions to the atmosphere (*Id.*). Models estimate that between 2003 and 2012, the oceans absorbed 27% of CO_2 from the atmosphere (*Id.*). Over the next millennium, the oceans will absorb 90% of anthropogenic CO_2 (Kleypas et al. 2006).

Therefore, the threshold of substantial release is exceeded by more than a million times over.

3. Recommendations for Testing

EPA should consider a test rule to fill the information gaps needed to make a determination of whether CO_2 presents an unreasonable risk of injury to the environment. Some recommendations for consideration include:

- Testing CO_2 reduction strategies. For example, research and development for emissions reduction strategies that include alternative practices, conservation, alternative fuels. Testing CO_2 sequestration and capture approaches, and assessing attainable CO_2 emissions reductions for industries with significant CO_2 emissions.
- Conducting a vulnerability assessment for marine and coastal species and ecosystems. Determining atmospheric CO_2 levels necessary to conserve marine ecosystems from dangerous ocean acidification. Emissions scenarios are important for informing policy approaches to acidification.
- Forecasting species' responses to ocean acidification using modeling tools to predict range shifts, demographic and population trends, and physiological responses across taxonomic groups using a range of climate models, emissions scenarios, and management timelines (25, 50, 100 years). Identify wildlife species and ecosystems imperiled by ocean acidification by evaluating range shift models and population viability models run under future ocean acidification levels. Recommend conservation actions, including protected status, for species that are most at risk. Protect species across their range since populations are likely to have different adaptations to local oceanic conditions.
- Determining the economic values of ecosystems that are at risk from ocean acidification and the costs of reducing CO_2 emissions to preserve those ecosystems.

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Additionally, EPA can use guidance on research needs based on existing research plans. There are a number of sources recommending research and data needs (National Research Council 2013; Washington State Blue Ribbon Panel 2012; National Research Council 2010).

According to TSCA, developing the data is "the responsibility of those who manufacture and those who process such chemical substances and mixtures."[75] For example, responsibility could be apportioned based on the historical carbon emissions from the EPA Greenhouse Gas Emission Inventory together with current emissions. Typically for test rules with multiple responsible parties consortiums are set up to comply.[76] Here, for example, utilities, cement and lime manufacturers, waste incinerators, and other large producers of CO_2 should be responsible for developing unbiased, independent data.

While this may seem like a complicated undertaking, EPA has successfully completed more complex test rules. For example, from 1998 through the present, the agency used three sets of regulatory test rules under TSCA to collect chemical data for almost 3,000 high production volume (HPV) chemicals, including over 10,000 individual studies with data from domestic and foreign producers.[77]

EPA must develop test rules under TSCA section 4 for research and data development focused on information essential for making a definitive TSCA section 6 finding. These would include risk, benefit and cost information.

D. Inadequacy of Existing CO_2 Reduction Strategies

Petitioners are aware that the Agency has recently planned and initiated several emission reduction actions aimed at slowing the rate at which carbon emissions are increasing. However, these actions by themselves, while laudable, will not stabilize atmospheric CO_2 at a level which will prevent widespread harm from ocean acidification.

1. Global Greenhouse Gas Emissions Are Increasing Substantially

The atmospheric concentration of CO_2 reached 400 parts per million (ppm) for the first time in human history in May, 2013, compared to the pre-industrial concentration of ~280 ppm (Scripps Institution of Oceanography 2013). The current CO_2 concentration has not been exceeded during the past 800,000 years and likely not during the past 15 to 20 million years (Denman et al. 2007; Tripati et al. 2009). Atmospheric CO_2 emissions have risen particularly rapidly since the 2000s (Raupach et al. 2007; Friedlingstein et al. 2010). The global fossil fuel CO_2 emissions growth rate was 1.0% per year in the 1990s compared with 3.1% per year since 2000, and this growth rate has largely tracked or exceeded the most fossil-fuel-intensive emissions scenarios projected by the IPCC (A1FI and RCP 8.5) since 2000 (Raupach et al. 2007, Peters et al. 2012). The CO_2 emissions growth rate fell slightly in 2009 due largely to the global financial and economic

[75] 15 U.S.C. § 2601
[76] 15 U.S.C. § 2602 (b)(3)(A)
[77] EPA, High Production Volume (HPV) Challenge; http://www.epa.gov/chemrtk/index.htm (last accessed June 28, 2015).

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crisis; however, the decrease was less than half of what was expected and was short-lived (Fiedlingstein et al. 2010). In 2014 and 2015, global CO_2 concentrations exceeded 400ppm.[78]

2. U.S. Measures to Reduce Greenhouse Gas Emissions Are Insufficient

EPA has taken some initial steps toward curbing greenhouse pollution under the Act. In 2009, the agency issued a formal finding that greenhouse pollution endangers public health and welfare and moved to limit emissions from passenger cars and trucks. The EPA also acknowledged that major new or modified "stationary" sources of greenhouse pollution, like power plants and factories, must obtain permits and control their emissions before beginning construction. However, it narrowed the scope of this requirement considerably under its so-called "tailoring rule," which initially limits the permitting program to only a few hundred very large sources of greenhouse gases, letting a huge number of smaller — but still significant — sources off the hook.

While existing domestic laws including the Clean Air Act, Energy Policy and Conservation Act, Clean Water Act, Endangered Species Act and others provide authority to executive branch agencies to require greenhouse gas emissions reductions from virtually all major sources in the United States, these agencies are either failing to implement or only partially implementing these laws for greenhouse gases. The landmark 2014 pact with China to reduce greenhouse gas emissions is significant, but there is little to ensure it is enforced and implemented. According to the plan, United States will reduce CO_2 emissions 26 to 28% below 2005 levels by 2025.

Proposed power plant rules also fail to do enough to cut CO_2 pollution. Using the Clean Air Act, the president aims to reduce existing power plant emissions 30 percent below 2005 levels (or about 7.7 percent below 1990 levels, the base year for the international climate treaty) by 2030. But international scientists warned years ago that developed countries like the United States must reduce their emissions 25 percent to 40 percent below 1990 levels by 2020 to avoid tipping the scales further toward a climate catastrophe. Likewise, the recently announced plans to limit power plant emissions (Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units) focuses on emission reduction. Power plants are responsible for about a third of our carbon emissions, and the rule is designed to reduce those emissions by almost a third by 2030. This would result in a 10% decrease in 15 years. Stabilizing atmospheric concentration to prevent further acidification of the oceans would require about an 80% decrease in all emissions. Clearly this is a good first step, but by itself inadequate to address acidification.

EPA has issued a rulemaking regulating greenhouse gas emissions from automobiles that will reduce greenhouse emissions emitted per vehicle mile traveled by passenger vehicles in the future. But because the improvements are modest and more vehicles are projected to drive more miles in the future, the rule will not reduce emissions from this sector overall but will only slow the rate of increase.[79] Meanwhile, even the government concedes that "these reductions in emissions are not sufficient by themselves to reduce total HD vehicle emissions below their 2005

[78] NOAA, Trends in Atmospheric Carbon Dioxide, http://www.esrl.noaa.gov/gmd/ccgg/trends/
[79] EPA, Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule, 75 Fed. Reg. 25324 (May 7, 2010).

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levels by 2020."[80] This means that the vehicle rule is far from achieving emissions goals agreed to by the U.S. in the Copenhagen Accord, which aim to keep global warming below 2˚C.

The EPA has also to date issued only a single proposed rule under the new source pollution standard program for stationary sources of pollution, for electric generating units (power plants). While there is enormous potential to reduce emissions through this program overall and through the power plants rule in particular, the EPA has instead proposed a weak and flawed rule that it admits will not reduce emissions from these sources between now and 2020 compared to what would be expected without the rule.[81] Indeed, in the rulemaking the EPA conceded that new power plant rule on greenhouse gas emissions "will not have direct impact on U.S. emissions of greenhouse gases under expected economic conditions."[82]

While full implementation of our flagship environmental laws, particularly the Clean Air Act, would provide an effective and comprehensive greenhouse gas reduction strategy, due to their non-implementation, existing domestic regulatory mechanisms must be considered inadequate to protect marine species from climate change and ocean acidification.

3. International Measures to Reduce Greenhouse Gas Emissions Are Inadequate

International initiatives are also currently inadequate to effectively address climate change. The United Nations Framework Convention on Climate Change, negotiated in 1992 at Rio de Janeiro, Brazil, provides the forum for the international negotiations. In the Framework Convention, signed and ratified by the United States, the world agreed to take the actions necessary to avoid dangerous climate change. Parties to the Convention also agreed as a matter of fairness that the world's rich, developed countries, having caused the vast majority of emissions responsible for the problem, would take the lead in solving it. It was not until the 1997 meeting in Kyoto, Japan, that the first concrete, legally binding agreement for reducing emissions was signed: the Kyoto Protocol. The Protocol requires the world's richest countries to reduce emissions an average of 5 percent below 1990 levels by 2012, while developing nations also take steps to reduce emissions without being subject to binding emissions targets as they continue to raise their standard of living. The United States has been a major barrier to progress in the international negotiations. After the Clinton administration extracted many concessions from the rest of the world in exchange for the United States signing on in Kyoto, the Senate rejected the equity principles behind the Convention, saying the United States should not agree to reduce its own emissions unless all other countries — regardless of their responsibility or ability — were similarly bound. Citing the same excuses, President George W. Bush repudiated the Kyoto Protocol entirely. Thus the United States is the only industrialized country in the world that has yet to ratify the Kyoto Protocol. The United States negotiating team under both the George W. Bush and the Obama administrations has pursued two primary objectives in the international talks: to refuse any legally binding emissions reduction commitments until all other

[80] NHTSA, Medium- and Heavy-Duty Fuel Efficiency Improvement Program – Final Environmental Impact Statement (June 2011).
[81] EPA, Standards of Performance for Greenhouse Gas Emissions for New Stationary Sources: Electric Utility Generating Units, 77 Fed. Reg. 22392, 22430-33 (April 13, 2012).
[82] *Id.* at 22401.

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countries— but particularly China and India — do so, and to push back the date for a new agreement. Not surprisingly, the United States had failed to meet its (never ratified) Kyoto pledge to reduce emissions to 7.2% below 1990 levels by 2012; to the contrary, U.S. emissions have increased by 10.5% since 1990 (EPA 2012).

Moreover, the Kyoto Protocol's first commitment period only sets targets for action through 2012, and there is still no binding international agreement governing greenhouse gas emissions in the years beyond 2012. While the 2009 U.N. Climate Change Conference in Copenhagen called on countries to hold the increase in global temperature below 2□C (an inadequate target for avoiding dangerous climate change), the non-binding "Copenhagen Accord" that emerged from the conference, and the subsequent "Cancún Accords" of 2010 and "Durban Platform" of 2011 failed to enact binding regulations that limit emissions to reach this goal.[83] Even if countries were to meet their Copenhagen and Cancún pledges, analyses have found that collective national pledges to cut greenhouse gas emissions are inadequate to achieve the 2°C target, and instead suggest emission scenarios leading to 2.5□C to 5□C warming (Rogelj et al. 2010; UNEP 2011; UNEP 2010). As of July 2013, many governments were not implementing the policies needed to meet their inadequate 2020 emission reduction pledges, making it more difficult to keep global temperature rise to 2□C and likely leading to a temperature rise of at least 3.5□C (USGCRP 2013). As noted in the NMFS Management Report, the U.S. has yet to issue regulations to limit greenhouse gas emissions in accordance with its pledge under the Copenhagen Accord (NMFS 2012).

CONCLUSION

In conclusion, this petition requires EPA to make a determination whether CO_2 poses an unreasonable risk to the environment therefore requiring regulation under section 6 of TSCA. In an extensive review of the literature on the impact of ocean acidification on marine fauna and ecosystem processes, the authors found that while additional research is called for, sufficient information exists to state with certainty that deleterious impacts on some marine species are unavoidable, and that substantial alteration of marine ecosystems is likely over the next century. (Fabry et al. 2008). If, nonetheless, EPA determines that the information is insufficient to make such a finding it must develop testing rules pursuant to TSCA section 4.

[83] The non-legally binding Copenhagen Accord of 2009 and Cancún Accords of 2010 recognize the objective of limiting warming to 2°C above pre-industrial temperatures, but do not enact binding regulations to achieve this goal (http://cancun.unfccc.int/cancun-agreements/main-objectives-of-the-agreements/#c33; unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf). According to the Durban Platform, developed and developing nations agreed to a process to develop a "new protocol, another legal instrument, or agreed outcome with legal force that will be applicable to all Parties to the UN climate convention"; this legal instrument must be developed as of 2015 and will not take effect until 2020 (unfccc.int/resource/docs/2011/cop17/eng/l10.pdf).

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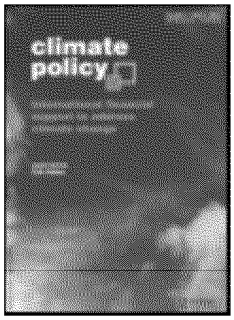

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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climate policy

B research article

Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Benefit–cost analysis can serve as an informative input into the policy-making process, but only to the degree it characterizes the major impacts of the regulation under consideration. Recently, the US, amongst other nations, has begun to use estimates of the social cost of CO_2 (SC-CO_2) to develop analyses that more fully capture the climate change impacts of GHG abatement. The SC-CO_2 represents the aggregate willingness to pay to avoid the damages associated with an additional tonne of CO_2 emissions. In comparison, the social costs of non-CO_2 GHGs have received little attention from researchers and policy analysts, despite their non-negligible climate impact. This article addresses this issue by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. By extending existing integrated assessment models, it is possible to develop a set of social cost estimates for these gases that are consistent with the SC-CO_2 estimates currently in use by the US federal government.

Policy relevance

Within the benefit–cost analyses that inform the design of major regulations, all Federal agencies within the US Government (USG) use a set of agreed upon SC-CO_2 estimates to value the impact of CO_2 emissions changes. However, the value of changes in non-CO_2 GHG emissions has not been included in USG policy analysis to date. This article addresses that omission by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. These new estimates are designed to be compatible with the USG SC-CO_2 estimates currently in use and may therefore be directly applied to value emissions changes for these non-CO_2 gases within the benefit–cost analyses used to evaluate future policies.

Keywords: integrated assessment; non-CO_2 GHGs; social cost of carbon

1. Introduction

The social cost of CO_2 (SC-CO_2) is a measure of the monetary value of the damages occurring both within and outside economic markets as the result of an additional unit of CO_2 emissions. Specifically, it represents society's aggregate willingness to pay to prevent future impacts that occur when one additional unit of CO_2 is emitted into the atmosphere in a particular year. Estimates of SC-CO_2

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therefore provide a way to value changes in CO_2 emissions in benefit–cost analyses (BCAs) of policy alternatives. Without an estimate of the SC-CO_2, the benefits of mitigating the climate change impacts from CO_2 emissions would implicitly be valued at zero in BCAs, thereby significantly weakening the information provided by such analyses. Since 2009, the US Federal Government (USG) has used a set of agreed-upon SC-CO_2 estimates in the BCAs used to evaluate major regulations that impact CO_2 emissions (USG, 2010), including over 30 regulatory actions to date. The USG SC-CO_2 estimates are also increasingly being used in analysis and discussions outside the USG (e.g. by states, regional organizations, other nations, international organizations, NGOs, and academic researchers)[1] and have even figured in several recent public hearings and court cases (e.g. Keohane, 2010a, 2010b).

Although CO_2 is the primary anthropogenic GHG, other GHGs such as methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are also important contributors to climate change. The combined effect of all GHGs accumulated in the atmosphere is to increase the Earth's radiative forcing, which is the amount of energy from the Sun that is trapped in the Earth's atmosphere and therefore acts to warm the planet and change the climate. In 2011, the atmospheric CO_2 concentration contributed 64% of overall radiative forcing, while CH_4 and N_2O accounted for approximately 23% (Myhre et al., 2013). Non-CO_2 GHGs, notably CH_4 and N_2O, therefore contribute significantly to the negative impacts on human well-being from climate change. Furthermore, several recent studies have shown that consideration of non-CO_2 GHGs, particularly CH_4 and N_2O, is important for the design of cost-effective climate policy (Reilly et al., 1999; Tol, Heintz, & Lammers, 2003; Weyant, De La Chesnaye, & Blenford, 2006).

The monetary value of changes in emissions of non-CO_2 GHGs has not been included in USG policy analysis to date. This shortcoming prevents the development of accurate and comprehensive assessments of potential regulatory alternatives by the USG and others that rely on the USG SC-CO_2 estimates (Kopp & Mignone 2012; Marten & Newbold, 2012). For example, fossil fuels (e.g. coal and natural gas) have different compositions of GHG emissions across gases when considering the entire process of extraction, production, transmission, and combustion. Thus, if a regulation is anticipated to cause an industry to substitute between fuels, analysts may be providing inadequate information to decision makers and the public about its benefits if only the welfare implications of direct CO_2 emissions are considered while ignoring changes in CH_4 and other GHG emissions (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2011).

A key reason for the value of non-CO_2 GHG emissions impacts not being included in USG analyses so far is that existing estimates of the social cost of non-CO_2 GHGs presented in the literature are inconsistent with USG SC-CO_2 modelling assumptions. For example, the recent US Environmental Protection Agency BCA of new pollution standards for the oil and natural gas industry concluded that, because they are not consistent with the USG SC-CO_2, 'the methane climate benefit estimates available in the current literature are not acceptable to use to value the methane reductions finalized in this rulemaking' (USEPA, 2012). This article seeks to address that gap by developing a new set of social cost estimates for CH_4 and N_2O (SC-CH_4 and SC-N_2O, respectively) that are fully consistent with the modelling assumptions underlying the current USG SC-CO_2 estimates. This article also develops an approach to extending the models used by the USG to generate estimates of the social cost of additional GHGs that are consistent with the latest USG estimates of the SC-CO_2.

It is important to note at the outset that by restricting attention to the derivation of social cost estimates consistent with the USG SC-CO_2 estimates, any limitations that apply to inputs and modelling

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assumptions underlying the USG SC-CO_2 estimates (e.g. Arrow et al., 2013; Kopp & Mignone 2012; Marten, 2011; O'Neil, 2010; Warren, Mastrandrea, Hope, & Hof, 2010) also apply to the SC-CH_4 and SC-N_2O estimates derived here. Thus, while it is anticipated that the USG will continue to improve the models and data it uses to estimate the SC-CO_2, this article focuses on the more immediate task of developing a set of consistent estimates for the social cost of other GHG emissions so that they need not be implicitly assigned a value of zero in USG policy analyses.

The remainder of the article is organized as follows. Section 2 presents an overview of the USG SC-CO_2 estimation approach and how it compares to the existing literature on the social cost of non-CO_2 GHGs, including a discussion of some of the critiques of the approach. Section 3 presents the approach for estimating the SC-CH_4 and SC-N_2O in a manner consistent with the USG SC-CO_2 estimates. Section 4 presents the results and a comparison of the relative social costs to the previous literature and the global warming potential (GWP)-based metric that is often used as an approximation in the absence of direct estimates, and Section 5 provides concluding remarks.

2. Background

In 2009–2010 the USG formed an interagency working group to develop a set of SC-CO_2 estimates for use by all Executive Branch agencies to value marginal changes in CO_2 emissions in regulatory impact analyses (USG, 2010). The goal of this exercise was to improve the accuracy and consistency with which agencies value marginal changes in CO_2 emissions. Before the release of these estimates, CO_2 emissions changes were valued in some but not all regulatory analyses, and the SC-CO_2 estimates used by different agencies varied substantially. The USG recently updated their estimates for the SC-CO_2 by employing new versions of the three underlying integrated assessment models (IAMs), but leaving the original estimation approach and underlying assumptions unchanged (USG, 2013). This section provides a brief overview of the estimation approach and assumptions used by the USG for estimating SC-CO_2, describes some critiques of the approach by other researchers, and discusses the existing literature on the social cost of non-CO_2 GHGs.

2.1. USG SC-CO_2 estimation approach

To estimate the SC-CO_2 the USG used three IAMs that couple simplified models of atmospheric gas cycles and climate systems with highly aggregate models of the global economy and human behaviour to capture the effects that GHG emissions, through their effect on the climate, have on human welfare. Within IAMs, the modelling that guides the transition from emissions into climate impacts is based on scientific assessments, while the mapping of climate impacts into changes in human welfare is based on economic research that has studied the effect of climate on various market and non-market sectors. Nordhaus and Boyer (2000) provide a very informative and detailed description of how such models are developed.[2]

The three models used by the USG are those that feature most prominently in the published social cost of carbon literature: the Dynamic Integrated Climate and Economy (DICE) (Nordhaus, 2008; Nordhaus & Boyer, 2000), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2006b, 2008), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff, Hepburn, & Tol, 2009; Tol, 2002a, 2002b, 2009) models. The USG chose to use the IAMs'

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climate system submodels and the functions that map climate change into economic damages as implemented by the model developers, but adopted a common set of input assumptions for equilibrium climate sensitivity, discount rates, global population, economic output, and GHG emissions projections. The remainder of this section provides a brief description of these common assumptions and the steps used to calculate the SC-CO_2 estimates. Interested readers can find more details in the USG's 2010 technical support document (USG, 2010).

2.1.1. Reference socio-economic-emissions scenarios

The USG selected five scenarios of economic output, population, and GHG emissions projections using results from the 2009 Stanford Energy Modeling Forum exercise number 22 (EMF-22). Four of the scenarios are based on baseline runs from global economic models (MERGE, MESSAGE, MiniCAM, and IMAGE) and span a range of emissions projections and plausible outcomes for future population and economic output absent significant global action to address climate change. These scenarios allowed for internally consistent forecasts of economic output, population, and emissions for the years 2000–2100. The fifth scenario used by the USG is based on the average of the 550 ppm CO_2e stabilization runs for each of the four models from which baseline scenarios were selected to represent potential action by the rest of the world absent US action. Across the five scenarios, atmospheric CO_2 concentrations in 2100 ranged from approximately 450 to 890 ppm (550–1130 ppm in CO_2e). Over the time horizon, the forecasts of the average growth rate for global per capita economic output ranged from 1.5% to 2.0% per year, and the average global population growth rate ranged from 0.4% to 0.5% per year. To run the IAMs through the year 2300, the USG extrapolated the selected EMF scenarios using the following assumptions: starting in 2100 the population growth rate declines linearly to zero in 2200; starting in 2100 the growth rate of economic output per capita declines linearly to zero in 2300; for all years after 2100 the growth rate of the carbon intensity of the global economy (CO_2 emissions/economic output) remains constant at its 2090–2100 average; starting in 2100 net land-use CO_2 emissions decline linearly to zero in 2200; and for all years beyond 2100 non-CO_2 radiative forcing anomalies remain constant at their 2100 levels.

Several limitations of the simplifying assumptions underlying the USG approach to scenario development have been discussed by other researchers. O'Neil (2010) pointed out that the selected EMF scenarios do not reflect the full range of outcomes that appear in other studies in the literature, and Kopp and Mignone (2012) suggested that the selected scenarios may effectively over-sample the peaks of the distributions. As for the extrapolations, while running the models out for multi-century time horizons is not necessary for relatively short-lived GHGs like CH_4, it is important for understanding the impacts of long lived GHGs such as CO_2 and N_2O that will affect human welfare well beyond 2100. As emphasized by O'Neil (2010) and Kopp and Mignone (2012), the state of the world beyond 2100 is highly uncertain and the scenario extrapolation approach taken by the USG represents only one of many possibilities. Furthermore, the extrapolations for each component of the scenarios (economic output, population, emissions) are separate and nothing ensures internal consistency within the scenarios past 2100. As shown by Marten and Newbold (2012), the temporal decomposition of damages for a perturbation of CO_2 and N_2O are relatively similar in shape and therefore the general findings of studies that explore the sensitivity of the SC-CO_2 to these assumptions should also be applicable to the SC-N_2O.

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2.1.2. Equilibrium climate sensitivity

In reduced-form IAMs, the speed and magnitude of temperature change for a given emissions projection are influenced largely by the 'equilibrium climate sensitivity' (ECS) parameter. The ECS represents the long-term global average temperature response to a level of radiative forcing associated with a sustained doubling of atmospheric CO_2 concentration (around 550 ppm). To represent the uncertainty in the responsiveness of the climate system to changing atmospheric conditions, the USG used a probability distribution for the ECS parameter of the form suggested by Roe and Baker (2007). The USG calibrated the parameters of the probability distribution to have a median equal to 3 8C, two-thirds probability that the ECS lies between 2 and 4.5 8C, which was intended to be consistent with the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) consensus statement about the ECS (Meehl et al., 2007). The distribution was truncated from above at 10 8C. This specification of the ECS distribution is retained to maintain consistency with the USG estimates of the SC-CO_2, but it is noted that the recently released AR5 by the IPCC has revisited the equilibrium climate sensitivity and revised the range downwards to 1.5–4.5 8C and no longer provides a most likely value (Collins et al., 2013). The ultimate effect of updating the ECS distribution to be consistent with the IPCC AR5 findings will depend heavily on the central tendency selected for the distribution.

2.1.3. Discount rates

Because the damages from an additional tonne of CO_2 emissions occur over many decades, the discount rate, which reflects the tradeoff between present and future consumption, plays a critical role in estimating the SC-CO_2. In light of disagreement in the literature regarding the appropriate discount rate to use in this context and uncertainty about future conditions that impact the discount rate, the USG used three constant discount rates intended to span a plausible range: 2.5%, 3%, and 5% per year. It is worth noting that the debate regarding not only the appropriate discount rate but also its time path is ongoing (Arrow et al., 2013; Dasgupta, 2008). While the appropriate value for the discount rate will presumably remain an area of active debate for some time to come, there appears to be agreement that the use of a constant discount rate over long time horizons with uncertain changes in the consumption per capita growth is not theoretically consistent. This article uses the same three constant discount rates as the USG estimation process, but in Appendix C results are reported from a series of sensitivity analyses using a Ramsey discounting approach. Similar to Marten and Newbold (2012), it is found that applying Ramsey discounting using plausible values for the components of the consumption discount rate gives a range of social cost estimates that is broadly consistent with the range of results obtained using the constant discount rates.

2.1.4. Calculating the SC-CO_2

The process to estimate the SC-CO_2 for emissions in year t has four steps. First, each model is used to forecast monetized impacts associated with the baseline path of emissions, economic output, and population. Second, each model is re-run with an additional unit of CO_2 emissions in year t to forecast monetized impacts for all years beyond t along this perturbed path of emissions. Third, the marginal damages in each year are calculated as the difference between the monetized impacts forecast in steps 1 and 2. Finally, the resulting path of marginal damages is discounted and summed to calculate

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the present value of the marginal damages in the year when the additional unit of emissions used to perturb the model is emitted.

The USG repeated this process with each model, discount rate, and socio-economic-emissions scenario for each decade between 2010 and 2050. Because the ECS parameter is modelled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run represents a distribution over the SC-CO_2 in each year. These distributions were estimated using 10,000 simulations in each model run. Therefore, the exercise produced 45 separate distributions of the SC-CO_2 for a given emissions year, based on the three models, three discount rates, and five socio-economic-emissions scenarios considered. To provide a range of estimates that reflects this uncertainty but still emphasizes the central tendency, the distributions from each of the models and scenarios were equally weighted and combined to produce three separate probability distributions for the SC-CO_2 in a given year, one for each assumed discount rate. Four SC-CO_2 estimates were selected from these three probability distributions to reflect the global damages caused by one tonne of CO_2 emissions. Three estimates are based on the average SC-CO_2 across the three models and five socio-economic-emissions scenarios for the 5%, 3%, and 2.5% discount rates, respectively. The fourth value is the 95th percentile of the SC-CO_2 distribution at the 3% discount rate, and was chosen to represent potential higher-than-expected impacts from anthropogenic GHG emissions.

2.2. Existing estimates of the social cost of non-CO_2 GHG emissions

A significant limitation of the aforementioned USG interagency process is that the social costs of non-CO_2 GHG emissions were not estimated. Therefore, as an alternative to applying direct estimates for the social costs of non-CO_2 GHG emissions in the primary BCA, several recent USG regulatory analyses have approximated the benefits of non-CO_2 GHG emissions reductions in sensitivity analyses by transforming the non-CO_2 GHG emissions to 'CO_2-equivalents' using estimates of the GWP for the GHG in question and then using the USG SC-CO_2 for valuation (e.g. US EPA, 2012, 2013).

Gas comparison metrics, such as the GWP, have been designed to measure the impact of different GHGs relative to CO_2, where the point of comparison along the pathway from emissions to monetized damages (depicted in Figure 1) may differ across measures. The GWP, in particular, is designed to measure the additional radiative forcing (i.e. the amount of energy absorbed by atmospheric concentrations of GHGs) from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years). The GWP and other gas-comparison metrics are problematic as an SC-CO_2 scalar in BCA, as the remaining linkages in the pathway depicted in Figure 1 are complex and non-linear. Marten and Newbold (2012) demonstrate that using the GWP to adjust SC-CO_2 estimates to capture the impact of non-CO_2 gases provides a significant improvement over the implicit assumption that they are zero when such benefits are left unquantified, but may still underestimate mitigation benefits. Alternative gas comparison metrics that compare GHGs at different points in the chain of

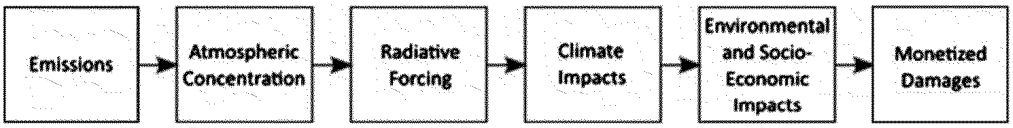

Figure 1 Path from GHG emissions to monetized damages

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causation (e.g. global temperature change potential (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005), peak commitment temperature (Smith et al., 2012), temperature proxy index (Tanaka, O'Neill, Rokityanskiy, Obersteiner, & Tol, 2009)) have also been shown to be imperfect substitutes for direct estimates.

Several researchers have directly estimated the social cost of non-CO_2 GHG emissions using IAMs, although the number of such estimates is small compared to the large number of SC-CO_2 estimates available in the literature. Among these previous direct estimates there is considerable variation in the model versions and input assumptions used. See Table 1 for a summary of the 11 non-CO_2 studies published to date.

As shown in Table 1, the estimates cover emissions years from 1990 to 2050, although the specific perturbation year is not stated in all studies. The studies also cover a wide range of constant and variable discount rate specifications and consider a range of baseline socio-economic and emissions scenarios that have been developed over the last 20 years. Finally, some studies in the literature have chosen not to report the social cost estimates directly. Instead, they opt to report only the 'global damage potential', which is a ratio of the social cost of gas X to the SC-CO_2. Normalizing the SC-CH_4 or

TABLE 1 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Model	Time horizon	Discount rate	Emissions year	Scenario[a]	Climate sensitivity
Reilly and Richards (1993)	N/A	140 years	2, 5, 8%	1990	N/A	N/A
Fankhauser (1994)	N/A	230 years	Ramsey	1991–2030	IS92[b]	N/A
Kandlikar (1995)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Kandlikar (1996)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Hammitt et al. (1996)	N/A	2200	1, 3, 5%	1995–2015	IS92a,c,e	1.5, 2,5, 4.5 8C
Tol (1999)	FUND 1.6	2100	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Tol et al. (2003)	FUND 1.7	2200	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Hope (2005)	PAGE95	2200	Ramsey	2000	SRES A2	Probabilistic, mode of 3 8C
Hope (2006a)	PAGE2002	2200	Ramsey	2001	SRES A2	Probabilistic, mean of 3 8C
Waldhoff et al. (2011)	FUND 3.5	3000	Ramsey	2010–2019	FUND, SRES A1B, A2, B1, B2	2, 3, 4.5 8C
Marten and Newbold (2012)	DICE2007 w/ MAGICC	2300	Ramsey, 2.5, 3, 5%	2010–2050	EMF-22 MiniCAM Base	Probabilistic,median of 3 8C

[a]IS90 scenarios are based on the IPCC First Assessment Report (IPCC, 1990); IS92 scenarios are based on the IPCC Supplementary Report (IPCC, 1992); SRES scenarios are based on the IPCC Special Report on Emissions (IPCC, 2000); the FUND scenario is the default scenario in the FUND model; EMF-22 scenarios are based on results from Stanford's Energy Modeling Forum's 22nd exercise (Clarke et al., 2009).[b]The particular IS92 scenario used was not specified.

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SC-N_2O estimate using the SC-CO_2, in part, controls for differences in the modelling to allow for a better comparison with other estimates in the literature.

Fankhauser (1994) was one of the first to develop estimates of the average SC-CH_4 and SC-N_2O for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt, Jain, Adams, and Wuebbles (1996) also developed estimates of SC-CH_4 and SC-N_2O for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006a) developed estimates for the SC-CH_4 in 2000 using the FUND and PAGE models, respectively. Waldhoff, Anthoff, Rose, and Tol (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal CO_2, CH_4, N_2O, and SF_6 emissions for the average year in the 2010 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios from the IPCC special report on emissions (IPCC, 2000) in addition to the default FUND scenario. In Section 4, the specific results of these previous studies are discussed with a comparison to the estimates obtained in the present study.

The above-mentioned previous studies provide a basic understanding of the relative social costs of different GHGs but do not provide sufficient information about how this relationship changes over time. Marten and Newbold (2012) used an IAM that couples the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) with economic components of the 2007 version of William Nordhaus' DICE model to directly estimate the social cost of marginal CO_2, CH_4, and N_2O emissions. They estimated the annual social costs for the years 2010–2050 along a single socio-economic-emissions pathway given uncertainty about the equilibrium climate sensitivity parameter. An advantage of their approach is that through the use of a more detailed, yet still relatively simple, climate model their results are not affected by over-simplification of temperature response or atmospheric chemistry, which have been shown to have non-negligible effects on the estimates of social costs (Marten, 2011; Warren et al., 2010).

The work of Marten and Newbold (2012) uses many of the assumptions used by the USG in its estimation of SC-CO_2, including discount rates, the equilibrium climate sensitivity distribution, and post-2100 socio-economic and emissions extrapolations. However, they focus on only one of the three models and one of the five socio-economic-emissions scenarios used by the USG. Furthermore, they use a different climate sub-model, which leads their estimate of the SC-CO_2 to be different from the USG estimate, even for the same IAM and scenario combination. Therefore, although these studies, including Marten and Newbold (2012), have increased our understanding about the relative social costs of GHG emissions, they have not provided a set of estimates that are entirely consistent with the USG SC-CO_2 estimates. In Section 4, the estimates derived in this article are compared with those of Marten and Newbold (2012) to more clearly demonstrate the similarities and differences in the two sets of estimates for SC-CH_4 and SC-N_2O.

3. Estimating the social cost of non-CO_2 GHGs consistent with USG SC-CO_2

The primary obstacle in estimating the social cost of non-CO_2 GHG emissions in a manner consistent with the USG SC-CO_2 estimates is that not all of the IAMs used include explicit representations of the non-CO_2 gases of interest. This section describes the degree to which non-CO_2 GHGs are currently

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represented in the default versions of DICE, PAGE, and FUND, and then discusses how they are amended to estimate the social cost of these gases.

3.1. Representation of non-CO_2 GHGs in DICE, PAGE, and FUND

The FUND model explicitly considers CH_4, N_2O, and SF_6 in addition to CO_2. The model uses one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels. For CH_4 and N_2O, FUND estimates the additional radiative forcing imposed by the atmospheric buildup of these gases using the simplified expressions presented in Chapter 6 of the IPCC's Third Assessment Report (TAR) (Ramaswamy et al., 2001). FUND also augments the TAR expression for the additional radiative forcing from CH_4 to account for the influences of stratospheric water vapour and tropospheric ozone changes. Because FUND uses CH_4 and N_2O emissions as inputs and internally computes their impact on the climate system, it is possible to directly estimate the social cost of those gases without modifying the model.

In the DICE model, the only GHG that is explicitly represented is CO_2; an exogenous radiative forcing projection is used to account for the impact of all other gases on the climate. To develop an exogenous radiative forcing pathway consistent with the emissions scenarios used to estimate the SC-CO_2, the USG decomposed the default DICE exogenous radiative forcing vector into CH_4, N_2O, F-gases, aerosols, and other residual forcing components. The USG then replaced the radiative forcing attributed to CH_4, N_2O, and F-gases with estimates associated with the EMF-22 scenarios. As non-CO_2 emissions are not a direct input into DICE, it is not possible to simply perturb the emissions projection and re-run the model to obtain a forecast of additional damages.

The 2002 version of the PAGE model, which was used by the USG in developing its first set of estimates (USG, 2010), includes an atmospheric model for CH_4 and SF_6, but represents the effects of other non-CO_2 GHGs in an exogenous radiative forcing projection. Presumably to simplify the process and maintain consistency with DICE, the USG did not use PAGE's internal CH_4 component. Instead, the same exogenous radiative forcing projection was used for the effect of CH_4, N_2O, and F-gas emissions as was used for DICE. Since then, a N_2O component has been added to the PAGE model, although in the recent 2013 SC-CO_2 update the USG maintained the approach of using the same single exogenous forcing projection as was applied to DICE (USG, 2013). Therefore PAGE, as implemented by the USG, faces the same limitations as DICE with respect to estimating the social costs of marginal non-CO_2 emissions that are consistent with the USG SC-CO_2 estimates. For these reasons, computing estimates for the social cost of non-CO_2 gases in DICE and PAGE requires either replacing the climate component of these models with a more complete representation, as was done with DICE by Marten and Newbold (2012), or deriving an estimate of the path of additional radiative forcing that would result from a perturbation of the gas in question. This article uses the latter approach for DICE and PAGE, as the former would represent a substantial change to the underlying IAMs and would have implications for the SC-CO_2 estimates, making this work inconsistent with the USG SC-CO_2 estimates currently used in regulatory analysis.

3.2. Estimating the social cost of non-CO_2 GHGs in DICE and PAGE

The process used in this article to estimate the social cost of non-CO_2 GHGs in DICE and PAGE as implemented by the USG requires first generating a forecast of the additional radiative forcing

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associated with a perturbation of a non-CO_2 gas's emissions in a single year, and then adding this radiative forcing perturbation to each model's exogenous radiative forcing projection. To determine the additional radiative forcing associated with the emission perturbation, there is a need to model the change in atmospheric concentration and the radiative forcing associated with the additional concentration. For both CH_4 and N_2O, a simple one-box atmospheric gas cycle model with a constant decay rate is used to estimate the atmospheric concentration of each gas based on its assumed emissions. The use of a one-box gas cycle for CH_4 and N_2O with constant decay follows the approach used by the IPCC to compute GWPs (Forster et al., 2007) and the FUND model (Anthoff & Tol, 2013). In both the baseline and the perturbed case, the contribution of the gas to the global radiative forcing anomaly is determined by the forcing relationships presented in the IPCC TAR (Ramaswamy et al., 2001), which were not updated by the IPCC in AR4. The incremental radiative forcing is defined by the difference between the baseline forcing path and the emissions path that includes a one tonne perturbation in a given year. Next, the path of additional radiative forcing is added to the stream of exogenous radiative forcing in each IAM to estimate the climate damages in the perturbed scenario. These damages are then compared to the baseline damages to determine the social cost of gas X (SC-X). Specifically, the process is as follows:

1. Run the IAM as described in the SC-CO_2 technical support document (USG, 2010) to estimate baseline damages.
2. Estimate the baseline atmospheric concentration for gas X.
3. Estimate the baseline radiative forcing contribution of gas X.
4. Perturb the stream of gas X emissions by one tonne in year t.
5. Estimate atmospheric concentration for gas X in the perturbed scenario.
6. Estimate the radiative forcing contribution of gas X in the perturbed scenario.
7. Compute the incremental radiative forcing as the difference between the results of steps 3 and 6.
8. Add the additional radiative forcing from step 7 to the exogenous radiative forcing path used in the IAM in step 1.
9. Re-run the IAM to compute the damages along the perturbed emissions path.
10. Compute the social cost of gas X for emission year t as the present value of the difference in damages estimated in steps 1 and 9.

Two practical issues associated with implementation are worth noting. First, while the SC-X estimates are associated with a one tonne perturbation, to avoid computational rounding error a 1 Mt perturbation is used and then the resulting change in damages is scaled to get the average effect per tonne. Experiments conducted by Griffiths et al. (2012) to assess the applicability of the SC-CO_2 to non-marginal emission changes show that the average per tonne SC-CO_2 estimate is relatively constant over large differences in perturbation size. Additional experiments in the context of this article found that alternative perturbation sizes do not significantly change the average one tonne social cost estimate. Second, the additional radiative forcing due to the emissions perturbation is computed based on an annual time step, but because DICE and PAGE use longer time steps the average radiative forcing over the time step is added to the model's exogenous radiative forcing vectors.

The remainder of this section describes the procedure for modelling the incremental radiative forcing of a perturbation for CH_4 and N_2O, and explores the sensitivity of these projections to

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two issues. First, it evaluates whether the simple one-box gas cycle model with a constant decay rate produces a close approximation to the forecasts of future atmospheric CH_4 and N_2O concentrations based on a more sophisticated climate model. Second, it explores the sensitivity of the results to the method used for extrapolating non-CO_2 emissions from 2100 to 2300. This is important, because the USG did not specify a particular set of emissions pathways for each constituent gas, instead assuming only that non-CO_2 radiative forcing remains constant past 2100. Such a situation could arise from a myriad of possible individual gas projections and the USG did not specify which it was assuming.

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3.3. Methane

A simple one-box atmospheric gas cycle model for methane specifies the concentration in year t, $C_t^{CH_4}$ [ppb], such that

$$C_t^{CH_4} = C_{t-1}^{CH_4} + d_{CH_4}(C_{pre}^{CH_4} - C_{t-1}^{CH_4}) + g_{CH_4}E_{t-1}^{CH_4}, \tag{1}$$

where d_{CH_4} defines the rate of decay, $C_{pre}^{CH_4}$ [ppb] is the pre-industrial atmospheric concentration, and g_{CH_4} [ppb/Mt] converts emissions, $E_{t-1}^{CH_4}$ [Mt], from mass to atmospheric volume. The mass to volume conversion factor is g_{CH_4} ¼ 0.3597 ppb/Mt and $C_{pre}^{CH_4}$ ¼ 700 ppb, following the IPCC TAR. The rate of decay is set to d_{CH_4} ¼ 1/12 following the IPCC AR4 stated CH_4 lifetime of 12 years. The iteration begins in the year 2006 using the emissions from the EMF-22 scenario (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used so that $C_{2005}^{CH_4}$ ¼ 1774 ppb.

The contribution of atmospheric methane to global radiative forcing, denoted $Q_t^{CH_4}$, is defined using the relationship in Table 6.2 of the IPCC TAR:

$$Q_t^{CH_4} = f\ 0.036\ \ C_t^{CH_4} - \ C_{pre}^{CH_4} - [f(C_t^{CH_4}, C_{pre}^{N_2O}) - (C_{pre}^{CH_4}, C_{pre}^{N_2O})]\ , \tag{2}$$

where $C_{pre}^{N_2O}$ [ppb] is the pre-industrial atmospheric concentration of nitrous oxide and

$$f(C^{CH_4}, C^{N_2O}) = 0.47 \ln 1 + 2.01 \times 10^{-5}(C^{CH_4}C^{N_2O})]^{0.75} + 5.31 \times 10^{-15}C^{CH_4}(C^{CH_4}C^{N_2O})^{1.52}\ . \tag{3}$$

The function in expression (3) accounts for the overlapping absorption bands of CH_4 and N_2O, thereby reducing their effective absorption. Parameter f is used to proxy for indirect effects of CH_4 that include the enhancement of stratospheric water vapour and tropospheric ozone changes. Following the IPCC AR4, an enhancement effect of 40% (25% from tropospheric ozone change and 15% for stratospheric water vapour enhancement) is used, such that f ¼ 1.4. The pre-industrial concentration of N_2O is set consistent with the IPCC TAR, such that $C_{pre}^{N_2O}$ ¼ 270 ppb.

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A key simplification in this approach is the constant decay rate used in the atmospheric gas cycle model. As discussed by IPCC Working Group I in Chapter 4 of the TAR, the lifetime of methane emissions in the atmosphere depends on temperature and the concentrations of CO, NOx, and other VOCs in the atmosphere (Ehhalt et al., 2001). Sensitivity analysis is used to understand the potential implications of ignoring these interactions by comparing the incremental atmospheric concentration projected by the simple model described above to the analogous projection from the climate model MAGICC,[3] which, while still relatively simple, incorporates these interactions between the lifetime of CH_4 in the atmosphere and the other gases and climate variables. This exercise uses CH_4 emissions from the EMF-22 MiniCAM reference scenario and considers a one tonne perturbation of CH_4 in 2015. It is noted that these results are robust across alternative emissions levels.[4]

Figure 2(a) presents the projected average decadal increment to atmospheric concentrations using both the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. At the time of the perturbation (2015), the inter-annual time step of MAGICC allows for an uptake of the additional emissions into the atmosphere, whereas the strict annual time step of the simple model causes a year to pass before the change is registered. After the initial year, the models originally differ by around 15%. This difference falls to under 10% within the first decade, with the faster effective growth in the simple model causing its additional concentration to eventually fall below that of MAGICC.

The difference in the incremental radiative forcing from the perturbation between the simple model and MAGICC is also of importance. Although MAGICC relies on similar equations to derive the radiative forcing of atmospheric CH_4 concentrations, it differs in the way it handles indirect effects of CH_4 on tropospheric ozone and stratospheric water vapour, in addition to including other temperature-related feedbacks. Figure 2(b) presents the average additional radiative forcing per decade attributed to the 2015 CH_4 perturbation in both models. The average increase in radiative forcing over the decade is considered because this is the input required by DICE due to its ten-year time step and therefore a more relevant comparison (PAGE requires a similar multi-year average). When considering the average additional radiative forcing over the decade, the initial difference in concentration between MAGICC and the simple model has a minimal effect and the difference in radiative forcing between the two models is less than 2% over the first two decades. However, this difference grows to –18% over the subsequent two decades. This escalation in the difference is in part due to the use of a constant decay rate in the simple model, whereas MAGICC takes into account the growing atmospheric concentrations of other gases and increasing atmospheric temperature, which increase the lifetime of atmospheric CH_4.

To understand the effect that this difference would have on an estimate of the SC-CH_4, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of CH_4, as computed using both the simple model and MAGICC, is added to the exogenous forcing projection. As above, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 2 presents the results of this experiment. In line with the results comparing the radiative forcing perturbations above, the two approaches produce similar social cost estimates for emissions in 2015, where additional analysis has shown these results to hold with PAGE as well. The impact of assuming a constant decay rate is greater further out into the future, due to the projected increase in the atmospheric concentration of other relevant gases and atmospheric temperature that are accounted for in MAGICC, and the social cost

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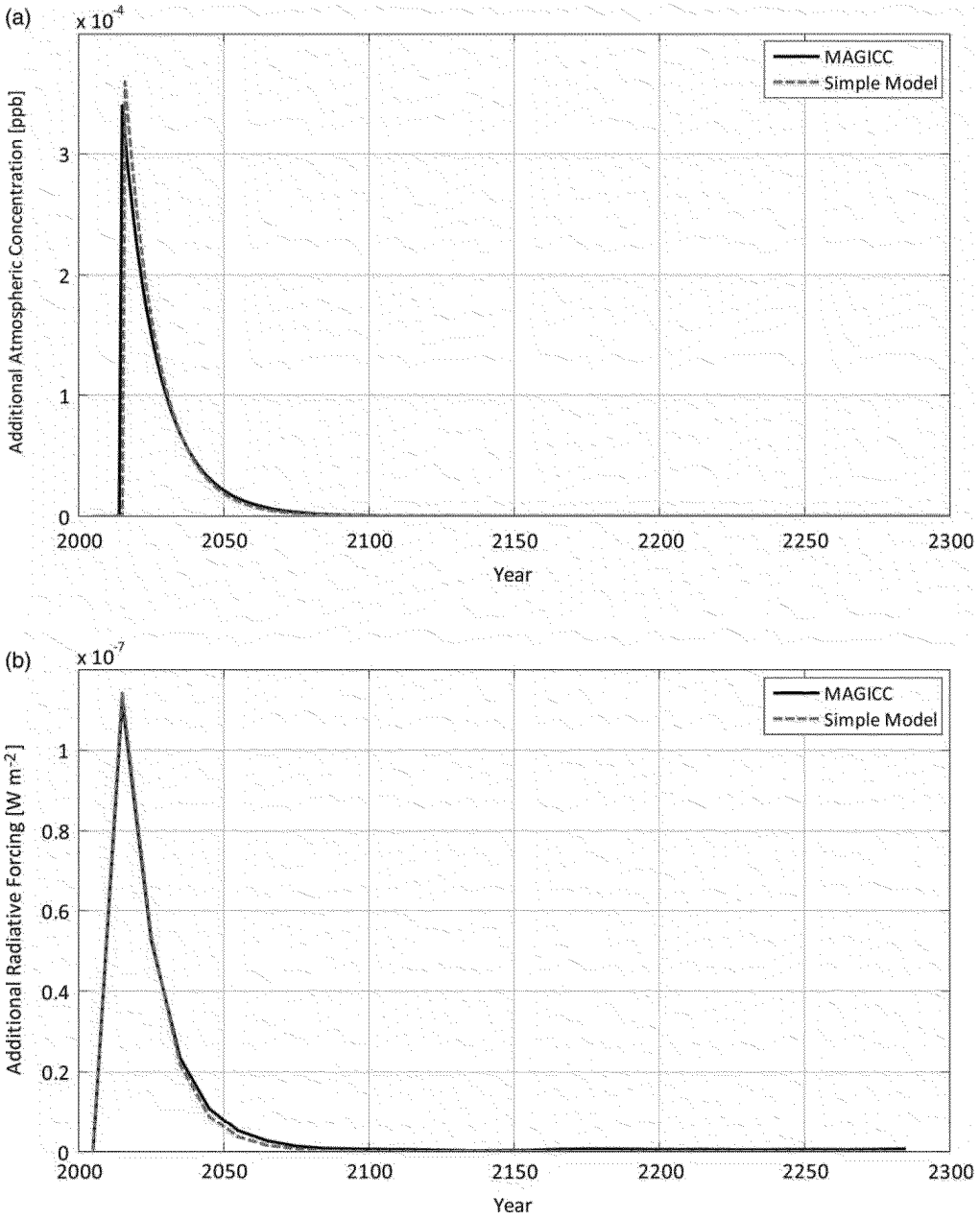

Figure 2 Effects of perturbation in 2015 CH_4 emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

estimates begin to diverge for later emissions years. For the same reason, the two approaches will show greater differences for lower discount rates that give increased weight to future time periods. While over-simplification of the climate system can, in some circumstances, have significant effects on

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TABLE 2 Effect of CH_4 gas cycle model on SC-CH_4 (2007$ per tonne CH_4): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	1135	1183	2 4%
	3.0%	822	851	2 3%
	5.0%	349	354	2 2%
2045	2.5%	2490	2707	2 8%
	3.0%	1933	2084	2 7%
	5.0%	956	1006	2 5%

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social cost estimates (e.g. Marten 2011), the near-term differences based on this simplification seem relatively small considering the precision of such social cost estimates.

3.4. Nitrous oxide

The simple one-box atmospheric gas cycle model for N_2O takes a similar form to the model used for CH_4, such that the concentration of nitrous oxide in year t, $C_t^{N_2O}$ [ppb], is specified as

$$C_t^{N_2O} = C_{t-1}^{N_2O} + d_{N_2O}(C_{pre}^{N_2O} - C_{t-1}^{N_2O}) + g_{N_2O}E_{t-1}^{N_2O}, \tag{4}$$

where d_{N_2O} is the rate of decay, and g_{N_2O} [ppb N_2O/Mt N] converts emissions, $E_{t-1}^{N_2O}$ [Mt N], from mass to atmospheric volume. Following the IPCC AR4, the mass to volume conversion factor is g_{N_2O} ¼ 0.2079 ppb N_2O/Mt N and the rate of decay is d_{N_2O} ¼ 1/114 based on a 114-year lifetime. As with CH_4, the iteration begins in the year 2006 using the emissions from the EMF-22 scenarios (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used, such that $C_{2005}^{N_2O}$ ¼ 319 ppb.

The contribution of atmospheric N_2O to global radiative forcing, denoted $Q_t^{N_2O}$, is defined using the relationship in Table 6.2 of the IPCC TAR, such that

$$Q_t^{CH_4} = 0.12 \left[C_t^{N_2O} - C_{pre}^{N_2O} - [f(C_{pre}^{CH_4}, C_t^{N_2O}) - f(C_{pre}^{CH_4}, C_{pre}^{N_2O})] \right], \tag{5}$$

where $f(C^{CH_4}, C^{N_2O})$ is defined in expression (3).

As with CH_4, a key simplifying assumption is the constant decay rate used in the simple gas cycle model (and potentially the time it takes the gas to become well mixed within the atmosphere). As discussed in the IPCC TAR, the decay rate of N_2O will depend on the atmospheric concentration of N_2O and so will not be constant in reality. To examine the extent to which this impacts the results of the simple model, an analogous set of experiments as conducted for CH_4 were performed. Given future

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N_2O emissions based on the EMF-22 MiniCAM reference scenario, a one tonne N_2O perturbation in 2015 is considered. Figure 3(a) shows the projected atmospheric concentration increase from the perturbation using the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. This comparison illustrates that the simple model tracks the output of MAGICC well for the entire 300-year time horizon. Outside the initial perturbation year, the two projections do not differ by more than 2% within the first century, with the largest difference occurring in the perturbation year, for the same reasons as with CH_4.

Figure 3(b) presents the estimates of average additional radiative forcing per decade as a result of the N_2O perturbation using both models. The additional radiative forcing from the N_2O perturbation in the one-box model is forecast to be slightly lower (7%) in the first decade compared to MAGICC. Subsequently, the difference is within 2% through to 2300.

As with CH_4, to assess the effect that this difference would have on the SC-N_2O, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of N_2O computed using both the simple model and MAGICC is added to the exogenous forcing projection. As before, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 3 presents the results of this experiment. As the comparisons of the projected radiative forcing perturbations would suggest, the difference between the social cost estimates for the two approaches is relatively small. In contrast to the case of CH_4, here an increase in the discount rate increases rather than decreases the divergence between the estimates due to the greater weight being placed on the earlier years when the radiative forcing perturbations have a slightly higher degree of divergence.

3.5. Effect of post-2100 non-CO_2 radiative forcing assumptions

The EMF-22 socio-economic-emissions scenarios used by the USG include years only up to 2100, while the USG ran the IAMs out to 2300. Therefore, additional assumptions were required to extrapolate the scenarios beyond 2100. For the purposes of this study, the most important of these assumptions is that non-CO_2 radiative forcing will remain constant at its 2100 level until 2300. Such a broad assumption was sufficient for the purposes of the USG in estimating the SC-CO_2. However, estimating the social cost of non-CO_2 GHGs requires explicit projections of baseline emissions of non-CO_2 gases in order to correctly determine the effect of the perturbation. The USG's broad assumption regarding the extrapolation of non-CO_2 gases is therefore problematic as constant non-CO_2 radiative forcing post 2100 may occur in an infinite number of ways. For instance, one way to achieve this outcome is to assume that emissions of each non-CO_2 gas falls to a level equal to its respective rate of decay in 2100. This assumption would keep atmospheric concentrations, and in turn radiative forcing, constant. Based on the simple gas cycle models laid out in the earlier sections this implies that, for gas X,

$$E_t^X = \frac{-d_X(C_{pre}^X - C_{2100}^X)}{g_X} \forall t \ . \ 2100. \tag{6}$$

To put this assumption into context, the solid lines in Figure 4(a) and (b) present the emissions paths for CH_4 and N_2O, respectively, under the MiniCAM EMF-22 reference scenario extrapolated using

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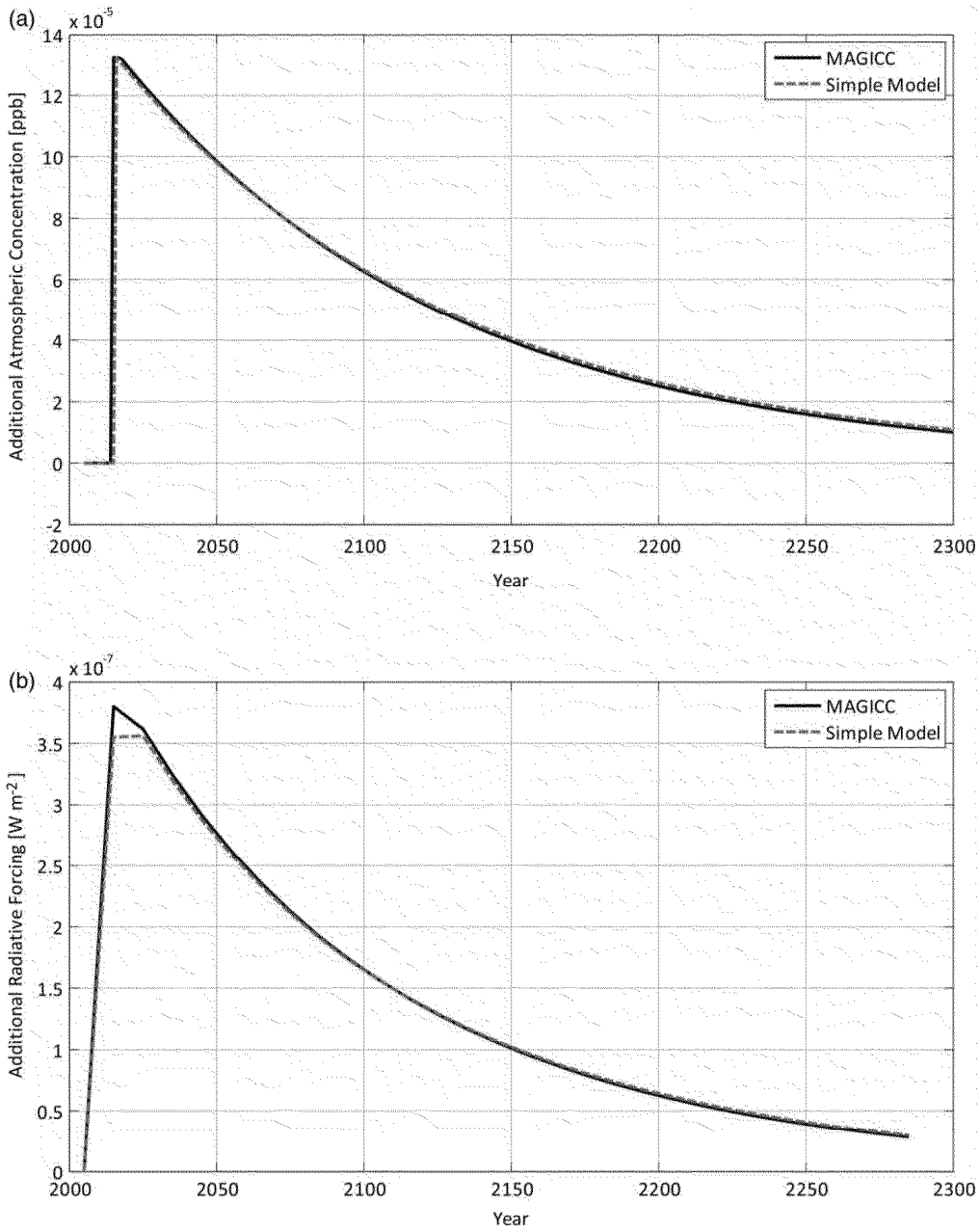

Figure 3 Effects of perturbation in 2015 N_2O emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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TABLE 3 Effect of climate model on SC-N_2O (2007$ per tonne N_2O): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	19,689	19,819	2 1%
	3.0%	12,390	12,525	2 1%
	5.0%	3,346	3,419	2 2%
2045	2.5%	36,968	37,358	2 1%
	3.0%	25,030	25,427	2 2%
	5.0%	8,280	8,528	2 3%

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expression (6), while the dashed lines show two alternative extrapolation approaches, one where emissions are held constant at their 2100 level and one that assumes emissions intensity (emissions/economic output) continues to decline at the same rate forecast by the EMF-22 scenario in 2090–2100 (dotted line). This latter alternative is analogous to the USG assumption regarding industrial CO_2 emissions. The two alternatives will not result in the radiative forcing contribution of gas X remaining constant post-2100, but do not in themselves violate the assumption that overall non-CO_2 radiative forcing remains constant. Noteworthy is the fact that the assumption in (6) is almost analogous to keeping CH_4 emissions constant at their 2100 levels, whereas for N_2O the assumption requires a sudden decrease in emissions of over 35%.

While Figure 4 illustrates that these three extrapolation approaches can lead to vastly different projections for emissions after 2100, the relevant comparison is how these assumptions affect the additional radiative forcing from a perturbation of the gas and in turn the SC-X estimates. Figure 5(a–d) present the additional radiative forcing resulting from a one tonne perturbation based on the simple model presented in Sections 3.1 and 3.2. Figure 5(a) and (b) demonstrates the difference for a perturbation in 2015, whereas Figure 5(c) and (d) represents perturbations in 2045. For CH_4, the cumulative radiative forcing from the projection over the time horizon differs by less than 0.001%, even for a

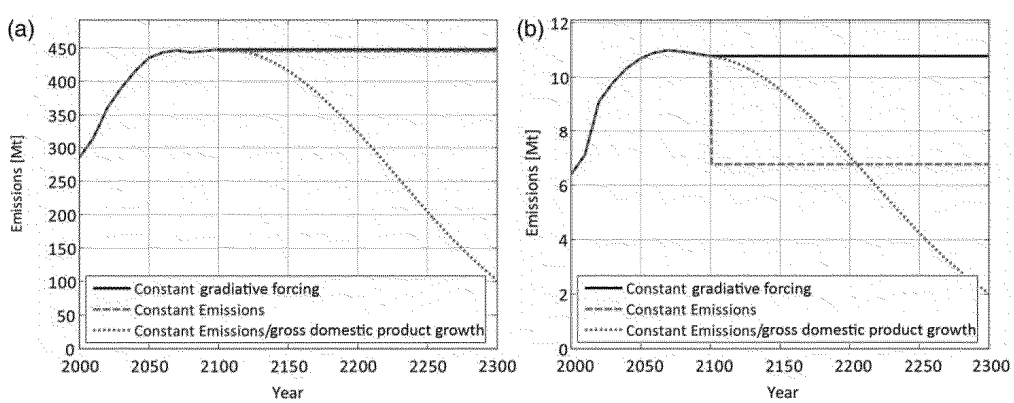

Figure 4 EMF-22 MiniCAM extended emissions scenario: (a) CH_4 emissions; (b) N_2O emissions

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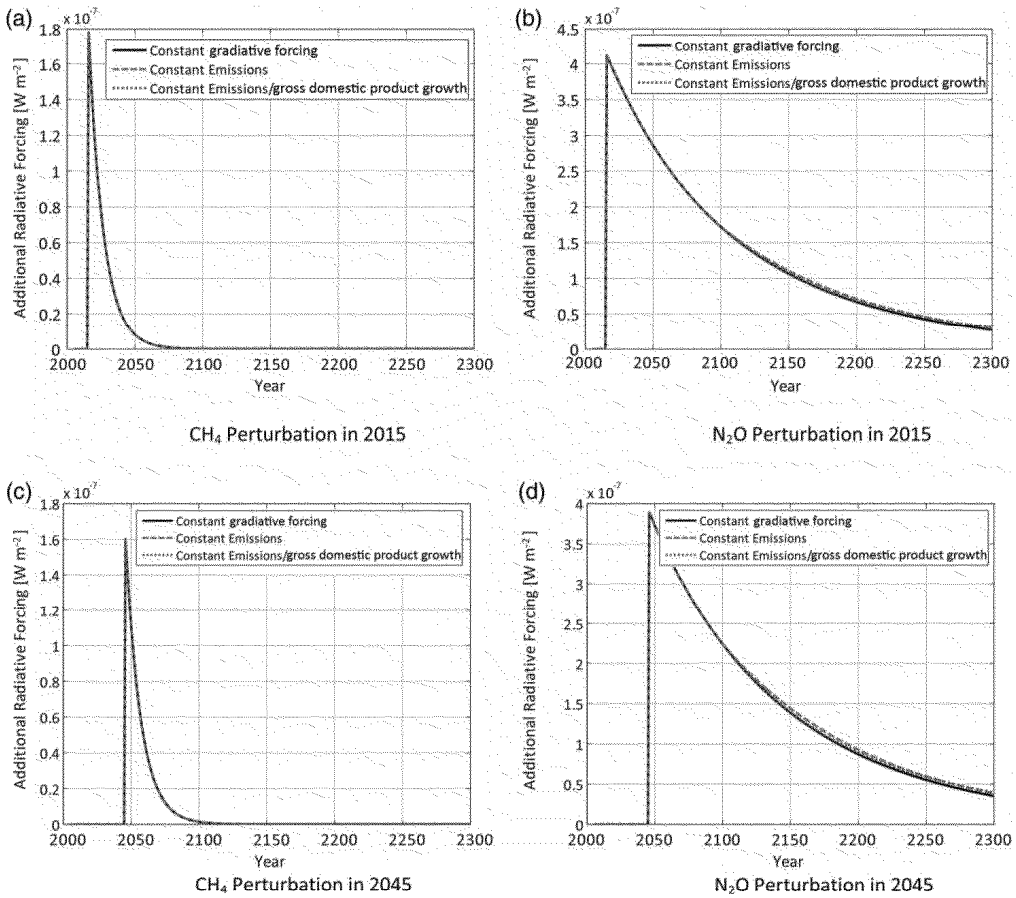

Figure 5 Effect of extrapolation approach on radiative forcing perturbation from simple model: (a) CH_4 perturbation in 2015; (b) N_2O perturbation in 2015; (c) CH_4 perturbation in 2045; (d) N_2O perturbation in 2045

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perturbation in 2045. Accordingly, the relevant annual difference is smaller even than one-thousandth of a percent. This result occurs because of the short atmospheric lifetime of the gas, which renders assumptions regarding CH_4 emissions after 2100 unimportant for near-term perturbations. Post-2100 emissions will have a larger effect in the case of N_2O, which has a much longer atmospheric residence time. However, even for a perturbation in 2045, the difference in cumulative additional radiative forcing is less than 2.5% across the extrapolation assumptions.

To examine the impact of these assumptions on SC-CH_4 and SC-N_2O, an experiment was conducted using the DICE model based on the EMF-22 MiniCAM socio-economic-emissions scenario. The results of this experiment are presented in Table 4 for the perturbation year 2045 (noting that the extrapolation method will have greater impact on future emissions years). As may be seen, the relatively short atmospheric lifetime of CH_4 leads to a situation in which post-2100 assumptions do not affect SC-CH_4 estimates, even in 2045. For the longer-lived gas N_2O, in emission year 2045, where the effect of the post-2100 extrapolation approach would be largest, the difference across the three

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TABLE 4 Effect of post-2100 extrapolation on the 2045 SC-X (2007$ per tonne): DICE2010, MiniCAM

Gas	Discount rate	Constant RF	Constant emissions	Constant emissions intensity growth
CH_4	2.5%	2,490	2,490	2,490
	3.0%	1,933	1,933	1,933
	5.0%	956	956	956
N_2O	2.5%	36,968	36,588	36,662
	3.0%	25,030	24,837	24,868
	5.0%	8,280	8,261	8,263

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assumptions is less than 1% and the projections are equivalent to two significant digits. Therefore, in the remainder of this article, non-CO_2 emissions are extrapolated past 2100 using expression (6) to ensure that the gas-specific contribution to overall radiative forcing remains constant in the simple model. While additional study may lead to improvements of long-term forecasts of CH_4 and N_2O emissions and possible correlations, compared to the paths in Figure 5(a), the very minimal effect of such assumptions on the social cost estimates suggests the impact of such efforts would be minimal in this context.

4. Results

For FUND, the social cost of non-CO_2 GHGs is estimated by perturbing the paths of emissions directly, while for DICE and PAGE the approach presented in Section 3 is used. In both cases, all additional assumptions made by the USG are applied, including the five EMF-22 socio-economic-emissions scenarios, the Roe and Baker (2007) distribution for the equilibrium climate sensitivity, and constant discount rates of 2.5%, 3.0%, and 5.0%. Following the USG, the estimates for the expected social cost are averaged across scenarios and models, with each model and scenario given equal weight. Estimates are not combined across discount rates, and a fourth estimate is included representing the 95th percentile when using the 3.0% discount rate. By using the same assumptions and procedures as the USG, estimates of the SC-CO_2 derived in this article are identical to the values used in US Federal rule making. Specifically, these estimates are equivalent to the recent 2013 update of the USG SC-CO_2, which revised the original 2010 USG upwards based on new versions of the IAMs used. The non-CO_2 results, as well as the USG SC-CO_2 estimates, are presented in Table 5 for emissions years 2020 and 2050.[5] Results for additional years, and the results of sensitivity analyses using Ramsey discounting, may be found in Appendix B and C, respectively.

As expected, considering their higher radiative efficacy, the social costs associated with a tonne of CH_4 and N_2O emissions are substantially higher than for CO_2. The values are higher at lower discount rates, although the impact of the discount rate is lower for CH_4 given its relatively short lifetime. Similar to CO_2, the social cost estimates for CH_4 and N_2O increase over time as the climate and economic systems become more stressed, although the growth rate of the social cost estimate may differ between the gases, as discussed in the following.

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TABLE 5 SC-X (2007$ per tonne)

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CO_2	12	43	64	128
	CH_4	550	1,200	1,600	3,200
	N_2O	4,800	15,000	22,000	41,000
2050	CO_2	26	71	97	220
	CH_4	1,400	2,500	3,100	6,900
	N_2O	11,000	27,000	38,000	74,000

To better understand how the social costs of CH_4 and N_2O compare to CO_2, Table 6 presents the global damage potentials corresponding to the social cost estimates from Table 5. (The disaggregated results, by model and scenario, for 2020 are provided in Appendix B.) As explained in Section 2, the global damage potential for gas X is the ratio of SC-X to SC-CO_2, and therefore by construction captures all the important linkages between emissions and monetized climate change damages (to the degree they are captured by the IAMs) directly within the gas comparison metric. As noted by Frankhauser (1994), this is preferred to the commonly used GWP gas comparison metric, which only measures the additional radiative forcing from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years) and ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages.

The global damage potential of CH_4 decreases with the discount rate due to the relatively shorter atmospheric lifetime. This difference in atmospheric lifetime leads to a situation where lowering the discount rate has a greater impact on the SC-CO_2 than the SC-CH_4. This finding is robust across the models. The estimates in Table 6 also present the same result for N_2O in the aggregate case, although this characteristic is not consistent across the models or the previous literature. Based on the disaggregated results (presented in Appendix B), the results from the DICE model suggests the global damage potential for N_2O increases with lower discount rates due to a lower effective decay rate over the relevant time horizon for N_2O than CO_2. This result is consistent with previous findings by Marten and Newbold (2012). However, for FUND the opposite is seen to hold. Waldhoff et al. (2011) show that this result is primarily due to the inclusion of increased production in the agriculture and forestry sectors from CO_2 fertilization effects. At lower discount rates these benefits place a greater downward

TABLE 6 Global damage potential

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CH_4	46	29	25	25
	N_2O	397	359	353	317
2050	CH_4	52	36	32	31
	N_2O	414	388	387	338

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impact on the SC-CO_2, thereby lowering the global damage potential. If one were to remove those impacts from the FUND model the global damage potential for N_2O becomes relatively insensitive to the discount rate. One would expect the role of the discount rate in determining the global damage potential in PAGE to be the same as in DICE, but the results suggest that this is not the case. It seems most likely that this is because the PAGE model has only ten time steps to cover the entire time horizon, which results in very large, up to 100-year, time steps further out in time. As noted in Section 3, the additional radiative forcing from the N_2O perturbation is implemented as the average across the model's time steps. It seems that PAGE does not average radiative forcing over the time step for CO_2, which causes the global damage potential for N_2O to decrease with the discount rate. It is not clear if this result would hold if the size of the time steps in the model were reduced.

A comparison across models further highlights the importance of CO_2 fertilization impacts on the global damage potential. CO_2 emissions, and the resulting increase in atmospheric concentration, have the potential to increase yields in the agriculture and forestry sector. This characteristic is not shared by other GHG emissions. Accordingly, the FUND model, which explicitly captures this effect, exerts downward pressure on the SC-CO_2 that is not present for the SC-CH_4 and SC-N_2O, allowing for the possibility of substantially higher global damage potential estimates. The results based on the FUND model presented in this article exhibit this effect; however, the CO_2 fertilization effect is not explicitly modelled in DICE and PAGE and therefore they are found to produce lower estimates of the global damage potential. For example, using the 3% discount rate, the global damage potential for CH_4 as estimated by FUND ranges between 58 and 88 depending on the scenario, whereas it ranges from 19 to 28 for DICE and PAGE. As the DICE and PAGE models only consider two natural system impacts, temperature and sea level, if they do implicitly include potential CO_2 fertilization benefits, they are included by using the temperature anomaly as a proxy for the increasing atmospheric CO_2 concentration. Fertilization benefits would therefore be allowed to falsely accrue to perturbations of other GHG emissions besides CO_2. It is not clear the degree to which these models try to incorporate CO_2 fertilization effects and therefore the degree to which this issue is of concern.

Finally, the results in this article show that the 100-year GWP (25 for CH_4 and 298 for N_2O; Forster et al., 2007) probably provides an underestimate of the global damage potential of each gas, a finding consistent with previous studies by Marten and Newbold (2012) and Waldhoff et al. (2011). Unlike the GWP as calculated by the IPCC, the global damage potential will be dependent upon the year of the emissions perturbations, so the degree of underestimation varies by year. For CH_4, the global damage potential in Table 6 is 0–84% higher than the GWP in 2020, increasing to 24–108% in 2050. For N_2O, the global damage potential is 6–33% higher than the GWP in 2020, increasing to 13–39% in 2050. While inaccurate, using the GWP to convert emissions reductions into CO_2 equivalents that can be valued with the SC-CO_2 would probably provide a conservative estimate for the abatement benefits.

For the comparison above, the GWP estimates presented in the AR4 by the IPCC (Forster et al., 2007) were used to maintain consistency with the assumptions regarding the direct and indirect effect of CH_4 and N_2O concentrations within the modelling. The recent AR5 by the IPCC (Myhre et al., 2013) has increased the estimate of the indirect effects of CH_4, which gives a higher 100-year GWP for CH_4 of 28. A reduction in their estimate of the radiative efficacy of N_2O has decreased its 100-year GWP to 265. It is likely that updated modelling of the social cost estimates based on similar assumptions would maintain the finding that the GWP is an underestimate of the global damage potential.

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4.1. Comparison with previous estimates

For comparison, Table 7 presents the social cost estimates, when available, and the global damage potential estimates for CH_4 and N_2O from three recent studies in the literature whose features are more up to date and therefore more directly comparable with this study: Hope (2006a), Waldhoff et al. (2011), and Marten and Newbold (2012). A direct comparison to the longer list of studies presented in Table 1 is more difficult as they are based on models and socio-economic and emissions scenarios that were developed up to 20 years ago in a rapidly evolving field.

The social cost estimates presented in Table 5 are higher than the estimates in Hope (2006a) and Waldhoff et al. (2011) for CH_4, and in the range of Waldhoff et al. (2011) for N_2O. This result holds whether the comparison is made with the aggregate results in Table 5 or the disaggregated model-specific results. One reason for the significant difference in the SC-CH_4 estimates is that the earlier studies rely on older model versions (PAGE2002 and FUND3.5), neither of which include the indirect effects of CH_4 emissions on radiative forcing, but are included within this analysis. As noted in Section 3.3 the indirect effects of CH_4 are modelled as a 40% increase in its effective radiative forcing. The result of this change alone would likely be a greater than 40% increase in the SC-CH_4 due to the nonlinear damage functions. Furthermore, the assumptions regarding preference parameters in the main cases of Hope (2006a) and Waldhoff et al. (2011) lead to effective discount rates that are significantly higher than 3%. Other differences in input assumptions (e.g. equilibrium climate sensitivity, socio-economic emissions scenario) will also lead to differences, although these are likely to be of second-order importance given the relative similarity in the assumptions.

However, the results in Table 5 averaged across the combinations of the three models and five scenarios are relatively similar to those of Marten and Newbold (2012), which focused on a single scenario

TABLE 7 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Discount Rate	Emissions Year	Social cost (2007$/tonne X)[a]		Global damage potential (SC-X/SC-CO_2)	
			SC-CH_4	SC-N_2O	CH_4	N_2O
Hope (2006a)	Ramsey	2001	125	–	20	–
Waldhoff et al. (2011)[b]	Ramsey	2010–2019	265	7,616	26	738
			–	–	8–221	383–3,503
Marten and Newbold (2012)	2.5%	2020	1,500	26,000	23	403
		2050	3,500	50,000	32	444
	3%	2020	1,100	17,000	27	400
		2050	2,900	34,000	36	439
	5%	2020	550	4,900	42	380
		2050	1,500	12,000	53	415

[a]All values are discounted to the year of the emissions perturbation.
[b]The first row presents the base case and the second row presents the range found from sensitivity analysis (over socio-economic scenario, climate sensitivity, pure rate of time preference, climate sensitivity and CO_2 fertilization).

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and model. This result is in part based on the fact that both sets of results include the indirect effects of CH_4, use the same discount rates and equilibrium climate sensitivity distribution, and relatively similar scenarios. The estimates in this study are slightly higher for the SC-CH_4 and slightly lower for the SC-N_2O compared to Marten and Newbold (2012). Of particular interest is the specific comparison of this article's estimates based on DICE 2010 and the MiniCAM scenario to those of Marten and Newbold (2012) using the same scenario, discount rates, and equilibrium climate sensitivity but an the older 2007 version of the DICE model and a more complete climate sub-model. In this case, estimates for both the SC-CH_4 and SC-N_2O (presented in Appendix B) are notably lower. The myriad of differences between the model vintages and climate sub-models make it difficult to assess which differences are most important for explaining this relationship.

As previously noted, the global damage potential may provide a better value with which to compare across studies that estimate the social cost of non-CO_2 GHG emissions, as it helps to control for some of the underlying differences in assumptions across studies. For example, the global damage potential is far less sensitive to the discount rate used than the SC-X values themselves. However, the global damage potential does not address the lack of indirect CH_4 effects, as may be seen in the lower estimates of Hope (2006a) and Waldhoff et al. (2011). In these cases the exclusion of the 40% additional increase in radiative forcing from the indirect effects of the CH_4 perturbation explains the majority of the difference. In comparison to Marten and Newbold (2012), the results presented in Table 6 are relatively similar for CH_4 in both the aggregate and disaggregated results. For N_2O, similar results are found in the DICE estimates, but notable differences are found in how the aggregate results respond to the discount rate, due to the differences in this relationship between the models as noted above.

5. Concluding remarks

This article presents a simple and transparent approach to estimating the social cost of CH_4 (SC-CH_4) and N_2O (SC-N_2O) in a manner that is consistent with estimates of the social cost of CO_2 (SC-CO_2) already in use in benefit–cost analysis (BCA) for US Federal regulations. This approach is used to estimate the SC-CH_4 and SC-N_2O for the period 2010–2050. These directly modelled estimates are found to be larger than approximations of the social costs of these gases based on the application of common physical gas comparison metrics, such as global warming potentials (GWPs), to the SC-CO_2. This result generalizes the empirical findings of Marten and Newbold (2012) that using a GWP-based approximation approach will likely offer a conservative estimate of the social cost of non-CO_2 GHGs.

The social costs associated with emissions of non-CO_2 GHGs are substantial and should be included within the BCAs used to assess the overall welfare implications of policy alternatives. For example, by not including monetized values of the benefits from reducing CH_4 and N_2O emissions, the BCA for recent standards regulating the fuel efficiency and GHG emissions of light duty vehicles implicitly assigned them a value of zero (US EPA, 2010). However, the results of this article suggest that those reductions have benefits of US$85–493 million (2007$) for CH_4 and $1.5–12 million (2007$) for N_2O in the year 2020 alone. Failing to account for such impacts could limit the ability of the analysis to serve as a transparent and informative input into the decision-making process about the relative benefits and costs of regulatory alternatives. That said, by restricting the article to a derivation of social cost estimates consistent with the USG SC-CO_2 estimates, the myriad issues related to

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whether those estimates can themselves be improved are set aside.[6] Any limitations that apply to the USG SC-CO_2 estimates therefore also apply to the SC-CH_4 and SC-N_2O estimates derived here.

Supplemental data

Supplemental data for this article can be accessed 10.1080/14693062.2014.912981.

Notes

1. Examples include Minnesota's draft methodology for setting the value of a tariff to compensate solar panel owners for the surplus power they deliver to utilities (http://www.eenews.net/stories/1059992297, http://mn.gov/commerce/energy/images/DRAFT-MN-VOS-Methodology-111913.pdf), the Northwest Power and Conservation Council's symposium supporting the development of the 7th Power Plan (http://www.nwcouncil.org/energy/powerplan/7/symposiums/greenhouse/agenda), BCA of Canada's Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations (http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html), analysis of climate change projects at the Inter-American Development Bank (correspondence with Patrick Doyle, Senior Climate and Energy Officer, Structured and Corporate Finance Department), the International Monetary Fund's recent Energy Subsidy Reform report (http://www.imf.org/external/np/pp/eng/2013/012813.pdf), and Parry and Strand (2012).
2. An alternative approach for estimating the social cost of GHG emissions could be based on stated preference (SP) surveys designed to elicit respondents' maximum willingness-to-pay for various levels of GHG emission reductions (e.g. Longo, Markandya, & Petrucci, 2008; Soliño, 2010). This approach would not suffer from the difficulties associated with creating and parameterizing a numerical integrated assessment model. However, it would suffer from its own set of difficulties, including well-known general limitations that affect all SP studies including the potential for 'hypothetical bias' (e.g. Carson, 2012; Hausman, 2012; Kling, Phaneuf, & Zhao, 2012), plus difficulties that may be specific to this application stemming from the generally limited knowledge base regarding the potential climatic, biophysical, and especially economic impacts of GHG emissions on current and far future generations that most respondents will bring to the survey.
3. The fork of MAGICC version 5.3 included in Pacific Northwest National Laboratory's open source model GCAM version 2 (Calvin et al., 2009) is used without carbon cycle feedbacks and, unless otherwise specified, an equilibrium climate sensitivity of 3 8C. We note that sensitivity analysis found the general results of this side analysis to be robust to other values of the equilibrium climate sensitivity.
4. The EMF-22 scenario is extended past 2100 assuming that emissions stay constant at the 2100 level. This assumption is revisited later in this article.
5. The PAGE 2009 model restricts the user to representing the entire time horizon, in this case out to 2300, with only ten time steps. This leads to the unrealistic situation in a small number of simulations where the marginal unit of emissions can cause 'catastrophic' climate impacts to occur one period earlier, which could be 100 years earlier in some cases. We consider these occurrences to be a limitation of the model and drop them from the overall distribution of estimates. Appendix A contains further details about this issue.
6. In addition to the critiques previously cited, we point the interested reader to the work of Marten et al. (2013) and Oppenheimer (2013) for a review of literature that considers potential improvements in the assessment and valuation of climate change impacts.

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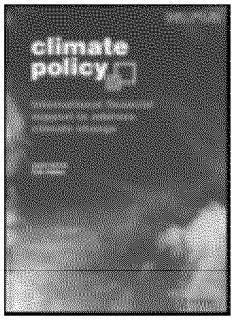

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Benefit–cost analysis can serve as an informative input into the policy-making process, but only to the degree it characterizes the major impacts of the regulation under consideration. Recently, the US, amongst other nations, has begun to use estimates of the social cost of CO_2 (SC-CO_2) to develop analyses that more fully capture the climate change impacts of GHG abatement. The SC-CO_2 represents the aggregate willingness to pay to avoid the damages associated with an additional tonne of CO_2 emissions. In comparison, the social costs of non-CO_2 GHGs have received little attention from researchers and policy analysts, despite their non-negligible climate impact. This article addresses this issue by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. By extending existing integrated assessment models, it is possible to develop a set of social cost estimates for these gases that are consistent with the SC-CO_2 estimates currently in use by the US federal government.

Policy relevance

Within the benefit–cost analyses that inform the design of major regulations, all Federal agencies within the US Government (USG) use a set of agreed upon SC-CO_2 estimates to value the impact of CO_2 emissions changes. However, the value of changes in non-CO_2 GHG emissions has not been included in USG policy analysis to date. This article addresses that omission by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. These new estimates are designed to be compatible with the USG SC-CO_2 estimates currently in use and may therefore be directly applied to value emissions changes for these non-CO_2 gases within the benefit–cost analyses used to evaluate future policies.

Keywords: integrated assessment; non-CO_2 GHGs; social cost of carbon

1. Introduction

The social cost of CO_2 (SC-CO_2) is a measure of the monetary value of the damages occurring both within and outside economic markets as the result of an additional unit of CO_2 emissions. Specifically, it represents society's aggregate willingness to pay to prevent future impacts that occur when one additional unit of CO_2 is emitted into the atmosphere in a particular year. Estimates of SC-CO_2

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therefore provide a way to value changes in CO_2 emissions in benefit–cost analyses (BCAs) of policy alternatives. Without an estimate of the SC-CO_2, the benefits of mitigating the climate change impacts from CO_2 emissions would implicitly be valued at zero in BCAs, thereby significantly weakening the information provided by such analyses. Since 2009, the US Federal Government (USG) has used a set of agreed-upon SC-CO_2 estimates in the BCAs used to evaluate major regulations that impact CO_2 emissions (USG, 2010), including over 30 regulatory actions to date. The USG SC-CO_2 estimates are also increasingly being used in analysis and discussions outside the USG (e.g. by states, regional organizations, other nations, international organizations, NGOs, and academic researchers)[1] and have even figured in several recent public hearings and court cases (e.g. Keohane, 2010a, 2010b).

Although CO_2 is the primary anthropogenic GHG, other GHGs such as methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are also important contributors to climate change. The combined effect of all GHGs accumulated in the atmosphere is to increase the Earth's radiative forcing, which is the amount of energy from the Sun that is trapped in the Earth's atmosphere and therefore acts to warm the planet and change the climate. In 2011, the atmospheric CO_2 concentration contributed 64% of overall radiative forcing, while CH_4 and N_2O accounted for approximately 23% (Myhre et al., 2013). Non-CO_2 GHGs, notably CH_4 and N_2O, therefore contribute significantly to the negative impacts on human well-being from climate change. Furthermore, several recent studies have shown that consideration of non-CO_2 GHGs, particularly CH_4 and N_2O, is important for the design of cost-effective climate policy (Reilly et al., 1999; Tol, Heintz, & Lammers, 2003; Weyant, De La Chesnaye, & Blenford, 2006).

The monetary value of changes in emissions of non-CO_2 GHGs has not been included in USG policy analysis to date. This shortcoming prevents the development of accurate and comprehensive assessments of potential regulatory alternatives by the USG and others that rely on the USG SC-CO_2 estimates (Kopp & Mignone 2012; Marten & Newbold, 2012). For example, fossil fuels (e.g. coal and natural gas) have different compositions of GHG emissions across gases when considering the entire process of extraction, production, transmission, and combustion. Thus, if a regulation is anticipated to cause an industry to substitute between fuels, analysts may be providing inadequate information to decision makers and the public about its benefits if only the welfare implications of direct CO_2 emissions are considered while ignoring changes in CH_4 and other GHG emissions (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2011).

A key reason for the value of non-CO_2 GHG emissions impacts not being included in USG analyses so far is that existing estimates of the social cost of non-CO_2 GHGs presented in the literature are inconsistent with USG SC-CO_2 modelling assumptions. For example, the recent US Environmental Protection Agency BCA of new pollution standards for the oil and natural gas industry concluded that, because they are not consistent with the USG SC-CO_2, 'the methane climate benefit estimates available in the current literature are not acceptable to use to value the methane reductions finalized in this rulemaking' (USEPA, 2012). This article seeks to address that gap by developing a new set of social cost estimates for CH_4 and N_2O (SC-CH_4 and SC-N_2O, respectively) that are fully consistent with the modelling assumptions underlying the current USG SC-CO_2 estimates. This article also develops an approach to extending the models used by the USG to generate estimates of the social cost of additional GHGs that are consistent with the latest USG estimates of the SC-CO_2.

It is important to note at the outset that by restricting attention to the derivation of social cost estimates consistent with the USG SC-CO_2 estimates, any limitations that apply to inputs and modelling

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assumptions underlying the USG SC-CO_2 estimates (e.g. Arrow et al., 2013; Kopp & Mignone 2012; Marten, 2011; O'Neil, 2010; Warren, Mastrandrea, Hope, & Hof, 2010) also apply to the SC-CH_4 and SC-N_2O estimates derived here. Thus, while it is anticipated that the USG will continue to improve the models and data it uses to estimate the SC-CO_2, this article focuses on the more immediate task of developing a set of consistent estimates for the social cost of other GHG emissions so that they need not be implicitly assigned a value of zero in USG policy analyses.

The remainder of the article is organized as follows. Section 2 presents an overview of the USG SC-CO_2 estimation approach and how it compares to the existing literature on the social cost of non-CO_2 GHGs, including a discussion of some of the critiques of the approach. Section 3 presents the approach for estimating the SC-CH_4 and SC-N_2O in a manner consistent with the USG SC-CO_2 estimates. Section 4 presents the results and a comparison of the relative social costs to the previous literature and the global warming potential (GWP)-based metric that is often used as an approximation in the absence of direct estimates, and Section 5 provides concluding remarks.

2. Background

In 2009–2010 the USG formed an interagency working group to develop a set of SC-CO_2 estimates for use by all Executive Branch agencies to value marginal changes in CO_2 emissions in regulatory impact analyses (USG, 2010). The goal of this exercise was to improve the accuracy and consistency with which agencies value marginal changes in CO_2 emissions. Before the release of these estimates, CO_2 emissions changes were valued in some but not all regulatory analyses, and the SC-CO_2 estimates used by different agencies varied substantially. The USG recently updated their estimates for the SC-CO_2 by employing new versions of the three underlying integrated assessment models (IAMs), but leaving the original estimation approach and underlying assumptions unchanged (USG, 2013). This section provides a brief overview of the estimation approach and assumptions used by the USG for estimating SC-CO_2, describes some critiques of the approach by other researchers, and discusses the existing literature on the social cost of non-CO_2 GHGs.

2.1. USG SC-CO_2 estimation approach

To estimate the SC-CO_2 the USG used three IAMs that couple simplified models of atmospheric gas cycles and climate systems with highly aggregate models of the global economy and human behaviour to capture the effects that GHG emissions, through their effect on the climate, have on human welfare. Within IAMs, the modelling that guides the transition from emissions into climate impacts is based on scientific assessments, while the mapping of climate impacts into changes in human welfare is based on economic research that has studied the effect of climate on various market and non-market sectors. Nordhaus and Boyer (2000) provide a very informative and detailed description of how such models are developed.[2]

The three models used by the USG are those that feature most prominently in the published social cost of carbon literature: the Dynamic Integrated Climate and Economy (DICE) (Nordhaus, 2008; Nordhaus & Boyer, 2000), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2006b, 2008), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff, Hepburn, & Tol, 2009; Tol, 2002a, 2002b, 2009) models. The USG chose to use the IAMs'

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climate system submodels and the functions that map climate change into economic damages as implemented by the model developers, but adopted a common set of input assumptions for equilibrium climate sensitivity, discount rates, global population, economic output, and GHG emissions projections. The remainder of this section provides a brief description of these common assumptions and the steps used to calculate the SC-CO_2 estimates. Interested readers can find more details in the USG's 2010 technical support document (USG, 2010).

2.1.1. Reference socio-economic-emissions scenarios

The USG selected five scenarios of economic output, population, and GHG emissions projections using results from the 2009 Stanford Energy Modeling Forum exercise number 22 (EMF-22). Four of the scenarios are based on baseline runs from global economic models (MERGE, MESSAGE, MiniCAM, and IMAGE) and span a range of emissions projections and plausible outcomes for future population and economic output absent significant global action to address climate change. These scenarios allowed for internally consistent forecasts of economic output, population, and emissions for the years 2000–2100. The fifth scenario used by the USG is based on the average of the 550 ppm CO_2e stabilization runs for each of the four models from which baseline scenarios were selected to represent potential action by the rest of the world absent US action. Across the five scenarios, atmospheric CO_2 concentrations in 2100 ranged from approximately 450 to 890 ppm (550–1130 ppm in CO_2e). Over the time horizon, the forecasts of the average growth rate for global per capita economic output ranged from 1.5% to 2.0% per year, and the average global population growth rate ranged from 0.4% to 0.5% per year. To run the IAMs through the year 2300, the USG extrapolated the selected EMF scenarios using the following assumptions: starting in 2100 the population growth rate declines linearly to zero in 2200; starting in 2100 the growth rate of economic output per capita declines linearly to zero in 2300; for all years after 2100 the growth rate of the carbon intensity of the global economy (CO_2 emissions/economic output) remains constant at its 2090–2100 average; starting in 2100 net land-use CO_2 emissions decline linearly to zero in 2200; and for all years beyond 2100 non-CO_2 radiative forcing anomalies remain constant at their 2100 levels.

Several limitations of the simplifying assumptions underlying the USG approach to scenario development have been discussed by other researchers. O'Neil (2010) pointed out that the selected EMF scenarios do not reflect the full range of outcomes that appear in other studies in the literature, and Kopp and Mignone (2012) suggested that the selected scenarios may effectively over-sample the peaks of the distributions. As for the extrapolations, while running the models out for multi-century time horizons is not necessary for relatively short-lived GHGs like CH_4, it is important for understanding the impacts of long lived GHGs such as CO_2 and N_2O that will affect human welfare well beyond 2100. As emphasized by O'Neil (2010) and Kopp and Mignone (2012), the state of the world beyond 2100 is highly uncertain and the scenario extrapolation approach taken by the USG represents only one of many possibilities. Furthermore, the extrapolations for each component of the scenarios (economic output, population, emissions) are separate and nothing ensures internal consistency within the scenarios past 2100. As shown by Marten and Newbold (2012), the temporal decomposition of damages for a perturbation of CO_2 and N_2O are relatively similar in shape and therefore the general findings of studies that explore the sensitivity of the SC-CO_2 to these assumptions should also be applicable to the SC-N_2O.

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2.1.2. Equilibrium climate sensitivity

In reduced-form IAMs, the speed and magnitude of temperature change for a given emissions projection are influenced largely by the 'equilibrium climate sensitivity' (ECS) parameter. The ECS represents the long-term global average temperature response to a level of radiative forcing associated with a sustained doubling of atmospheric CO_2 concentration (around 550 ppm). To represent the uncertainty in the responsiveness of the climate system to changing atmospheric conditions, the USG used a probability distribution for the ECS parameter of the form suggested by Roe and Baker (2007). The USG calibrated the parameters of the probability distribution to have a median equal to 3 8C, two-thirds probability that the ECS lies between 2 and 4.5 8C, which was intended to be consistent with the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) consensus statement about the ECS (Meehl et al., 2007). The distribution was truncated from above at 10 8C. This specification of the ECS distribution is retained to maintain consistency with the USG estimates of the SC-CO_2, but it is noted that the recently released AR5 by the IPCC has revisited the equilibrium climate sensitivity and revised the range downwards to 1.5–4.5 8C and no longer provides a most likely value (Collins et al., 2013). The ultimate effect of updating the ECS distribution to be consistent with the IPCC AR5 findings will depend heavily on the central tendency selected for the distribution.

2.1.3. Discount rates

Because the damages from an additional tonne of CO_2 emissions occur over many decades, the discount rate, which reflects the tradeoff between present and future consumption, plays a critical role in estimating the SC-CO_2. In light of disagreement in the literature regarding the appropriate discount rate to use in this context and uncertainty about future conditions that impact the discount rate, the USG used three constant discount rates intended to span a plausible range: 2.5%, 3%, and 5% per year. It is worth noting that the debate regarding not only the appropriate discount rate but also its time path is ongoing (Arrow et al., 2013; Dasgupta, 2008). While the appropriate value for the discount rate will presumably remain an area of active debate for some time to come, there appears to be agreement that the use of a constant discount rate over long time horizons with uncertain changes in the consumption per capita growth is not theoretically consistent. This article uses the same three constant discount rates as the USG estimation process, but in Appendix C results are reported from a series of sensitivity analyses using a Ramsey discounting approach. Similar to Marten and Newbold (2012), it is found that applying Ramsey discounting using plausible values for the components of the consumption discount rate gives a range of social cost estimates that is broadly consistent with the range of results obtained using the constant discount rates.

2.1.4. Calculating the SC-CO_2

The process to estimate the SC-CO_2 for emissions in year t has four steps. First, each model is used to forecast monetized impacts associated with the baseline path of emissions, economic output, and population. Second, each model is re-run with an additional unit of CO_2 emissions in year t to forecast monetized impacts for all years beyond t along this perturbed path of emissions. Third, the marginal damages in each year are calculated as the difference between the monetized impacts forecast in steps 1 and 2. Finally, the resulting path of marginal damages is discounted and summed to calculate

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the present value of the marginal damages in the year when the additional unit of emissions used to perturb the model is emitted.

The USG repeated this process with each model, discount rate, and socio-economic-emissions scenario for each decade between 2010 and 2050. Because the ECS parameter is modelled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run represents a distribution over the SC-CO_2 in each year. These distributions were estimated using 10,000 simulations in each model run. Therefore, the exercise produced 45 separate distributions of the SC-CO_2 for a given emissions year, based on the three models, three discount rates, and five socio-economic-emissions scenarios considered. To provide a range of estimates that reflects this uncertainty but still emphasizes the central tendency, the distributions from each of the models and scenarios were equally weighted and combined to produce three separate probability distributions for the SC-CO_2 in a given year, one for each assumed discount rate. Four SC-CO_2 estimates were selected from these three probability distributions to reflect the global damages caused by one tonne of CO_2 emissions. Three estimates are based on the average SC-CO_2 across the three models and five socio-economic-emissions scenarios for the 5%, 3%, and 2.5% discount rates, respectively. The fourth value is the 95th percentile of the SC-CO_2 distribution at the 3% discount rate, and was chosen to represent potential higher-than-expected impacts from anthropogenic GHG emissions.

2.2. Existing estimates of the social cost of non-CO_2 GHG emissions

A significant limitation of the aforementioned USG interagency process is that the social costs of non-CO_2 GHG emissions were not estimated. Therefore, as an alternative to applying direct estimates for the social costs of non-CO_2 GHG emissions in the primary BCA, several recent USG regulatory analyses have approximated the benefits of non-CO_2 GHG emissions reductions in sensitivity analyses by transforming the non-CO_2 GHG emissions to 'CO_2-equivalents' using estimates of the GWP for the GHG in question and then using the USG SC-CO_2 for valuation (e.g. US EPA, 2012, 2013).

Gas comparison metrics, such as the GWP, have been designed to measure the impact of different GHGs relative to CO_2, where the point of comparison along the pathway from emissions to monetized damages (depicted in Figure 1) may differ across measures. The GWP, in particular, is designed to measure the additional radiative forcing (i.e. the amount of energy absorbed by atmospheric concentrations of GHGs) from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years). The GWP and other gas-comparison metrics are problematic as an SC-CO_2 scalar in BCA, as the remaining linkages in the pathway depicted in Figure 1 are complex and non-linear. Marten and Newbold (2012) demonstrate that using the GWP to adjust SC-CO_2 estimates to capture the impact of non-CO_2 gases provides a significant improvement over the implicit assumption that they are zero when such benefits are left unquantified, but may still underestimate mitigation benefits. Alternative gas comparison metrics that compare GHGs at different points in the chain of

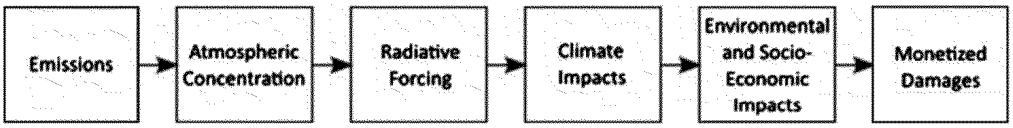

Figure 1 Path from GHG emissions to monetized damages

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causation (e.g. global temperature change potential (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005), peak commitment temperature (Smith et al., 2012), temperature proxy index (Tanaka, O'Neill, Rokityanskiy, Obersteiner, & Tol, 2009)) have also been shown to be imperfect substitutes for direct estimates.

Several researchers have directly estimated the social cost of non-CO_2 GHG emissions using IAMs, although the number of such estimates is small compared to the large number of SC-CO_2 estimates available in the literature. Among these previous direct estimates there is considerable variation in the model versions and input assumptions used. See Table 1 for a summary of the 11 non-CO_2 studies published to date.

As shown in Table 1, the estimates cover emissions years from 1990 to 2050, although the specific perturbation year is not stated in all studies. The studies also cover a wide range of constant and variable discount rate specifications and consider a range of baseline socio-economic and emissions scenarios that have been developed over the last 20 years. Finally, some studies in the literature have chosen not to report the social cost estimates directly. Instead, they opt to report only the 'global damage potential', which is a ratio of the social cost of gas X to the SC-CO_2. Normalizing the SC-CH_4 or

TABLE 1 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Model	Time horizon	Discount rate	Emissions year	Scenario[a]	Climate sensitivity
Reilly and Richards (1993)	N/A	140 years	2, 5, 8%	1990	N/A	N/A
Fankhauser (1994)	N/A	230 years	Ramsey	1991–2030	IS92[b]	N/A
Kandlikar (1995)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Kandlikar (1996)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Hammitt et al. (1996)	N/A	2200	1, 3, 5%	1995–2015	IS92a,c,e	1.5, 2,5, 4.5 8C
Tol (1999)	FUND 1.6	2100	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Tol et al. (2003)	FUND 1.7	2200	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Hope (2005)	PAGE95	2200	Ramsey	2000	SRES A2	Probabilistic, mode of 3 8C
Hope (2006a)	PAGE2002	2200	Ramsey	2001	SRES A2	Probabilistic, mean of 3 8C
Waldhoff et al. (2011)	FUND 3.5	3000	Ramsey	2010–2019	FUND, SRES A1B, A2, B1, B2	2, 3, 4.5 8C
Marten and Newbold (2012)	DICE2007 w/ MAGICC	2300	Ramsey, 2.5, 3, 5%	2010–2050	EMF-22 MiniCAM Base	Probabilistic,median of 3 8C

[a]IS90 scenarios are based on the IPCC First Assessment Report (IPCC, 1990); IS92 scenarios are based on the IPCC Supplementary Report (IPCC, 1992); SRES scenarios are based on the IPCC Special Report on Emissions (IPCC, 2000); the FUND scenario is the default scenario in the FUND model; EMF-22 scenarios are based on results from Stanford's Energy Modeling Forum's 22nd exercise (Clarke et al., 2009).[b]The particular IS92 scenario used was not specified.

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SC-N_2O estimate using the SC-CO_2, in part, controls for differences in the modelling to allow for a better comparison with other estimates in the literature.

Fankhauser (1994) was one of the first to develop estimates of the average SC-CH_4 and SC-N_2O for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt, Jain, Adams, and Wuebbles (1996) also developed estimates of SC-CH_4 and SC-N_2O for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006a) developed estimates for the SC-CH_4 in 2000 using the FUND and PAGE models, respectively. Waldhoff, Anthoff, Rose, and Tol (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal CO_2, CH_4, N_2O, and SF_6 emissions for the average year in the 2010 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios from the IPCC special report on emissions (IPCC, 2000) in addition to the default FUND scenario. In Section 4, the specific results of these previous studies are discussed with a comparison to the estimates obtained in the present study.

The above-mentioned previous studies provide a basic understanding of the relative social costs of different GHGs but do not provide sufficient information about how this relationship changes over time. Marten and Newbold (2012) used an IAM that couples the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) with economic components of the 2007 version of William Nordhaus' DICE model to directly estimate the social cost of marginal CO_2, CH_4, and N_2O emissions. They estimated the annual social costs for the years 2010–2050 along a single socio-economic-emissions pathway given uncertainty about the equilibrium climate sensitivity parameter. An advantage of their approach is that through the use of a more detailed, yet still relatively simple, climate model their results are not affected by over-simplification of temperature response or atmospheric chemistry, which have been shown to have non-negligible effects on the estimates of social costs (Marten, 2011; Warren et al., 2010).

The work of Marten and Newbold (2012) uses many of the assumptions used by the USG in its estimation of SC-CO_2, including discount rates, the equilibrium climate sensitivity distribution, and post-2100 socio-economic and emissions extrapolations. However, they focus on only one of the three models and one of the five socio-economic-emissions scenarios used by the USG. Furthermore, they use a different climate sub-model, which leads their estimate of the SC-CO_2 to be different from the USG estimate, even for the same IAM and scenario combination. Therefore, although these studies, including Marten and Newbold (2012), have increased our understanding about the relative social costs of GHG emissions, they have not provided a set of estimates that are entirely consistent with the USG SC-CO_2 estimates. In Section 4, the estimates derived in this article are compared with those of Marten and Newbold (2012) to more clearly demonstrate the similarities and differences in the two sets of estimates for SC-CH_4 and SC-N_2O.

3. Estimating the social cost of non-CO_2 GHGs consistent with USG SC-CO_2

The primary obstacle in estimating the social cost of non-CO_2 GHG emissions in a manner consistent with the USG SC-CO_2 estimates is that not all of the IAMs used include explicit representations of the non-CO_2 gases of interest. This section describes the degree to which non-CO_2 GHGs are currently

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represented in the default versions of DICE, PAGE, and FUND, and then discusses how they are amended to estimate the social cost of these gases.

3.1. Representation of non-CO_2 GHGs in DICE, PAGE, and FUND

The FUND model explicitly considers CH_4, N_2O, and SF_6 in addition to CO_2. The model uses one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels. For CH_4 and N_2O, FUND estimates the additional radiative forcing imposed by the atmospheric buildup of these gases using the simplified expressions presented in Chapter 6 of the IPCC's Third Assessment Report (TAR) (Ramaswamy et al., 2001). FUND also augments the TAR expression for the additional radiative forcing from CH_4 to account for the influences of stratospheric water vapour and tropospheric ozone changes. Because FUND uses CH_4 and N_2O emissions as inputs and internally computes their impact on the climate system, it is possible to directly estimate the social cost of those gases without modifying the model.

In the DICE model, the only GHG that is explicitly represented is CO_2; an exogenous radiative forcing projection is used to account for the impact of all other gases on the climate. To develop an exogenous radiative forcing pathway consistent with the emissions scenarios used to estimate the SC-CO_2, the USG decomposed the default DICE exogenous radiative forcing vector into CH_4, N_2O, F-gases, aerosols, and other residual forcing components. The USG then replaced the radiative forcing attributed to CH_4, N_2O, and F-gases with estimates associated with the EMF-22 scenarios. As non-CO_2 emissions are not a direct input into DICE, it is not possible to simply perturb the emissions projection and re-run the model to obtain a forecast of additional damages.

The 2002 version of the PAGE model, which was used by the USG in developing its first set of estimates (USG, 2010), includes an atmospheric model for CH_4 and SF_6, but represents the effects of other non-CO_2 GHGs in an exogenous radiative forcing projection. Presumably to simplify the process and maintain consistency with DICE, the USG did not use PAGE's internal CH_4 component. Instead, the same exogenous radiative forcing projection was used for the effect of CH_4, N_2O, and F-gas emissions as was used for DICE. Since then, a N_2O component has been added to the PAGE model, although in the recent 2013 SC-CO_2 update the USG maintained the approach of using the same single exogenous forcing projection as was applied to DICE (USG, 2013). Therefore PAGE, as implemented by the USG, faces the same limitations as DICE with respect to estimating the social costs of marginal non-CO_2 emissions that are consistent with the USG SC-CO_2 estimates. For these reasons, computing estimates for the social cost of non-CO_2 gases in DICE and PAGE requires either replacing the climate component of these models with a more complete representation, as was done with DICE by Marten and Newbold (2012), or deriving an estimate of the path of additional radiative forcing that would result from a perturbation of the gas in question. This article uses the latter approach for DICE and PAGE, as the former would represent a substantial change to the underlying IAMs and would have implications for the SC-CO_2 estimates, making this work inconsistent with the USG SC-CO_2 estimates currently used in regulatory analysis.

3.2. Estimating the social cost of non-CO_2 GHGs in DICE and PAGE

The process used in this article to estimate the social cost of non-CO_2 GHGs in DICE and PAGE as implemented by the USG requires first generating a forecast of the additional radiative forcing

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associated with a perturbation of a non-CO_2 gas's emissions in a single year, and then adding this radiative forcing perturbation to each model's exogenous radiative forcing projection. To determine the additional radiative forcing associated with the emission perturbation, there is a need to model the change in atmospheric concentration and the radiative forcing associated with the additional concentration. For both CH_4 and N_2O, a simple one-box atmospheric gas cycle model with a constant decay rate is used to estimate the atmospheric concentration of each gas based on its assumed emissions. The use of a one-box gas cycle for CH_4 and N_2O with constant decay follows the approach used by the IPCC to compute GWPs (Forster et al., 2007) and the FUND model (Anthoff & Tol, 2013). In both the baseline and the perturbed case, the contribution of the gas to the global radiative forcing anomaly is determined by the forcing relationships presented in the IPCC TAR (Ramaswamy et al., 2001), which were not updated by the IPCC in AR4. The incremental radiative forcing is defined by the difference between the baseline forcing path and the emissions path that includes a one tonne perturbation in a given year. Next, the path of additional radiative forcing is added to the stream of exogenous radiative forcing in each IAM to estimate the climate damages in the perturbed scenario. These damages are then compared to the baseline damages to determine the social cost of gas X (SC-X). Specifically, the process is as follows:

1. Run the IAM as described in the SC-CO_2 technical support document (USG, 2010) to estimate baseline damages.
2. Estimate the baseline atmospheric concentration for gas X.
3. Estimate the baseline radiative forcing contribution of gas X.
4. Perturb the stream of gas X emissions by one tonne in year t.
5. Estimate atmospheric concentration for gas X in the perturbed scenario.
6. Estimate the radiative forcing contribution of gas X in the perturbed scenario.
7. Compute the incremental radiative forcing as the difference between the results of steps 3 and 6.
8. Add the additional radiative forcing from step 7 to the exogenous radiative forcing path used in the IAM in step 1.
9. Re-run the IAM to compute the damages along the perturbed emissions path.
10. Compute the social cost of gas X for emission year t as the present value of the difference in damages estimated in steps 1 and 9.

Two practical issues associated with implementation are worth noting. First, while the SC-X estimates are associated with a one tonne perturbation, to avoid computational rounding error a 1 Mt perturbation is used and then the resulting change in damages is scaled to get the average effect per tonne. Experiments conducted by Griffiths et al. (2012) to assess the applicability of the SC-CO_2 to non-marginal emission changes show that the average per tonne SC-CO_2 estimate is relatively constant over large differences in perturbation size. Additional experiments in the context of this article found that alternative perturbation sizes do not significantly change the average one tonne social cost estimate. Second, the additional radiative forcing due to the emissions perturbation is computed based on an annual time step, but because DICE and PAGE use longer time steps the average radiative forcing over the time step is added to the model's exogenous radiative forcing vectors.

The remainder of this section describes the procedure for modelling the incremental radiative forcing of a perturbation for CH_4 and N_2O, and explores the sensitivity of these projections to

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two issues. First, it evaluates whether the simple one-box gas cycle model with a constant decay rate produces a close approximation to the forecasts of future atmospheric CH_4 and N_2O concentrations based on a more sophisticated climate model. Second, it explores the sensitivity of the results to the method used for extrapolating non-CO_2 emissions from 2100 to 2300. This is important, because the USG did not specify a particular set of emissions pathways for each constituent gas, instead assuming only that non-CO_2 radiative forcing remains constant past 2100. Such a situation could arise from a myriad of possible individual gas projections and the USG did not specify which it was assuming.

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3.3. Methane

A simple one-box atmospheric gas cycle model for methane specifies the concentration in year t, $C_t^{CH_4}$ [ppb], such that

$$C_t^{CH_4} = C_{t-1}^{CH_4} + d_{CH_4}(C_{pre}^{CH_4} - C_{t-1}^{CH_4}) + g_{CH_4}E_{t-1}^{CH_4}, \tag{1}$$

where d_{CH_4} defines the rate of decay, $C_{pre}^{CH_4}$ [ppb] is the pre-industrial atmospheric concentration, and g_{CH_4} [ppb/Mt] converts emissions, $E_{t-1}^{CH_4}$ [Mt], from mass to atmospheric volume. The mass to volume conversion factor is g_{CH_4} ¼ 0.3597 ppb/Mt and $C_{pre}^{CH_4}$ ¼ 700 ppb, following the IPCC TAR. The rate of decay is set to d_{CH_4} ¼ 1/12 following the IPCC AR4 stated CH_4 lifetime of 12 years. The iteration begins in the year 2006 using the emissions from the EMF-22 scenario (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used so that $C_{2005}^{CH_4}$ ¼ 1774 ppb.

The contribution of atmospheric methane to global radiative forcing, denoted $Q_t^{CH_4}$, is defined using the relationship in Table 6.2 of the IPCC TAR:

$$Q_t^{CH_4} = f\ 0.036\ \left(C_t^{CH_4} - C_{pre}^{CH_4}\right) - \left[f(C_t^{CH_4}, C_{pre}^{N_2O}) - (C_{pre}^{CH_4}, C_{pre}^{N_2O})\right], \tag{2}$$

where $C_{pre}^{N_2O}$ [ppb] is the pre-industrial atmospheric concentration of nitrous oxide and

$$f(C^{CH_4}, C^{N_2O}) = 0.47 \ln\left[1 + 2.01 \times 10^{-5}(C^{CH_4}C^{N_2O})\right]^{0.75} + 5.31 \times 10^{-15}C^{CH_4}(C^{CH_4}C^{N_2O})^{1.52}. \tag{3}$$

The function in expression (3) accounts for the overlapping absorption bands of CH_4 and N_2O, thereby reducing their effective absorption. Parameter f is used to proxy for indirect effects of CH_4 that include the enhancement of stratospheric water vapour and tropospheric ozone changes. Following the IPCC AR4, an enhancement effect of 40% (25% from tropospheric ozone change and 15% for stratospheric water vapour enhancement) is used, such that f ¼ 1.4. The pre-industrial concentration of N_2O is set consistent with the IPCC TAR, such that $C_{pre}^{N_2O}$ ¼ 270 ppb.

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A key simplification in this approach is the constant decay rate used in the atmospheric gas cycle model. As discussed by IPCC Working Group I in Chapter 4 of the TAR, the lifetime of methane emissions in the atmosphere depends on temperature and the concentrations of CO, NOx, and other VOCs in the atmosphere (Ehhalt et al., 2001). Sensitivity analysis is used to understand the potential implications of ignoring these interactions by comparing the incremental atmospheric concentration projected by the simple model described above to the analogous projection from the climate model MAGICC,[3] which, while still relatively simple, incorporates these interactions between the lifetime of CH_4 in the atmosphere and the other gases and climate variables. This exercise uses CH_4 emissions from the EMF-22 MiniCAM reference scenario and considers a one tonne perturbation of CH_4 in 2015. It is noted that these results are robust across alternative emissions levels.[4]

Figure 2(a) presents the projected average decadal increment to atmospheric concentrations using both the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. At the time of the perturbation (2015), the inter-annual time step of MAGICC allows for an uptake of the additional emissions into the atmosphere, whereas the strict annual time step of the simple model causes a year to pass before the change is registered. After the initial year, the models originally differ by around 15%. This difference falls to under 10% within the first decade, with the faster effective growth in the simple model causing its additional concentration to eventually fall below that of MAGICC.

The difference in the incremental radiative forcing from the perturbation between the simple model and MAGICC is also of importance. Although MAGICC relies on similar equations to derive the radiative forcing of atmospheric CH_4 concentrations, it differs in the way it handles indirect effects of CH_4 on tropospheric ozone and stratospheric water vapour, in addition to including other temperature-related feedbacks. Figure 2(b) presents the average additional radiative forcing per decade attributed to the 2015 CH_4 perturbation in both models. The average increase in radiative forcing over the decade is considered because this is the input required by DICE due to its ten-year time step and therefore a more relevant comparison (PAGE requires a similar multi-year average). When considering the average additional radiative forcing over the decade, the initial difference in concentration between MAGICC and the simple model has a minimal effect and the difference in radiative forcing between the two models is less than 2% over the first two decades. However, this difference grows to –18% over the subsequent two decades. This escalation in the difference is in part due to the use of a constant decay rate in the simple model, whereas MAGICC takes into account the growing atmospheric concentrations of other gases and increasing atmospheric temperature, which increase the lifetime of atmospheric CH_4.

To understand the effect that this difference would have on an estimate of the SC-CH_4, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of CH_4, as computed using both the simple model and MAGICC, is added to the exogenous forcing projection. As above, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 2 presents the results of this experiment. In line with the results comparing the radiative forcing perturbations above, the two approaches produce similar social cost estimates for emissions in 2015, where additional analysis has shown these results to hold with PAGE as well. The impact of assuming a constant decay rate is greater further out into the future, due to the projected increase in the atmospheric concentration of other relevant gases and atmospheric temperature that are accounted for in MAGICC, and the social cost

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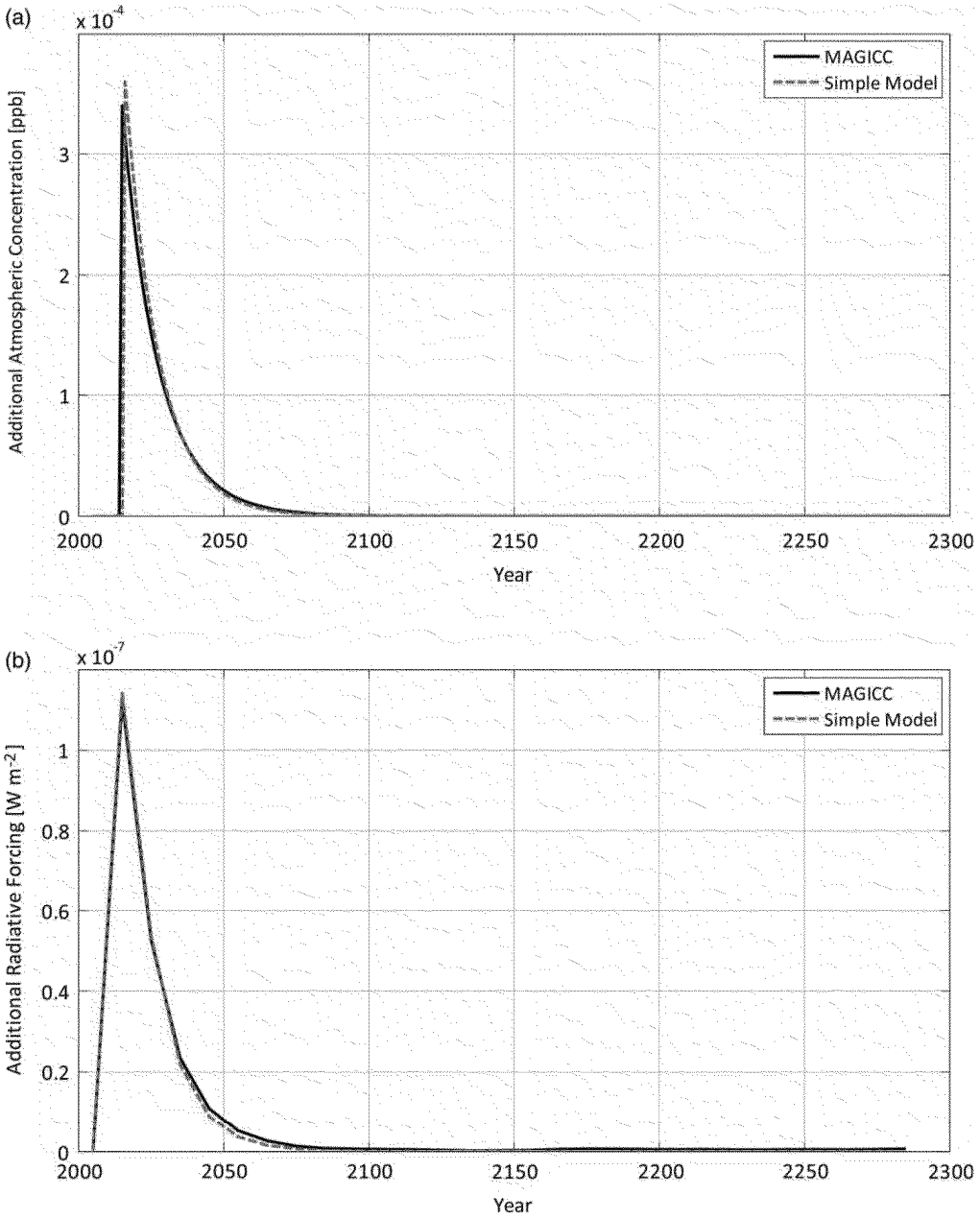

Figure 2 Effects of perturbation in 2015 CH_4 emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

estimates begin to diverge for later emissions years. For the same reason, the two approaches will show greater differences for lower discount rates that give increased weight to future time periods. While over-simplification of the climate system can, in some circumstances, have significant effects on

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TABLE 2 Effect of CH_4 gas cycle model on SC-CH_4 (2007$ per tonne CH_4): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	1135	1183	2 4%
	3.0%	822	851	2 3%
	5.0%	349	354	2 2%
2045	2.5%	2490	2707	2 8%
	3.0%	1933	2084	2 7%
	5.0%	956	1006	2 5%

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social cost estimates (e.g. Marten 2011), the near-term differences based on this simplification seem relatively small considering the precision of such social cost estimates.

3.4. Nitrous oxide

The simple one-box atmospheric gas cycle model for N_2O takes a similar form to the model used for CH_4, such that the concentration of nitrous oxide in year t, $C_t^{N_2O}$ [ppb], is specified as

$$C_t^{N_2O} = C_{t-1}^{N_2O} + d_{N_2O}(C_{pre}^{N_2O} - C_{t-1}^{N_2O}) + g_{N_2O}E_{t-1}^{N_2O}, \tag{4}$$

where d_{N_2O} is the rate of decay, and g_{N_2O} [ppb N_2O/Mt N] converts emissions, $E_{t-1}^{N_2O}$ [Mt N], from mass to atmospheric volume. Following the IPCC AR4, the mass to volume conversion factor is g_{N_2O} ¼ 0.2079 ppb N_2O/Mt N and the rate of decay is d_{N_2O} ¼ 1/114 based on a 114-year lifetime. As with CH_4, the iteration begins in the year 2006 using the emissions from the EMF-22 scenarios (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used, such that $C_{2005}^{N_2O}$ ¼ 319 ppb.

The contribution of atmospheric N_2O to global radiative forcing, denoted $Q_t^{N_2O}$, is defined using the relationship in Table 6.2 of the IPCC TAR, such that

$$Q_t^{CH_4} = 0.12 \left[C_t^{N_2O} - C_{pre}^{N_2O} - [f(C_{pre}^{CH_4}, C_t^{N_2O}) - f(C_{pre}^{CH_4}, C_{pre}^{N_2O})], \right. \tag{5}$$

where $f(C^{CH_4}, C^{N_2O})$ is defined in expression (3).

As with CH_4, a key simplifying assumption is the constant decay rate used in the simple gas cycle model (and potentially the time it takes the gas to become well mixed within the atmosphere). As discussed in the IPCC TAR, the decay rate of N_2O will depend on the atmospheric concentration of N_2O and so will not be constant in reality. To examine the extent to which this impacts the results of the simple model, an analogous set of experiments as conducted for CH_4 were performed. Given future

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N_2O emissions based on the EMF-22 MiniCAM reference scenario, a one tonne N_2O perturbation in 2015 is considered. Figure 3(a) shows the projected atmospheric concentration increase from the perturbation using the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. This comparison illustrates that the simple model tracks the output of MAGICC well for the entire 300-year time horizon. Outside the initial perturbation year, the two projections do not differ by more than 2% within the first century, with the largest difference occurring in the perturbation year, for the same reasons as with CH_4.

Figure 3(b) presents the estimates of average additional radiative forcing per decade as a result of the N_2O perturbation using both models. The additional radiative forcing from the N_2O perturbation in the one-box model is forecast to be slightly lower (7%) in the first decade compared to MAGICC. Subsequently, the difference is within 2% through to 2300.

As with CH_4, to assess the effect that this difference would have on the SC-N_2O, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of N_2O computed using both the simple model and MAGICC is added to the exogenous forcing projection. As before, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 3 presents the results of this experiment. As the comparisons of the projected radiative forcing perturbations would suggest, the difference between the social cost estimates for the two approaches is relatively small. In contrast to the case of CH_4, here an increase in the discount rate increases rather than decreases the divergence between the estimates due to the greater weight being placed on the earlier years when the radiative forcing perturbations have a slightly higher degree of divergence.

3.5. Effect of post-2100 non-CO_2 radiative forcing assumptions

The EMF-22 socio-economic-emissions scenarios used by the USG include years only up to 2100, while the USG ran the IAMs out to 2300. Therefore, additional assumptions were required to extrapolate the scenarios beyond 2100. For the purposes of this study, the most important of these assumptions is that non-CO_2 radiative forcing will remain constant at its 2100 level until 2300. Such a broad assumption was sufficient for the purposes of the USG in estimating the SC-CO_2. However, estimating the social cost of non-CO_2 GHGs requires explicit projections of baseline emissions of non-CO_2 gases in order to correctly determine the effect of the perturbation. The USG's broad assumption regarding the extrapolation of non-CO_2 gases is therefore problematic as constant non-CO_2 radiative forcing post 2100 may occur in an infinite number of ways. For instance, one way to achieve this outcome is to assume that emissions of each non-CO_2 gas falls to a level equal to its respective rate of decay in 2100. This assumption would keep atmospheric concentrations, and in turn radiative forcing, constant. Based on the simple gas cycle models laid out in the earlier sections this implies that, for gas X,

$$E_t^X = \frac{-d_X(C_{pre}^X - C_{2100}^X)}{g_X} \forall t \ . \ 2100. \tag{6}$$

To put this assumption into context, the solid lines in Figure 4(a) and (b) present the emissions paths for CH_4 and N_2O, respectively, under the MiniCAM EMF-22 reference scenario extrapolated using

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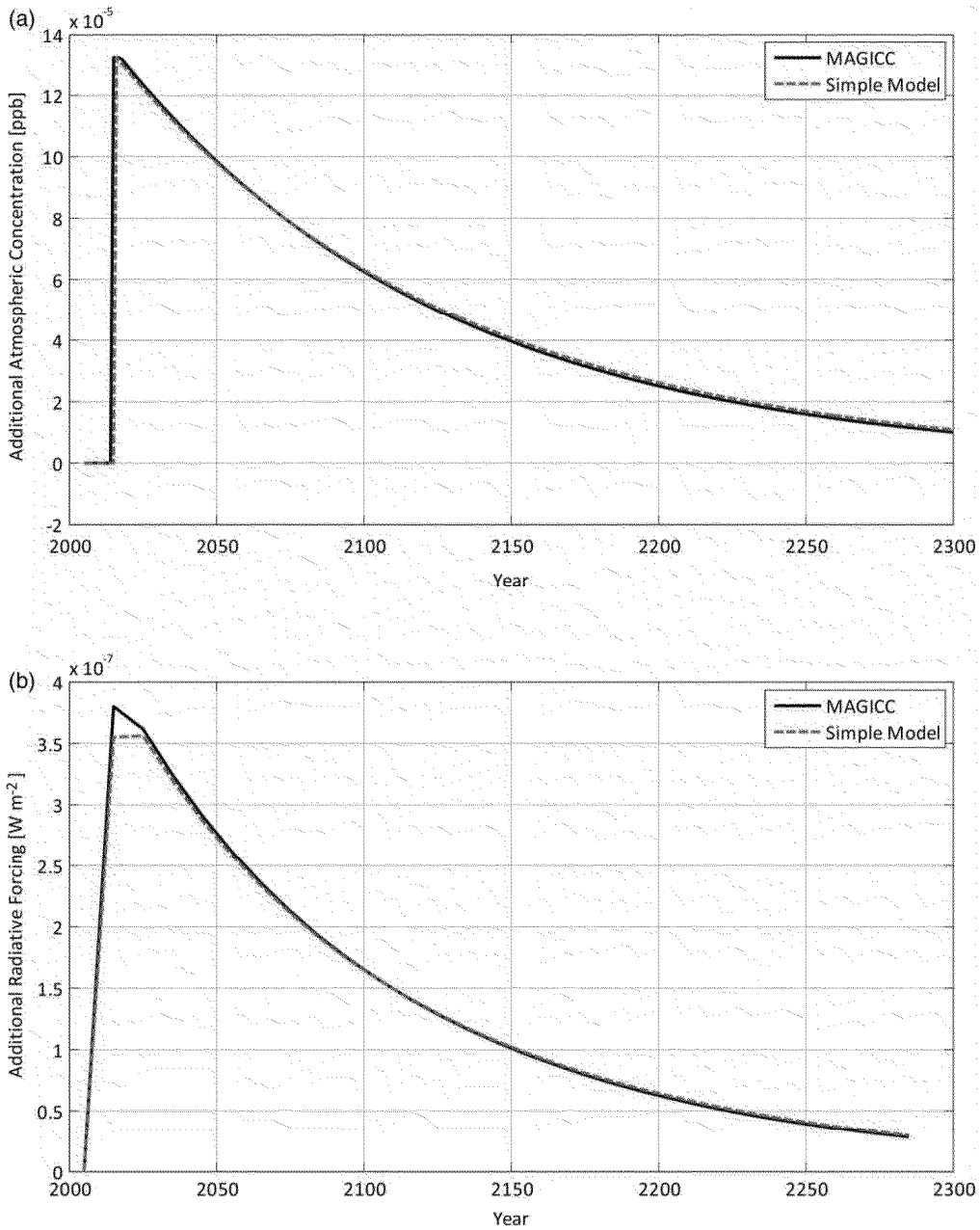

Figure 3 Effects of perturbation in 2015 N_2O emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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TABLE 3 Effect of climate model on SC-N_2O (2007$ per tonne N_2O): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	19,689	19,819	2 1%
	3.0%	12,390	12,525	2 1%
	5.0%	3,346	3,419	2 2%
2045	2.5%	36,968	37,358	2 1%
	3.0%	25,030	25,427	2 2%
	5.0%	8,280	8,528	2 3%

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expression (6), while the dashed lines show two alternative extrapolation approaches, one where emissions are held constant at their 2100 level and one that assumes emissions intensity (emissions/economic output) continues to decline at the same rate forecast by the EMF-22 scenario in 2090–2100 (dotted line). This latter alternative is analogous to the USG assumption regarding industrial CO_2 emissions. The two alternatives will not result in the radiative forcing contribution of gas X remaining constant post-2100, but do not in themselves violate the assumption that overall non-CO_2 radiative forcing remains constant. Noteworthy is the fact that the assumption in (6) is almost analogous to keeping CH_4 emissions constant at their 2100 levels, whereas for N_2O the assumption requires a sudden decrease in emissions of over 35%.

While Figure 4 illustrates that these three extrapolation approaches can lead to vastly different projections for emissions after 2100, the relevant comparison is how these assumptions affect the additional radiative forcing from a perturbation of the gas and in turn the SC-X estimates. Figure 5(a–d) present the additional radiative forcing resulting from a one tonne perturbation based on the simple model presented in Sections 3.1 and 3.2. Figure 5(a) and (b) demonstrates the difference for a perturbation in 2015, whereas Figure 5(c) and (d) represents perturbations in 2045. For CH_4, the cumulative radiative forcing from the projection over the time horizon differs by less than 0.001%, even for a

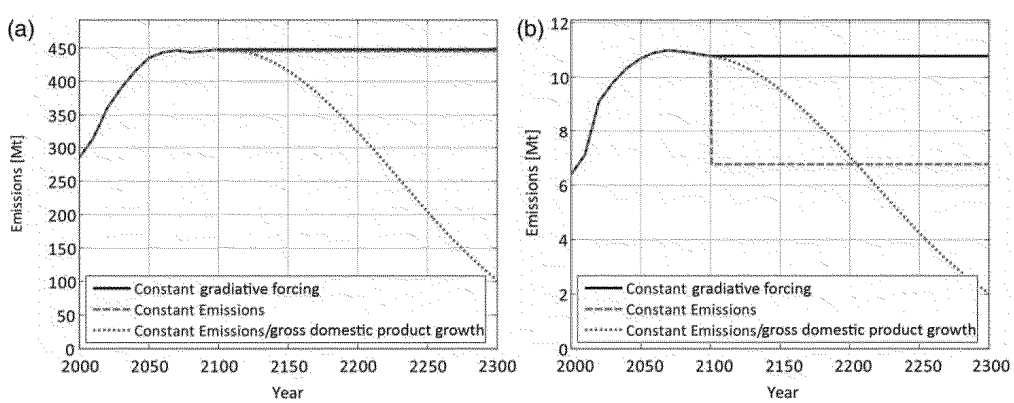

Figure 4 EMF-22 MiniCAM extended emissions scenario: (a) CH_4 emissions; (b) N_2O emissions

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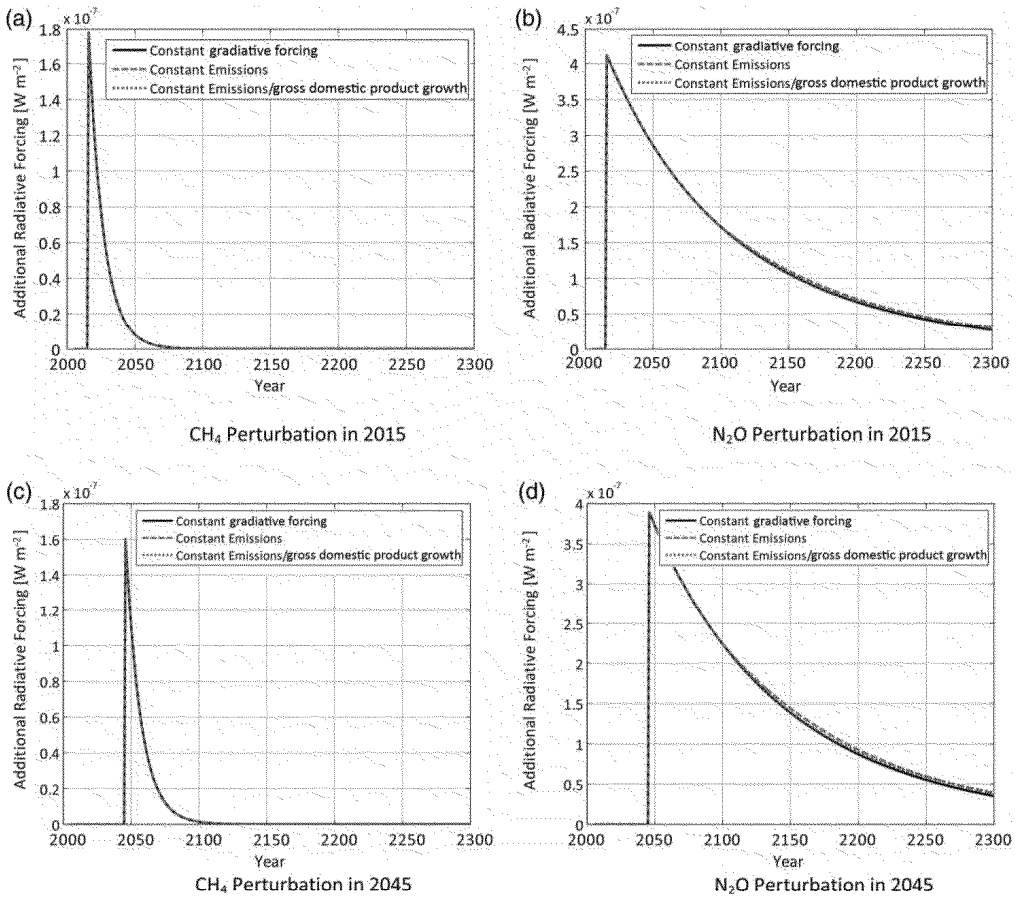

Figure 5 Effect of extrapolation approach on radiative forcing perturbation from simple model: (a) CH_4 perturbation in 2015; (b) N_2O perturbation in 2015; (c) CH_4 perturbation in 2045; (d) N_2O perturbation in 2045

perturbation in 2045. Accordingly, the relevant annual difference is smaller even than one-thousandth of a percent. This result occurs because of the short atmospheric lifetime of the gas, which renders assumptions regarding CH_4 emissions after 2100 unimportant for near-term perturbations. Post-2100 emissions will have a larger effect in the case of N_2O, which has a much longer atmospheric residence time. However, even for a perturbation in 2045, the difference in cumulative additional radiative forcing is less than 2.5% across the extrapolation assumptions.

To examine the impact of these assumptions on SC-CH_4 and SC-N_2O, an experiment was conducted using the DICE model based on the EMF-22 MiniCAM socio-economic-emissions scenario. The results of this experiment are presented in Table 4 for the perturbation year 2045 (noting that the extrapolation method will have greater impact on future emissions years). As may be seen, the relatively short atmospheric lifetime of CH_4 leads to a situation in which post-2100 assumptions do not affect SC-CH_4 estimates, even in 2045. For the longer-lived gas N_2O, in emission year 2045, where the effect of the post-2100 extrapolation approach would be largest, the difference across the three

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TABLE 4 Effect of post-2100 extrapolation on the 2045 SC-X (2007$ per tonne): DICE2010, MiniCAM

Gas	Discount rate	Constant RF	Constant emissions	Constant emissions intensity growth
CH_4	2.5%	2,490	2,490	2,490
	3.0%	1,933	1,933	1,933
	5.0%	956	956	956
N_2O	2.5%	36,968	36,588	36,662
	3.0%	25,030	24,837	24,868
	5.0%	8,280	8,261	8,263

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assumptions is less than 1% and the projections are equivalent to two significant digits. Therefore, in the remainder of this article, non-CO_2 emissions are extrapolated past 2100 using expression (6) to ensure that the gas-specific contribution to overall radiative forcing remains constant in the simple model. While additional study may lead to improvements of long-term forecasts of CH_4 and N_2O emissions and possible correlations, compared to the paths in Figure 5(a), the very minimal effect of such assumptions on the social cost estimates suggests the impact of such efforts would be minimal in this context.

4. Results

For FUND, the social cost of non-CO_2 GHGs is estimated by perturbing the paths of emissions directly, while for DICE and PAGE the approach presented in Section 3 is used. In both cases, all additional assumptions made by the USG are applied, including the five EMF-22 socio-economic-emissions scenarios, the Roe and Baker (2007) distribution for the equilibrium climate sensitivity, and constant discount rates of 2.5%, 3.0%, and 5.0%. Following the USG, the estimates for the expected social cost are averaged across scenarios and models, with each model and scenario given equal weight. Estimates are not combined across discount rates, and a fourth estimate is included representing the 95th percentile when using the 3.0% discount rate. By using the same assumptions and procedures as the USG, estimates of the SC-CO_2 derived in this article are identical to the values used in US Federal rule making. Specifically, these estimates are equivalent to the recent 2013 update of the USG SC-CO_2, which revised the original 2010 USG upwards based on new versions of the IAMs used. The non-CO_2 results, as well as the USG SC-CO_2 estimates, are presented in Table 5 for emissions years 2020 and 2050.[5] Results for additional years, and the results of sensitivity analyses using Ramsey discounting, may be found in Appendix B and C, respectively.

As expected, considering their higher radiative efficacy, the social costs associated with a tonne of CH_4 and N_2O emissions are substantially higher than for CO_2. The values are higher at lower discount rates, although the impact of the discount rate is lower for CH_4 given its relatively short lifetime. Similar to CO_2, the social cost estimates for CH_4 and N_2O increase over time as the climate and economic systems become more stressed, although the growth rate of the social cost estimate may differ between the gases, as discussed in the following.

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TABLE 5 SC-X (2007$ per tonne)

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CO_2	12	43	64	128
	CH_4	550	1,200	1,600	3,200
	N_2O	4,800	15,000	22,000	41,000
2050	CO_2	26	71	97	220
	CH_4	1,400	2,500	3,100	6,900
	N_2O	11,000	27,000	38,000	74,000

To better understand how the social costs of CH_4 and N_2O compare to CO_2, Table 6 presents the global damage potentials corresponding to the social cost estimates from Table 5. (The disaggregated results, by model and scenario, for 2020 are provided in Appendix B.) As explained in Section 2, the global damage potential for gas X is the ratio of SC-X to SC-CO_2, and therefore by construction captures all the important linkages between emissions and monetized climate change damages (to the degree they are captured by the IAMs) directly within the gas comparison metric. As noted by Frankhauser (1994), this is preferred to the commonly used GWP gas comparison metric, which only measures the additional radiative forcing from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years) and ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages.

The global damage potential of CH_4 decreases with the discount rate due to the relatively shorter atmospheric lifetime. This difference in atmospheric lifetime leads to a situation where lowering the discount rate has a greater impact on the SC-CO_2 than the SC-CH_4. This finding is robust across the models. The estimates in Table 6 also present the same result for N_2O in the aggregate case, although this characteristic is not consistent across the models or the previous literature. Based on the disaggregated results (presented in Appendix B), the results from the DICE model suggests the global damage potential for N_2O increases with lower discount rates due to a lower effective decay rate over the relevant time horizon for N_2O than CO_2. This result is consistent with previous findings by Marten and Newbold (2012). However, for FUND the opposite is seen to hold. Waldhoff et al. (2011) show that this result is primarily due to the inclusion of increased production in the agriculture and forestry sectors from CO_2 fertilization effects. At lower discount rates these benefits place a greater downward

TABLE 6 Global damage potential

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CH_4	46	29	25	25
	N_2O	397	359	353	317
2050	CH_4	52	36	32	31
	N_2O	414	388	387	338

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impact on the SC-CO_2, thereby lowering the global damage potential. If one were to remove those impacts from the FUND model the global damage potential for N_2O becomes relatively insensitive to the discount rate. One would expect the role of the discount rate in determining the global damage potential in PAGE to be the same as in DICE, but the results suggest that this is not the case. It seems most likely that this is because the PAGE model has only ten time steps to cover the entire time horizon, which results in very large, up to 100-year, time steps further out in time. As noted in Section 3, the additional radiative forcing from the N_2O perturbation is implemented as the average across the model's time steps. It seems that PAGE does not average radiative forcing over the time step for CO_2, which causes the global damage potential for N_2O to decrease with the discount rate. It is not clear if this result would hold if the size of the time steps in the model were reduced.

A comparison across models further highlights the importance of CO_2 fertilization impacts on the global damage potential. CO_2 emissions, and the resulting increase in atmospheric concentration, have the potential to increase yields in the agriculture and forestry sector. This characteristic is not shared by other GHG emissions. Accordingly, the FUND model, which explicitly captures this effect, exerts downward pressure on the SC-CO_2 that is not present for the SC-CH_4 and SC-N_2O, allowing for the possibility of substantially higher global damage potential estimates. The results based on the FUND model presented in this article exhibit this effect; however, the CO_2 fertilization effect is not explicitly modelled in DICE and PAGE and therefore they are found to produce lower estimates of the global damage potential. For example, using the 3% discount rate, the global damage potential for CH_4 as estimated by FUND ranges between 58 and 88 depending on the scenario, whereas it ranges from 19 to 28 for DICE and PAGE. As the DICE and PAGE models only consider two natural system impacts, temperature and sea level, if they do implicitly include potential CO_2 fertilization benefits, they are included by using the temperature anomaly as a proxy for the increasing atmospheric CO_2 concentration. Fertilization benefits would therefore be allowed to falsely accrue to perturbations of other GHG emissions besides CO_2. It is not clear the degree to which these models try to incorporate CO_2 fertilization effects and therefore the degree to which this issue is of concern.

Finally, the results in this article show that the 100-year GWP (25 for CH_4 and 298 for N_2O; Forster et al., 2007) probably provides an underestimate of the global damage potential of each gas, a finding consistent with previous studies by Marten and Newbold (2012) and Waldhoff et al. (2011). Unlike the GWP as calculated by the IPCC, the global damage potential will be dependent upon the year of the emissions perturbations, so the degree of underestimation varies by year. For CH_4, the global damage potential in Table 6 is 0–84% higher than the GWP in 2020, increasing to 24–108% in 2050. For N_2O, the global damage potential is 6–33% higher than the GWP in 2020, increasing to 13–39% in 2050. While inaccurate, using the GWP to convert emissions reductions into CO_2 equivalents that can be valued with the SC-CO_2 would probably provide a conservative estimate for the abatement benefits.

For the comparison above, the GWP estimates presented in the AR4 by the IPCC (Forster et al., 2007) were used to maintain consistency with the assumptions regarding the direct and indirect effect of CH_4 and N_2O concentrations within the modelling. The recent AR5 by the IPCC (Myhre et al., 2013) has increased the estimate of the indirect effects of CH_4, which gives a higher 100-year GWP for CH_4 of 28. A reduction in their estimate of the radiative efficacy of N_2O has decreased its 100-year GWP to 265. It is likely that updated modelling of the social cost estimates based on similar assumptions would maintain the finding that the GWP is an underestimate of the global damage potential.

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4.1. Comparison with previous estimates

For comparison, Table 7 presents the social cost estimates, when available, and the global damage potential estimates for CH_4 and N_2O from three recent studies in the literature whose features are more up to date and therefore more directly comparable with this study: Hope (2006a), Waldhoff et al. (2011), and Marten and Newbold (2012). A direct comparison to the longer list of studies presented in Table 1 is more difficult as they are based on models and socio-economic and emissions scenarios that were developed up to 20 years ago in a rapidly evolving field.

The social cost estimates presented in Table 5 are higher than the estimates in Hope (2006a) and Waldhoff et al. (2011) for CH_4, and in the range of Waldhoff et al. (2011) for N_2O. This result holds whether the comparison is made with the aggregate results in Table 5 or the disaggregated model-specific results. One reason for the significant difference in the SC-CH_4 estimates is that the earlier studies rely on older model versions (PAGE2002 and FUND3.5), neither of which include the indirect effects of CH_4 emissions on radiative forcing, but are included within this analysis. As noted in Section 3.3 the indirect effects of CH_4 are modelled as a 40% increase in its effective radiative forcing. The result of this change alone would likely be a greater than 40% increase in the SC-CH_4 due to the nonlinear damage functions. Furthermore, the assumptions regarding preference parameters in the main cases of Hope (2006a) and Waldhoff et al. (2011) lead to effective discount rates that are significantly higher than 3%. Other differences in input assumptions (e.g. equilibrium climate sensitivity, socio-economic emissions scenario) will also lead to differences, although these are likely to be of second-order importance given the relative similarity in the assumptions.

However, the results in Table 5 averaged across the combinations of the three models and five scenarios are relatively similar to those of Marten and Newbold (2012), which focused on a single scenario

TABLE 7 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Discount Rate	Emissions Year	Social cost (2007$/tonne X)[a]		Global damage potential (SC-X/SC-CO_2)	
			SC-CH_4	SC-N_2O	CH_4	N_2O
Hope (2006a)	Ramsey	2001	125	–	20	–
Waldhoff et al. (2011)[b]	Ramsey	2010–2019	265	7,616	26	738
			–	–	8–221	383–3,503
Marten and Newbold (2012)	2.5%	2020	1,500	26,000	23	403
		2050	3,500	50,000	32	444
	3%	2020	1,100	17,000	27	400
		2050	2,900	34,000	36	439
	5%	2020	550	4,900	42	380
		2050	1,500	12,000	53	415

[a]All values are discounted to the year of the emissions perturbation.
[b]The first row presents the base case and the second row presents the range found from sensitivity analysis (over socio-economic scenario, climate sensitivity, pure rate of time preference, climate sensitivity and CO_2 fertilization).

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and model. This result is in part based on the fact that both sets of results include the indirect effects of CH_4, use the same discount rates and equilibrium climate sensitivity distribution, and relatively similar scenarios. The estimates in this study are slightly higher for the SC-CH_4 and slightly lower for the SC-N_2O compared to Marten and Newbold (2012). Of particular interest is the specific comparison of this article's estimates based on DICE 2010 and the MiniCAM scenario to those of Marten and Newbold (2012) using the same scenario, discount rates, and equilibrium climate sensitivity but an the older 2007 version of the DICE model and a more complete climate sub-model. In this case, estimates for both the SC-CH_4 and SC-N_2O (presented in Appendix B) are notably lower. The myriad of differences between the model vintages and climate sub-models make it difficult to assess which differences are most important for explaining this relationship.

As previously noted, the global damage potential may provide a better value with which to compare across studies that estimate the social cost of non-CO_2 GHG emissions, as it helps to control for some of the underlying differences in assumptions across studies. For example, the global damage potential is far less sensitive to the discount rate used than the SC-X values themselves. However, the global damage potential does not address the lack of indirect CH_4 effects, as may be seen in the lower estimates of Hope (2006a) and Waldhoff et al. (2011). In these cases the exclusion of the 40% additional increase in radiative forcing from the indirect effects of the CH_4 perturbation explains the majority of the difference. In comparison to Marten and Newbold (2012), the results presented in Table 6 are relatively similar for CH_4 in both the aggregate and disaggregated results. For N_2O, similar results are found in the DICE estimates, but notable differences are found in how the aggregate results respond to the discount rate, due to the differences in this relationship between the models as noted above.

5. Concluding remarks

This article presents a simple and transparent approach to estimating the social cost of CH_4 (SC-CH_4) and N_2O (SC-N_2O) in a manner that is consistent with estimates of the social cost of CO_2 (SC-CO_2) already in use in benefit–cost analysis (BCA) for US Federal regulations. This approach is used to estimate the SC-CH_4 and SC-N_2O for the period 2010–2050. These directly modelled estimates are found to be larger than approximations of the social costs of these gases based on the application of common physical gas comparison metrics, such as global warming potentials (GWPs), to the SC-CO_2. This result generalizes the empirical findings of Marten and Newbold (2012) that using a GWP-based approximation approach will likely offer a conservative estimate of the social cost of non-CO_2 GHGs.

The social costs associated with emissions of non-CO_2 GHGs are substantial and should be included within the BCAs used to assess the overall welfare implications of policy alternatives. For example, by not including monetized values of the benefits from reducing CH_4 and N_2O emissions, the BCA for recent standards regulating the fuel efficiency and GHG emissions of light duty vehicles implicitly assigned them a value of zero (US EPA, 2010). However, the results of this article suggest that those reductions have benefits of US$85–493 million (2007$) for CH_4 and $1.5–12 million (2007$) for N_2O in the year 2020 alone. Failing to account for such impacts could limit the ability of the analysis to serve as a transparent and informative input into the decision-making process about the relative benefits and costs of regulatory alternatives. That said, by restricting the article to a derivation of social cost estimates consistent with the USG SC-CO_2 estimates, the myriad issues related to

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whether those estimates can themselves be improved are set aside.[6] Any limitations that apply to the USG SC-CO_2 estimates therefore also apply to the SC-CH_4 and SC-N_2O estimates derived here.

Supplemental data

Supplemental data for this article can be accessed 10.1080/14693062.2014.912981.

Notes

1. Examples include Minnesota's draft methodology for setting the value of a tariff to compensate solar panel owners for the surplus power they deliver to utilities (http://www.eenews.net/stories/1059992297, http://mn.gov/commerce/energy/images/DRAFT-MN-VOS-Methodology-111913.pdf), the Northwest Power and Conservation Council's symposium supporting the development of the 7th Power Plan (http://www.nwcouncil.org/energy/powerplan/7/symposiums/greenhouse/agenda), BCA of Canada's Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations (http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html), analysis of climate change projects at the Inter-American Development Bank (correspondence with Patrick Doyle, Senior Climate and Energy Officer, Structured and Corporate Finance Department), the International Monetary Fund's recent Energy Subsidy Reform report (http://www.imf.org/external/np/pp/eng/2013/012813.pdf), and Parry and Strand (2012).
2. An alternative approach for estimating the social cost of GHG emissions could be based on stated preference (SP) surveys designed to elicit respondents' maximum willingness-to-pay for various levels of GHG emission reductions (e.g. Longo, Markandya, & Petrucci, 2008; Soliño, 2010). This approach would not suffer from the difficulties associated with creating and parameterizing a numerical integrated assessment model. However, it would suffer from its own set of difficulties, including well-known general limitations that affect all SP studies including the potential for 'hypothetical bias' (e.g. Carson, 2012; Hausman, 2012; Kling, Phaneuf, & Zhao, 2012), plus difficulties that may be specific to this application stemming from the generally limited knowledge base regarding the potential climatic, biophysical, and especially economic impacts of GHG emissions on current and far future generations that most respondents will bring to the survey.
3. The fork of MAGICC version 5.3 included in Pacific Northwest National Laboratory's open source model GCAM version 2 (Calvin et al., 2009) is used without carbon cycle feedbacks and, unless otherwise specified, an equilibrium climate sensitivity of 3 8C. We note that sensitivity analysis found the general results of this side analysis to be robust to other values of the equilibrium climate sensitivity.
4. The EMF-22 scenario is extended past 2100 assuming that emissions stay constant at the 2100 level. This assumption is revisited later in this article.
5. The PAGE 2009 model restricts the user to representing the entire time horizon, in this case out to 2300, with only ten time steps. This leads to the unrealistic situation in a small number of simulations where the marginal unit of emissions can cause 'catastrophic' climate impacts to occur one period earlier, which could be 100 years earlier in some cases. We consider these occurrences to be a limitation of the model and drop them from the overall distribution of estimates. Appendix A contains further details about this issue.
6. In addition to the critiques previously cited, we point the interested reader to the work of Marten et al. (2013) and Oppenheimer (2013) for a review of literature that considers potential improvements in the assessment and valuation of climate change impacts.

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National Freedom of Information Officer
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Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1) All records discussing, describing, referring to or interpreting the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*").

2) To the extent not provided in response to request #1, all records of information relied upon by the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*") in the development of the *2010 TSD on SCC* and the *2013 TSD on SCC*, including but not limited to:

   a) Any presentations, reports, studies, computer or other analytical models, and data (including modeling data) created by or on behalf of the *IWG on SCC*, or provided to or obtained by the *IWG on SCC*.

   b) Any records that discuss, describe, interpret or otherwise relate to the Integrated Assessment Models ("IAMs") referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to:

      i) any inputs and assumptions (including but not limited to assumptions on discounting, equilibrium climate sensitivity, and socioeconomic variables);

      ii) the results of any modeling runs or scenarios generated by the IAMs (in both paper copies and in original electronic form); and

      iii) the source codes for the DICE, PAGE and FUND models referred to in the *2010 TSD on SCC* or *2013 TSD on SCC* (in the original electronic form, such as native modeling formats).

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c) Any records that identify, discuss, interpret or relate to any uncertainties or error rates of the *2010 TSD on SCC* or the *2013 TSD on SCC* or any of the IAMs referenced in or relied upon by the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to any limitations in using the DICE, PAGE or FUND models to make predictions beyond the year 2100.

d) Any records that discuss, interpret or explain why the social cost of carbon estimated by the *2013 TSD on SCC* is approximately 60% higher than that estimated by the *2010 TSD on SCC*.

e) Any records that discuss, interpret, relate to, explain or make recommendations or decisions regarding global versus domestic measures of the social cost of carbon with respect to the work of the *IWG on SCC* and the *2010 TSD on SCC* or *2013 TSD on SCC*, including but not limited to the calculation or use of a domestic SCC for the United States.

3) Any records discussing, interpreting, transmitting or relating to any critiques, analyses or studies of the *2010 TSD on SCC* or *2013 TSD on SCC*, or any data, information or models relied on or referred to in the *2010 TSD on SCC* or *2013 TSD on SCC*, including but not limited to the work or statements of Robert Pindyck.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and all other types of records in the possession, control or custody of EPA or contractors working for EPA.

For all records responsive to these requests that are not produced based on an asserted exemption from disclosure, please prepare a privilege and/or exemption log describing, at a minimum: (i) the type of record withheld; (ii) the date(s) of the creation of the record; (iii) the subject of the record; (iv) the identity of the author and all recipients of the records; and (v) a detailed description of the basis upon which EPA is withholding the record (e.g., the claim of privilege, FOIA exemption, etc.). To the extent any responsive documents are withheld based upon a claim of privilege or other exemption from disclosure, please produce redacted copies of all non-privileged or non-exempt factual material contained within such documents.

As required by law, please provide the above records within twenty (20) business days of receipt of this FOIA Request. 5 U.S.C. § 552(a)(6)(A)(i). If it appears that it may not be possible to provide all of the records by the statutorily-mandated deadline, please provide the responsive records that are available as of the deadline (i.e., do not withhold responsive records past the

deadline while searching for additional records), and please contact me promptly regarding any scheduling issues.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $500, I ask that you contact me prior to proceeding.

Thank you for your prompt attention to this request. Please direct any inquiries, notices, or determinations to me at (713) 495-4508 or cbell@sidley.com.

Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009618 (2)

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Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1. All records identifying the dates and attendees of meetings, or dates of and participants in teleconferences or webinars involving, the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*"), or any committee, working group, sub-committee, task force or project group thereof.
2. Any government contracts used to hire anyone to assist in the preparation of the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*"), including but not limited to, any government contracts used to hire anyone to perform the Integrated Assessment Modeling referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*.
3. Any records that describe, identify, contain, interpret or provide the dates or substance of briefings of political appointees in the Executive Branch on the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to, PowerPoint presentations. In the response, please produce the requested briefing records in their native original electronic form (PowerPoint, Word, etc.).
4. All electronic mail, WebEx documents, Google Docs, text messages, instant messages, voice mails, facsimiles or any other records relating to the *2010 TSD on SCC* or *2013 TSD on SCC* that were sent to any person outside the *IWG on SCC*, including but not limited to documents sent to or received from: any of the authors of the publications listed in the References section of the *2010 TSD on SCC* or *2013 TSD on SCC*; any other academics; government contractors; consultants; Sierra Club, Natural Resources Defense Council or other

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nongovernmental groups; and any other third-party whatsoever that was not part of the *IWG on SCC*.

5. All records discussing, describing, interpreting or relating to the applicability of or compliance with the Information Quality Act (P.L. 106-554, Section 515, 144 Stat. 2763 (2001)), or any Information Quality Act Guidelines published by the Office of Management and Budget, with respect to the work of the *IWG on SCC* or development, publication, use or dissemination of the *2010 TSD on SCC* or the *2013 TSD on SCC*.

6. All records discussing, interpreting or relating to the applicability of the Administrative Procedure Act (5 U.S.C. § 500 et seq.) to the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to whether those documents should have been published for public review and comment.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and all other types of records in the possession, control or custody of EPA or contractors working for EPA.

For all records responsive to these requests that are not produced based on an asserted exemption from disclosure, please prepare a privilege and/or exemption log describing, at a minimum: (i) the type of record withheld; (ii) the date(s) of the creation of the record; (iii) the subject of the record; (iv) the identity of the author and all recipients of the records; and (v) a detailed description of the basis upon which EPA is withholding the record (e.g., the claim of privilege, FOIA exemption, etc.). To the extent any responsive documents are withheld based upon a claim of privilege or other exemption from disclosure, please produce redacted copies of all non-privileged or non-exempt factual material contained within such documents.

As required by law, please provide the above records within twenty (20) business days of receipt of this FOIA Request. 5 U.S.C. § 552(a)(6)(A)(i). If it appears that it may not be possible to provide all of the records by the statutorily-mandated deadline, please provide the responsive records that are available as of the deadline (i.e., do not withhold responsive records past the deadline while searching for additional records), and please contact me promptly regarding any scheduling issues.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $500, I ask that you contact me prior to proceeding.

SIDLEY AUSTIN LLP
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Thank you for your prompt attention to this request. Please direct any inquiries, notices, or determinations to me at (713) 495-4508 or cbell@sidley.com.

Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009617

(5)

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August 23, 2013

National Freedom of Information Officer
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, NW (2822T)
Washington, DC 20460

Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1. All records discussing, describing, referring or providing direction to, communicating to or about, or interpreting the formation, organization, structure, authority, activities, meetings, recommendations or decisions of the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*").
2. All records describing or discussing any past, on-going (as of the date of this submission) or planned work of the *IWG on SCC*.
3. All records describing, discussing or interpreting how the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*") have been or are to be used by Federal agencies, including but not limited to the use of these documents in the development and promulgation of regulations and in making policy decisions.
4. All records discussing or interpreting how the *2010 TSD on SCC* or the *2013 TSD on SCC* have been used or relied on, or are planned to be used, by EPA in any regulation proposed or promulgated by EPA, or in any policy decisions made by or guidance documents created by EPA.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and

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EPA TRACKING NUMBER EPA-HQ-2013-005473

Pursuant to the Freedom of Information Act ("FOIA") 5 U.S.C. § 552, and the implementing regulations of the U.S. Environmental Protection Agency ("EPA"), 40 C.F.R. Part 2, I am requesting a copy of the following EPA records:

1. All petitions for rulemaking of any kind submitted to the EPA Administrator related to any statute or regulation under which the EPA Administrator has the authority to promulgate regulations from January 1, 2013, to the present. These include, but are not limited to, petitions under the Clean Air Act, the Clean Water Act, the Resource Conservation and Recovery Act, the Comprehensive Environmental Response, Compensation, and Liability Act, the Toxic Substances Control Act, and the Federal Insecticide, Fungicide, and Rodenticide Act.

2. All notices of intent to sue EPA or its Administrator, dated from January 1, 2013, to the present, under any of the statutes listed above or under the Administrative Procedure Act for:

a. Failure to timely act on any petition for rulemaking;

b. Failure to meet any statutory, regulatory, or other deadline; or

c. Failure to meet any nondiscretionary obligation..

This request is only seeking for the specific items referred to above, all of which would have been submitted to EPA by third parties. Therefore, this request does not seek any records that are exempt from disclosure.

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Please direct any inquiries, notices, or determinations to me at (202) 736-8281. Thank you for your anticipated assistance.

Description Available to the Public : Yes

Has Request Been Modified? ☐

Attached Supporting Files

No supporting files have been added.

EPA TRACKING NUMBER EPA-HQ-2013-009523 (1)

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1) All records discussing, describing, referring to or interpreting the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*").

2) To the extent not provided in response to request #1, all records of information relied upon by the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*") in the development of the *2010 TSD on SCC* and the *2013 TSD on SCC*, including but not limited to:

   a) Any presentations, reports, studies, computer or other analytical models, and data (including modeling data) created by or on behalf of the *IWG on SCC*, or provided to or obtained by the *IWG on SCC*.

   b) Any records that discuss, describe, interpret or otherwise relate to the Integrated Assessment Models ("IAMs") referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to:

      i) any inputs and assumptions (including but not limited to assumptions on discounting, equilibrium climate sensitivity, and socioeconomic variables);

      ii) the results of any modeling runs or scenarios generated by the IAMs (in both paper copies and in original electronic form); and

      iii) the source codes for the DICE, PAGE and FUND models referred to in the *2010 TSD on SCC* or *2013 TSD on SCC* (in the original electronic form, such as native modeling formats).

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c) Any records that identify, discuss, interpret or relate to any uncertainties or error rates of the *2010 TSD on SCC* or the *2013 TSD on SCC* or any of the IAMs referenced in or relied upon by the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to any limitations in using the DICE, PAGE or FUND models to make predictions beyond the year 2100.

d) Any records that discuss, interpret or explain why the social cost of carbon estimated by the *2013 TSD on SCC* is approximately 60% higher than that estimated by the *2010 TSD on SCC*.

e) Any records that discuss, interpret, relate to, explain or make recommendations or decisions regarding global versus domestic measures of the social cost of carbon with respect to the work of the *IWG on SCC* and the *2010 TSD on SCC* or *2013 TSD on SCC*, including but not limited to the calculation or use of a domestic SCC for the United States.

3) Any records discussing, interpreting, transmitting or relating to any critiques, analyses or studies of the *2010 TSD on SCC* or *2013 TSD on SCC*, or any data, information or models relied on or referred to in the *2010 TSD on SCC* or *2013 TSD on SCC*, including but not limited to the work or statements of Robert Pindyck.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and all other types of records in the possession, control or custody of EPA or contractors working for EPA.

For all records responsive to these requests that are not produced based on an asserted exemption from disclosure, please prepare a privilege and/or exemption log describing, at a minimum: (i) the type of record withheld; (ii) the date(s) of the creation of the record; (iii) the subject of the record; (iv) the identity of the author and all recipients of the records; and (v) a detailed description of the basis upon which EPA is withholding the record (e.g., the claim of privilege, FOIA exemption, etc.). To the extent any responsive documents are withheld based upon a claim of privilege or other exemption from disclosure, please produce redacted copies of all non-privileged or non-exempt factual material contained within such documents.

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Thank you for your prompt attention to this request. Please direct any inquiries, notices, or determinations to me at (713) 495-4508 or cbell@sidley.com.

Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009618 (2)

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August 23, 2013

National Freedom of Information Officer
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, NW (2822T)
Washington, DC 20460

Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1. All records identifying the dates and attendees of meetings, or dates of and participants in teleconferences or webinars involving, the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*"), or any committee, working group, sub-committee, task force or project group thereof.
2. Any government contracts used to hire anyone to assist in the preparation of the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*"), including but not limited to, any government contracts used to hire anyone to perform the Integrated Assessment Modeling referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*.
3. Any records that describe, identify, contain, interpret or provide the dates or substance of briefings of political appointees in the Executive Branch on the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to, PowerPoint presentations. In the response, please produce the requested briefing records in their native original electronic form (PowerPoint, Word, etc.).
4. All electronic mail, WebEx documents, Google Docs, text messages, instant messages, voice mails, facsimiles or any other records relating to the *2010 TSD on SCC* or *2013 TSD on SCC* that were sent to any person outside the *IWG on SCC*, including but not limited to documents sent to or received from: any of the authors of the publications listed in the References section of the *2010 TSD on SCC* or *2013 TSD on SCC*; any other academics; government contractors; consultants; Sierra Club, Natural Resources Defense Council or other

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nongovernmental groups; and any other third-party whatsoever that was not part of the *IWG on SCC*.

5. All records discussing, describing, interpreting or relating to the applicability of or compliance with the Information Quality Act (P.L. 106-554, Section 515, 144 Stat. 2763 (2001)), or any Information Quality Act Guidelines published by the Office of Management and Budget, with respect to the work of the *IWG on SCC* or development, publication, use or dissemination of the *2010 TSD on SCC* or the *2013 TSD on SCC*.

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For all records responsive to these requests that are not produced based on an asserted exemption from disclosure, please prepare a privilege and/or exemption log describing, at a minimum: (i) the type of record withheld; (ii) the date(s) of the creation of the record; (iii) the subject of the record; (iv) the identity of the author and all recipients of the records; and (v) a detailed description of the basis upon which EPA is withholding the record (e.g., the claim of privilege, FOIA exemption, etc.). To the extent any responsive documents are withheld based upon a claim of privilege or other exemption from disclosure, please produce redacted copies of all non-privileged or non-exempt factual material contained within such documents.

As required by law, please provide the above records within twenty (20) business days of receipt of this FOIA Request. 5 U.S.C. § 552(a)(6)(A)(i). If it appears that it may not be possible to provide all of the records by the statutorily-mandated deadline, please provide the responsive records that are available as of the deadline (i.e., do not withhold responsive records past the deadline while searching for additional records), and please contact me promptly regarding any scheduling issues.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $500, I ask that you contact me prior to proceeding.

SIDLEY AUSTIN LLP
SIDLEY

Thank you for your prompt attention to this request. Please direct any inquiries, notices, or determinations to me at (713) 495-4508 or cbell@sidley.com.

Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009617

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August 23, 2013

National Freedom of Information Officer
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, NW (2822T)
Washington, DC 20460

Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1. All records discussing, describing, referring or providing direction to, communicating to or about, or interpreting the formation, organization, structure, authority, activities, meetings, recommendations or decisions of the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*").
2. All records describing or discussing any past, on-going (as of the date of this submission) or planned work of the *IWG on SCC*.
3. All records describing, discussing or interpreting how the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*") have been or are to be used by Federal agencies, including but not limited to the use of these documents in the development and promulgation of regulations and in making policy decisions.
4. All records discussing or interpreting how the *2010 TSD on SCC* or the *2013 TSD on SCC* have been used or relied on, or are planned to be used, by EPA in any regulation proposed or promulgated by EPA, or in any policy decisions made by or guidance documents created by EPA.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and

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EPA TRACKING NUMBER EPA-HQ-2013-005473

Pursuant to the Freedom of Information Act ("FOIA") 5 U.S.C. § 552, and the implementing regulations of the U.S. Environmental Protection Agency ("EPA"), 40 C.F.R. Part 2, I am requesting a copy of the following EPA records:

1. All petitions for rulemaking of any kind submitted to the EPA Administrator related to any statute or regulation under which the EPA Administrator has the authority to promulgate regulations from January 1, 2013, to the present. These include, but are not limited to, petitions under the Clean Air Act, the Clean Water Act, the Resource Conservation and Recovery Act, the Comprehensive Environmental Response, Compensation, and Liability Act, the Toxic Substances Control Act, and the Federal Insecticide, Fungicide, and Rodenticide Act.

2. All notices of intent to sue EPA or its Administrator, dated from January 1, 2013, to the present, under any of the statutes listed above or under the Administrative Procedure Act for:

a. Failure to timely act on any petition for rulemaking;

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Please direct any inquiries, notices, or determinations to me at (202) 736-8281. Thank you for your anticipated assistance.

Description Available to the Public : Yes

Has Request Been Modified? ☐

Attached Supporting Files

No supporting files have been added.

EPA TRACKING NUMBER EPA-HQ-2013-009523 (1)

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   a) Any presentations, reports, studies, computer or other analytical models, and data (including modeling data) created by or on behalf of the *IWG on SCC*, or provided to or obtained by the *IWG on SCC*.

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      i) any inputs and assumptions (including but not limited to assumptions on discounting, equilibrium climate sensitivity, and socioeconomic variables);

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Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009618 (2)

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2. Any government contracts used to hire anyone to assist in the preparation of the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*"), including but not limited to, any government contracts used to hire anyone to perform the Integrated Assessment Modeling referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*.
3. Any records that describe, identify, contain, interpret or provide the dates or substance of briefings of political appointees in the Executive Branch on the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to, PowerPoint presentations. In the response, please produce the requested briefing records in their native original electronic form (PowerPoint, Word, etc.).
4. All electronic mail, WebEx documents, Google Docs, text messages, instant messages, voice mails, facsimiles or any other records relating to the *2010 TSD on SCC* or *2013 TSD on SCC* that were sent to any person outside the *IWG on SCC*, including but not limited to documents sent to or received from: any of the authors of the publications listed in the References section of the *2010 TSD on SCC* or *2013 TSD on SCC*; any other academics; government contractors; consultants; Sierra Club, Natural Resources Defense Council or other

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nongovernmental groups; and any other third-party whatsoever that was not part of the *IWG on SCC*.

5. All records discussing, describing, interpreting or relating to the applicability of or compliance with the Information Quality Act (P.L. 106-554, Section 515, 144 Stat. 2763 (2001)), or any Information Quality Act Guidelines published by the Office of Management and Budget, with respect to the work of the *IWG on SCC* or development, publication, use or dissemination of the *2010 TSD on SCC* or the *2013 TSD on SCC*.

6. All records discussing, interpreting or relating to the applicability of the Administrative Procedure Act (5 U.S.C. § 500 et seq.) to the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to whether those documents should have been published for public review and comment.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and all other types of records in the possession, control or custody of EPA or contractors working for EPA.

For all records responsive to these requests that are not produced based on an asserted exemption from disclosure, please prepare a privilege and/or exemption log describing, at a minimum: (i) the type of record withheld; (ii) the date(s) of the creation of the record; (iii) the subject of the record; (iv) the identity of the author and all recipients of the records; and (v) a detailed description of the basis upon which EPA is withholding the record (e.g., the claim of privilege, FOIA exemption, etc.). To the extent any responsive documents are withheld based upon a claim of privilege or other exemption from disclosure, please produce redacted copies of all non-privileged or non-exempt factual material contained within such documents.

As required by law, please provide the above records within twenty (20) business days of receipt of this FOIA Request. 5 U.S.C. § 552(a)(6)(A)(i). If it appears that it may not be possible to provide all of the records by the statutorily-mandated deadline, please provide the responsive records that are available as of the deadline (i.e., do not withhold responsive records past the deadline while searching for additional records), and please contact me promptly regarding any scheduling issues.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $500, I ask that you contact me prior to proceeding.

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Thank you for your prompt attention to this request. Please direct any inquiries, notices, or determinations to me at (713) 495-4508 or cbell@sidley.com.

Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009617

(5)

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Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1. All records discussing, describing, referring or providing direction to, communicating to or about, or interpreting the formation, organization, structure, authority, activities, meetings, recommendations or decisions of the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*").
2. All records describing or discussing any past, on-going (as of the date of this submission) or planned work of the *IWG on SCC*.
3. All records describing, discussing or interpreting how the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*") have been or are to be used by Federal agencies, including but not limited to the use of these documents in the development and promulgation of regulations and in making policy decisions.
4. All records discussing or interpreting how the *2010 TSD on SCC* or the *2013 TSD on SCC* have been used or relied on, or are planned to be used, by EPA in any regulation proposed or promulgated by EPA, or in any policy decisions made by or guidance documents created by EPA.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and

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EPA Tracking Number EPA-HQ-2013-005473

Pursuant to the Freedom of Information Act ("FOIA") 5 U.S.C. § 552, and the implementing regulations of the U.S. Environmental Protection Agency ("EPA"), 40 C.F.R. Part 2, I am requesting a copy of the following EPA records:

1. All petitions for rulemaking of any kind submitted to the EPA Administrator related to any statute or regulation under which the EPA Administrator has the authority to promulgate regulations from January 1, 2013, to the present. These include, but are not limited to, petitions under the Clean Air Act, the Clean Water Act, the Resource Conservation and Recovery Act, the Comprehensive Environmental Response, Compensation, and Liability Act, the Toxic Substances Control Act, and the Federal Insecticide, Fungicide, and Rodenticide Act.

2. All notices of intent to sue EPA or its Administrator, dated from January 1, 2013, to the present, under any of the statutes listed above or under the Administrative Procedure Act for:

a. Failure to timely act on any petition for rulemaking;

b. Failure to meet any statutory, regulatory, or other deadline; or

c. Failure to meet any nondiscretionary obligation..

This request is only seeking for the specific items referred to above, all of which would have been submitted to EPA by third parties. Therefore, this request does not seek any records that are exempt from disclosure.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $250, I ask that you contact me prior to proceeding.

Please direct any inquiries, notices, or determinations to me at (202) 736-8281. Thank you for your anticipated assistance.

Description Available to the Public : Yes

Has Request Been Modified? ☐

Attached Supporting Files

No supporting files have been added.

EPA TRACKING NUMBER EPA-HQ-2013-009523 (1)

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Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1) All records discussing, describing, referring to or interpreting the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*").

2) To the extent not provided in response to request #1, all records of information relied upon by the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*") in the development of the *2010 TSD on SCC* and the *2013 TSD on SCC*, including but not limited to:

   a) Any presentations, reports, studies, computer or other analytical models, and data (including modeling data) created by or on behalf of the *IWG on SCC*, or provided to or obtained by the *IWG on SCC*.

   b) Any records that discuss, describe, interpret or otherwise relate to the Integrated Assessment Models ("IAMs") referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to:

      i) any inputs and assumptions (including but not limited to assumptions on discounting, equilibrium climate sensitivity, and socioeconomic variables);

      ii) the results of any modeling runs or scenarios generated by the IAMs (in both paper copies and in original electronic form); and

      iii) the source codes for the DICE, PAGE and FUND models referred to in the *2010 TSD on SCC* or *2013 TSD on SCC* (in the original electronic form, such as native modeling formats).

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c) Any records that identify, discuss, interpret or relate to any uncertainties or error rates of the *2010 TSD on SCC* or the *2013 TSD on SCC* or any of the IAMs referenced in or relied upon by the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to any limitations in using the DICE, PAGE or FUND models to make predictions beyond the year 2100.

d) Any records that discuss, interpret or explain why the social cost of carbon estimated by the *2013 TSD on SCC* is approximately 60% higher than that estimated by the *2010 TSD on SCC*.

e) Any records that discuss, interpret, relate to, explain or make recommendations or decisions regarding global versus domestic measures of the social cost of carbon with respect to the work of the *IWG on SCC* and the *2010 TSD on SCC* or *2013 TSD on SCC*, including but not limited to the calculation or use of a domestic SCC for the United States.

3) Any records discussing, interpreting, transmitting or relating to any critiques, analyses or studies of the *2010 TSD on SCC* or *2013 TSD on SCC*, or any data, information or models relied on or referred to in the *2010 TSD on SCC* or *2013 TSD on SCC*, including but not limited to the work or statements of Robert Pindyck.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and all other types of records in the possession, control or custody of EPA or contractors working for EPA.

For all records responsive to these requests that are not produced based on an asserted exemption from disclosure, please prepare a privilege and/or exemption log describing, at a minimum: (i) the type of record withheld; (ii) the date(s) of the creation of the record; (iii) the subject of the record; (iv) the identity of the author and all recipients of the records; and (v) a detailed description of the basis upon which EPA is withholding the record (e.g., the claim of privilege, FOIA exemption, etc.). To the extent any responsive documents are withheld based upon a claim of privilege or other exemption from disclosure, please produce redacted copies of all non-privileged or non-exempt factual material contained within such documents.

As required by law, please provide the above records within twenty (20) business days of receipt of this FOIA Request. 5 U.S.C. § 552(a)(6)(A)(i). If it appears that it may not be possible to provide all of the records by the statutorily-mandated deadline, please provide the responsive records that are available as of the deadline (i.e., do not withhold responsive records past the

deadline while searching for additional records), and please contact me promptly regarding any scheduling issues.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $500, I ask that you contact me prior to proceeding.

Thank you for your prompt attention to this request. Please direct any inquiries, notices, or determinations to me at (713) 495-4508 or cbell@sidley.com.

Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009618 (2)

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Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1. All records identifying the dates and attendees of meetings, or dates of and participants in teleconferences or webinars involving, the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*"), or any committee, working group, sub-committee, task force or project group thereof.
2. Any government contracts used to hire anyone to assist in the preparation of the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*"), including but not limited to, any government contracts used to hire anyone to perform the Integrated Assessment Modeling referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*.
3. Any records that describe, identify, contain, interpret or provide the dates or substance of briefings of political appointees in the Executive Branch on the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to, PowerPoint presentations. In the response, please produce the requested briefing records in their native original electronic form (PowerPoint, Word, etc.).
4. All electronic mail, WebEx documents, Google Docs, text messages, instant messages, voice mails, facsimiles or any other records relating to the *2010 TSD on SCC* or *2013 TSD on SCC* that were sent to any person outside the *IWG on SCC*, including but not limited to documents sent to or received from: any of the authors of the publications listed in the References section of the *2010 TSD on SCC* or *2013 TSD on SCC*; any other academics; government contractors; consultants; Sierra Club, Natural Resources Defense Council or other

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nongovernmental groups; and any other third-party whatsoever that was not part of the *IWG on SCC*.

5. All records discussing, describing, interpreting or relating to the applicability of or compliance with the Information Quality Act (P.L. 106-554, Section 515, 144 Stat. 2763 (2001)), or any Information Quality Act Guidelines published by the Office of Management and Budget, with respect to the work of the *IWG on SCC* or development, publication, use or dissemination of the *2010 TSD on SCC* or the *2013 TSD on SCC*.

6. All records discussing, interpreting or relating to the applicability of the Administrative Procedure Act (5 U.S.C. § 500 et seq.) to the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to whether those documents should have been published for public review and comment.

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Thank you for your prompt attention to this request. Please direct any inquiries, notices, or determinations to me at (713) 495-4508 or cbell@sidley.com.

Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009617

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Washington, DC 20460

Dear Sir or Madam:

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1. All records discussing, describing, referring or providing direction to, communicating to or about, or interpreting the formation, organization, structure, authority, activities, meetings, recommendations or decisions of the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*").
2. All records describing or discussing any past, on-going (as of the date of this submission) or planned work of the *IWG on SCC*.
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4. All records discussing or interpreting how the *2010 TSD on SCC* or the *2013 TSD on SCC* have been used or relied on, or are planned to be used, by EPA in any regulation proposed or promulgated by EPA, or in any policy decisions made by or guidance documents created by EPA.

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EPA Tracking Number EPA-HQ-2013-005473

Pursuant to the Freedom of Information Act ("FOIA") 5 U.S.C. § 552, and the implementing regulations of the U.S. Environmental Protection Agency ("EPA"), 40 C.F.R. Part 2, I am requesting a copy of the following EPA records:

1. All petitions for rulemaking of any kind submitted to the EPA Administrator related to any statute or regulation under which the EPA Administrator has the authority to promulgate regulations from January 1, 2013, to the present. These include, but are not limited to, petitions under the Clean Air Act, the Clean Water Act, the Resource Conservation and Recovery Act, the Comprehensive Environmental Response, Compensation, and Liability Act, the Toxic Substances Control Act, and the Federal Insecticide, Fungicide, and Rodenticide Act.

2. All notices of intent to sue EPA or its Administrator, dated from January 1, 2013, to the present, under any of the statutes listed above or under the Administrative Procedure Act for:

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b. Failure to meet any statutory, regulatory, or other deadline; or

c. Failure to meet any nondiscretionary obligation..

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Please direct any inquiries, notices, or determinations to me at (202) 736-8281. Thank you for your anticipated assistance.

Description Available to the Public : Yes

Has Request Been Modified? ☐

Attached Supporting Files

No supporting files have been added.

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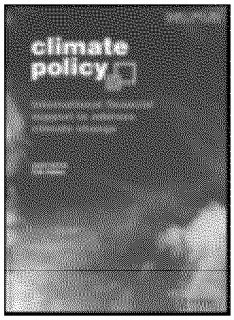

Climate Policy

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

Alex L. Marten[a], Elizabeth A. Kopits[a], Charles W. Griffiths[a], Stephen C. Newbold[a] & Ann Wolverton[a]

[a] National Center for Environmental Economics, US Environmental Protection Agency, 1200 Pennsylvania Avenue, Washington, DC 20460, USA

Published online: 20 May 2014.

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http://dx.doi.org/10.1080/14693062.2014.912981

climate policy

B research article

Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

ALEX L. MARTEN*, ELIZABETH A. KOPITS, CHARLES W. GRIFFITHS, STEPHEN C. NEWBOLD, ANN WOLVERTON†

National Center for Environmental Economics, US Environmental Protection Agency, 1200 Pennsylvania Avenue, Washington, DC 20460, USA

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Benefit–cost analysis can serve as an informative input into the policy-making process, but only to the degree it characterizes the major impacts of the regulation under consideration. Recently, the US, amongst other nations, has begun to use estimates of the social cost of CO_2 (SC-CO_2) to develop analyses that more fully capture the climate change impacts of GHG abatement. The SC-CO_2 represents the aggregate willingness to pay to avoid the damages associated with an additional tonne of CO_2 emissions. In comparison, the social costs of non-CO_2 GHGs have received little attention from researchers and policy analysts, despite their non-negligible climate impact. This article addresses this issue by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. By extending existing integrated assessment models, it is possible to develop a set of social cost estimates for these gases that are consistent with the SC-CO_2 estimates currently in use by the US federal government.

Policy relevance

Within the benefit–cost analyses that inform the design of major regulations, all Federal agencies within the US Government (USG) use a set of agreed upon SC-CO_2 estimates to value the impact of CO_2 emissions changes. However, the value of changes in non-CO_2 GHG emissions has not been included in USG policy analysis to date. This article addresses that omission by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. These new estimates are designed to be compatible with the USG SC-CO_2 estimates currently in use and may therefore be directly applied to value emissions changes for these non-CO_2 gases within the benefit–cost analyses used to evaluate future policies.

Keywords: integrated assessment; non-CO_2 GHGs; social cost of carbon

1. Introduction

The social cost of CO_2 (SC-CO_2) is a measure of the monetary value of the damages occurring both within and outside economic markets as the result of an additional unit of CO_2 emissions. Specifically, it represents society's aggregate willingness to pay to prevent future impacts that occur when one additional unit of CO_2 is emitted into the atmosphere in a particular year. Estimates of SC-CO_2

B *Corresponding author. E-mail: marten.alex@epa.gov
†The views expressed in this article are those of the authors and do not necessarily reflect the views or policies of the US Environmental Protection Agency.

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therefore provide a way to value changes in CO_2 emissions in benefit–cost analyses (BCAs) of policy alternatives. Without an estimate of the SC-CO_2, the benefits of mitigating the climate change impacts from CO_2 emissions would implicitly be valued at zero in BCAs, thereby significantly weakening the information provided by such analyses. Since 2009, the US Federal Government (USG) has used a set of agreed-upon SC-CO_2 estimates in the BCAs used to evaluate major regulations that impact CO_2 emissions (USG, 2010), including over 30 regulatory actions to date. The USG SC-CO_2 estimates are also increasingly being used in analysis and discussions outside the USG (e.g. by states, regional organizations, other nations, international organizations, NGOs, and academic researchers)[1] and have even figured in several recent public hearings and court cases (e.g. Keohane, 2010a, 2010b).

Although CO_2 is the primary anthropogenic GHG, other GHGs such as methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are also important contributors to climate change. The combined effect of all GHGs accumulated in the atmosphere is to increase the Earth's radiative forcing, which is the amount of energy from the Sun that is trapped in the Earth's atmosphere and therefore acts to warm the planet and change the climate. In 2011, the atmospheric CO_2 concentration contributed 64% of overall radiative forcing, while CH_4 and N_2O accounted for approximately 23% (Myhre et al., 2013). Non-CO_2 GHGs, notably CH_4 and N_2O, therefore contribute significantly to the negative impacts on human well-being from climate change. Furthermore, several recent studies have shown that consideration of non-CO_2 GHGs, particularly CH_4 and N_2O, is important for the design of cost-effective climate policy (Reilly et al., 1999; Tol, Heintz, & Lammers, 2003; Weyant, De La Chesnaye, & Blenford, 2006).

The monetary value of changes in emissions of non-CO_2 GHGs has not been included in USG policy analysis to date. This shortcoming prevents the development of accurate and comprehensive assessments of potential regulatory alternatives by the USG and others that rely on the USG SC-CO_2 estimates (Kopp & Mignone 2012; Marten & Newbold, 2012). For example, fossil fuels (e.g. coal and natural gas) have different compositions of GHG emissions across gases when considering the entire process of extraction, production, transmission, and combustion. Thus, if a regulation is anticipated to cause an industry to substitute between fuels, analysts may be providing inadequate information to decision makers and the public about its benefits if only the welfare implications of direct CO_2 emissions are considered while ignoring changes in CH_4 and other GHG emissions (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2011).

A key reason for the value of non-CO_2 GHG emissions impacts not being included in USG analyses so far is that existing estimates of the social cost of non-CO_2 GHGs presented in the literature are inconsistent with USG SC-CO_2 modelling assumptions. For example, the recent US Environmental Protection Agency BCA of new pollution standards for the oil and natural gas industry concluded that, because they are not consistent with the USG SC-CO_2, 'the methane climate benefit estimates available in the current literature are not acceptable to use to value the methane reductions finalized in this rulemaking' (USEPA, 2012). This article seeks to address that gap by developing a new set of social cost estimates for CH_4 and N_2O (SC-CH_4 and SC-N_2O, respectively) that are fully consistent with the modelling assumptions underlying the current USG SC-CO_2 estimates. This article also develops an approach to extending the models used by the USG to generate estimates of the social cost of additional GHGs that are consistent with the latest USG estimates of the SC-CO_2.

It is important to note at the outset that by restricting attention to the derivation of social cost estimates consistent with the USG SC-CO_2 estimates, any limitations that apply to inputs and modelling

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assumptions underlying the USG SC-CO_2 estimates (e.g. Arrow et al., 2013; Kopp & Mignone 2012; Marten, 2011; O'Neil, 2010; Warren, Mastrandrea, Hope, & Hof, 2010) also apply to the SC-CH_4 and SC-N_2O estimates derived here. Thus, while it is anticipated that the USG will continue to improve the models and data it uses to estimate the SC-CO_2, this article focuses on the more immediate task of developing a set of consistent estimates for the social cost of other GHG emissions so that they need not be implicitly assigned a value of zero in USG policy analyses.

The remainder of the article is organized as follows. Section 2 presents an overview of the USG SC-CO_2 estimation approach and how it compares to the existing literature on the social cost of non-CO_2 GHGs, including a discussion of some of the critiques of the approach. Section 3 presents the approach for estimating the SC-CH_4 and SC-N_2O in a manner consistent with the USG SC-CO_2 estimates. Section 4 presents the results and a comparison of the relative social costs to the previous literature and the global warming potential (GWP)-based metric that is often used as an approximation in the absence of direct estimates, and Section 5 provides concluding remarks.

2. Background

In 2009–2010 the USG formed an interagency working group to develop a set of SC-CO_2 estimates for use by all Executive Branch agencies to value marginal changes in CO_2 emissions in regulatory impact analyses (USG, 2010). The goal of this exercise was to improve the accuracy and consistency with which agencies value marginal changes in CO_2 emissions. Before the release of these estimates, CO_2 emissions changes were valued in some but not all regulatory analyses, and the SC-CO_2 estimates used by different agencies varied substantially. The USG recently updated their estimates for the SC-CO_2 by employing new versions of the three underlying integrated assessment models (IAMs), but leaving the original estimation approach and underlying assumptions unchanged (USG, 2013). This section provides a brief overview of the estimation approach and assumptions used by the USG for estimating SC-CO_2, describes some critiques of the approach by other researchers, and discusses the existing literature on the social cost of non-CO_2 GHGs.

2.1. USG SC-CO_2 estimation approach

To estimate the SC-CO_2 the USG used three IAMs that couple simplified models of atmospheric gas cycles and climate systems with highly aggregate models of the global economy and human behaviour to capture the effects that GHG emissions, through their effect on the climate, have on human welfare. Within IAMs, the modelling that guides the transition from emissions into climate impacts is based on scientific assessments, while the mapping of climate impacts into changes in human welfare is based on economic research that has studied the effect of climate on various market and non-market sectors. Nordhaus and Boyer (2000) provide a very informative and detailed description of how such models are developed.[2]

The three models used by the USG are those that feature most prominently in the published social cost of carbon literature: the Dynamic Integrated Climate and Economy (DICE) (Nordhaus, 2008; Nordhaus & Boyer, 2000), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2006b, 2008), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff, Hepburn, & Tol, 2009; Tol, 2002a, 2002b, 2009) models. The USG chose to use the IAMs'

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climate system submodels and the functions that map climate change into economic damages as implemented by the model developers, but adopted a common set of input assumptions for equilibrium climate sensitivity, discount rates, global population, economic output, and GHG emissions projections. The remainder of this section provides a brief description of these common assumptions and the steps used to calculate the SC-CO_2 estimates. Interested readers can find more details in the USG's 2010 technical support document (USG, 2010).

2.1.1. Reference socio-economic-emissions scenarios

The USG selected five scenarios of economic output, population, and GHG emissions projections using results from the 2009 Stanford Energy Modeling Forum exercise number 22 (EMF-22). Four of the scenarios are based on baseline runs from global economic models (MERGE, MESSAGE, MiniCAM, and IMAGE) and span a range of emissions projections and plausible outcomes for future population and economic output absent significant global action to address climate change. These scenarios allowed for internally consistent forecasts of economic output, population, and emissions for the years 2000–2100. The fifth scenario used by the USG is based on the average of the 550 ppm CO_2e stabilization runs for each of the four models from which baseline scenarios were selected to represent potential action by the rest of the world absent US action. Across the five scenarios, atmospheric CO_2 concentrations in 2100 ranged from approximately 450 to 890 ppm (550–1130 ppm in CO_2e). Over the time horizon, the forecasts of the average growth rate for global per capita economic output ranged from 1.5% to 2.0% per year, and the average global population growth rate ranged from 0.4% to 0.5% per year. To run the IAMs through the year 2300, the USG extrapolated the selected EMF scenarios using the following assumptions: starting in 2100 the population growth rate declines linearly to zero in 2200; starting in 2100 the growth rate of economic output per capita declines linearly to zero in 2300; for all years after 2100 the growth rate of the carbon intensity of the global economy (CO_2 emissions/economic output) remains constant at its 2090–2100 average; starting in 2100 net land-use CO_2 emissions decline linearly to zero in 2200; and for all years beyond 2100 non-CO_2 radiative forcing anomalies remain constant at their 2100 levels.

Several limitations of the simplifying assumptions underlying the USG approach to scenario development have been discussed by other researchers. O'Neil (2010) pointed out that the selected EMF scenarios do not reflect the full range of outcomes that appear in other studies in the literature, and Kopp and Mignone (2012) suggested that the selected scenarios may effectively over-sample the peaks of the distributions. As for the extrapolations, while running the models out for multi-century time horizons is not necessary for relatively short-lived GHGs like CH_4, it is important for understanding the impacts of long lived GHGs such as CO_2 and N_2O that will affect human welfare well beyond 2100. As emphasized by O'Neil (2010) and Kopp and Mignone (2012), the state of the world beyond 2100 is highly uncertain and the scenario extrapolation approach taken by the USG represents only one of many possibilities. Furthermore, the extrapolations for each component of the scenarios (economic output, population, emissions) are separate and nothing ensures internal consistency within the scenarios past 2100. As shown by Marten and Newbold (2012), the temporal decomposition of damages for a perturbation of CO_2 and N_2O are relatively similar in shape and therefore the general findings of studies that explore the sensitivity of the SC-CO_2 to these assumptions should also be applicable to the SC-N_2O.

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2.1.2. Equilibrium climate sensitivity

In reduced-form IAMs, the speed and magnitude of temperature change for a given emissions projection are influenced largely by the 'equilibrium climate sensitivity' (ECS) parameter. The ECS represents the long-term global average temperature response to a level of radiative forcing associated with a sustained doubling of atmospheric CO_2 concentration (around 550 ppm). To represent the uncertainty in the responsiveness of the climate system to changing atmospheric conditions, the USG used a probability distribution for the ECS parameter of the form suggested by Roe and Baker (2007). The USG calibrated the parameters of the probability distribution to have a median equal to 3 8C, two-thirds probability that the ECS lies between 2 and 4.5 8C, which was intended to be consistent with the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) consensus statement about the ECS (Meehl et al., 2007). The distribution was truncated from above at 10 8C. This specification of the ECS distribution is retained to maintain consistency with the USG estimates of the SC-CO_2, but it is noted that the recently released AR5 by the IPCC has revisited the equilibrium climate sensitivity and revised the range downwards to 1.5–4.5 8C and no longer provides a most likely value (Collins et al., 2013). The ultimate effect of updating the ECS distribution to be consistent with the IPCC AR5 findings will depend heavily on the central tendency selected for the distribution.

2.1.3. Discount rates

Because the damages from an additional tonne of CO_2 emissions occur over many decades, the discount rate, which reflects the tradeoff between present and future consumption, plays a critical role in estimating the SC-CO_2. In light of disagreement in the literature regarding the appropriate discount rate to use in this context and uncertainty about future conditions that impact the discount rate, the USG used three constant discount rates intended to span a plausible range: 2.5%, 3%, and 5% per year. It is worth noting that the debate regarding not only the appropriate discount rate but also its time path is ongoing (Arrow et al., 2013; Dasgupta, 2008). While the appropriate value for the discount rate will presumably remain an area of active debate for some time to come, there appears to be agreement that the use of a constant discount rate over long time horizons with uncertain changes in the consumption per capita growth is not theoretically consistent. This article uses the same three constant discount rates as the USG estimation process, but in Appendix C results are reported from a series of sensitivity analyses using a Ramsey discounting approach. Similar to Marten and Newbold (2012), it is found that applying Ramsey discounting using plausible values for the components of the consumption discount rate gives a range of social cost estimates that is broadly consistent with the range of results obtained using the constant discount rates.

2.1.4. Calculating the SC-CO_2

The process to estimate the SC-CO_2 for emissions in year t has four steps. First, each model is used to forecast monetized impacts associated with the baseline path of emissions, economic output, and population. Second, each model is re-run with an additional unit of CO_2 emissions in year t to forecast monetized impacts for all years beyond t along this perturbed path of emissions. Third, the marginal damages in each year are calculated as the difference between the monetized impacts forecast in steps 1 and 2. Finally, the resulting path of marginal damages is discounted and summed to calculate

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the present value of the marginal damages in the year when the additional unit of emissions used to perturb the model is emitted.

The USG repeated this process with each model, discount rate, and socio-economic-emissions scenario for each decade between 2010 and 2050. Because the ECS parameter is modelled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run represents a distribution over the SC-CO_2 in each year. These distributions were estimated using 10,000 simulations in each model run. Therefore, the exercise produced 45 separate distributions of the SC-CO_2 for a given emissions year, based on the three models, three discount rates, and five socio-economic-emissions scenarios considered. To provide a range of estimates that reflects this uncertainty but still emphasizes the central tendency, the distributions from each of the models and scenarios were equally weighted and combined to produce three separate probability distributions for the SC-CO_2 in a given year, one for each assumed discount rate. Four SC-CO_2 estimates were selected from these three probability distributions to reflect the global damages caused by one tonne of CO_2 emissions. Three estimates are based on the average SC-CO_2 across the three models and five socio-economic-emissions scenarios for the 5%, 3%, and 2.5% discount rates, respectively. The fourth value is the 95th percentile of the SC-CO_2 distribution at the 3% discount rate, and was chosen to represent potential higher-than-expected impacts from anthropogenic GHG emissions.

2.2. Existing estimates of the social cost of non-CO_2 GHG emissions

A significant limitation of the aforementioned USG interagency process is that the social costs of non-CO_2 GHG emissions were not estimated. Therefore, as an alternative to applying direct estimates for the social costs of non-CO_2 GHG emissions in the primary BCA, several recent USG regulatory analyses have approximated the benefits of non-CO_2 GHG emissions reductions in sensitivity analyses by transforming the non-CO_2 GHG emissions to 'CO_2-equivalents' using estimates of the GWP for the GHG in question and then using the USG SC-CO_2 for valuation (e.g. US EPA, 2012, 2013).

Gas comparison metrics, such as the GWP, have been designed to measure the impact of different GHGs relative to CO_2, where the point of comparison along the pathway from emissions to monetized damages (depicted in Figure 1) may differ across measures. The GWP, in particular, is designed to measure the additional radiative forcing (i.e. the amount of energy absorbed by atmospheric concentrations of GHGs) from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years). The GWP and other gas-comparison metrics are problematic as an SC-CO_2 scalar in BCA, as the remaining linkages in the pathway depicted in Figure 1 are complex and non-linear. Marten and Newbold (2012) demonstrate that using the GWP to adjust SC-CO_2 estimates to capture the impact of non-CO_2 gases provides a significant improvement over the implicit assumption that they are zero when such benefits are left unquantified, but may still underestimate mitigation benefits. Alternative gas comparison metrics that compare GHGs at different points in the chain of

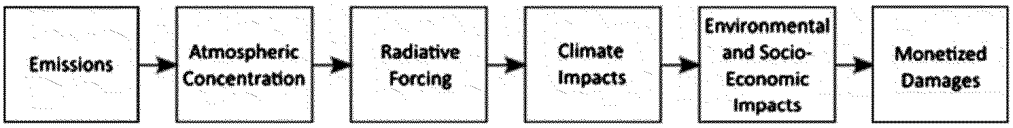

Figure 1 Path from GHG emissions to monetized damages

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causation (e.g. global temperature change potential (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005), peak commitment temperature (Smith et al., 2012), temperature proxy index (Tanaka, O'Neill, Rokityanskiy, Obersteiner, & Tol, 2009)) have also been shown to be imperfect substitutes for direct estimates.

Several researchers have directly estimated the social cost of non-CO_2 GHG emissions using IAMs, although the number of such estimates is small compared to the large number of SC-CO_2 estimates available in the literature. Among these previous direct estimates there is considerable variation in the model versions and input assumptions used. See Table 1 for a summary of the 11 non-CO_2 studies published to date.

As shown in Table 1, the estimates cover emissions years from 1990 to 2050, although the specific perturbation year is not stated in all studies. The studies also cover a wide range of constant and variable discount rate specifications and consider a range of baseline socio-economic and emissions scenarios that have been developed over the last 20 years. Finally, some studies in the literature have chosen not to report the social cost estimates directly. Instead, they opt to report only the 'global damage potential', which is a ratio of the social cost of gas X to the SC-CO_2. Normalizing the SC-CH_4 or

TABLE 1 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Model	Time horizon	Discount rate	Emissions year	Scenario[a]	Climate sensitivity
Reilly and Richards (1993)	N/A	140 years	2, 5, 8%	1990	N/A	N/A
Fankhauser (1994)	N/A	230 years	Ramsey	1991–2030	IS92[b]	N/A
Kandlikar (1995)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Kandlikar (1996)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Hammitt et al. (1996)	N/A	2200	1, 3, 5%	1995–2015	IS92a,c,e	1.5, 2,5, 4.5 8C
Tol (1999)	FUND 1.6	2100	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Tol et al. (2003)	FUND 1.7	2200	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Hope (2005)	PAGE95	2200	Ramsey	2000	SRES A2	Probabilistic, mode of 3 8C
Hope (2006a)	PAGE2002	2200	Ramsey	2001	SRES A2	Probabilistic, mean of 3 8C
Waldhoff et al. (2011)	FUND 3.5	3000	Ramsey	2010–2019	FUND, SRES A1B, A2, B1, B2	2, 3, 4.5 8C
Marten and Newbold (2012)	DICE2007 w/ MAGICC	2300	Ramsey, 2.5, 3, 5%	2010–2050	EMF-22 MiniCAM Base	Probabilistic,median of 3 8C

[a]IS90 scenarios are based on the IPCC First Assessment Report (IPCC, 1990); IS92 scenarios are based on the IPCC Supplementary Report (IPCC, 1992); SRES scenarios are based on the IPCC Special Report on Emissions (IPCC, 2000); the FUND scenario is the default scenario in the FUND model; EMF-22 scenarios are based on results from Stanford's Energy Modeling Forum's 22nd exercise (Clarke et al., 2009).[b]The particular IS92 scenario used was not specified.

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SC-N_2O estimate using the SC-CO_2, in part, controls for differences in the modelling to allow for a better comparison with other estimates in the literature.

Fankhauser (1994) was one of the first to develop estimates of the average SC-CH_4 and SC-N_2O for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt, Jain, Adams, and Wuebbles (1996) also developed estimates of SC-CH_4 and SC-N_2O for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006a) developed estimates for the SC-CH_4 in 2000 using the FUND and PAGE models, respectively. Waldhoff, Anthoff, Rose, and Tol (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal CO_2, CH_4, N_2O, and SF_6 emissions for the average year in the 2010 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios from the IPCC special report on emissions (IPCC, 2000) in addition to the default FUND scenario. In Section 4, the specific results of these previous studies are discussed with a comparison to the estimates obtained in the present study.

The above-mentioned previous studies provide a basic understanding of the relative social costs of different GHGs but do not provide sufficient information about how this relationship changes over time. Marten and Newbold (2012) used an IAM that couples the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) with economic components of the 2007 version of William Nordhaus' DICE model to directly estimate the social cost of marginal CO_2, CH_4, and N_2O emissions. They estimated the annual social costs for the years 2010–2050 along a single socio-economic-emissions pathway given uncertainty about the equilibrium climate sensitivity parameter. An advantage of their approach is that through the use of a more detailed, yet still relatively simple, climate model their results are not affected by over-simplification of temperature response or atmospheric chemistry, which have been shown to have non-negligible effects on the estimates of social costs (Marten, 2011; Warren et al., 2010).

The work of Marten and Newbold (2012) uses many of the assumptions used by the USG in its estimation of SC-CO_2, including discount rates, the equilibrium climate sensitivity distribution, and post-2100 socio-economic and emissions extrapolations. However, they focus on only one of the three models and one of the five socio-economic-emissions scenarios used by the USG. Furthermore, they use a different climate sub-model, which leads their estimate of the SC-CO_2 to be different from the USG estimate, even for the same IAM and scenario combination. Therefore, although these studies, including Marten and Newbold (2012), have increased our understanding about the relative social costs of GHG emissions, they have not provided a set of estimates that are entirely consistent with the USG SC-CO_2 estimates. In Section 4, the estimates derived in this article are compared with those of Marten and Newbold (2012) to more clearly demonstrate the similarities and differences in the two sets of estimates for SC-CH_4 and SC-N_2O.

3. Estimating the social cost of non-CO_2 GHGs consistent with USG SC-CO_2

The primary obstacle in estimating the social cost of non-CO_2 GHG emissions in a manner consistent with the USG SC-CO_2 estimates is that not all of the IAMs used include explicit representations of the non-CO_2 gases of interest. This section describes the degree to which non-CO_2 GHGs are currently

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represented in the default versions of DICE, PAGE, and FUND, and then discusses how they are amended to estimate the social cost of these gases.

3.1. Representation of non-CO_2 GHGs in DICE, PAGE, and FUND

The FUND model explicitly considers CH_4, N_2O, and SF_6 in addition to CO_2. The model uses one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels. For CH_4 and N_2O, FUND estimates the additional radiative forcing imposed by the atmospheric buildup of these gases using the simplified expressions presented in Chapter 6 of the IPCC's Third Assessment Report (TAR) (Ramaswamy et al., 2001). FUND also augments the TAR expression for the additional radiative forcing from CH_4 to account for the influences of stratospheric water vapour and tropospheric ozone changes. Because FUND uses CH_4 and N_2O emissions as inputs and internally computes their impact on the climate system, it is possible to directly estimate the social cost of those gases without modifying the model.

In the DICE model, the only GHG that is explicitly represented is CO_2; an exogenous radiative forcing projection is used to account for the impact of all other gases on the climate. To develop an exogenous radiative forcing pathway consistent with the emissions scenarios used to estimate the SC-CO_2, the USG decomposed the default DICE exogenous radiative forcing vector into CH_4, N_2O, F-gases, aerosols, and other residual forcing components. The USG then replaced the radiative forcing attributed to CH_4, N_2O, and F-gases with estimates associated with the EMF-22 scenarios. As non-CO_2 emissions are not a direct input into DICE, it is not possible to simply perturb the emissions projection and re-run the model to obtain a forecast of additional damages.

The 2002 version of the PAGE model, which was used by the USG in developing its first set of estimates (USG, 2010), includes an atmospheric model for CH_4 and SF_6, but represents the effects of other non-CO_2 GHGs in an exogenous radiative forcing projection. Presumably to simplify the process and maintain consistency with DICE, the USG did not use PAGE's internal CH_4 component. Instead, the same exogenous radiative forcing projection was used for the effect of CH_4, N_2O, and F-gas emissions as was used for DICE. Since then, a N_2O component has been added to the PAGE model, although in the recent 2013 SC-CO_2 update the USG maintained the approach of using the same single exogenous forcing projection as was applied to DICE (USG, 2013). Therefore PAGE, as implemented by the USG, faces the same limitations as DICE with respect to estimating the social costs of marginal non-CO_2 emissions that are consistent with the USG SC-CO_2 estimates. For these reasons, computing estimates for the social cost of non-CO_2 gases in DICE and PAGE requires either replacing the climate component of these models with a more complete representation, as was done with DICE by Marten and Newbold (2012), or deriving an estimate of the path of additional radiative forcing that would result from a perturbation of the gas in question. This article uses the latter approach for DICE and PAGE, as the former would represent a substantial change to the underlying IAMs and would have implications for the SC-CO_2 estimates, making this work inconsistent with the USG SC-CO_2 estimates currently used in regulatory analysis.

3.2. Estimating the social cost of non-CO_2 GHGs in DICE and PAGE

The process used in this article to estimate the social cost of non-CO_2 GHGs in DICE and PAGE as implemented by the USG requires first generating a forecast of the additional radiative forcing

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associated with a perturbation of a non-CO_2 gas's emissions in a single year, and then adding this radiative forcing perturbation to each model's exogenous radiative forcing projection. To determine the additional radiative forcing associated with the emission perturbation, there is a need to model the change in atmospheric concentration and the radiative forcing associated with the additional concentration. For both CH_4 and N_2O, a simple one-box atmospheric gas cycle model with a constant decay rate is used to estimate the atmospheric concentration of each gas based on its assumed emissions. The use of a one-box gas cycle for CH_4 and N_2O with constant decay follows the approach used by the IPCC to compute GWPs (Forster et al., 2007) and the FUND model (Anthoff & Tol, 2013). In both the baseline and the perturbed case, the contribution of the gas to the global radiative forcing anomaly is determined by the forcing relationships presented in the IPCC TAR (Ramaswamy et al., 2001), which were not updated by the IPCC in AR4. The incremental radiative forcing is defined by the difference between the baseline forcing path and the emissions path that includes a one tonne perturbation in a given year. Next, the path of additional radiative forcing is added to the stream of exogenous radiative forcing in each IAM to estimate the climate damages in the perturbed scenario. These damages are then compared to the baseline damages to determine the social cost of gas X (SC-X). Specifically, the process is as follows:

1. Run the IAM as described in the SC-CO_2 technical support document (USG, 2010) to estimate baseline damages.
2. Estimate the baseline atmospheric concentration for gas X.
3. Estimate the baseline radiative forcing contribution of gas X.
4. Perturb the stream of gas X emissions by one tonne in year t.
5. Estimate atmospheric concentration for gas X in the perturbed scenario.
6. Estimate the radiative forcing contribution of gas X in the perturbed scenario.
7. Compute the incremental radiative forcing as the difference between the results of steps 3 and 6.
8. Add the additional radiative forcing from step 7 to the exogenous radiative forcing path used in the IAM in step 1.
9. Re-run the IAM to compute the damages along the perturbed emissions path.
10. Compute the social cost of gas X for emission year t as the present value of the difference in damages estimated in steps 1 and 9.

Two practical issues associated with implementation are worth noting. First, while the SC-X estimates are associated with a one tonne perturbation, to avoid computational rounding error a 1 Mt perturbation is used and then the resulting change in damages is scaled to get the average effect per tonne. Experiments conducted by Griffiths et al. (2012) to assess the applicability of the SC-CO_2 to non-marginal emission changes show that the average per tonne SC-CO_2 estimate is relatively constant over large differences in perturbation size. Additional experiments in the context of this article found that alternative perturbation sizes do not significantly change the average one tonne social cost estimate. Second, the additional radiative forcing due to the emissions perturbation is computed based on an annual time step, but because DICE and PAGE use longer time steps the average radiative forcing over the time step is added to the model's exogenous radiative forcing vectors.

The remainder of this section describes the procedure for modelling the incremental radiative forcing of a perturbation for CH_4 and N_2O, and explores the sensitivity of these projections to

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two issues. First, it evaluates whether the simple one-box gas cycle model with a constant decay rate produces a close approximation to the forecasts of future atmospheric CH_4 and N_2O concentrations based on a more sophisticated climate model. Second, it explores the sensitivity of the results to the method used for extrapolating non-CO_2 emissions from 2100 to 2300. This is important, because the USG did not specify a particular set of emissions pathways for each constituent gas, instead assuming only that non-CO_2 radiative forcing remains constant past 2100. Such a situation could arise from a myriad of possible individual gas projections and the USG did not specify which it was assuming.

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3.3. Methane

A simple one-box atmospheric gas cycle model for methane specifies the concentration in year t, $C_t^{CH_4}$ [ppb], such that

$$C_t^{CH_4} = C_{t-1}^{CH_4} + d_{CH_4}(C_{pre}^{CH_4} - C_{t-1}^{CH_4}) + g_{CH_4}E_{t-1}^{CH_4}, \tag{1}$$

where d_{CH_4} defines the rate of decay, $C_{pre}^{CH_4}$ [ppb] is the pre-industrial atmospheric concentration, and g_{CH_4} [ppb/Mt] converts emissions, $E_{t-1}^{CH_4}$ [Mt], from mass to atmospheric volume. The mass to volume conversion factor is g_{CH_4} ¼ 0.3597 ppb/Mt and $C_{pre}^{CH_4}$ ¼ 700 ppb, following the IPCC TAR. The rate of decay is set to d_{CH_4} ¼ 1/12 following the IPCC AR4 stated CH_4 lifetime of 12 years. The iteration begins in the year 2006 using the emissions from the EMF-22 scenario (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used so that $C_{2005}^{CH_4}$ ¼ 1774 ppb.

The contribution of atmospheric methane to global radiative forcing, denoted $Q_t^{CH_4}$, is defined using the relationship in Table 6.2 of the IPCC TAR:

$$Q_t^{CH_4} = f\ 0.036\ \left(C_t^{CH_4} - C_{pre}^{CH_4}\right) - \left[f(C_t^{CH_4}, C_{pre}^{N_2O}) - (C_{pre}^{CH_4}, C_{pre}^{N_2O})\right], \tag{2}$$

where $C_{pre}^{N_2O}$ [ppb] is the pre-industrial atmospheric concentration of nitrous oxide and

$$f(C^{CH_4}, C^{N_2O}) = 0.47 \ln\left[1 + 2.01 \times 10^{-5}(C^{CH_4}C^{N_2O})\right]^{0.75} + 5.31 \times 10^{-15}C^{CH_4}(C^{CH_4}C^{N_2O})^{1.52}. \tag{3}$$

The function in expression (3) accounts for the overlapping absorption bands of CH_4 and N_2O, thereby reducing their effective absorption. Parameter f is used to proxy for indirect effects of CH_4 that include the enhancement of stratospheric water vapour and tropospheric ozone changes. Following the IPCC AR4, an enhancement effect of 40% (25% from tropospheric ozone change and 15% for stratospheric water vapour enhancement) is used, such that f ¼ 1.4. The pre-industrial concentration of N_2O is set consistent with the IPCC TAR, such that $C_{pre}^{N_2O}$ ¼ 270 ppb.

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A key simplification in this approach is the constant decay rate used in the atmospheric gas cycle model. As discussed by IPCC Working Group I in Chapter 4 of the TAR, the lifetime of methane emissions in the atmosphere depends on temperature and the concentrations of CO, NOx, and other VOCs in the atmosphere (Ehhalt et al., 2001). Sensitivity analysis is used to understand the potential implications of ignoring these interactions by comparing the incremental atmospheric concentration projected by the simple model described above to the analogous projection from the climate model MAGICC,[3] which, while still relatively simple, incorporates these interactions between the lifetime of CH_4 in the atmosphere and the other gases and climate variables. This exercise uses CH_4 emissions from the EMF-22 MiniCAM reference scenario and considers a one tonne perturbation of CH_4 in 2015. It is noted that these results are robust across alternative emissions levels.[4]

Figure 2(a) presents the projected average decadal increment to atmospheric concentrations using both the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. At the time of the perturbation (2015), the inter-annual time step of MAGICC allows for an uptake of the additional emissions into the atmosphere, whereas the strict annual time step of the simple model causes a year to pass before the change is registered. After the initial year, the models originally differ by around 15%. This difference falls to under 10% within the first decade, with the faster effective growth in the simple model causing its additional concentration to eventually fall below that of MAGICC.

The difference in the incremental radiative forcing from the perturbation between the simple model and MAGICC is also of importance. Although MAGICC relies on similar equations to derive the radiative forcing of atmospheric CH_4 concentrations, it differs in the way it handles indirect effects of CH_4 on tropospheric ozone and stratospheric water vapour, in addition to including other temperature-related feedbacks. Figure 2(b) presents the average additional radiative forcing per decade attributed to the 2015 CH_4 perturbation in both models. The average increase in radiative forcing over the decade is considered because this is the input required by DICE due to its ten-year time step and therefore a more relevant comparison (PAGE requires a similar multi-year average). When considering the average additional radiative forcing over the decade, the initial difference in concentration between MAGICC and the simple model has a minimal effect and the difference in radiative forcing between the two models is less than 2% over the first two decades. However, this difference grows to –18% over the subsequent two decades. This escalation in the difference is in part due to the use of a constant decay rate in the simple model, whereas MAGICC takes into account the growing atmospheric concentrations of other gases and increasing atmospheric temperature, which increase the lifetime of atmospheric CH_4.

To understand the effect that this difference would have on an estimate of the SC-CH_4, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of CH_4, as computed using both the simple model and MAGICC, is added to the exogenous forcing projection. As above, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 2 presents the results of this experiment. In line with the results comparing the radiative forcing perturbations above, the two approaches produce similar social cost estimates for emissions in 2015, where additional analysis has shown these results to hold with PAGE as well. The impact of assuming a constant decay rate is greater further out into the future, due to the projected increase in the atmospheric concentration of other relevant gases and atmospheric temperature that are accounted for in MAGICC, and the social cost

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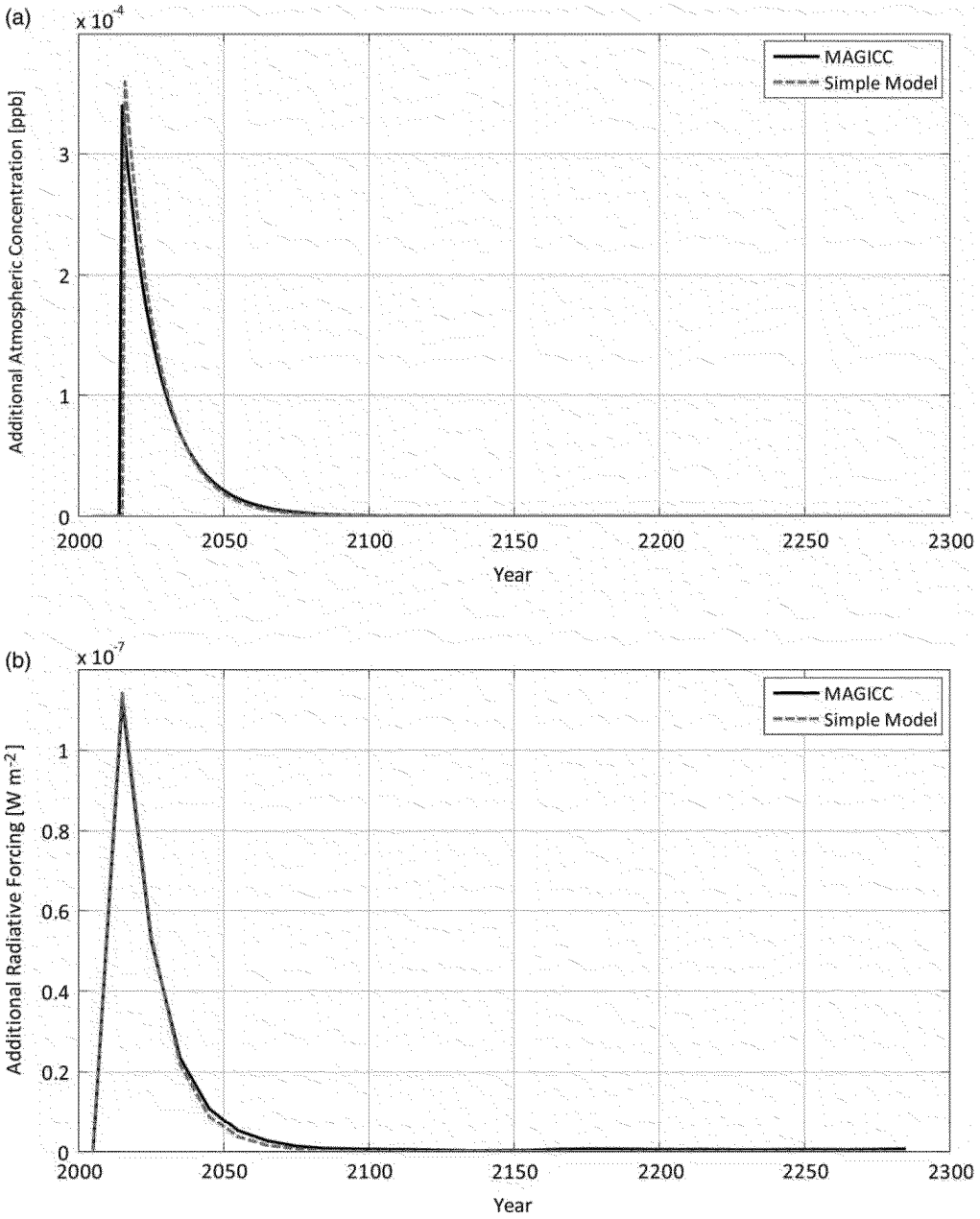

Figure 2 Effects of perturbation in 2015 CH_4 emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

estimates begin to diverge for later emissions years. For the same reason, the two approaches will show greater differences for lower discount rates that give increased weight to future time periods. While over-simplification of the climate system can, in some circumstances, have significant effects on

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TABLE 2 Effect of CH_4 gas cycle model on SC-CH_4 (2007$ per tonne CH_4): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	1135	1183	2 4%
	3.0%	822	851	2 3%
	5.0%	349	354	2 2%
2045	2.5%	2490	2707	2 8%
	3.0%	1933	2084	2 7%
	5.0%	956	1006	2 5%

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social cost estimates (e.g. Marten 2011), the near-term differences based on this simplification seem relatively small considering the precision of such social cost estimates.

3.4. Nitrous oxide

The simple one-box atmospheric gas cycle model for N_2O takes a similar form to the model used for CH_4, such that the concentration of nitrous oxide in year t, $C_t^{N_2O}$ [ppb], is specified as

$$C_t^{N_2O} = C_{t-1}^{N_2O} + d_{N_2O}(C_{pre}^{N_2O} - C_{t-1}^{N_2O}) + g_{N_2O}E_{t-1}^{N_2O}, \tag{4}$$

where d_{N_2O} is the rate of decay, and g_{N_2O} [ppb N_2O/Mt N] converts emissions, $E_{t-1}^{N_2O}$ [Mt N], from mass to atmospheric volume. Following the IPCC AR4, the mass to volume conversion factor is g_{N_2O} ¼ 0.2079 ppb N_2O/Mt N and the rate of decay is d_{N_2O} ¼ 1/114 based on a 114-year lifetime. As with CH_4, the iteration begins in the year 2006 using the emissions from the EMF-22 scenarios (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used, such that $C_{2005}^{N_2O}$ ¼ 319 ppb.

The contribution of atmospheric N_2O to global radiative forcing, denoted $Q_t^{N_2O}$, is defined using the relationship in Table 6.2 of the IPCC TAR, such that

$$Q_t^{CH_4} = 0.12 \left[C_t^{N_2O} - C_{pre}^{N_2O} - [f(C_{pre}^{CH_4}, C_t^{N_2O}) - f(C_{pre}^{CH_4}, C_{pre}^{N_2O})], \right. \tag{5}$$

where $f(C^{CH_4}, C^{N_2O})$ is defined in expression (3).

As with CH_4, a key simplifying assumption is the constant decay rate used in the simple gas cycle model (and potentially the time it takes the gas to become well mixed within the atmosphere). As discussed in the IPCC TAR, the decay rate of N_2O will depend on the atmospheric concentration of N_2O and so will not be constant in reality. To examine the extent to which this impacts the results of the simple model, an analogous set of experiments as conducted for CH_4 were performed. Given future

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N_2O emissions based on the EMF-22 MiniCAM reference scenario, a one tonne N_2O perturbation in 2015 is considered. Figure 3(a) shows the projected atmospheric concentration increase from the perturbation using the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. This comparison illustrates that the simple model tracks the output of MAGICC well for the entire 300-year time horizon. Outside the initial perturbation year, the two projections do not differ by more than 2% within the first century, with the largest difference occurring in the perturbation year, for the same reasons as with CH_4.

Figure 3(b) presents the estimates of average additional radiative forcing per decade as a result of the N_2O perturbation using both models. The additional radiative forcing from the N_2O perturbation in the one-box model is forecast to be slightly lower (7%) in the first decade compared to MAGICC. Subsequently, the difference is within 2% through to 2300.

As with CH_4, to assess the effect that this difference would have on the SC-N_2O, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of N_2O computed using both the simple model and MAGICC is added to the exogenous forcing projection. As before, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 3 presents the results of this experiment. As the comparisons of the projected radiative forcing perturbations would suggest, the difference between the social cost estimates for the two approaches is relatively small. In contrast to the case of CH_4, here an increase in the discount rate increases rather than decreases the divergence between the estimates due to the greater weight being placed on the earlier years when the radiative forcing perturbations have a slightly higher degree of divergence.

3.5. Effect of post-2100 non-CO_2 radiative forcing assumptions

The EMF-22 socio-economic-emissions scenarios used by the USG include years only up to 2100, while the USG ran the IAMs out to 2300. Therefore, additional assumptions were required to extrapolate the scenarios beyond 2100. For the purposes of this study, the most important of these assumptions is that non-CO_2 radiative forcing will remain constant at its 2100 level until 2300. Such a broad assumption was sufficient for the purposes of the USG in estimating the SC-CO_2. However, estimating the social cost of non-CO_2 GHGs requires explicit projections of baseline emissions of non-CO_2 gases in order to correctly determine the effect of the perturbation. The USG's broad assumption regarding the extrapolation of non-CO_2 gases is therefore problematic as constant non-CO_2 radiative forcing post 2100 may occur in an infinite number of ways. For instance, one way to achieve this outcome is to assume that emissions of each non-CO_2 gas falls to a level equal to its respective rate of decay in 2100. This assumption would keep atmospheric concentrations, and in turn radiative forcing, constant. Based on the simple gas cycle models laid out in the earlier sections this implies that, for gas X,

$$E_t^X = \frac{-d_X(C_{pre}^X - C_{2100}^X)}{g_X} \forall t \ . \ 2100. \tag{6}$$

To put this assumption into context, the solid lines in Figure 4(a) and (b) present the emissions paths for CH_4 and N_2O, respectively, under the MiniCAM EMF-22 reference scenario extrapolated using

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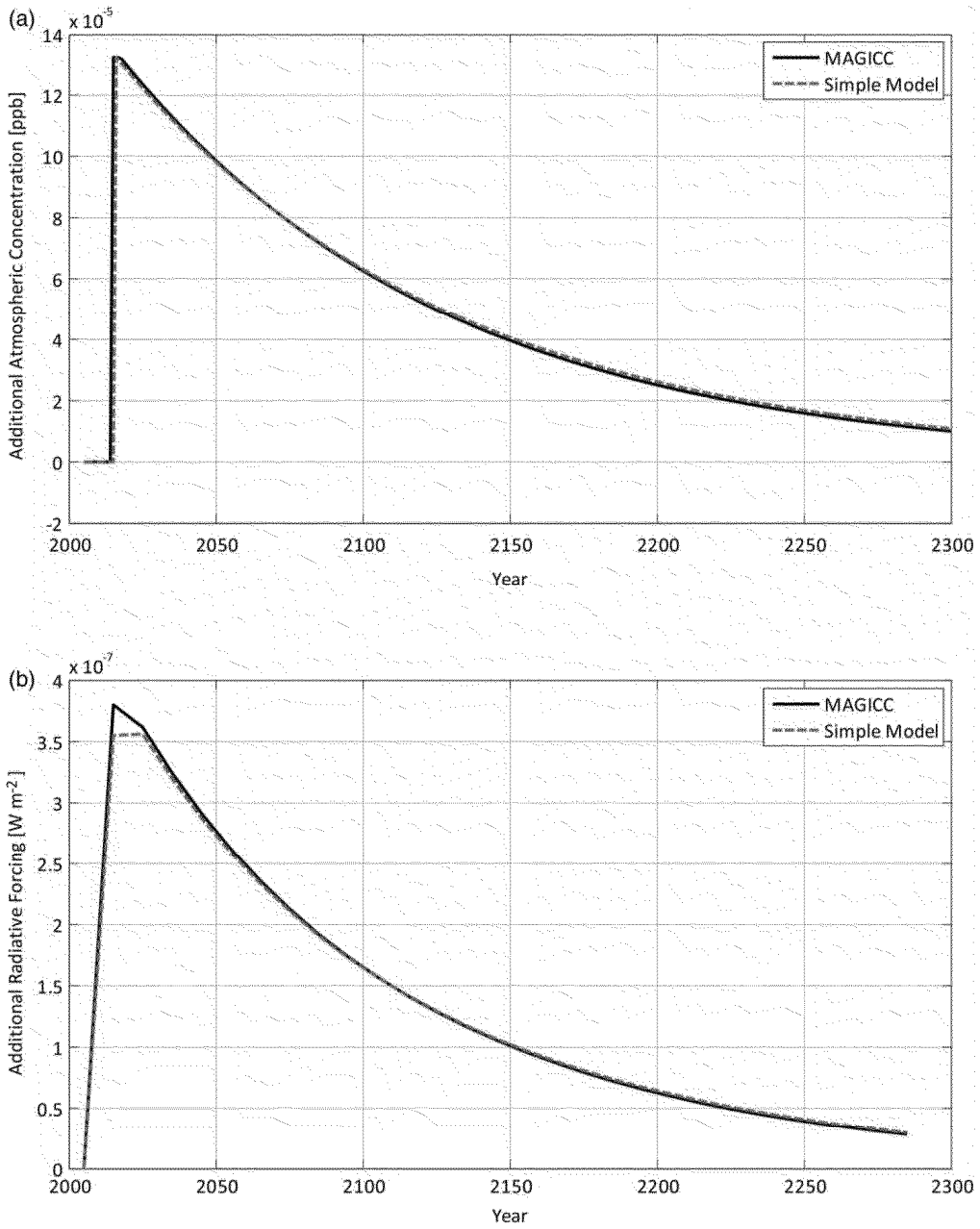

Figure 3 Effects of perturbation in 2015 N_2O emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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TABLE 3 Effect of climate model on SC-N_2O (2007$ per tonne N_2O): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	19,689	19,819	2 1%
	3.0%	12,390	12,525	2 1%
	5.0%	3,346	3,419	2 2%
2045	2.5%	36,968	37,358	2 1%
	3.0%	25,030	25,427	2 2%
	5.0%	8,280	8,528	2 3%

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expression (6), while the dashed lines show two alternative extrapolation approaches, one where emissions are held constant at their 2100 level and one that assumes emissions intensity (emissions/economic output) continues to decline at the same rate forecast by the EMF-22 scenario in 2090–2100 (dotted line). This latter alternative is analogous to the USG assumption regarding industrial CO_2 emissions. The two alternatives will not result in the radiative forcing contribution of gas X remaining constant post-2100, but do not in themselves violate the assumption that overall non-CO_2 radiative forcing remains constant. Noteworthy is the fact that the assumption in (6) is almost analogous to keeping CH_4 emissions constant at their 2100 levels, whereas for N_2O the assumption requires a sudden decrease in emissions of over 35%.

While Figure 4 illustrates that these three extrapolation approaches can lead to vastly different projections for emissions after 2100, the relevant comparison is how these assumptions affect the additional radiative forcing from a perturbation of the gas and in turn the SC-X estimates. Figure 5(a–d) present the additional radiative forcing resulting from a one tonne perturbation based on the simple model presented in Sections 3.1 and 3.2. Figure 5(a) and (b) demonstrates the difference for a perturbation in 2015, whereas Figure 5(c) and (d) represents perturbations in 2045. For CH_4, the cumulative radiative forcing from the projection over the time horizon differs by less than 0.001%, even for a

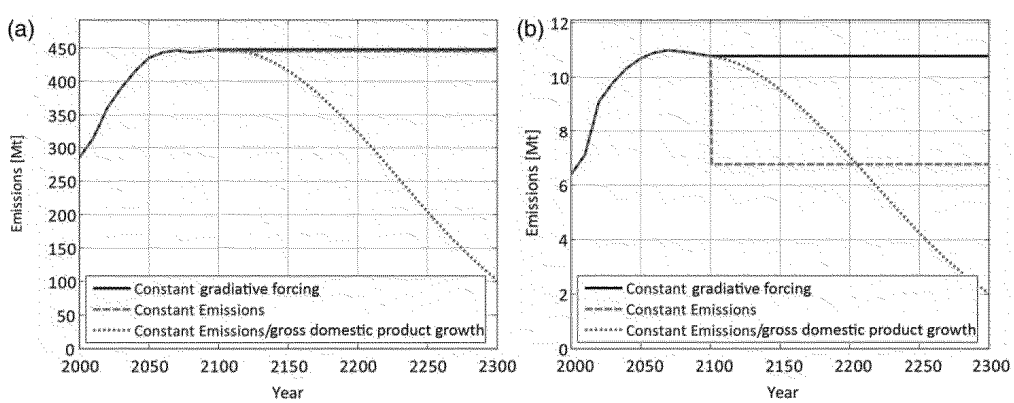

Figure 4 EMF-22 MiniCAM extended emissions scenario: (a) CH_4 emissions; (b) N_2O emissions

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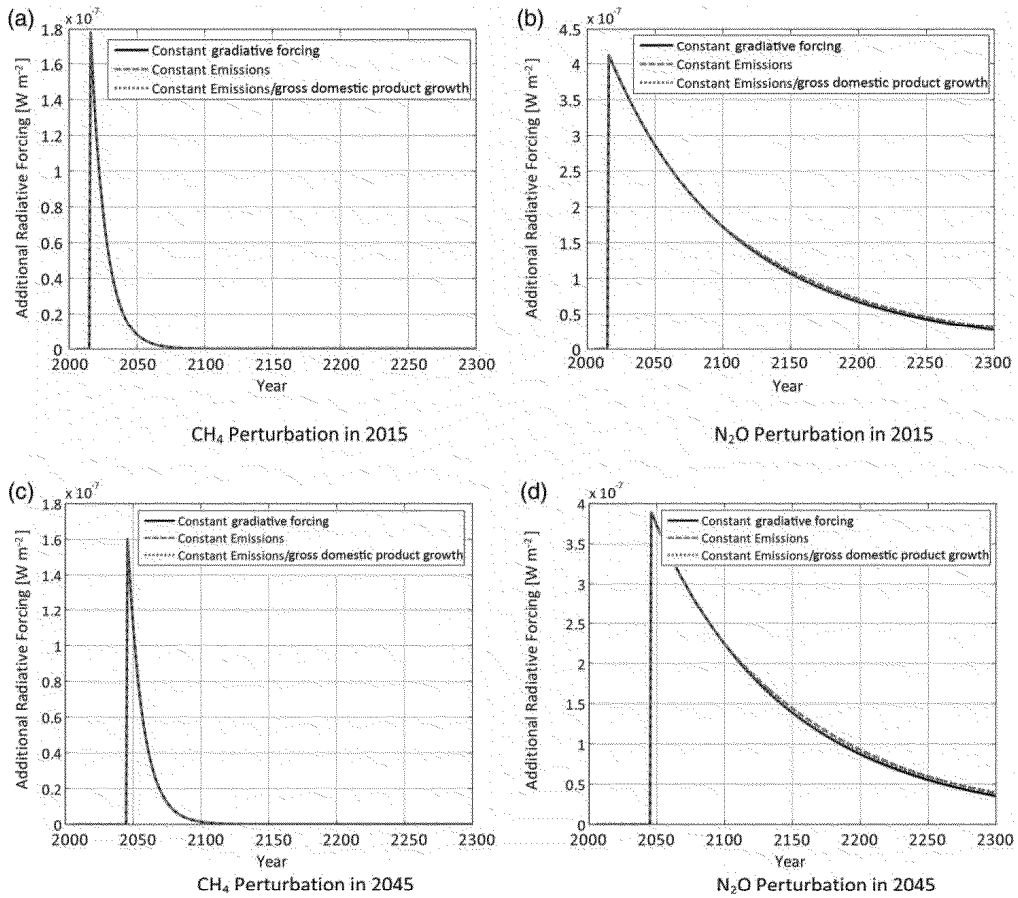

Figure 5 Effect of extrapolation approach on radiative forcing perturbation from simple model: (a) CH_4 perturbation in 2015; (b) N_2O perturbation in 2015; (c) CH_4 perturbation in 2045; (d) N_2O perturbation in 2045

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perturbation in 2045. Accordingly, the relevant annual difference is smaller even than one-thousandth of a percent. This result occurs because of the short atmospheric lifetime of the gas, which renders assumptions regarding CH_4 emissions after 2100 unimportant for near-term perturbations. Post-2100 emissions will have a larger effect in the case of N_2O, which has a much longer atmospheric residence time. However, even for a perturbation in 2045, the difference in cumulative additional radiative forcing is less than 2.5% across the extrapolation assumptions.

To examine the impact of these assumptions on SC-CH_4 and SC-N_2O, an experiment was conducted using the DICE model based on the EMF-22 MiniCAM socio-economic-emissions scenario. The results of this experiment are presented in Table 4 for the perturbation year 2045 (noting that the extrapolation method will have greater impact on future emissions years). As may be seen, the relatively short atmospheric lifetime of CH_4 leads to a situation in which post-2100 assumptions do not affect SC-CH_4 estimates, even in 2045. For the longer-lived gas N_2O, in emission year 2045, where the effect of the post-2100 extrapolation approach would be largest, the difference across the three

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TABLE 4 Effect of post-2100 extrapolation on the 2045 SC-X (2007$ per tonne): DICE2010, MiniCAM

Gas	Discount rate	Constant RF	Constant emissions	Constant emissions intensity growth
CH_4	2.5%	2,490	2,490	2,490
	3.0%	1,933	1,933	1,933
	5.0%	956	956	956
N_2O	2.5%	36,968	36,588	36,662
	3.0%	25,030	24,837	24,868
	5.0%	8,280	8,261	8,263

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assumptions is less than 1% and the projections are equivalent to two significant digits. Therefore, in the remainder of this article, non-CO_2 emissions are extrapolated past 2100 using expression (6) to ensure that the gas-specific contribution to overall radiative forcing remains constant in the simple model. While additional study may lead to improvements of long-term forecasts of CH_4 and N_2O emissions and possible correlations, compared to the paths in Figure 5(a), the very minimal effect of such assumptions on the social cost estimates suggests the impact of such efforts would be minimal in this context.

4. Results

For FUND, the social cost of non-CO_2 GHGs is estimated by perturbing the paths of emissions directly, while for DICE and PAGE the approach presented in Section 3 is used. In both cases, all additional assumptions made by the USG are applied, including the five EMF-22 socio-economic-emissions scenarios, the Roe and Baker (2007) distribution for the equilibrium climate sensitivity, and constant discount rates of 2.5%, 3.0%, and 5.0%. Following the USG, the estimates for the expected social cost are averaged across scenarios and models, with each model and scenario given equal weight. Estimates are not combined across discount rates, and a fourth estimate is included representing the 95th percentile when using the 3.0% discount rate. By using the same assumptions and procedures as the USG, estimates of the SC-CO_2 derived in this article are identical to the values used in US Federal rule making. Specifically, these estimates are equivalent to the recent 2013 update of the USG SC-CO_2, which revised the original 2010 USG upwards based on new versions of the IAMs used. The non-CO_2 results, as well as the USG SC-CO_2 estimates, are presented in Table 5 for emissions years 2020 and 2050.[5] Results for additional years, and the results of sensitivity analyses using Ramsey discounting, may be found in Appendix B and C, respectively.

As expected, considering their higher radiative efficacy, the social costs associated with a tonne of CH_4 and N_2O emissions are substantially higher than for CO_2. The values are higher at lower discount rates, although the impact of the discount rate is lower for CH_4 given its relatively short lifetime. Similar to CO_2, the social cost estimates for CH_4 and N_2O increase over time as the climate and economic systems become more stressed, although the growth rate of the social cost estimate may differ between the gases, as discussed in the following.

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TABLE 5 SC-X (2007$ per tonne)

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CO_2	12	43	64	128
	CH_4	550	1,200	1,600	3,200
	N_2O	4,800	15,000	22,000	41,000
2050	CO_2	26	71	97	220
	CH_4	1,400	2,500	3,100	6,900
	N_2O	11,000	27,000	38,000	74,000

To better understand how the social costs of CH_4 and N_2O compare to CO_2, Table 6 presents the global damage potentials corresponding to the social cost estimates from Table 5. (The disaggregated results, by model and scenario, for 2020 are provided in Appendix B.) As explained in Section 2, the global damage potential for gas X is the ratio of SC-X to SC-CO_2, and therefore by construction captures all the important linkages between emissions and monetized climate change damages (to the degree they are captured by the IAMs) directly within the gas comparison metric. As noted by Frankhauser (1994), this is preferred to the commonly used GWP gas comparison metric, which only measures the additional radiative forcing from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years) and ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages.

The global damage potential of CH_4 decreases with the discount rate due to the relatively shorter atmospheric lifetime. This difference in atmospheric lifetime leads to a situation where lowering the discount rate has a greater impact on the SC-CO_2 than the SC-CH_4. This finding is robust across the models. The estimates in Table 6 also present the same result for N_2O in the aggregate case, although this characteristic is not consistent across the models or the previous literature. Based on the disaggregated results (presented in Appendix B), the results from the DICE model suggests the global damage potential for N_2O increases with lower discount rates due to a lower effective decay rate over the relevant time horizon for N_2O than CO_2. This result is consistent with previous findings by Marten and Newbold (2012). However, for FUND the opposite is seen to hold. Waldhoff et al. (2011) show that this result is primarily due to the inclusion of increased production in the agriculture and forestry sectors from CO_2 fertilization effects. At lower discount rates these benefits place a greater downward

TABLE 6 Global damage potential

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CH_4	46	29	25	25
	N_2O	397	359	353	317
2050	CH_4	52	36	32	31
	N_2O	414	388	387	338

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impact on the SC-CO_2, thereby lowering the global damage potential. If one were to remove those impacts from the FUND model the global damage potential for N_2O becomes relatively insensitive to the discount rate. One would expect the role of the discount rate in determining the global damage potential in PAGE to be the same as in DICE, but the results suggest that this is not the case. It seems most likely that this is because the PAGE model has only ten time steps to cover the entire time horizon, which results in very large, up to 100-year, time steps further out in time. As noted in Section 3, the additional radiative forcing from the N_2O perturbation is implemented as the average across the model's time steps. It seems that PAGE does not average radiative forcing over the time step for CO_2, which causes the global damage potential for N_2O to decrease with the discount rate. It is not clear if this result would hold if the size of the time steps in the model were reduced.

A comparison across models further highlights the importance of CO_2 fertilization impacts on the global damage potential. CO_2 emissions, and the resulting increase in atmospheric concentration, have the potential to increase yields in the agriculture and forestry sector. This characteristic is not shared by other GHG emissions. Accordingly, the FUND model, which explicitly captures this effect, exerts downward pressure on the SC-CO_2 that is not present for the SC-CH_4 and SC-N_2O, allowing for the possibility of substantially higher global damage potential estimates. The results based on the FUND model presented in this article exhibit this effect; however, the CO_2 fertilization effect is not explicitly modelled in DICE and PAGE and therefore they are found to produce lower estimates of the global damage potential. For example, using the 3% discount rate, the global damage potential for CH_4 as estimated by FUND ranges between 58 and 88 depending on the scenario, whereas it ranges from 19 to 28 for DICE and PAGE. As the DICE and PAGE models only consider two natural system impacts, temperature and sea level, if they do implicitly include potential CO_2 fertilization benefits, they are included by using the temperature anomaly as a proxy for the increasing atmospheric CO_2 concentration. Fertilization benefits would therefore be allowed to falsely accrue to perturbations of other GHG emissions besides CO_2. It is not clear the degree to which these models try to incorporate CO_2 fertilization effects and therefore the degree to which this issue is of concern.

Finally, the results in this article show that the 100-year GWP (25 for CH_4 and 298 for N_2O; Forster et al., 2007) probably provides an underestimate of the global damage potential of each gas, a finding consistent with previous studies by Marten and Newbold (2012) and Waldhoff et al. (2011). Unlike the GWP as calculated by the IPCC, the global damage potential will be dependent upon the year of the emissions perturbations, so the degree of underestimation varies by year. For CH_4, the global damage potential in Table 6 is 0–84% higher than the GWP in 2020, increasing to 24–108% in 2050. For N_2O, the global damage potential is 6–33% higher than the GWP in 2020, increasing to 13–39% in 2050. While inaccurate, using the GWP to convert emissions reductions into CO_2 equivalents that can be valued with the SC-CO_2 would probably provide a conservative estimate for the abatement benefits.

For the comparison above, the GWP estimates presented in the AR4 by the IPCC (Forster et al., 2007) were used to maintain consistency with the assumptions regarding the direct and indirect effect of CH_4 and N_2O concentrations within the modelling. The recent AR5 by the IPCC (Myhre et al., 2013) has increased the estimate of the indirect effects of CH_4, which gives a higher 100-year GWP for CH_4 of 28. A reduction in their estimate of the radiative efficacy of N_2O has decreased its 100-year GWP to 265. It is likely that updated modelling of the social cost estimates based on similar assumptions would maintain the finding that the GWP is an underestimate of the global damage potential.

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4.1. Comparison with previous estimates

For comparison, Table 7 presents the social cost estimates, when available, and the global damage potential estimates for CH_4 and N_2O from three recent studies in the literature whose features are more up to date and therefore more directly comparable with this study: Hope (2006a), Waldhoff et al. (2011), and Marten and Newbold (2012). A direct comparison to the longer list of studies presented in Table 1 is more difficult as they are based on models and socio-economic and emissions scenarios that were developed up to 20 years ago in a rapidly evolving field.

The social cost estimates presented in Table 5 are higher than the estimates in Hope (2006a) and Waldhoff et al. (2011) for CH_4, and in the range of Waldhoff et al. (2011) for N_2O. This result holds whether the comparison is made with the aggregate results in Table 5 or the disaggregated model-specific results. One reason for the significant difference in the SC-CH_4 estimates is that the earlier studies rely on older model versions (PAGE2002 and FUND3.5), neither of which include the indirect effects of CH_4 emissions on radiative forcing, but are included within this analysis. As noted in Section 3.3 the indirect effects of CH_4 are modelled as a 40% increase in its effective radiative forcing. The result of this change alone would likely be a greater than 40% increase in the SC-CH_4 due to the nonlinear damage functions. Furthermore, the assumptions regarding preference parameters in the main cases of Hope (2006a) and Waldhoff et al. (2011) lead to effective discount rates that are significantly higher than 3%. Other differences in input assumptions (e.g. equilibrium climate sensitivity, socio-economic emissions scenario) will also lead to differences, although these are likely to be of second-order importance given the relative similarity in the assumptions.

However, the results in Table 5 averaged across the combinations of the three models and five scenarios are relatively similar to those of Marten and Newbold (2012), which focused on a single scenario

TABLE 7 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Discount Rate	Emissions Year	Social cost (2007$/tonne X)[a]		Global damage potential (SC-X/SC-CO_2)	
			SC-CH_4	SC-N_2O	CH_4	N_2O
Hope (2006a)	Ramsey	2001	125	–	20	–
Waldhoff et al. (2011)[b]	Ramsey	2010–2019	265	7,616	26	738
			–	–	8–221	383–3,503
Marten and Newbold (2012)	2.5%	2020	1,500	26,000	23	403
		2050	3,500	50,000	32	444
	3%	2020	1,100	17,000	27	400
		2050	2,900	34,000	36	439
	5%	2020	550	4,900	42	380
		2050	1,500	12,000	53	415

[a]All values are discounted to the year of the emissions perturbation.
[b]The first row presents the base case and the second row presents the range found from sensitivity analysis (over socio-economic scenario, climate sensitivity, pure rate of time preference, climate sensitivity and CO_2 fertilization).

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and model. This result is in part based on the fact that both sets of results include the indirect effects of CH_4, use the same discount rates and equilibrium climate sensitivity distribution, and relatively similar scenarios. The estimates in this study are slightly higher for the SC-CH_4 and slightly lower for the SC-N_2O compared to Marten and Newbold (2012). Of particular interest is the specific comparison of this article's estimates based on DICE 2010 and the MiniCAM scenario to those of Marten and Newbold (2012) using the same scenario, discount rates, and equilibrium climate sensitivity but an the older 2007 version of the DICE model and a more complete climate sub-model. In this case, estimates for both the SC-CH_4 and SC-N_2O (presented in Appendix B) are notably lower. The myriad of differences between the model vintages and climate sub-models make it difficult to assess which differences are most important for explaining this relationship.

As previously noted, the global damage potential may provide a better value with which to compare across studies that estimate the social cost of non-CO_2 GHG emissions, as it helps to control for some of the underlying differences in assumptions across studies. For example, the global damage potential is far less sensitive to the discount rate used than the SC-X values themselves. However, the global damage potential does not address the lack of indirect CH_4 effects, as may be seen in the lower estimates of Hope (2006a) and Waldhoff et al. (2011). In these cases the exclusion of the 40% additional increase in radiative forcing from the indirect effects of the CH_4 perturbation explains the majority of the difference. In comparison to Marten and Newbold (2012), the results presented in Table 6 are relatively similar for CH_4 in both the aggregate and disaggregated results. For N_2O, similar results are found in the DICE estimates, but notable differences are found in how the aggregate results respond to the discount rate, due to the differences in this relationship between the models as noted above.

5. Concluding remarks

This article presents a simple and transparent approach to estimating the social cost of CH_4 (SC-CH_4) and N_2O (SC-N_2O) in a manner that is consistent with estimates of the social cost of CO_2 (SC-CO_2) already in use in benefit–cost analysis (BCA) for US Federal regulations. This approach is used to estimate the SC-CH_4 and SC-N_2O for the period 2010–2050. These directly modelled estimates are found to be larger than approximations of the social costs of these gases based on the application of common physical gas comparison metrics, such as global warming potentials (GWPs), to the SC-CO_2. This result generalizes the empirical findings of Marten and Newbold (2012) that using a GWP-based approximation approach will likely offer a conservative estimate of the social cost of non-CO_2 GHGs.

The social costs associated with emissions of non-CO_2 GHGs are substantial and should be included within the BCAs used to assess the overall welfare implications of policy alternatives. For example, by not including monetized values of the benefits from reducing CH_4 and N_2O emissions, the BCA for recent standards regulating the fuel efficiency and GHG emissions of light duty vehicles implicitly assigned them a value of zero (US EPA, 2010). However, the results of this article suggest that those reductions have benefits of US$85–493 million (2007$) for CH_4 and $1.5–12 million (2007$) for N_2O in the year 2020 alone. Failing to account for such impacts could limit the ability of the analysis to serve as a transparent and informative input into the decision-making process about the relative benefits and costs of regulatory alternatives. That said, by restricting the article to a derivation of social cost estimates consistent with the USG SC-CO_2 estimates, the myriad issues related to

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whether those estimates can themselves be improved are set aside.[6] Any limitations that apply to the USG SC-CO_2 estimates therefore also apply to the SC-CH_4 and SC-N_2O estimates derived here.

Supplemental data

Supplemental data for this article can be accessed 10.1080/14693062.2014.912981.

Notes

1. Examples include Minnesota's draft methodology for setting the value of a tariff to compensate solar panel owners for the surplus power they deliver to utilities (http://www.eenews.net/stories/1059992297, http://mn.gov/commerce/energy/images/DRAFT-MN-VOS-Methodology-111913.pdf), the Northwest Power and Conservation Council's symposium supporting the development of the 7th Power Plan (http://www.nwcouncil.org/energy/powerplan/7/symposiums/greenhouse/agenda), BCA of Canada's Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations (http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html), analysis of climate change projects at the Inter-American Development Bank (correspondence with Patrick Doyle, Senior Climate and Energy Officer, Structured and Corporate Finance Department), the International Monetary Fund's recent Energy Subsidy Reform report (http://www.imf.org/external/np/pp/eng/2013/012813.pdf), and Parry and Strand (2012).
2. An alternative approach for estimating the social cost of GHG emissions could be based on stated preference (SP) surveys designed to elicit respondents' maximum willingness-to-pay for various levels of GHG emission reductions (e.g. Longo, Markandya, & Petrucci, 2008; Soliño, 2010). This approach would not suffer from the difficulties associated with creating and parameterizing a numerical integrated assessment model. However, it would suffer from its own set of difficulties, including well-known general limitations that affect all SP studies including the potential for 'hypothetical bias' (e.g. Carson, 2012; Hausman, 2012; Kling, Phaneuf, & Zhao, 2012), plus difficulties that may be specific to this application stemming from the generally limited knowledge base regarding the potential climatic, biophysical, and especially economic impacts of GHG emissions on current and far future generations that most respondents will bring to the survey.
3. The fork of MAGICC version 5.3 included in Pacific Northwest National Laboratory's open source model GCAM version 2 (Calvin et al., 2009) is used without carbon cycle feedbacks and, unless otherwise specified, an equilibrium climate sensitivity of 3 8C. We note that sensitivity analysis found the general results of this side analysis to be robust to other values of the equilibrium climate sensitivity.
4. The EMF-22 scenario is extended past 2100 assuming that emissions stay constant at the 2100 level. This assumption is revisited later in this article.
5. The PAGE 2009 model restricts the user to representing the entire time horizon, in this case out to 2300, with only ten time steps. This leads to the unrealistic situation in a small number of simulations where the marginal unit of emissions can cause 'catastrophic' climate impacts to occur one period earlier, which could be 100 years earlier in some cases. We consider these occurrences to be a limitation of the model and drop them from the overall distribution of estimates. Appendix A contains further details about this issue.
6. In addition to the critiques previously cited, we point the interested reader to the work of Marten et al. (2013) and Oppenheimer (2013) for a review of literature that considers potential improvements in the assessment and valuation of climate change impacts.

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National Freedom of Information Officer
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1200 Pennsylvania Avenue, NW (2822T)
Washington, DC 20460

Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1) All records discussing, describing, referring to or interpreting the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*").

2) To the extent not provided in response to request #1, all records of information relied upon by the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*") in the development of the *2010 TSD on SCC* and the *2013 TSD on SCC*, including but not limited to:

   a) Any presentations, reports, studies, computer or other analytical models, and data (including modeling data) created by or on behalf of the *IWG on SCC*, or provided to or obtained by the *IWG on SCC*.

   b) Any records that discuss, describe, interpret or otherwise relate to the Integrated Assessment Models ("IAMs") referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to:

      i) any inputs and assumptions (including but not limited to assumptions on discounting, equilibrium climate sensitivity, and socioeconomic variables);

      ii) the results of any modeling runs or scenarios generated by the IAMs (in both paper copies and in original electronic form); and

      iii) the source codes for the DICE, PAGE and FUND models referred to in the *2010 TSD on SCC* or *2013 TSD on SCC* (in the original electronic form, such as native modeling formats).

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c) Any records that identify, discuss, interpret or relate to any uncertainties or error rates of the *2010 TSD on SCC* or the *2013 TSD on SCC* or any of the IAMs referenced in or relied upon by the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to any limitations in using the DICE, PAGE or FUND models to make predictions beyond the year 2100.

d) Any records that discuss, interpret or explain why the social cost of carbon estimated by the *2013 TSD on SCC* is approximately 60% higher than that estimated by the *2010 TSD on SCC*.

e) Any records that discuss, interpret, relate to, explain or make recommendations or decisions regarding global versus domestic measures of the social cost of carbon with respect to the work of the *IWG on SCC* and the *2010 TSD on SCC* or *2013 TSD on SCC*, including but not limited to the calculation or use of a domestic SCC for the United States.

3) Any records discussing, interpreting, transmitting or relating to any critiques, analyses or studies of the *2010 TSD on SCC* or *2013 TSD on SCC*, or any data, information or models relied on or referred to in the *2010 TSD on SCC* or *2013 TSD on SCC*, including but not limited to the work or statements of Robert Pindyck.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and all other types of records in the possession, control or custody of EPA or contractors working for EPA.

For all records responsive to these requests that are not produced based on an asserted exemption from disclosure, please prepare a privilege and/or exemption log describing, at a minimum: (i) the type of record withheld; (ii) the date(s) of the creation of the record; (iii) the subject of the record; (iv) the identity of the author and all recipients of the records; and (v) a detailed description of the basis upon which EPA is withholding the record (e.g., the claim of privilege, FOIA exemption, etc.). To the extent any responsive documents are withheld based upon a claim of privilege or other exemption from disclosure, please produce redacted copies of all non-privileged or non-exempt factual material contained within such documents.

As required by law, please provide the above records within twenty (20) business days of receipt of this FOIA Request. 5 U.S.C. § 552(a)(6)(A)(i). If it appears that it may not be possible to provide all of the records by the statutorily-mandated deadline, please provide the responsive records that are available as of the deadline (i.e., do not withhold responsive records past the

deadline while searching for additional records), and please contact me promptly regarding any scheduling issues.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $500, I ask that you contact me prior to proceeding.

Thank you for your prompt attention to this request. Please direct any inquiries, notices, or determinations to me at (713) 495-4508 or cbell@sidley.com.

Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009618 (2)

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Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1. All records identifying the dates and attendees of meetings, or dates of and participants in teleconferences or webinars involving, the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*"), or any committee, working group, sub-committee, task force or project group thereof.
2. Any government contracts used to hire anyone to assist in the preparation of the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*"), including but not limited to, any government contracts used to hire anyone to perform the Integrated Assessment Modeling referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*.
3. Any records that describe, identify, contain, interpret or provide the dates or substance of briefings of political appointees in the Executive Branch on the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to, PowerPoint presentations. In the response, please produce the requested briefing records in their native original electronic form (PowerPoint, Word, etc.).
4. All electronic mail, WebEx documents, Google Docs, text messages, instant messages, voice mails, facsimiles or any other records relating to the *2010 TSD on SCC* or *2013 TSD on SCC* that were sent to any person outside the *IWG on SCC*, including but not limited to documents sent to or received from: any of the authors of the publications listed in the References section of the *2010 TSD on SCC* or *2013 TSD on SCC*; any other academics; government contractors; consultants; Sierra Club, Natural Resources Defense Council or other

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nongovernmental groups; and any other third-party whatsoever that was not part of the *IWG on SCC*.

5. All records discussing, describing, interpreting or relating to the applicability of or compliance with the Information Quality Act (P.L. 106-554, Section 515, 144 Stat. 2763 (2001)), or any Information Quality Act Guidelines published by the Office of Management and Budget, with respect to the work of the *IWG on SCC* or development, publication, use or dissemination of the *2010 TSD on SCC* or the *2013 TSD on SCC*.

6. All records discussing, interpreting or relating to the applicability of the Administrative Procedure Act (5 U.S.C. § 500 et seq.) to the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to whether those documents should have been published for public review and comment.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and all other types of records in the possession, control or custody of EPA or contractors working for EPA.

For all records responsive to these requests that are not produced based on an asserted exemption from disclosure, please prepare a privilege and/or exemption log describing, at a minimum: (i) the type of record withheld; (ii) the date(s) of the creation of the record; (iii) the subject of the record; (iv) the identity of the author and all recipients of the records; and (v) a detailed description of the basis upon which EPA is withholding the record (e.g., the claim of privilege, FOIA exemption, etc.). To the extent any responsive documents are withheld based upon a claim of privilege or other exemption from disclosure, please produce redacted copies of all non-privileged or non-exempt factual material contained within such documents.

As required by law, please provide the above records within twenty (20) business days of receipt of this FOIA Request. 5 U.S.C. § 552(a)(6)(A)(i). If it appears that it may not be possible to provide all of the records by the statutorily-mandated deadline, please provide the responsive records that are available as of the deadline (i.e., do not withhold responsive records past the deadline while searching for additional records), and please contact me promptly regarding any scheduling issues.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $500, I ask that you contact me prior to proceeding.

SIDLEY AUSTIN LLP
SIDLEY

Thank you for your prompt attention to this request. Please direct any inquiries, notices, or determinations to me at (713) 495-4508 or cbell@sidley.com.

Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009517

(5)

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August 23, 2013

National Freedom of Information Officer
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, NW (2822T)
Washington, DC 20460

Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1. All records discussing, describing, referring or providing direction to, communicating to or about, or interpreting the formation, organization, structure, authority, activities, meetings, recommendations or decisions of the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*").
2. All records describing or discussing any past, on-going (as of the date of this submission) or planned work of the *IWG on SCC*.
3. All records describing, discussing or interpreting how the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*") have been or are to be used by Federal agencies, including but not limited to the use of these documents in the development and promulgation of regulations and in making policy decisions.
4. All records discussing or interpreting how the *2010 TSD on SCC* or the *2013 TSD on SCC* have been used or relied on, or are planned to be used, by EPA in any regulation proposed or promulgated by EPA, or in any policy decisions made by or guidance documents created by EPA.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and

Sidley Austin (TX) LLP is a Delaware limited liability partnership doing business as Sidley Austin LLP and practicing in affiliation with other Sidley Austin partnerships.

EPA TRACKING NUMBER EPA-HQ-2013-005473

Pursuant to the Freedom of Information Act ("FOIA") 5 U.S.C. § 552, and the implementing regulations of the U.S. Environmental Protection Agency ("EPA"), 40 C.F.R. Part 2, I am requesting a copy of the following EPA records:

1. All petitions for rulemaking of any kind submitted to the EPA Administrator related to any statute or regulation under which the EPA Administrator has the authority to promulgate regulations from January 1, 2013, to the present. These include, but are not limited to, petitions under the Clean Air Act, the Clean Water Act, the Resource Conservation and Recovery Act, the Comprehensive Environmental Response, Compensation, and Liability Act, the Toxic Substances Control Act, and the Federal Insecticide, Fungicide, and Rodenticide Act.

2. All notices of intent to sue EPA or its Administrator, dated from January 1, 2013, to the present, under any of the statutes listed above or under the Administrative Procedure Act for:

a. Failure to timely act on any petition for rulemaking;

b. Failure to meet any statutory, regulatory, or other deadline; or

c. Failure to meet any nondiscretionary obligation..

This request is only seeking for the specific items referred to above, all of which would have been submitted to EPA by third parties. Therefore, this request does not seek any records that are exempt from disclosure.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $250, I ask that you contact me prior to proceeding.

Please direct any inquiries, notices, or determinations to me at (202) 736-8281. Thank you for your anticipated assistance.

Description Available to the Public : Yes

Has Request Been Modified? ☐

Attached Supporting Files

No supporting files have been added.

BEFORE THE ENVIRONMENTAL PROTECTION AGENCY

PETITION FOR RULEMAKING PURSUANT TO SECTION 21 OF THE TOXIC SUBSTANCES CONTROL ACT, 15 U.S.C. § 2620, CONCERNING THE REGULATION OF CARBON DIOXIDE

Credit: NOAA

CENTER FOR BIOLOGICAL DIVERSITY

DONN J. VIVIANI, PhD

PETITIONERS

June 30, 2015

NOTICE OF PETITION

Gina McCarthy
Administrator
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, N.W.
Washington, D.C. 20460
Email: McCarthy.Gina@cpa.gov

PETITIONERS

Center for Biological Diversity
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4907 Yorktown Blvd
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The Center for Biological Diversity ("Center") is a non-profit, public interest environmental organization dedicated to the protection of native species and their habitats through science, policy and environmental law. The Center has over 800,000 members and online activists throughout the United States and around the world. The Center's Oceans Program and its supporters are specifically concerned with the conservation of marine species, the preservation of ocean ecosystems and the effective implementation of U.S. environmental laws, including the Toxic Substances Control Act. The Center submits this petition on its own behalf and on behalf of its members and staff with an interest in protecting the marine environment.

Donn J. Viviani, PhD, is a retired U.S. Environmental Protection Agency scientist. He was the Director of the Climate Policy Assessment Division in the Office of Policy, Economics and Innovation. He also served as Chairman of the Great Lakes Water Board's Toxic Substances Committee and as a member of the Science Coordinating Committee for the International Joint Commission for the Great Lakes. Dr. Viviani enjoys the ocean and submits this petition, in part, so his grandchildren will be able to enjoy it as well. Dr. Viviani also submits a supplement to the petition, under his signature only, and respectively requests that it be considered.

ACTION REQUESTED

Pursuant to section 21 of the Toxic Substances Control Act ("TSCA" or the "Act"), 15 U.S.C. § 2620, and section 553(e) of the Administrative Procedure Act ("APA"), 5 U.S.C. § 553(e), the Center for Biological Diversity and Donn J. Viviani (collectively, "Petitioners") hereby petition the Administrator of the U.S. Environmental Protection Agency ("EPA") to promulgate regulations protecting public health and the environment from the serious harms associated with anthropogenic emissions of carbon dioxide, including ocean acidification. Specifically, Petitioners request that EPA adopt a rule under section 6 of the Act, 15 U.S.C. § 2605, requiring manufacturers and processors to mitigate these emissions.

This petition sets in motion a specific process, placing definite response requirements on EPA. Specifically, TSCA stipulates that the agency "*shall* either grant or deny the petition" within 90 days following its receipt, "promptly commenc[ing] an appropriate [rulemaking]

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proceeding" if such action is warranted. 15 U.S.C. § 2620(b)(3) (emphasis added). Conversely, should EPA deny this petition, the agency must publish the reasons for denial in the Federal Register. 15 U.S.C. § 2620(b)(3); *see also* 5 U.S.C. § 555(e) ("Prompt notice shall be given of the denial in whole or in part of a written application, petition, or other request of an interested person made in connection with any agency proceeding."). Pursuant to 15 U.S.C. § 2620(b)(4), petitioners may file suit in federal district court to challenge an adverse or untimely determination. *See also* 5 U.S.C. §§ 702, 706.

As described in this petition, anthropogenic emissions of carbon dioxide satisfy the standard for regulation set forth at 15 U.S.C. § 2605. For example, EPA has acknowledged that these emissions have the potential to alter ocean chemistry, thus imperiling important marine ecosystems and presenting an unreasonable risk of injury to the environment. Accordingly, the agency must promptly commence the proposed rulemaking to reduce and mitigate these harms. In the event that EPA concludes that there are insufficient data and experience upon which to determine or predict the effects of carbon dioxide emissions, we alternatively request that the agency adopt a rule under section 4 of the Act, 15 U.S.C. § 2603, requiring manufacturers and processors responsible for the generation of carbon dioxide to undertake testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Dated this 30th day of June 2015.

/s/ Miyoko Sakashita
Miyoko Sakashita, Oceans Director
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INTRODUCTION

Ocean acidification — caused by carbon dioxide ("CO_2") emissions — is a severe threat to the marine environment and the health of people who depend on oceans and coasts. Because of the unreasonable risk that CO_2 poses to the environment and human health, this petition seeks rulemaking under the Toxic Substances Control Act ("TSCA") to regulate CO_2 from cradle to grave.

About 28% of CO_2 emissions from power generation, cement production, industry, and other sources are absorbed by the ocean. These CO_2 emissions cause seawater to become more acidic and corrosive to sea life. Anthropogenic CO_2 emissions have increased the acidity of the oceans on average by 30%, and by the end of the century scientists predict that the oceans will become 150-170% more acidic.

While the most dangerous consequences of CO_2 on our oceans are still to come, harmful impacts on the environment are already well-documented.

- Billions of oyster larvae have perished in the Pacific Northwest due to ocean acidification;
- 53% of pteropods, plankton that form the base of the marine food web, along the West Coast have severely dissolved shells because of the corrosive nearshore conditions; and
- Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%.

These are just some of the harmful environmental impacts of ocean acidification caused by CO_2 emissions. Anthropogenic CO_2 emissions are contributing to increasingly corrosive conditions for marine animals, and will continue to grow more severe absent actions to promptly reduce CO_2 pollution in the atmosphere.

TSCA was enacted in part to address the threat of ozone depletion caused by chlorofuorocarbon (CFC) emissions. And here again TSCA regulation is needed where airborne emissions are causing damage to our environment — this time threatening ocean ecosystems, fish and shellfish industries, and communities that depend on oceans and coral reefs.

Petitioners specifically request that EPA take the following actions:

1. **Make a determination under TSCA § 6 that CO_2 presents an unreasonable risk of injury to health or the environment; and**
2. **Initiate rulemaking to control CO_2; or**
3. **If EPA finds data inadequate to make a §6 determination then EPA must initiate rulemaking for testing under TSCA § 4.**

This petition presents scientific evidence that establishes that CO_2 presents an unreasonable risk of injury to the environment, and therefore EPA must take action under TSCA section 6.

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I. The Toxic Substances Control Act

Congress enacted TSCA, 15 U.S.C. §§ 2601 *et seq.*, "to assure that … innovation and commerce in … chemical substances and mixtures do not present an unreasonable risk of injury to health or the environment."[1] Accordingly, lawmakers required those responsible for the manufacture and processing of these compounds to develop "adequate data" describing their effects, and authorized EPA to devise and implement reasonable controls to prevent the risk of injury to health or the environment.[2]

Section 6 of TSCA mandates that EPA "shall" regulate a chemical substance for which

> there is a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance or mixture, or that any combination of such activities, presents or will present an unreasonable risk of injury to health or the environment.[3]

Permissible regulations include requirements prohibiting or "limiting the amount of such substance … which may be manufactured, processed, or distributed in commerce."[4] EPA can also require processors "to give public notice of such risk [of injury], and . . . to replace or repurchase such substance . . . to adequately protect health or the environment."[5] In assessing risk, EPA must consider:

> (A) the effects of such substance or mixture on health and the magnitude of the exposure of human beings to such substance or mixture,
> (B) the effects of such substance or mixture on the environment and the magnitude of the exposure of the environment to such substance or mixture,
> (C) the benefits of such substance or mixture for various uses and the availability of substitutes for such uses, and
> (D) the reasonably ascertainable economic consequences of the rule, after consideration of the effect on the national economy, small business, technological innovation, the environment, and public health.[6]

Thus, if there is a reasonable basis to conclude that a proposed rule is necessary to protect the environment, then EPA must grant a petition for rulemaking and initiate rulemaking procedures. Factual certainty is not required; instead, the agency may "base its action on scientific theories, consideration of projections from available data, modeling using reasonable assumptions, and extrapolations from limited data."[7] Even if EPA determines that another federal law "could

---

[1] 15 U.S.C. § 2601(b)(3) (2012). Within the meaning of TSCA, the term "chemical substance" includes "any organic or inorganic substance of a particular molecular identity." *Id.* § 2602(2).
[2] *Id.* § 2601(b)(1) & (2).
[3] *Id.* § 2605(a) (emphasis added).
[4] *Id.* § 2605(a)(1)(B).
[5] *Id.* § 2605(b)(2)(B).
[6] *Id.* § 2605(c)(1). E.
[7] Lead Fishing Sinkers; Response to Citizens' Petition and Proposed Ban, 59 Fed. Reg. 11,122, 11,138 (Mar. 9, 1994) (*citing* H.R. Rep. No. 1341, 9th Cong., 2d Sess. 32 (1976)).

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[sufficiently] eliminate[] or reduce[]" the risk associated with a particular chemical substance, the agency may elect to regulate the substance under TSCA, provided that a "comparison of the estimated costs" and "relative efficiency" reveals that such action promotes the public interest.[8]

In the event that EPA lacks adequate data and experience upon which to determine the health and environmental risks associated with a particular chemical substance, the agency "*shall* by rule require that testing be conducted on such substance."[9] Specifically, Section 4 of the Act authorizes EPA to compel manufacturers and processors to evaluate the safety of substances that "may present an unreasonable risk of injury to health or the environment" or that "[are] or will be produced in substantial quantities" and, thus, "may reasonably be anticipated to enter the environment in substantial quantities" or result in "significant or substantial human exposure."[10] TSCA provides for testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Over forty years ago, the Council on Environmental Quality warned of the "high priority need" for a new legal authority capable of ensuring the safe use of toxic chemicals.[11] Despite TSCA's powerful potential, however, EPA has accomplished very little under the Act. This petition presents substantial scientific evidence demonstrating that anthropogenic emissions of CO_2 pose an unreasonable risk to human and environmental health. Indeed, studies show that significant and potentially irreversible harm has already occurred. As the Council recognized decades ago, "[w]e should no longer be limited to repairing [this] damage after it has been done; nor should we continue to allow the entire population or the entire environment to be used as a laboratory." Instead, EPA must take prompt action to reduce and mitigate the anthropogenic production of CO_2.

II. EPA Must Issue a Rule to Regulate or Require Tests for CO_2 Causing Ocean Acidification

CO_2 presents an unreasonable risk of injury to the environment because its exposure to the ocean changes seawater chemistry with harmful impacts on marine life and ecosystems. Substantial evidence supports this conclusion and is discussed in this petition. Accordingly, this petition seeks a rulemaking to regulate CO_2 under TSCA.

This petition requires EPA to make a determination under TSCA section 6 if the injury to the environment and health from CO_2 is unreasonable. Alternately, if the Agency demonstrates that the existing science is insufficient to make a determination under TSCA section 6, EPA must initiate test rules under TSCA section 4 to develop the missing information needed to determine if the TSCA section 6 trigger is met and how best to mitigate the harm.

A. TSCA Authorizes EPA to Act on CO_2

To enable the achievement of TSCA's ambitious objectives, Congress broadly defined EPA's jurisdiction under the Act. As described above, TSCA explicitly directs EPA to initiate

[8] *Id.*
[9] *Id.* § 2603 (emphasis added).
[10] *Id.*
[11] Council on Envtl. Quality, Toxic Substances at v (April 1971).

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rulemaking upon finding that "the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance" threatens public health or the environment.[12] TSCA then authorizes the regulation of "chemical substances" that are "in commerce," a test met by CO_2. Indeed, CO_2 is already on the TSCA inventory as a "chemical in commerce."[13] CO_2 necessarily qualifies as a "chemical substance," a category that includes "any organic or inorganic substance of a particular molecular identity."[14] Moreover, the anthropogenic emissions at issue are in commerce; federal courts have previously concluded that air emissions[15] and "incidental byproducts of industrial chemical processes" are within the scope of EPA's authority under the Act.[16] Existing scientific evidence demonstrates that the anthropogenic production of CO_2 has already damaged marine ecosystems and endangered vulnerable portions of the human population. For the reasons described below, EPA must promptly reduce and mitigate these harms.

1. CO_2 Is a Chemical Substance

First, carbon dioxide is a "chemical substance" falling within the scope of the Act. The Act defines "chemical substance" as "any organic or inorganic substance of a particular molecular identity, including any combination of such substances occurring in whole or in part as a result of a chemical reaction or occurring in nature and (ii) any element or uncombined radical."[17]. CO_2 meets this definition. CO_2 is a chemical substance that occurs both in nature and as a result of a chemical reaction. It consists of a carbon atom bonded to two oxygen atoms:

$$O=C=O$$

It is identified by molecular formula CO_2 and by CAS number 124-38-9.

2. CO_2 Is in Commerce

Second, CO_2 is in commerce, and it is already on the TSCA inventory (CAS 124-38-9) with "chemical in commerce" as the stated reason for regulation.[18] Under TSCA's statutory text, "commerce" is defined as "trade, traffic, transportation, or other commerce . . . between a place in a State and any place outside of such state, or . . . which affects trade, traffic, transportation, or commerce."[19] CO_2 is primarily produced as a byproduct from the combustion of fossil fuels; according to the EPA, CO_2 emissions account for 77% of greenhouse gas emissions worldwide.[20]

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[12] *Id.* §§ 2605(a), 2603(a)(1)(A)(i), 2506(a). Although TSCA does not define "disposal," other federal environmental laws explain that this term encompasses "the discharge, deposit, injection, dumping, spilling, leaking, or placing of any solid waste or hazardous waste into or on any land or water so that such solid waste or hazardous waste or any constituent thereof may enter the environment or be emitted into the air or discharged into any waters, including ground waters." 42 U.S.C. §§ 6903(3), 9601(29).
[13] EPA, Substance Registry at http://1.usa.gov/1IBS1w6 (last accessed June 28, 2015).
[14] 15 U.S.C. § 2602(2). This definition excludes specific compounds already subject to federal control, such as pesticides, tobacco products, nuclear materials and food, drugs and cosmetics. *Id.* § 2602(2)(B).
[15] *Citizens for a Better Env't v. Thomas*, 704 F. Supp. 149, 152 (E.D. Ill. 1989).
[16] *Envtl. Def. Fund v. Envtl. Prot. Agency*, 636 F.2d 1267, 1271 (D.C. Cir. 1980).
[17] 15 U.S.C. § 2602(2)(A).
[18] EPA, Substance Registry at http://1.usa.gov/1IBS1w6.
[19] 15 U.S.C. § 2602(3).
[20] EPA, Global Greenhouse Gas Emissions Data, http://www.epa.gov/climatechange/ghgemissions/global.html (last updated June 21, 2013; last accessed June 28, 2015).

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The most voluminous sources of greenhouse gas emissions are energy suppliers,[21] industry,[22] land use and forestry,[23] agriculture,[24] transportation,[25] commercial and residential buildings,[26] and waste and wastewater.[27] All of these emitters produce CO_2 as a byproduct of their ordinary processes.

TSCA's statutory and regulatory text support the proposition that CO_2 emitted as a byproduct of industrial processes can be regulated under TSCA because CO_2 in this context is manufactured, meaning "produce[d] . . . with the purpose of obtaining an immediate or eventual commercial advantage."[28] All of the industries listed above which emit CO_2 are performed to obtain an immediate or eventual commercial advantage, as all of these industries are commercial and part of a competitive market. Therefore, incidental production of CO_2 is manufactured or produced "for a commercial purpose," and is found "in commerce" pursuant to TSCA regulations.

Accordingly, CO_2 emissions fit the regulatory definition of a chemical substance produced for a commercial purpose. This is bolstered by the broad definition of "commerce" in the TSCA statute; at the very least, CO_2 emissions "affect" trade, traffic, transportation, and commerce.

TSCA's purpose and regulatory text support the regulation of chemical substances that are an incidental byproduct, and indeed EPA has regulated chemical byproducts under TSCA before. For example, PCBs are regulated under TSCA even when they are only incidentally produced as a byproduct of industrial processes.[29] EPA regulates PCB "byproducts" for which there are no separate commercial intents, and TSCA regulates inadvertently vented PCB emissions.[30] Moreover, EPA's authority under TSCA broadly defines what it regulates under "disposal" of PCBs to include intentional and accidental disposal.[31] EPA has also previously prohibited wastes from chemical manufacturing under TSCA.[32]

---

[21] Which emit greenhouse gases through "[t]he burning of coal, natural gas, and oil for electricity and heat." *Id.*

[22] Which emit greenhouse gases through "fossil fuels burned on-site at facilities for energy" and "chemical, metallurgical, and mineral transformation processes not associated with energy consumption." *Id.*

[23] Which emit "carbon dioxide . . . from deforestation, land clearing for agriculture, and fires or decay of peat soils." *Id.*

[24] "Greenhouse emissions from agriculture mostly come from the management of agricultural soils, livestock, rice production, and biomass burning." *Id.*

[25] Which emit greenhouse gases through "fossil fuels burned for road, rail, air, and marine transportation." *Id.*

[26] Which emit greenhouse gases from "on-site energy generation and burning fuels or heat in buildings or cooking in homes." *Id.*

[27] Which emit carbon dioxide through the "incineration of some waste products that were made with fossil fuels, such as plastics and synthetic textiles." *Id.*

[28] 40 C.F.R. § 710.3; 40 C.F.R. § 704.3 ("Manufacture for commercial purposes also applies to substances that are produced coincidentally during the manufacture, processing, use, or disposal of another substance or mixture, including both byproducts that are separated from that other substance or mixture and impurities that remain in that substance or mixture. Such byproducts and impurities may, or may not, in themselves have commercial value. They are nonetheless produced for the purpose of obtaining a commercial advantage since they are part of the manufacture of a chemical product for a commercial purpose.").

[29] 44 Fed. Reg. 31525 (May 31, 1979); 40 C.F.R. § 761.

[30] *See, e.g.,* 40 C.F.R. Part 761.

[31] 40 C.F.R. § 761.3.

[32] 45 Fed. Reg. 592 (March 11, 1980);40 C.F.R. § 775 (1980) (prohibiting disposal of 2,3,7,8-tetracholorodibenzo-p-dioxin (TCDD) a manufacturing waste).

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Further, CO_2 emissions are in commerce as they are traded, bought, and sold as carbon offsets. CO_2 is also produced for commerical purposes including for uses in fertilizer, beverage carbonation, dry ice, refrigeration, pressurization, fire extinguishment, and packaging.

B. EPA Should Initiate Rulemaking to Control CO_2 under TSCA

Petitioners request that EPA make finding that CO_2 presents or will present an unreasonable risk of injury to the environment or health. TSCA requires that EPA "shall" initiate rulemaking upon finding "a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use or disposal of a chemical substance of mixture … presents or will present an unreasonable risk of injury to health or the environment."[33]

The information and supporting documents provided in this petition indicate that CO_2 is already causing injury to the environment due to ocean acidification. The scientific evidence further supports that the injury to the environment and health will grow more severe as CO_2 pollution continues. EPA cannot deny that CO_2 is harming the environment. Indeed, EPA acknowledges that ocean acidification poses risk:

> Ocean acidification, like Climate change is primarily caused by increasing carbon dioxide (CO_2) concentrations in the atmosphere. As a result of absorbing large quantities of human made CO_2 emissions the ocean chemistry is changing, which is likely to negatively affect important marine ecosystems and species including coral reefs, shellfish, and fisheries.

(Environmental Protection Agency 2010).

EPA must find that such injury is an unreasonable risk.[34] While Congress did not define the phrase "unreasonable risk," EPA has interpreted relevant legislative history to require that the agency:

> balance the benefits derived from risk reduction against the social and economic costs incurred, taking into account such factors as the extent and magnitude of risk posed; the societal consequences of removing or restricting use of products; availability and potential hazards of substitutes; and impacts on industry, employment, and international trade.[35]

No specific factual determination is necessary to establish "unreasonable risk." For example, even under the stricter standard of 15 U.S.C. § 2606, EPA need not present evidence of actual injury before obtaining emergency injunctive relief to control "immanently hazardous chemical substance[s] or mixture[s]."[36] For the reasons discussed below, application of the agency's balancing test supports the additional regulation of CO_2.

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[33] 15 U.S.C. § 2605(a).
[34] *Id.*
[35] EPA, Guidance for Petitioning the Environmental Protection Agency Under Section 21 of the Toxic Substances Control Act, 50 Fed. Reg. 46,825 (Nov. 13, 1985).
[36] *See* H.R. Conf. Rep. No. 94-1679 78 (1976).

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According to scientific experts: "Reducing CO_2 emissions is the only way to minimise [sic] long-term, large-scale risks" (IBGP et al. 2013).

1. CO_2 Pollution Presents an Unreasonable Risk of Injury to the Environment

There is clear consensus among leading national and international scientific bodies that anthropogenic CO_2 causes changes in ocean chemistry that harm the marine environment. The Intergovernmental Panel on Climate Change ("IPCC") determined that human sources of CO_2 have caused a significant decline in surface ocean pH (Rhein et al. 2013), and over 90 national academies of sciences, including the United States', have signed a statement that ocean acidification will "cause grave harm to important marine ecosystems as CO_2 concentrations reach 450 ppm and above" (Interacademy Panel 2009). The Interacademy Panel concluded that CO_2 has increased ocean acidity with "potentially profound consequences for marine plants and animals" including severe threats to coral reefs, polar ecosystems, and a likely reduction in marine food supplies (*Id.*). The National Research Council also acknowledges that "existing data support a growing consensus in the research community that most documented responses to acidification reflect impairment of physiological capacity or performance" for marine life with likely substantial socioeconomic impacts (National Research Council 2013). The U.S. National Climate Assessment concluded that ocean acidification will alter marine ecosystems in dramatic ways including threatening coral reef habitats and causing reduced growth and survival of shellfish in all regions (Doney et al. 2014).

EPA acknowledges that "ocean acidification presents a suite of environmental changes that would likely negatively affect ocean ecosystems, fisheries, and other marine resources." 75 Fed. Reg. 13538 (Mar. 22, 2010). EPA previously concluded that greenhouse gases, including CO_2, endanger public health and the environment in part because of ocean acidification.[37]

There is no doubt that CO_2 pollution is changing ocean chemistry and harming the marine environment. Unabated, there will be severe and detrimental impacts on marine ecosystems, the economy, and public health. Accordingly, EPA must find that CO_2 poses an unreasonable risk to the environment and health.

a. CO_2 Causes Irreversible Ocean Acidification

Ocean acidification is a major threat to the marine environment. The oceans have absorbed CO_2 emitted into the atmosphere from power plants, manufacturing, cement production, and land use changes. Between 1750 and 2011, human activities have released 375 gigatons of carbon into the atmosphere, and approximately half of that has been absorbed by the oceans (Rhein et al. 2013). Each day about 22 million metric tons of CO_2 is taken up by the oceans (Feely et al. 2008). This uptake of CO_2 is changing ocean chemistry, causing the oceans to become more acidic. Since the industrial revolution surface ocean pH has declined by 0.11 units on average, corresponding with

[37] EPA, Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act 80 (Dec. 7, 2009).

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a 30% increase in acidity (Orr et al. 2005; Caldeira & Wickett 2005).[38] If emissions continue unabated, ocean acidity will increase up to 170% by the end of the century (IBGP et al. 2013).

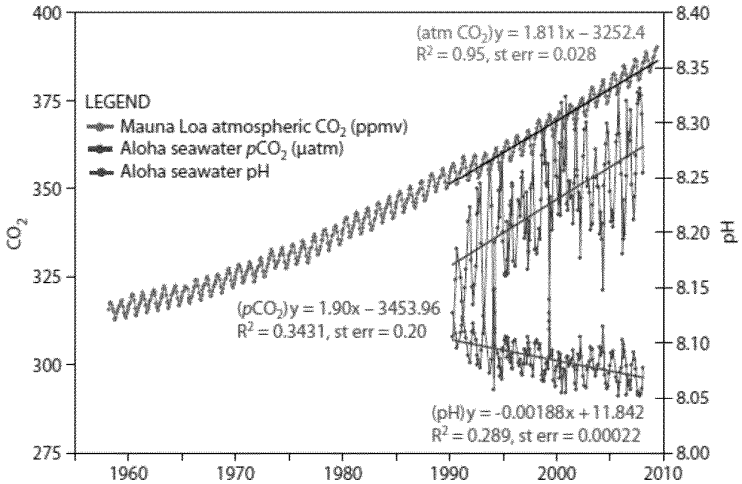

Figure 1. Time series of atmospheric CO 2 at Mauna Loa (ppmv) and surface ocean pH and pCO2 (µatm) at Ocean Station Aloha in the subtropical North Pacific Ocean (see inset map). Note that the increase in oceanic CO 2 over the period of observations is consistent with the atmospheric increase within the statistical limits of the measurements. (Feely et al. 2009).

Anthropogenic ocean acidification exceeds the trend in natural variability significantly, up to 30 times in some regions (Friedrich et al. 2012). The rate of change in ocean acidity is unprecedented in the past 300 million years, a period that includes four mass extinctions (Honisch et al. 2012; Zeebe 2012). The seawater chemistry change is an order of magnitude faster than what occurred 55 million years ago during Paleocene-Eocene Thermal Maximum, which is considered to be the closest analogue to the present, and during that period 96% of marine species went extinct (*Id.*). The current changes in seawater chemistry are irreversible on human timescales (Royal Society 2005).

CO_2's impact on ocean chemistry is fundamentally altering the marine environment with negative impacts on marine species, habitats and ecosystems.

i. What Is Ocean Acidification

When the ocean absorbs CO_2 from the atmosphere it changes ocean chemistry. CO_2 that is absorbed by seawater reacts to form carbonic acid, which dissociates to form bicarbonate and releases hydrogen ions. This reaction reduces the amount of carbonate ions and decreases pH. The oceans store a significant amount of the CO_2 pollution from human activities (Royal Society 2005). While this has provided society with an important service of buffering against climate change impacts, it comes at a cost to the marine environment.

[38] Because the pH scale is logarithmic a small decrease is a significant change in acidity; for example, a decrease of 0.1 pH is an approximate 30 percent increase in acidity.

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Globally, surface water pH has declined 0.11 units on average between 1750 and 1994 (Sabine et al. 2004). Long-term monitoring has documented the impact of increasing atmospheric CO_2 on declining seawater pH in the Pacific and Atlantic Oceans (*see* Figure 2). Results from time-series stations in the North Atlantic and North Pacific show a decrease of about 0.002 pH per year (Rhein et al. 2013).

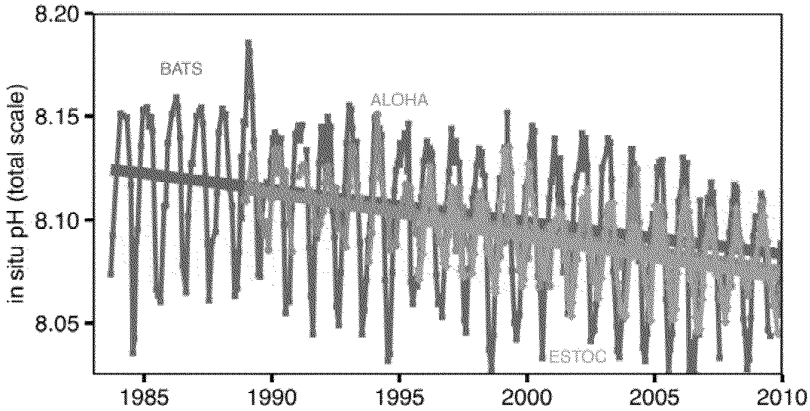

Figure 2. Long-term trends of surface seawater pH at three subtropical ocean time series in the North Atlantic and North Pacific Oceans, including (a) Bermuda Atlantic Time-series Study (BATS, 31°40'N, 64°10'W; green) and Hydrostation S (32°10', 64°30'W) from 1983 to present (updated from Bates, 2007); (b) Hawaii Ocean Time-series (HOT) at Station ALOHA (A Long-term Oligotrophic Habitat Assessment; 22°45'N, 158°00'W; orange) from 1988 to present (updated from Dore et al., 2009) and (c) European Station for Time series in the Ocean (ESTOC, 29°10'N, 15°30'W; blue) from 1994 to present (updated from González-Dávila et al., 2010). Atmospheric pCO2 (black) from the Mauna Loa Observatory Hawaii is shown in the top panel. Lines show linear fits to the data, whereas Table 3.2 give results for harmonic fits to the data (updated from Orr, 2011).(Rhein et al. 2013)

Ocean acidification not only makes the oceans more acidic, but it also reduces the amount of carbonate ions available for animals to build the shells and skeletons they need to survive. Carbonate is an important constituent of seawater because many organisms form their shells and skeletons by complexing calcium and carbonate. Waters that are supersaturated with aragonite are generally good for shell-building, while undersaturated waters (<1.0 Ω_{ar}) are corrosive to some marine animals. Corals require supersaturated waters above 3.3 Ω_{ar} (Meissner et al. 2012). Globally, there has been a decrease of about -0.4 Ω_{ar} (Gruber et al. 2012). The aragonite saturation state has declined 16% since the Industrial Revolution due, in large part, to anthropogenic CO_2 (Feely et al. 2012a; Ishii et al. 2011). Modeling of the oceans' aragonite saturation predicts that by the end of the century up to 75% of ocean volume could be undersaturated with respect to aragonite (Joos et al. 2011).

ii. Observed and Predicted Acidification

CO_2 has already had measurable impacts on seawater chemistry. Some regions, such as those with upwelling systems or high latitudes, are especially vulnerable to ocean acidification.

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1. Pacific Coast

The West Coast is already experiencing adverse impacts of ocean acidification. As early as 2008, a survey off the coasts of Washington, Oregon, and California revealed that this region is already experiencing corrosive waters not expected until mid-century (See figure 3) (Feely 2008). Researchers found seawater undersaturated with respect to aragonite upwelling onto large portions of the continental shelf, reaching shallow depths of 40 to 120 meters (*Id.*). According to the study, the waters were last at the surface approximately 50 years ago when atmospheric CO_2 concentrations were much lower (Feely et al. 2008). Feely et al. report that in the Pacific Ocean there has been a decrease of the saturation state of surface seawater with respect to aragonite and calcite as well as an upward shoaling of the saturation horizon by about 1-2 meters per year on average, due in large part to anthropogenic CO_2 (R. A. Feely, Sabine, et al. 2012). As a result, marine organisms in surface waters, in the water column, and on the sea floor along the West Coast of the United States are already being exposed to corrosive water during the upwelling season.

Modeling of the California Current System demonstrates that the area is rapidly approaching year-round undersaturation with respect to aragonite and it is departing significantly from natural variability (Hauri et al. 2013). Time series monitoring shows that the aragonite saturation state along the California coast is much lower than would be expected in the North Pacific (Harris, DeGrandpre et al. 2013). Surface Ω_{ar} values ranged between 0.66 and 3.9 compared to an estimated pre-industrial range of 1.0 to 4.7. While some areas, like Puget Sound, already exhibit undersaturated conditions every year (Feely, Klinger, et al. 2012; Reum et al. 2014), scientists predict that most shallow shelf areas along the West Coast will become undersaturated with respect to aragonite within the next 20-30 years (Capone & Hutchins 2013; Gruber et al. 2012).

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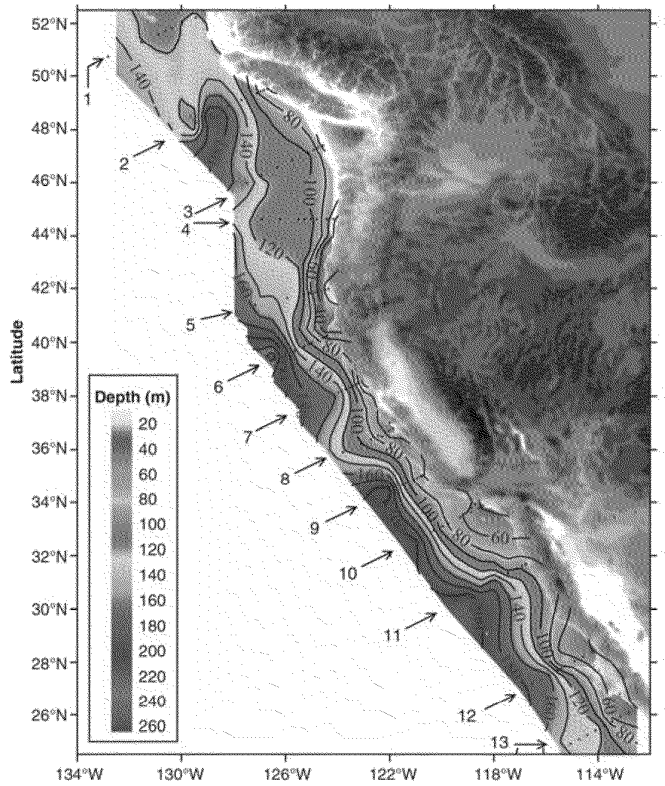

Figure 3. Distribution of the depths of the undersaturated water (aragonite saturation < 1.0; pH < 7.75) on the continental shelf of western North America from Queen Charlotte Sound, Canada, to San Gregorio Baja California Sur,Mexico. On transect line 5, the corrosive water reaches all the way to the surface in the inshore waters near the coast. The black dots represent station locations (Feely et al. 2008).

2. *Alaskan Waters*

High latitude waters are the "bellwether" of ocean acidification because these will be the first ocean regions to become persistently undersaturated with respect to aragonite as a result of greenhouse gas pollution (Fabry et al. 2009; Steinacher et al. 2009). High-latitude waters have naturally lower carbonate ion concentrations and saturation states due to a combination of cold temperatures which increase the solubility of CO_2 and ocean mixing patterns (Fabry et al. 2009; Mathis et al. 2011a). As early as 2016, 10% of Arctic surface waters are expected to be undersaturated with respect to aragonite for at least one month per year (Steinacher et al. 2009).

Recent observations of calcium carbonate saturation states in the North Pacific and Bering Sea have found that full water column undersaturation of calcium carbonate due to ocean acidification is already prevalent. Mathis et al. (2011a) reported that extensive areas of bottom waters over the Bering Sea shelf are becoming undersaturated with respect to aragonite for at least several months (July to September), and some areas of bottom water were already observed to be undersaturated with respect to calcite (Fabry et al. 2009, Mathis et al. 2011a).

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Scientists predict that polar waters will be corrosive to shellbuilding animals within decades (IBGP et al. 2013). A 2015 study of observations in the Chukchi and Beaufort Seas in the Arctic indicates that within 15 years waters will become so corrosive that it will be difficult for marine animals to build and maintain their shells (Mathis et al. 2015). The highly productive fisheries of Alaska are in some of the most rapidly changing seawater conditions (Mathis et al. 2014).

3. Sub-tropical Waters

Subtropical waters have experienced declining saturation states due to ocean acidification. Within decades, scientists believe that ocean acidification will impair coral growth (IBGP et al. 2013). Models show that by the end of the century, most coral reef areas will no longer have aragonite saturation states that are optimal for coral growth. A 10-year study of the Caribbean region found a strong regional decrease in aragonite saturation state between 1996-2006, from 4.05 to 3.9, resulting from CO_2 (Gledhill et al. 2008). Modeling predicts that under various emissions scenarios the coral reefs in the Caribbean will be thermally and chemically stressed between now and 2030 (Meissner et al. 2012). Even under the most optimistic scenario, 98% of reefs will be stressed by 2050 (*Id.*). In the Pacific subtropical ocean near Hawaii, there are nearly 20 years of time-series measurements of significant decreasing seawater pH that match the ocean's uptake of atmospheric CO_2 (Dore et al. 2009)

4. Atlantic Coast

Even ocean waters not at high latitude, in upwelling systems, or containing coral reefs ecosystems are, or will soon be, exhibiting signs of ocean acidification. Observations of East Coast waters during all seasons show that while they remain supersaturated with respect to aragonite, by the end of this century, saturation states of aragonite and calcite will decrease by 20–40%, with the lowest Ωar dropping to 1.3 in some seasons (Jiang et al. 2010). A survey of the Atlantic Coast showed that waters in the Northeast and particularly the Gulf of Maine are the most susceptible to ocean acidification (Wang 2013).

iii. CO_2 Kills and Injures Marine Life

High-CO_2 waters seriously harm marine wildlife and the entire ocean ecosystem. When CO_2 concentrations in seawater increase, the availability of carbonate ions decreases, making it more difficult for marine organisms to form, build, and maintain the calcium carbonate shells and skeletons required for their survival. As seawater becomes more corrosive, it can kill fish eggs and inhibit the development of, and essentially dissolve, the shells of small crustaceans, baby shellfish, and other tiny creatures at the base of the food web (Fabry 2008). Ocean acidification also harms and stresses fish, squid, and other animals that do not build shells (*Id.*). Not only does ocean acidification directly threaten various types of marine animals, it also has implications for the broader marine environment and food web.

The harmful effects of ocean acidification have already begun to occur. For example, ocean acidification has caused:

- A massive die-off of oysters in the Pacific Northwest (Barton et al. 2012; R. a. Feely, Sabine, et al. 2012; Washington State Blue Ribbon Panel 2012);

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- Declines in abundance and size of the California mussel, blue mussel and goose barnacle in tidepools correlated with a severely declining pH (Wootton et al. 2008);
- Sluggish growth of corals in the Caribbean and Great Barrier Reef (De'ath et al. 2009; De'ath et al. 2012; Gledhill et al. 2008); and
- Shells of plankton to dissolve off the California Coast and thinner and weaker shells of plankton in the Southern Ocean (Bednarsek 2014; Moy et al. 2009).

In a meta-analysis of over 400 experiments examining the impacts of ocean acidification on marine organisms, Kroeker et al. (2013) found the biological effects to be generally large and negative. This analysis was restricted to experiments with pH manipulations of less than 0.5 units, in order to reflect the predicted level of ocean acidification by the end of the century (IPCC 2007). By limiting the analysis to small variations in pH, this study shows that within the foreseeable future ocean acidification will have "profound repercussions for marine organisms" (Kroeker et al. 2010). While the negative effect of ocean acidification was most pronounced for calcification and survival (27% reductions in both responses), the study also revealed significant negative effects on growth and reproduction (11 to 19%, respectively). In addition, abundance was reduced by 15%. The strength of this analysis suggests that the patterns highlighted in this study are a robust representation of the current literature on ocean acidification.

While most of the worst consequences of ocean acidification are predicted for the future, scientists have already observed damage from CO_2 in the oceans. Additionally, the impacts of ocean acidification can affect the entire marine food web by altering habitat, prey availability, and species interactions.

b. High-CO_2 Waters Injure the Growth, Survival, Fitness, and Reproduction of Marine Animals

The primary known harm of CO_2 in the oceans is that it impairs the growth and survival of animals that build shells. Because ocean acidification reduces the availability of carbonate ions that marine animals use to calcify their shells and skeletons, CO_2 reduces the ability of these animals to build their protective structures (Doney et al. 2009). Acidified waters can also damage and dissolve shells.

These negative effects have been observed in the ocean as well as documented in laboratory studies. Corals, coralline algae, plankton, mollusks, and other shellfish exposed to future levels of ocean acidification have all experienced problems (Kleypas & Yates 2009; Kuffner et al. 2007; Barton et al. 2012; Talmage & Gobler 2011; Talmage & Gobler 2009; Orr et al. 2005; Riebesell et al. 2000).

i. Molluscs, Echinoderms, and Crustaceans

High CO_2 waters are lethal to shellfish. Since 2005, waters off the coast of Washington and Oregon have been killing oysters and other molluscs. Shellfish hatcheries in Washington and Oregon reported massive mortalities of oyster larvae (Washington State Blue Ribbon Panel 2012).Wild oysters also failed to reproduce in Willapa Bay, Washington (*Id.*). Scientists have definitively linked oyster production failures to high-CO_2 ocean waters that were used to raise larvae (Barton et al. 2012).

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In response to reported shellfish hatchery problems in Oregon, Barton et al. reported the results of their observations from the Whiskey Creek Hatchery on Netarts Bay in the summer of 2009 (Barton et al. 2012). Unlike previous laboratory experiments, this study analyzed calcifying organism responses in the ambient-water CO_2 chemistry of Oregon's coastal waters. Larval production and mid-stage growth (~120 um to ~150 um) of the oyster, *Crassostrea gigas*, were both significantly negatively correlated with the chemistry of waters in which larval oysters were spawned and reared for the first 48 hours of life. Although the impact of the exposure was not immediate, the delayed reaction caused a significant decline in growth for mid-sized oyster larvae and reduced overall production. The findings corroborate other laboratory studies that show that many marine species, especially at the larval stage, are adversely affected by ocean acidification.

Scientific studies have demonstrated that even modest pH declines affect the sensitive and vulnerable early developmental stages of organisms because these life histories have specific environmental needs (Kurihara 2008) (*see* Figure 10, below, showing negative effects from low pH treatments). A number of studies have found a delay in development or less development, degraded shells, decreased rate of metamorphosis, shell thickness, and loss of hinge integrity (Ross et al. 2011a). The resulting reduced larval size can reduce the feeding efficiency of larvae, and smaller larvae are more susceptible to starvation because they encounter comparatively less food (Kurihara & Shirayama 2004). Sub-lethal effects of elevated acidity can severely alter the composition and fitness of larvae, and given the high mortality rates of larvae in the water column and during the transition to benthic settler, small perturbations to larvae potentially may have large alterations to settlement dynamics, post-settlement mortality, recruitment, and ultimately adult populations (Ross et al. 2011).

Watson et al. (2009) exposed one day-old oyster larvae to a range of pH conditions, from 7.6 to 8.1, for 10 days and showed significant decline in the survival and growth of young larvae at lower pH. Waldbusser et al. (2010), in a study on the Chesapeake Bay, showed that even modest changes in pH present conditions that are corrosive to shells and have physiological impacts on adult and larval oysters. Biocalcification declined significantly with a reduction of 0.2 pH units, making juvenile bivalves more susceptible to predation and other mortality factors (*Id.*).

Negative effects have been seen on the metamorphosis, size, and survival of larval hard clams (*Mercenaria mercenaria*), bay scallops (*Argopecten irradians*), and Eastern oysters (*Crassostrea virginica*) at levels of CO_2 predicted to occur in the 21st century (Talmage & Gobler 2011). At 650 ppm, or an approximate drop of 0.3-0.4 from pre-industrial values, both *M. mercenaria* and *A. irrandians* larvae exhibited dramatic declines (over 50%) in survivorship as well as significantly delayed matamorphosis and significantly smaller size. *C. virginica* also experienced lowered growth and delayed metamorphosis at this level, an indicator that current and future increases in CO_2 populations may deplete or alter the composition of shellfish populations in coastal ecosystems (*Id.*).

The Olympia oyster, *Ostrea lurida*, a foundation species in estuaries along the Pacific coast, exhibits clear decline in larval growth and settlement as levels of CO_2 affect seawater pH. (Hettinger et al. 2012). Oysters in this experiment were raised at three levels of seawater pH,

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including a control (8.0) and two additional levels (7.9 and 7.8). Larvae reared under pH 7.8 exhibited a 15% decrease in larval shell growth rate, and a 7% decrease in shell area at settlement, compared to larvae reared under control conditions. Impacts were even more pronounced a week after settlement, with juveniles that had been reared as larvae under reduced pH exhibiting a 41% decrease in shell growth rate.

Oysters on the Atlantic coast also experience the ill effects of ocean acidification. Dickinson et al. (2012) found negative effects on juvenile eastern oysters after exposure to water with a 0.2 pH change. Exposure of the oysters to elevated acidity led to a significant increase in mortality, reduction of tissue energy stores and negative soft tissue growth, indicating energy deficiency. Under ocean acidification conditions, thermal tolerance is impaired in oyster larvae, leading to reduced development, size and increased abnormality (Ross et al. 2011; Parker et al. 2010). Similar results have been found in red abalone, with thermal tolerance impaired at pH 7.87 compared to control (pH 8.05) (Zippay and Hoffman 2010).

In studies with edible mussel (*Mytilus edulis*) and Pacific oyster (*Crassostrea gigas*) researchers found a strong decline of calcification under ocean acidification conditions (Gazeau et al. 2007). Based upon these results, researchers concluded that mussel and oyster calcification may decrease by 25% and 10%, respectively, by the end of the century." (*Id.*). Oysters and mussels also exhibit development abnormalities when exposed to acidification (Kurihara 2008). When oyster eggs were reared under pH 7.8, they showed malformations of their shell, and when reared under pH 7.4, more than 70% of the larvae were either completely non-shelled, or only partially shelled, and only 4% of CO_2 treated embryos developed into normal larvae by 48 hours after fertilization, in contrast to about 70% successful development in control embryos.

The shrimp *Palaemon pacificus* displayed variable responses at different developmental stages, pH and length of exposure (Kurihara 2008). Following long term (30 weeks) exposure of adults to pH 7.89 and 7.64, survival and egg production in early developmental stages decreased in both treatments. Findlay et al. (2010) found a slower rate of development of embryos in the common intertidal northern hemisphere barnacle *Semibalanus balanoides* with an estimated 19 days delay in reaching 50% hatching stage at pH 7.7. Other amphipods have exhibited metabolic changes in response to acidification levels greater than what is allowed under the federal criterion (Hauton et al. 2009).

Echinoderms exhibit delayed and asymmetrical development when exposed to acidified conditions. In the absence of adequate adaptation or acclimation, lowered pH levels will have a range of sub-lethal effects on sea urchins, brittlestar and seastar larvae from a range of geographical regions (Ross et al. 2011). Larvae of the ecological keystone brittlestar, *Ophiothrix fragilis*, either were abnormal, had altered skeletal proportions, or asymmetry during skeletogenesis, and there was a delay in development at pH levels of 7.9, or approximately 0.3 units below current surface levels (Gutowska et al. 2009). Other experiments on brittlestar in low pH waters resulted in dramatic results; acidification of 0.2 units induced 100% larval mortality within an eight day period. Control larvae showed 70% survival over the same period. Because the calcite skeleton of the larval brittlestar aids key functions such as feeding and vertical migration, and defense against predators, abnormal development of the skeleton will have drastic consequences for fitness. The developmental abnormalities may be exacerbated by temperature

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increases predicted for the end of the century; some scientists suggest that this may result in the disappearance of echinoderms from the surface oceans within the next 50-100 years (Ross et al. 2011a).

Reproductive success is compromised by ocean acidification. The fertilization rate of sea urchins decreases with increasing CO_2 concentrations (8.1 to 6.8 pH) (Kurihara 2008). In another sea urchin experiment utilizing six CO_2 concentrations, with a pH between 8.01 (control) and 6.83, cleavage rate, developmental speed, and larval morphology all declined with increased CO_2 concentration (Kurihara & Shirayama 2004). At a 0.2 change from control, effects could be seen on the morphology and development of the larvae, and these effects became more pronounced with greater pH changes (*Id.*) (*see* Figure 4, below). The authors concluded that "all the effects of raised CO_2 concentration observed in this study would have a negative impact on the survival of sea urchin embryos in their early life history." A recent study showed that sea urchin sperm flagellar motility was significantly reduced when seawater pH decreased by .3 units, from 8.0 to 7.7 (Suwa et al. 2010). As discussed above, decreased flagellar motility has severe consequences for fertilization and subsequent population dynamics; if sperm lose their ability to find eggs, the population size will necessarily diminish.

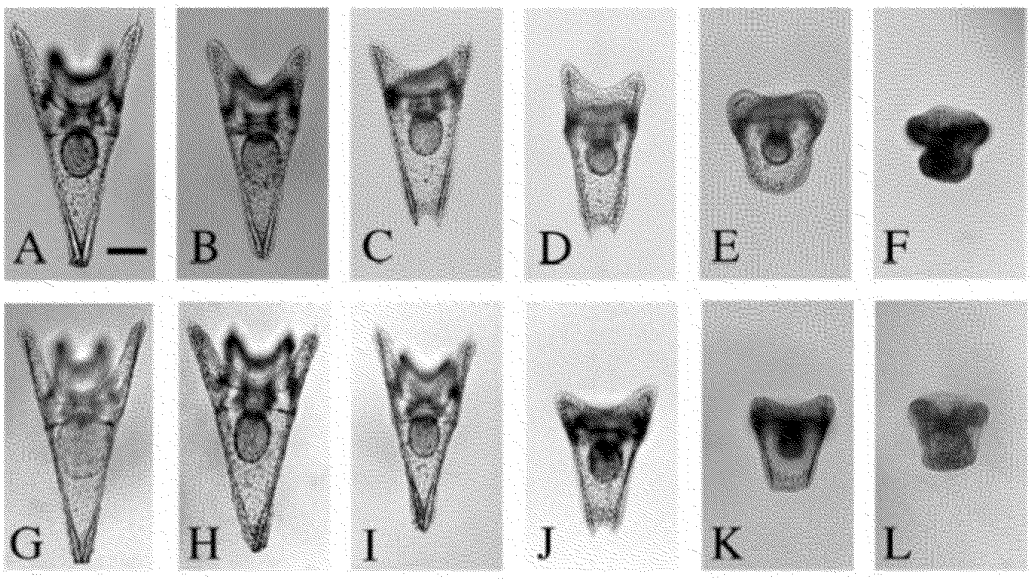

Fig. 6. *Hemicentrotus pulcherrimus*. Morphology of 4-armed pluteus larvae cultured for 3 d in (A–F) CO_2-seawater and (G–L) HCl-seawater. (A & G) control (pH 8.0); (B & H) +500 ppm (pH 7.8); (C & I) +1000 ppm (pH 7.6); (D & J) +2000 ppm (pH 7.4); (E & K) +5000 ppm (pH 7.0); (F & L) +10 000 ppm (pH 6.8). Scale bar = 50 µm

Figure 4. Declining development of sea urchin larvae exposed to acidified waters (Kurihara & Shirayama 2004).

Even moderate increases in atmospheric CO_2 and ensuing acidification adversely affect the growth of both gastropods and sea urchins (Shirayama & Thornton 2005). Before the end of this century, atmospheric CO_2 is likely to increase by more than 200 ppm, decreasing the pH of the ocean by approximately 0.3 units from pre-industrial levels. Two species of sea urchin as well as the gastropod *Strombus luhanus* were exposed for six months to waters with this level of elevated CO_2, and all three species exhibited similar consequences. Increased CO_2 negatively affected growth rate, calcification, shell height and body mass, and metabolic activity

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(Shirayama & Thornton 2005). The developing embryos of the gastropod and intertidal snail *Littorina obtusata* also demonstrate slower overall development time, altered embryonic movement, and modification of shell shape in hatchlings while exposed to acidified waters (pH 7.6) (Ellis et al. 2009).

Arnold et al. (2009) investigated the effect of ocean acidification on lobsters and found that indirect disruption of calcification and carapace mass may adversely affect the competitive fitness and recruitment success of larval lobsters with serious consequences for population dynamics and marine ecosystem function

Reduced metabolism is expected to impair predator-prey interactions, as well as have consequences for growth, reproduction, and survival. Metabolic suppression has previously been reported to occur in a variety of adult marine invertebrates, including crabs, squid, worms, bivalves, pteropods and amphipods (Albright 2011). Slowed metabolism is generally achieved by halting energy-expensive processes, such as protein synthesis, and therefore may lead to reductions in growth and reproductive potential (*Id.*). The blue mussel *Mytilus edulis* has strong physiological mechanisms by which it is able to protect body tissues against short-term exposure to acidified seawater, but these come at an energetic cost, and will result in reduced growth during long term exposures (Bibby et al. 2008). Consequently, the predicted long-term changes to sea water are likely to have a significant effect on the health and survival of blue mussel populations (*Id.*). Mussel beds are a dominant coastal habitat and provide food and structure for a diverse array of species in an otherwise physically stressful environment; any decline in their population structure will lead to a reduction in appropriate habitat for a myriad of other species.

In summary, acidified waters impact the development, growth, and reproductive success of a suite of echinoderms, crustaceans, and molluscs. A growing body of information is becoming available on the effecting of declining pH on these organisms and their ecosystems. The results of these studies are clear; as pH falls even 0.2 units from pre-industrial values, these organisms will struggle to survive in their increasingly acidic environment.

ii. Corals

Coral reef ecosystems, which are estimated to harbor one-third of marine species and which support the livelihoods of a half billion people, are particularly threatened by ocean acidification. Some corals are already experiencing reduced calcification (De'ath et al. 2009; Cooper et al. 2008; Bates et al. 2010; Gledhill et al. 2008). Due to the ocean acidification and warming, reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations of 450 ppm (Veron et al. 2009; Bijma et al. 2013). Prominent coral scientists have called for reducing atmospheric CO_2 to less than 350 ppm to protect coral reefs from collapse (Veron et al. 2009, Frieler et al. 2012). Coral reefs cannot exist below 7.8 pH units (Fabricius et al. 2011), and the threshold for coral growth is 3.3 Ω_{ar} (Meissner et al. 2012).

Ricke et al. (2013) analyzed aragonite saturation state (Ω_{ar}) surrounding reefs in CMIP5 simulations under several representative concentration pathway (RCP) scenarios (Ricke et al. 2013). The study found that in preindustrial times, 99.9% of reefs adjacent to open ocean in the CMIP5 ensemble were located in regions with $\Omega a > 3.5$. Accordingly, the study used $\Omega a = 3.5$ as

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an upper bound viability threshold for corals, while also examining thresholds of $\Omega a = 3.25$ and 3. Under a business-as-usual scenario (RCP 8.5), every coral reef considered was projected to be surrounded by water with $\Omega_{ar} < 3$ by the end of the 21st century and the reefs' long-term fate was independent of their specific saturation threshold. Under scenarios with significant CO_2 emissions abatement, the Ω_{ar} threshold for reefs was critical to projecting their fate. The study concluded that the "results indicate that to maintain a majority of reefs surrounded by waters with $\Omega_{ar} > 3{:}5$ to the end of the century, very aggressive reductions in emissions are required."

Corals are among the ecosystems most threatened by ocean acidification. To date, most scientific investigations into the effects of ocean acidification on coral reefs have been related to the reefs' unique ability to produce voluminous amounts of calcium carbonate (Kleypas & Yates 2009). The persistence of carbonate structures on coral reefs is essential in providing habitats for a large number of species and maintaining the extraordinary biodiversity associated with these ecosystems. As a consequence of ocean acidification, the ability of marine calcifiers to produce calcium carbonate will decrease, resulting in a transition from a condition of net accretion to one of net erosion, with drastic consequences for the role and function of these ecosystems (Kleypas & Yates 2009).

Coral reefs are predicted to drastically lower their calcification rates in the near future, and historical records show that calcification rates have already fallen relative to pre-industrial values. According to scientists, the main reef building organisms will calcify up to 50% less relative to pre-industrial rates by the middle of this century (*Id.*). A drop of approximately 60% coral reef calcification is projected for the end of the century, when pH is predicted to fall 0.5 units below pre-industrial values (Caldeira & Archer 2007). Many studies suggest calcification rates could be reduced between 20-60% at 560ppm, or 7.9 pH, and that a reduction of this magnitude would fundamentally alter reef structure and function (Convention on Biological Diversity 2009). According to the model of Silverman et al. (2009), developed from field observations from more than 9,000 reef locations, all coral reefs are expected to reduce calcification by more than 80% relative to their pre-industrial rate at 560 ppm (0.3 pH change), and at this point "all coral reefs will cease to grow and start to dissolve." The Interacademy Panel on International Issues concurs; "at current emission rates models suggest that all coral reefs and polar ecosystems will be severely affected by 2050 or potentially even earlier."

In a meta-analysis on coral calcification responses to ocean acidification, the coral calcification declined by a mean of 15% per unit decrease in aragonite saturation state ($2 < \Omega < 4$) (Chan and Connolly 2013). On current emission trends, calcification will decline 22% on average for corals by the end of the century (*Id.*). This falls to the lower range of responses that have been predicted by ocean acidification researchers and described above, which the authors believe reflects variation in the calcification responses of different corals.

Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%, (Caldeira & Archer 2007), and data from the Great Barrier Reef indicates a 14% decline in calcification rates between 1990 and 2005 (De'ath et al. 2009). Other studies in the Great Barrier reef indicate a decline of approximately 21%, and analysis of coral growth records confirm that this decline is unprecedented in recent centuries (Cooper et al. 2008). A model based on field samples shows that calcification of coral reefs in French

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Polynesia declined 15% between the pre-industrial period and 1992, and that rates will decline 40% by 2050, when CO_2 levels reach 560 ppm (pH 7.9) (Anthony et al. 2011). Near Bermuda, historical records show that coral skeletal density has decreased 33%, and coral calcification rates have declined by 52% as a result of changes in seawater carbonate chemistry (Bates et al. 2010). These observed changes have occurred even before a 0.2 unit decline in ocean pH; as atmospheric CO_2 continues to rise and lower pH values, calcification rates will maintain their precipitous decline.

Ocean acidification acts in concert with ocean warming and coral bleaching in furthering coral reef decline (Anlauf et al. 2011) (observing a 3% reduction in acidification with a 0.2 decline in pH, and a 30% decline when acidification is coupled with 1° C warming). While natural variability in the annual cycle and interannual variability may account for some of the observed change in coral growth rates, scientists are "virtually certain" that anthropogenic trends already exceed natural variability (Friedrich et al. 2012). Studies projecting the combined impacts of ocean acidification and ocean warming on corals predict that coral erosion will exceed calcification rates at atmospheric CO_2 concentrations of 450 to 500 ppm, (Hoegh-Guldberg et al. 2007), and all coral reefs will begin dissolve at CO_2 concentrations of 560 ppm (Silverman et al. 2009). These figures correspond to a 0.2 and 0.3 unit drop in pH, respectively, as compared to pre-industrial values. Van Hooidonk et al. (2014) presented updated global projections for threats to coral reefs from ocean warming and ocean acidification based on ensembles of IPCC AR5 climate models using the Representative Concentration Pathways (RCPs). For all tropical reef locations, the study projected absolute and percentage changes in aragonite saturation state (Ω_{ar}) for the period between 2006 and the onset of annual severe bleaching.

In the Caribbean, a recent study concluded that "coral reef communities are likely to be essentially gone from substantial parts of the Southeast Caribbean by the year 2035" (Buddemeier et al. 2011). The Great Barrier Reef has lost 50% of its coral cover since 1985 as a result of the combined effects of ocean acidification, global warming, coral bleaching, coral predation by starfish, and cyclone damage (De'ath et al. 2012). In short, due to the synergistic impacts of ocean acidification, mass bleaching, and local impacts, coral reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations 450 ppm, or pH 8.0, a level that is expected before mid-century (Veron et al. 2009).

Many experimental studies show declining calcification rates and other ill effects when corals are exposed to acidified waters. Decreases in calcification rates across a suite of benthic species and calcifying systems range from 3 to 60% for a doubling in pCO_2, which corresponds to a 0.3 reduction in pH (Abbasi & Abbasi 2011). The average response of corals is a 30% decline in calcification in response to a doubling in pCO_2 (*Id.*). In a study of an assemblage of corals exposed to conditions designed to mimic the change that may be experienced in the next 50-100 years (pH decline of 0.22 to 0.28 units), calcification rates declined between 44% and 80%.

The coral *Acropora palmata* (listed as threatened under the Endangered Species Act), once the dominant reef building coral in the Caribbean, experiences impaired fertilization, settlement, and growth with increasing pCO_2 (Albright et al. 2010). The cumulative impact of ocean acidification on fertilization and settlement success is an estimated 52% and 73% reduction in the number of larval settlers on the reef under pCO_2 conditions projected for the middle and end

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of this century, respectively (0.2 and 0.5 decline in pH) (*Id.*). After only 8 days of high CO_2 conditions (pH 7.75), *Acropora* experiences a statistically significant (18%) reduction in calcification rate (Murubini et al. 2003). Furthermore, there 22 coral species listed as threatened under the Endangered Species Act primarily because of threats from ocean warming, acidification and disease. The rule proposing listing for the corals found that ocean acidification was one of the highest priority threats for corals:

> Ocean acidification has the potential to cause substantial reduction in coral calcification and reef cementation. Further, ocean acidification adversely affects adult growth rates and fecundity, fertilization, pelagic planula settlement, polyp development, and juvenile growth.

77 Fed. Reg. at 73230 (Dec. 7, 2012). In other words, ocean acidification is driving the extinction of corals and the destruction of coral reef ecosystems.

Experimental studies evaluating the effects of ocean acidification on early life history stages of corals generally conclude that primary polyp growth is hindered by increasing acidity (Albright et al. 2010, Cohen & Holcomb 2009). Renegar and Riegl (2005) showed a significant decrease in the growth rate of *Acropora cervicornis* larvae at pH levels 0.3-0.5 units below control. Larvae of the common Atlantic golf ball coral, *Favia fragum*, shows significant delays in both the initiation of calcification and subsequent growth of the primary corallite in acidic waters (8.17 – 7.54 pH) (Cohen & Holcomb 2009). Visible changes in the skeletal development were observed in all non-control treatments, and in the most acidic waters skeletal development was 75% less than the control.

Acidification also affects cold water corals. Cold water corals have a worldwide but patchy distribution, and are often found in areas with highly productive fisheries (De Mol et al. 2002; Kenyon et al. 2003). Overall, more than two-thirds of all known coral species are cold water corals (Roberts & Hirshfield 2012; Cairns 2007). Recent exploration and research that has begun to search for, map, and observe cold water corals has found that these organisms are fragile, long-lived, slow-growing, very sensitive to physical or environmental disturbance and adapted for a specific environmental niche (McDonough & Puglise 2003). Alaskan waters are already showing widespread evidence of ocean acidification as a result of greenhouse gas emissions (Mathis et al. 2011a). By 2100, 70% of cold-water corals will be exposed to corrosive waters (Convention on Biological Diversity 2009). Conditions in waters typically inhabited by cold-water corals are even less favorable for calcification than those experienced by warm water corals; this may cause cold-water corals to be affected earlier and more strongly by CO_2-related ocean acidification than their warm water counterparts (Abbasi & Abbasi 2011).

The vulnerable early developmental and reproductive stages of cold water corals may be especially strongly impacted (Kurihara 2008; Dupont & Thorndyke 2009; Kroeker et al. 2010). In an experiment on the cold-water coral *Lophelia pertusa*, lowering the pH by 0.3 units relative to the ambient level resulted in calcification being reduced by 56% (Maier et al. 2009). Lower pH reduced calcification more in fast growing, young polyps (59% reduction) than in older polyps (40% reduction). Thus, corals' larvae and young corals are significantly more susceptible to ocean acidification than adults, and will likely show a higher degree of reduced calcification

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and growth with reduced pH, making young and larval corals less likely to survive to maturity as the ocean continues to absorb anthropogenic CO_2 and as climate change progresses.

In addition to reduced calcification rates, the strength of cementation may also be reduced in waters with a lower pH, promoting higher rates of physical and bio-erosion (Manzello et al. 2008). Once coral reefs experience lowered calcification and poor cementation, erosion and reef flattening can result, which severely reduced the structural heterogeneity of reefs and lowers its potential to support biodiversity. An important new study of reef bioerosion determined that the combined effects of lower calcification with increased bioerosion can significantly degrade coral reefs (Wissshak et al. 2012). In the study, a common bioeroding sponge in the Great Barrier Reef was observed on massive Porites. The sponge was more effective at bioerosion of the corals at high CO_2, ranging from 17% increase from present day levels to 61% increase at the highest CO_2 treatment. The researchers describe the important role of balancing the antagonistic processes of calcification and bioerosion in a reef for a healthy coral ecosystem, and predict detrimental consequences under ocean acidification as calcification declines and bioerosion increases.

Bioerosion may result in a loss of change in fish assemblages, lower densities of commercially important species, and lower rates of larval fish recruitment (Feary et al. 2007). Weaker reef calcification and cementation also increases the potential for reef damage as storm frequency and intensity increases with continued global warning, leading to further reef degradation (*Id.*). In a study looking at the impacts of storm damage and ocean acidification, researchers concluded that table coral populations are vulnerable to collapse (Madin et al. 2012). In the Indo-Pacific, table corals provide an important role in the reef ecosystem by creating reef structure and sheltering other reef species. They are also particularly vulnerable to ocean acidification, thermal stress, bleaching, disease and stress from storm waves. The table corals will become more vulnerable to storm waves as ocean acidification reduces calcification and increases bioerosion, therefore weakening their cementation and structure. Madin et al. (2012) found that a coral colony was four times more likely to be dislodged by a storm wave by the end of the century ocean acidification levels. Because of this vulnerability, the results showed that table corals are prone to large and rapid declines in coral cover.

Numerous biological responses independent of calcification are also negatively impacted by ocean acidification. Corals in acidifying waters are likely to be in a nutritionally or energetically stressed state and thus less likely to initiate reproduction, or successfully reproduce, due to negative impacts of ocean acidification on all stages of the reproductive cycle (Maier et al. 2009; McCulloch et al. 2012). Sperm flagellar motility also declines in response to decreasing pH. If sperm lose their ability to find eggs in the vast extent of the sea, the life of marine organisms is potentially limited. Sperm flagellar motility, which is indispensable for fertilization, is regulated by an elevation of intracellular sperm pH (Morita et al. 2010). While 69% of *Acropora* sperm were motile at pH 8.0, 46% were motile at pH 7.8, and fewer than 20% at pH 7.7 (*Id.*). Additionally, the physiological costs associated with reproduction are more likely to result in the demise of the organism due to the compounding stressors from ocean acidification and climate change (Wood et al. 2008, Cohen & Holcomb 2009). Significant reductions in metabolism have been observed for coral larvae following exposure to waters with a 0.2 decline in pH, levels projected to occur by the middle of this century (Albright & Langdon 2011).

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Albright et al. (2010) concluded that with increased CO_2 concentrations to those projected to occur in this century (560 atm to 800 atm, or a 0.3 to 0.5 decline in pH from pre-industrial values), the fertilization success of the tropical reef-building coral *Acropora palmata* decreased by 12-13%, settlement success reduced 45-69%, and linear extension was significantly reduced. The compounding effect of these impacts translated to 52-73% reduction in the number of larval settlers on the reef. Albright et al. (2010) predicted that the net impact on recruitment would actually be greater than that given that the depressed post-settlement growth is likely to result in elevated rates of post-settlement mortality. This corroborates other studies showing negative impacts on early-stage tropical corals.

Albright and Langdon (2011) tested the effects of ocean acidification on sexual recruitment of tropical corals. Larval metabolism was depressed by 27% at acidification levels expected by mid-century (0.3 pH reduction) and 63% at end-of-century acidification levels (0.4-0.5 pH reduction). Settlement was also reduced 42-45% and 55-60% at the mid and end-of-century levels respectively, relative to controls (Albright & Langdon 2011). Another study of larvae of tropical corals showed that short-term or long term exposure of larvae to ocean acidification decreased their metamorphosis (Suwa et al. 2010). This means that even when larval survivorship is unchanged, the success of recruiting new corals could be inhibited by ocean acidification (*Id.*).

Additionally, under conditions of acidification planktonic larvae lose their preference for settlement on the optimal crustose coralline algae communities (Doropoulos et al. 2012). Crustose coralline algae in turn, will experience a lower recruitment rate as marine waters become more acidic. Crustose coralline algae, a red calcifying algae, is of key importance in coral reef ecosystems, stabilizing reef structures and providing an important food source for benthic organisms (Convention on Biological Diversity 2009). Crustose coralline algae form a major calcifying component of the marine benthos from polar to tropical regions and are considered to influence the settlement of coral recruits. With a mean pH change of 0.26 between control and treatment, Kuffner et al. (2007) found that crustose coralline algae growth rates declined by 40%, and recruitment rate and percentage cover decreased by 78% and 92%, respectively.

In sum, reproduction is critical to maintaining a healthy coral reef population, and the long-term impacts of ocean acidification on reproduction, especially on larval settlement and growth, may significantly reduce the corals' ability to recover or maintain a population in the face of human caused disturbances and anthropogenic CO_2 emissions. This would result in a lack of reproductive capacity, genetic bottlenecks, and population collapse (Dupont et al. 2010; Ross et al. 2011).

As the world's oceans become more acidic and less saturated with carbonate minerals, corals are expected to build weaker skeletons and experience slower growth rates, which will make it more difficult for corals to retain competitive advantage over other marine organisms (Guinotte et al. 2006). As coral skeletons weaken, they will become increasingly at risk of storm damage and bioerosion, which will reduce the structural complexity of the reef system, reducing habitat quality and diversity alongside the loss of coastal protection functions (Hoegh-Guldberg et al. 2007). At greater than 550 ppm, coral reef ecosystems will be reduced to "crumbling

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frameworks." (*Id.*). Extensive studies have demonstrated that small changes in ocean chemistry will cause a suite of negative impacts, from reduced calcification rates to lowered reproductive success.

iii. Plankton

Plankton, which comprise the basis of the marine food web, are among the calcifying organisms adversely affected by ocean acidification. Changes to calcifying zooplankton, such as pteropods and foraminfera, have the potential to affect the ecological and tropic dynamics which govern the exchange of energy and cycling of nutrients throughout the marine food web (Gattuso & Hansson 2011). For example, the shelled pteropod, *Limacina helicina*, an Arctic pelagic mollusc, is a food source for higher predators such as fishes, whales and birds that are particularly important in high latitude areas. *L. helicina* makes up about 60 percent of the pink salmon diet (Comeau et al. 2012). A decline of pteropod population would likely cause dramatic changes to various pelagic ecosystems, and impact the commercially important salmon fishery; a 10% decrease in pteropods can lead to a 20% reduction in pink salmon body weight (Aydin 2005).

Pteropods form integral components of food webs, and are considered an overall indicator of ecosystem health (Orr et al. 2005). Studies have shown that pteropods exposed to a pH value predicted for the end of this century exhibited a 28% decrease in calcification (Comeau et al. 2009). Experiments on *L. helicina* showed that changes from 8.05 pH to 7.89 pH (Δ -0.16 units) cased shell dissolution and cracks appeared at 7.76pH, and linear extension of the shell decreased as a function of declining pH (Comeau et al. 2012). Samples show dissolution already happening in areas that have low aragonite saturation states. A sampling study off the coasts of California, Oregon, and Washington showed average to severe dissolution of *L. helicina* for 53% of onshore individuals and 24% of offshore individuals (Bednarsek 2014). A sampling study in 2008 of the Southern Ocean found severe dissolution of *L. helicina* in Ω_{ara} 1.0 (Bednarsek 2012). Another study found shell weights of one form of Antarctic species declined 35% from 1997-2006 (Roberts unpublished).

Ample studies corroborate that high CO_2 waters dissolve the shells of *L. helicina* and reduce calcification rates. Comeau et al. (2010) noted decreased calcification for *L. helicina* with decrease in aragonite saturation. Lishka (2012) looked at overwintering *L. helicina* and L. retroversa in the Arctic and noted that they do not calcify in the winter, and they are subject to dissolution under high CO_2 conditions. Bednarsek (2012) looked at *L. helicina* and *Clio pyramidata* from the Southern Ocean under different aragonite saturation states and recorded dissolution stages.

Modeling by Comeau et al. (2012) shows that by the end of the century *Limacina helicina* will not be able to calcify over much of the Arctic because of aragonite undersaturation—prediction may be conservative because it did not account for shell dissolution. Commentary suggests that as waters warm these pteropods will be trapped in acidified conditions and will "disappear entirely by the end of the century." Modeling suggests that waters in the California Current will be undersaturated year-round by 2050 (Gruber 2012). Modeling of the Arctic suggests that by mid-century the Bering Sea will be persistently undersaturated with respect to aragonite (Mathis 2011). An analysis of survey measurements in 2005-2006 and 1991-1992 demonstrated a

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shoaling of the aragonite saturation state in waters off Alaska (Feely et al. 2012). In the North Pacific the aragonite saturation state shoaled to depths less than 200 m between 40˚N and 50˚N (*Id.*). On average, the calcite saturation horizon in the Pacific shoaled about 1 m/yr from 1991 to 2006 (*Id.*).

Other species of plankton are also harmed by CO_2. Another pteropod, *Clio pyramidata,* kept in aragonite undersaturated waters began to dissolve within two days (Orr et al. 2005). Some coccolithophorids are also susceptible to ocean acidification. Studies showed that CO_2 related changes to seawater caused reduced calcification, resulting in malformed and incomplete shells. Calcification of cocolithophorids declined 15-44%, and their shells were malformed as pH changed up to about 0.3 units (Riebesell et al. 2000). Coccolithophorids are globally distributed and bloom in massive areas affecting the optical properties of the ocean, reflecting light from the earth, and play a major role in the ocean carbon cycle. Elevated CO_2 concentrations also reduce the shell mass of foraminifera (Kleypas et al. 2006). Modern shell weights of foraminifera in the Southern Ocean are 30–35% lower than those from preindustrial sediments, which is consistent with reduced calcification induced by ocean acidification (Moy et al. 2009).

iv. Cephlopods and Fish

The negative physiological effects of ocean acidification are not confined to invertebrates. For example, the gametes, embryos, and larvae of vertebrates such as fish are vulnerable to changes in ocean chemistry and have shown impairments in their homing and predator/prey detection capabilities.

Changes in the ocean's CO_2 concentration result in accumulation of CO_2 in the tissues and fluids of fish and other marine animals, called hypercapnia, and increased acidity in the body fluids, called acidosis. These impacts can cause a variety of problems for marine animals, including difficulties with acid-base regulation, calcification, growth, respiration, energy turnover, predation response, and mode of metabolism (Pörtner et al. 2005; Pörtner et al. 2004). Studies have shown adverse impacts in squid and fish, among other animals (Rosa & Seibel 2008; Ishimatsu et al. 2004; Pörtner et al. 2004). For example, when exposed to acidification, orange clownfish suffer a type of brain malfunction that interferes with their homing abilities and makes them 5-9 times more likely to swim toward a predator (Munday et al. 2009; Simpson et al. 2011; Ferrari et al. 2011).

Laboratory experiments have shown that ocean acidification at levels expected to occur within this century impairs larval orange clownfish and damselfish sensory abilities and behavior, making it more difficult for them to locate suitable settlement sites on reef habitat and avoid predators. Specifically, ocean acidification disrupts smell, hearing, and behavior of larval orange clownfish, (Munday et al. 2009; Nilsson et al. 2012), making larval clownfish attracted to odors from predators and unfavorable habitat (Munday et al. 2010; Dickson et al. 2010). Olfactory cues that prompted avoidance or neutral behavior in controls (pH 8.15) stimulated strong preference behavior in larvae raised at pH 7.8, in addition to significant reduction in response to usually positive preferences. Ocean acidification also impairs the hearing capacity of larval clownfish, which is predicted to have negative effects on settlement success and survival (Simpson et al. 2011).

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Similarly, research on six damselfish species found that ocean acidification impairs larval damselfish smell, vision, learning, behavior, and brain function, leading to higher risk of mortality. For example, in acidified waters, larval damselfish (1) become attracted to predator odors and display much riskier behaviors, making them more prone to predation; two species suffered a five-fold to nine-fold increase in predation rate at CO_2 levels of 700 to 850 ppm, or 0.3 pH units below control (Munday et al. 2009; Ferrari et al. 2011); (2) cannot discriminate between habitat olfactory cues, making it more difficult to locate appropriate settlement habitat (Devine et al. 2011); (3) settle on the reef during dangerous times—the full moon rather than new moon—when they are more vulnerable to predation (Devine et al. 2011); (4) fail to visually recognize or evade important predator species; (5) cannot learn to respond appropriately to a common predator by watching other fish react or by smelling injured fish, unlike fish under normal conditions (*Id.*); and (6) suffer disruption of an important neurotransmitter which is thought to result in the sensory and behavioral impairment observed in acidified conditions (Nilsson et al. 2012).

An animal's ability to transport oxygen is reduced by pH changes (Pörtner 2005). Water breathing animals have a limited capacity to compensate for changes in the acidity (Haugan 2006). For example, fish that take up oxygen and respire CO_2 through their gills are vulnerable because decreased pH can affect the respiratory gas exchange (Royal Society 2005). Changes in metabolic rate are caused by the changes in pH, carbonates, and CO_2 in marine animals (Haugan 2006).

Squid, for example, show a very high sensitivity to pH because of their energy intensive manner of swimming (Royal Society 2005). Because of their energy demand, even under a moderate 0.15 pH change squid have reduced capacity to carry oxygen and higher CO_2 pressures are likely to be lethal (Pörtner 2004). Even species more tolerant to pH changes experience decreased metabolism from increased CO_2 in the water (Pörtner 2004). For example, as much as 50% mortality was observed in copepods after only six days of exposure to waters with a pH level 0.2 units below the control (Pörtner 2005). Reducing pH by 0.3 pH cased a 31% decline in metabolic rate and a 45% decrease in activity level for the jumbo squid, an important predator in the Easter Pacific (Rosa & Seibel 2008).

In fish, pH also affects circulation. Fishexposed to high concentrations of CO_2 in seawater experience cardiac failure and increased mortality (Ishimatsu 2004). At lower concentrations sublethal effects can be expected that can seriously compromise the fitness of fish. Juvenile and larval stages of fish were found to be even more vulnerable (Ishimatsu 2004).

In sum, ocean acidification can have many adverse effects on marine animals that can reduce their fitness and survival (Royal Society 2005). Many marine animals have low thresholds for long-term CO_2 exposure (Pörtner 2005).

c. Other Environmental Impacts of Ocean Acidification

i. Increased Toxicity of Harmful Algal Blooms and Sediments

Ocean acidification may already be increasing the toxicity of harmful algal blooms known as "red tides." These toxic red tides poison shellfish, marine mammals, fish, and even cause

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paralytic shellfish poisoning in people. High CO_2 levels in seawater magnify the toxins of harmful algae. (Fu et al. 2012; Avery O Tatters et al. 2013; Tatters et al. 2012; Avery O. Tatters et al. 2013). Studies of the genus *Pseudo-nitzscia* show that the toxicity of diatoms which produce a neurotoxin increases significantly under ocean acidification conditions. A -0.5pH change caused toxin production in the diatoms to increase 4.2-fold and a -0.3pH unit change increased the toxicity 2.5-fold (Tatters et al. 2012). Many studies on the effects of ocean acidification and algal blooms have been conducted at CO_2 levels that are already occurring in California, and the increase in the toxicity of harmful algal blooms in Southern California (and resulting mass mortalities of fish and marine mammals) may be due, in part, to acidified waters (*Id.*) However, these studies suggest that the damage will become much worse.

Additionally, research shows that under conditions of ocean acidification sediments become more toxic (Roberts, Birchenough et al. 2013). Ocean acidification makes sediment-bound metals more available and thus more toxic for aquatic life (*Id.*) For example, ocean acidification increases the toxicity of copper (Campbell & Mangan 2014).

ii. Noise Pollution Increases in Low pH Waters

Ocean acidification can also decrease the sound absorption of seawater, causing sounds to travel further with potential impacts on marine mammals and other marine life sensitive to the sounds of vessel traffic, seismic surveys, and other noise pollution (Hester et al. 2008). Sound travels 10-15 percent further with a change of 0.1 pH, and it is predicted to increase about 40 percent by mid-century (Hester et al. 2008). Additionally, a decline of 0.3 pH units causes a 40 percent decrease in the sound absorption of surface seawater and sound may travel 70 percent farther, further affecting sensitive marine mammals (Brewer et al. 2009).

d. Ocean Acidification's Ecosystem Impacts

While the full implications of elevated CO_2 on marine ecosystems are not well-documented, there is high confidence that there will be negative ecosystem consequences from ocean acidification. The exact changes are difficult to predict, but some of the anticipated impacts include loss of diversity, loss of abundance of calcifying species, shifting prey and predator interactions, and loss of suitable habitat.

New mesocosm studies have sought to understand some of the potential ecosystem impacts of CO_2. Studies of biodiversity near underwater volcanic vents demonstrate reduced richness in high-CO_2 waters. For example, coral species diversity declined by about 39% between low and high-CO_2 sites, with the reefs shifting from complex communities to a coral reef dominated by massive Porites. Most importantly, the researchers found that coral reef development ceases at 7.7 pH, and they concluded that a pH decline below 7.8 would be "catastrophic for coral reefs" (Fabricius et al. 2011). Scientists also observed that in high-CO_2 waters the loss of complex coral reef habitat resulted in a loss of diversity of reef-associated species such as crustaceans and crinoids (Fabricius et al. 2014). Looking at the macroinvertebrates, the density declined 48% between control and high-CO_2 areas and taxa diversity declined by 77% (*Id.*).

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Loss of species diversity associated with ocean acidification can also result from changes in competitive interactions. A study of a rocky reef near volcanic vents documented that macro algae outcompeted calcareous species in low-pH waters (Kroeker et al. 2012). The researchers explained that under the high-CO_2 conditions the calcifying species grew more slowly while the seaweed took hold and that grazing of seaweed was depressed (*Id.*). In another study, while the areas near volcanic vents lacked scleractinian corals and had low abundance of sea urchins and coralline algae, invasive algal species benefited from the acidified conditions (Hall-Spencer et al. 2008).

Research on the diversity the intertidal community in the Pacific Northwest documented a shift from a ecosystem dominated by calcifying animals to one with non-calcifying organisms as pH declined. Researchers documented declines in abundance and size of the California mussel, blue mussel, and goose barnacle in tidepools on the Olympic Coast in Washington (Wootton et al. 2008). They found that in years with low pH waters the calcifying animals were replaced by non-calcifying organisms (*Id.*).

The synergistic impacts of ocean acidification and warming are also potentially severe. Ocean acidification may induce a negative climate feedback that may increase temperature rise. Mesocosm studies found that ocean acidification may amplify global warming through decreasing biogenic production of the marine sulfur component dimethylsulphide which can impact cloud albedo (Six 2013). Ocean acidification therefore may also contribute to climate change impacts on the environment.

2. Risk Reduction Costs and Benefits

EPA must make a determination whether the risk of ocean acidification is unreasonable and this constitutes a balancing of costs and benefits. While it is EPA's burden to conduct this analysis, petitioners present some limited data on (1) the socio-economic costs of CO_2 pollution in light of ocean acidification, (2) the feasibility of controls on CO_2 pollution, and (3) the social cost of carbon including the costs of delaying action to reduce and mitigate CO_2 pollution.

a. Socioeconomic Costs of Ocean Acidification

The release of CO_2 into the environment is already having social and economic impact, and these impacts are predicted to become even more concerning. Primary economic concerns are from the loss of fisheries and coral reefs. Ocean acidification also poses food security and nutrition risks.

U.N. Convention on Biological Diversity estimated costs on the predicted damage of ocean acidification and predicts that the oceans will lose more than $1 trillion in value annually from ocean acidification (Convention on Biological Diversity 2014). CO_2 related ocean warming and acidification will threaten marine food resources by disrupting marine communities, promoting harmful algal blooms and the spread of some diseases, and increasing contaminants in fish and shellfish (Tirado et al. 2010).

The United Nations Environment Programme reported that ocean acidification's impact on marine organisms is a threat to food security (UNEP 2010). The report documents that ocean

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acidification is measurable and increasing, which poses a threat to fisheries resources and the billions of people that have a marine-based diet (United Nations Environment Programme 2010). Seafood has been shown to prevent hundreds of thousands of premature deaths, as well as significantly reduce infant morbidity; a decline of seafood availability will decrease these benefits. Some populations, including subsistence fishing populations and poor communities, depend on seafood and mortality and morbidity can result from the loss of these food sources (Mozaffarian 2006). For example, 95% of Alaskan households do some sort of subsistence fishing, and 17% of the state's population, 120,000 people, depend on subsistence fishing (Mathis et al. 2014). Many subsistence fishers also have cultural ties threatened by ocean acidification. Accordingly, CO_2 can result in social and environmental justice concerns that must also be assessed and weighed (Convention on Biological Diversity 2014).

Not only will ocean acidification affect global food webs and ecosystems, it will have a direct effect on the global economy. The U.S. economy is very dependent on the health of the ocean. In 2009, the ocean economy contributed over $223 billion annually to the U.S. gross domestic product and provided more than 2.6 million jobs (NOAA, http://oceanservice.noaa.gov/facts/oceaneconomy.html). Cooley and Doney (2009) estimate that if just a 10-25% decrease in United States mollusk harvests from 2007 were to occur today, $75-187 million in direct revenue would be lost each year henceforth, with a net loss of $1.7-10 billion through mid-century, when pH levels are approximately 0.3 units below pre-industrial values. In Washington State alone, the seafood industry generates $1.7 billion for gross state product and employs 42,000 people (Washington State Blue Ribbon Panel 2012). Already, shellfish hatchery failures in Washington have caused an economic stir and caused some hatcheries to relocate. Alaska's commercial fishing industry is valued at over $4 billion a year, and supports 90,000 jobs—recreational fishing and fishing tourism add even more value. Meanwhile, Alaska is ranked among the most vulnerable areas to acidification.

Tropical coral reefs provide ecosystem services, such as habitat and nursery functions for commercial and recreational fisheries and coastal protection. As reefs decline in acidified waters, there will be an ecological shift to a new ecosystem state dominated by less commercially valuable species. In 2009, Brander et al. estimated the annual economic damage of ocean acidification-induced coral reef loss to escalate rapidly over time, reaching $870 billion by 2100 (Brander et al. 2009a). In 2014, Brander et al. increased the anticipated loss of ecosystem services from corals to be $1000 billion (UNEP 2014). Shoreline protection offered by coral reefs and the services it provides by preventing loss of life, property damage and erosion are also reduced by CO_2 emissions.

Lane et al. (2014) modeled three major U.S. locations for shallow water reefs -- South Florida, Puerto Rico, and Hawaii – to project future reef cover and the economic values generated by coral reefs for a greenhouse gas emissions mitigation scenario that represents international implementation of policies to reduce global emissions (resulting in a CO_2 concentration of 427 ppm in 2100), compared to a business as usual greenhouse gas emissions scenario resulting in a CO_2 concentration of 785 ppm in 2100. The study estimated that reducing emissions would result in an "avoided loss" in Hawaii of approximately $10.6 billion in recreational use values compared to business as usual. Reducing emissions was projected to provide fewer economic benefits in Puerto Rico and South Florida, where sea-surface temperatures are already close to

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bleaching thresholds and coral cover is projected to drop well below 5% cover under both scenarios by 2050, and below 1% cover under both scenarios by 2100 (Lane et al. 2014).

As discussed previously, the toxicity of harmful algal blooms increases under conditions of ocean acidification. These toxins not only poison marine mammals, but also cause paralytic shellfish poisoning in people. Scientists hypothesize that some of the increases red tides off the coast of Southern California may be related to ocean acidification, though this has yet to be confirmed. In turn, harmful algal blooms cost the United States approximately $82 million each year from impacts to fisheries, public health, management, and lost recreational opportunities (Hoagland and Scatasta 2006).

A recent study estimated that the damage our oceans will face from emissions-related problems will amount to $428 billion a year by 2050 and nearly $2 trillion per year by the century's end (Noone et al. 2012).

> Acidification impacts processes so fundamental to the overall structure and function of marine ecosystems that any significant changes could have far-reaching consequences for the oceans of the future and the millions of people that depend on its food and other resources for their livelihoods.

(Doney et al. 2009). There is also a significant cost to delaying action. According to a recent report by the Council of Economic Advisers, delaying the implementation of policies to mitigate climate change could significantly increase economic damages, in addition to worsening environmental harm.[39]

While there are still large unknowns on the biological consequences of ocean acidification, the science we have is clear: from shellfish to corals, and from pteropods to fish, our marine resources are threatened by the acidification of our ocean waters.

b. Risk Reduction Methods

There are several ways to reduce risk from CO_2. EPA should use a suite of tools to reduce emissions, sequester CO_2, mitigate harms, and promote alternatives. Under TSCA EPA has authority to:[40]

- prohibit or limit the amount of production or distribution of a substance in commerce;
- prohibit or limit the production or distribution of a substance for a particular use;
- limit the volume or concentration of the chemical produced;
- prohibit or regulate the manner or method of commercial use;
- require warning labels and/or instructions on containers or products;
- require notification of the risk of injury to distributors and, to the extent possible, consumers;

[39] Executive Office of the President of the United States, The Cost of Delaying Action to Stem Climate Change at 1 (July 2014).
[40] 15 U.S.C. § 260.

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- require record-keeping by producers;
- specify disposal methods; and
- require replacement or repurchase of products already distributed.

EPA also may impose any of these requirements in combination or for a specific geographical region. [41] Specifically, the agency must impose controls sufficient "to protect adequately against such risk using the least burdensome requirement."[42]

There is evidence that many industries could employ existing technology to achieve meaningful emissions reductions affordably. EPA's own data demonstrate that lower pollution rates are readily achievable for many industrial sources of CO_2. For example, the agency has identified dozens of "control measures and energy efficiency options that are currently available for pulp and paper mill processes," ranging from technological upgrades to improved equipment maintenance.[43] Similarly, EPA has compiled more than a decade of reports on "cost-effective" control strategies and other approaches available to reduce cement plant CO_2 emissions, "includ[ing], for example, energy efficiency measures, reductions in cement clinker content, and raw materials substitution."[44]

Although cost-effective strategies to reduce CO_2 emissions are available, existing controls have not reduced CO_2 emissions sufficiently to protect against environmental harm. For example, most natural gas power plants have *never* exceeded the agency's recently proposed emissions limit, thus indicating that existing and newly constructed facilities could easily satisfy a more stringent standard.[45] Because energy-related CO_2 pollution accounts for more than eighty percent of U.S. greenhouse gas production, readily achievable reductions in this sector would significantly benefit the environment.[46] Similarly, the pulp and paper industry ranks among the largest consumers of energy,[47] and emitted nearly 58 million metric tons of CO_2 equivalent gases in 2004.[48] Moreover, market incentives and regulatory controls are effective in increasing the rate of innovation for technologies that can reduce CO_2 emissions.

If a chemical presenting an unreasonable risk to health and the environment has already been distributed, EPA may prescribe procedures by which relevant manufacturers and purchasers must replace or repurchase that chemical.[49] In the present situation, we urge the agency to exercise its

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[41] *Id.*
[42] 15 U.S.C. § 2605(a).
[43] *See* EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 11 (2010).
[44] EPA, National Emission Standards for Hazardous Air Pollutants From the Portland Cement Manufacturing Industry and Standards of Performance for Portland Cement Plants, 75 Fed. Reg. 54,970, 54,997 (Sep. 9, 2010).
[45] Ctr. for Biological Diversity, Comments on Standards of Performance for Greenhouse Gas Emissions from New Stationary Sources: Electric Utility Generating Units (Proposed Rule) Docket No. EPA-HQ-OAR-2013-0495 at 13-14 (May 9, 2014).
[46] U.S. Dept. of State, U.S. Climate Action Report at 16 (2010).
[47] *See* U.S. Energy Information Administration, First Use of Energy for All Purposes (Fuel and Nonfuel), 2010 (Mar. 2013), http://www.eia.gov/consumption/manufacturing/data/2010/#r1.
[48] EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 7 (2010).
[49] 15 U.S.C. § 2605(a)(7)(C).

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authority to remediate existing harm by requiring that responsible parties mitigate past CO_2 emissions.

There are numerous approaches to mitigating and sequestering CO_2 emissions that EPA must evaluate. Effective land use and agricultural practices can significantly reduce carbon emissions and sequester CO_2. Federal programs aimed at consumers can reduce CO_2 emissions. For example, EPA's Energy Star program has prevented 1.8 billion tons of greenhouse gas emissions by providing information that helps customers select energy efficient devices. Sequestration of CO_2 in products, infrastructure, and waste management are among numerous methods that could be cost-effective to mitigate CO_2 pollution.

c. Social Costs of Carbon

In any analysis of the cost and benefits of reducing CO_2 pollution, the costs of failing to address the problem of global warming should be included. Most efforts to quantify the social costs of carbon underestimate the real-world costs of CO_2 pollution. Nevertheless, EPA may not ignore these costs.

Global emissions must be less than 1000 Gt of CO_2 between 2000 and 2050 to avoid dangerous climate change, which scientists have recommended that this means maintaining temperature change below 2° C.[50] This means keeping atmospheric CO_2 to 450 ppm, a threshold below which experts also use for ocean acidification (Veron et al. 2009; Silverman et al. 2009; Interacademy Panel 2009; McNeil & Matear 2008; Sea et al. 2007). For example, coral scientists predict that at 450 ppm, reef-building will be severely diminished or will cease altogether (Veron et al. 2009). But the global community has already used a substantial portion of this CO_2 budget, emitting 305 Gt of CO_2 between 2000 and 2008 alone.[51] As a result, the years between now and 2020 have been dubbed the "critical decade."[52] Because carbon emissions must peak soon and decline thereafter, the sooner emissions peak, the less severe the subsequent annual reductions will need to be;[53] correspondingly, if emissions are not sufficiently curbed in this decade, avoiding catastrophic damages will require much more drastic, disruptive and costly measures and may no longer be possible at all. Nonetheless, if action is taken immediately, it is both technologically and economically feasible to reduce emissions by 2020 and lay the groundwork for future emissions reductions.[54]

Every year that the world delays its efforts to reach sustainable levels of greenhouse gas emissions represents a lost opportunity of tremendous economic significance. McKinsey & Company estimated in 2009 that for every year of delay, 1.8 Gt of potential CO_2 abatement is foregone.[55] This delay, and the accompanying Gts of lost CO_2 abatement, has a price tag, as the

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[50] Australia Department of Climate Change and Energy Efficiency, The Critical Decade: Climate Science, Risks and Responses at 53 (May 2011), *available at* http://www.scribd.com/doc/56043375/The-Critical-Decade-Climate-Change-Commision-Report.
[51] *Id.*
[52] *Id.*
[53] UNEP, The Emissions Gap Report at 14 (Nov. 2010), *available at* http://www.unep.org/publications/ebooks/emissionsgapreport/; for a discussion of economic implications of these facts, *see infra.*
[54] *Id.* at 23.
[55] McKinsey & Company, Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve at 16 (2009), *available at* www.worldwildlife.org/climate/WWWFBinaryitem11334.pdf.

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damage caused by CO_2 emissions accelerate while the cumulative amount of greenhouse gases in the atmosphere rises, both because of the increasingly dire damages wrought by rising temperatures and other greenhouse gas effects, *and* because of the delay factor itself. If governments delay mitigation in the present, the emissions reduction curve in future years necessarily becomes much steeper, requiring much more drastic and costly emission reduction mechanisms with tremendous economy-wide disruptions, just to "catch up" with the lost opportunities from prior years to reach a sustainable emissions trajectory—or risk undergoing unsustainable climatic extremes.

Economists have sought to quantify the costs of waiting to embark upon an emissions reduction path. In 2007, researchers used the DICE model[56] to estimate the cost of delaying mitigation for a given period of time and then switching to an optimal abatement trajectory. According to their findings, the global cost of ten years of delay, relative to starting on an optimal trajectory in the present, ranges from hundreds of billions to several trillion dollars.[57] For instance, this study estimates that it would cost somewhere between $200 and $400 billion dollars to delay action for ten years and then embark upon a mitigation strategy that would result in stabilization at 3 °C (a level now universally understood to far exceed the dangerous). The cost of delaying mitigation soars into the trillions of dollars as the delay continues, until it ultimately becomes impossible to achieve a certain level of temperature stabilization. According to this study, more than thirty years' delay of changing the current course would make it impossible – no matter what the expense – to stabilize temperature rises at 2° C above pre-industrial levels.

EPA and other federal agencies have been using the social cost of carbon to estimate the climate benefits of rulemakings since it was first developed by a dozen agencies (including USDA, CEQ and EPA) and published by the Interagency Working Group in 2010.[58] The social cost of carbon, usually expressed as a dollar-per-ton figure, provides an estimate of the economic damages associated with an increase in CO_2 emissions, conventionally one metric ton, in a given year. The dollar figure can also represent the value of damages avoided for emission reductions achieved by federal rulemakings. The social cost of carbon is designed to provide a comprehensive estimate of climate change damages, including, but not limited to, changes in net agricultural productivity, human health, and property damages from increased flood risk. However, given current modeling and data limitations, even EPA has conceded that that the social cost of carbon protocol is likely a conservative estimate because it does not yet account for all important damages.[59] Nevertheless, the protocol is designed for use in regulatory processes like this one. In 2013 the Federal Interagency Working Group increased its estimates of the social cost of carbon, using the same 3% annual discount rate, by 50%.[60] The 2013 estimates are 50% higher for emissions in 2010, with greater percentage increases in subsequent years. Yet, even these social

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[56] DICE stands for the Dynamic Integrated Climate and Economy model developed by William Nordhaus in 1990.
[57] Keller, K. et al., The Regrets of Procrastination in Climate Policy, Environmental Research Letters (2007), *available at* iopscience.iop.org/1748-9326/2/2/024004/.
[58] EPA, The Social Cost of Carbon, http://www.epa.gov/climatechange/EPAactivities/economics/scc.html (last accessed June 28, 2015).
[59] *Id.*
[60] Interagency Working Group on Social Cost of Carbon, United States Government, Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 (Nov. 2013) at 3, available at http://www.whitehouse.gov/sites/default/files/omb/assets/inforeg/technical-updatesocial-cost-of-carbon-for-regulator-impact-analysis.pdf.

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cost of carbon figures significantly underestimate the true social cost of carbon, possibly by several orders of magnitude.

Economists have noted that the social cost of carbon is far greater than the $21 per ton of CO_2 assumed by interagency protocol in 2010 and greater than the 2013 revision.[61] There are several inadequacies that make the values too conservative. Foremost, the models fail to evaluate ocean acidification—to the contrary the models consider the ocean a sink for CO_2. The FUND model used in the Working Group's analysis wholly excludes consideration of climate-induced catastrophic events. But the Working Group weighs the values generated by each of the three models equally, even though the FUND model's values is significantly lower[62] than the others, and consequently pulls down the final value of the social cost of carbon. The potential for catastrophic climate events, and the increasing likelihood that tipping points will be reached even sooner than anticipated, are increasingly serious risks, however, and, despite the associated uncertainties, must be fully represented in any evaluation of the social cost of carbon. Instead, the Working Group employed a risk-neutral approach, clearly inappropriate in light of the vast majority of scientific studies. Also, the models used fail to account fully or even partially for certain highly complex aspects of climate change, including the possibility of interrelations between different sectors and accelerating damage feedback loops, non-CO_2 emissions,[63] and social and political instability. Moreover, the valuation techniques and discount rates used to reach these values are inherently problematic and fail to represent the full value of all losses from climate change, in significant part because some cannot be reduced to monetary terms.

Other evaluations of the social cost of carbon attempt to account for these omitted factors. The Stern Review, in particular, reaches a SCC of $85/ton of CO_2 (in 2000 dollars).[64] For comparison purposes with a Working Group value of $21 in 2005 dollars, this amount is equivalent to

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[61] F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon (2010) (the social cost of carbon could be over $800 per ton of CO2 equivalent; F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon, in Economics, vol. 6 (Apr. 4, 2012) (reaching similar conclusions), available online at http://www.economics-ejournal.org/economics/journalarticles/2012-10 (last visited June 27, 2014); P. Epstein et al., Full cost accounting for the life cycle of coal, Ann. N.Y. Acad. Sci. (2011) (estimating the social cost of coal at between $10 and $100 per ton of CO2 equivalent); L. Johnson & C. Hope, The social cost of carbon in U.S. regulatory impact analyses: an introduction and critique, J. Envtl. Stud. & Sci. (Sept. 9, 2012) (finding a social cost of a ton of CO2 emissions to be 2.6 to over 12 times larger than the Interagency Working Group's central estimate of $21 per ton of CO2) available online athttp://link.springer.com/article/10.1007%2Fs13412-012-0087-7 (last visited June 27, 2014) E. Stanton et al., Comments on the 2013 Technical Update of the Social Cost of Carbon, January 27, 2014.

[62] Interagency Working Group on the Social Cost of Carbon, Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, at 16-A-11, Fig. 16-A-4.2, *available at* http://www.rff.org/Publications/WPC/Pages/Estimating-the-Social-Cost-of-Carbon-for-Regulatory-Impact-Analysis.aspx.

[63] For instance, the estimated social cost of methane and SF_6, are, respectively, $105/tonne and $200,000/tonne. *See* Intergovernmental Panel on Climate Change, Climate Change 2007 Synthesis Report 822, *available at* http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html. For a critical analysis of the Working Group's assumptions, *see also* Ackerman, F. and Stanton, E. A., The Social Cost of Carbon A Report for the Economics for Equity and the Environment Network (April 1, 2010), *available at* http://www.e3network.org/papers/SocialCostOfCarbon_SEI_20100401.pdf.

[64] Nicholas Stern, Stern Review on the Economics of Climate Change Part III: The Economics of Stabilisation at 287 (2006), *available at* http://webarchive.nationalarchives.gov.uk/+/http:/www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm.

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$96.25/ton in 2005. The Stern Review uses the PAGE model, which explicitly models for the risk of catastrophic climate change.[65] In contrast with the Working Group, the Stern Review uses a mean temperature increase of 3.9 °C for its baseline scenario (consistent with the Third IPCC Report) and a 4.3 °C increase for its higher climate scenario. The resulting higher value of the social cost of carbon is thus very likely to be a closer approximation of the real cost of CO_2.

Meanwhile, the costs of reducing CO_2 emissions are well worth taking prompt action. The "central estimates of the annual costs of achieving stabilisation between 500 and 550ppm CO_2 are around 1% of global GDP, if we start to take strong action now. [...] It would already be very difficult and costly to aim to stabilise at 450ppm CO_2e. If we delay, the opportunity to stabilise at 500-550ppm CO_2e may slip away.'"(Stern 2006). Likewise, the benefits of addressing CO_2 for ocean acidification also have the ancillary effect of slowing global warming and preventing costs associated with climate change.

The recently proposed rule to reducing power plant CO_2 emissions calculates both costs and benefits—notably the benefits far exceed the costs. The recently proposed rules for reducing power plant carbon emissions, calculates both costs and benefits for a more modest reduction. EPA projects that the annual compliance cost will be $4.3 to $5.5 billion (in 2011 dollars, depending on discount rate) in 2020 and $5.5 billion (for a 5% discount rate) in 2030.[66] The total combined climate benefits and health co-benefits are estimated to be $15.6 to $88 billion in 2020 and $32.3 to $151 billion in 2030 (depending on discount rate and the options chosen).[67] The insurance industry also is well aware of the potential costs of failing to address CO2 emissions and its associated effects, including: "[h]urricanes and other flooding events … [h]ealth issues associated with heat waves… more airborne allergens, rising temperatures, greater humidity, more wildfires, and more dust and particulate pollution may considerably exacerbate upper respiratory disease (rhinitis, conjunctivitis, sinusitis, asthma) and cardiovascular disease."[68] A European insurance company estimates losses from extreme climate change events of 37% within a decade, over $1 trillion under bad circumstances.[69] The increasing frequency and severity of storms in the U.S. has caused damages to increase 60-fold from 1950s to the 1990s.[70]

Petitioners ask that action to mitigate ocean acidification under TSCA be initiated, either through TSCA section 6 (e.g., requiring "repurchasing" relief using sequestration, emission reductions, etc.), or through section 4 in order to determine the need for action under section 6 and the most effective mitigation strategies. In any case, petitioners suggest that costs be apportioned among

[65] According to the Working Group itself, DICE "offers the best insight into the SCC if the world were to experience catastrophic climate change." *See* Working Group, *supra* note 62, at 16-A-35.
[66] EPA, Regulatory Impact Analysis Technical Document EPA-452/R-14-002 (June 2014).
[67] *Id.*
[68] National Association of Insurance Commissioners, The Potential Impact of Climate Change on Insurance Regulation at 10 (2008).
[69] See e.g. Allianz, Climate Change and the Financial Sector: An Action Plan; Evan Mills, Responding to Climate Change: The Insurance Industry Perspective.
[70] Mills, E. Insurance in a Climate of Change, Science 308: 1040 (2005).

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CO_2 emission contributors according to the cumulative CO_2 emission inventory information EPA has collected.[71]

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In summary, the weight of the scientific information on ocean acidification is sufficient to make a determination that CO_2 poses an unreasonable risk, to the extent that EPA declines to find the data adequate, then EPA must develop a test rule under TSCA section 4 as described below.

C. Alternatively, EPA Must Require Testing to Develop Adequate Data

EPA must make a determination as to whether adequate data exist to evaluate the environmental and health effects of CO_2. There is well-established scientific information on the risk of CO_2 on the environment, but if EPA determines that the data are insufficient then it must develop a testing rule.

In enacting TSCA, Congress declared that "adequate data should be developed with respect to the effect of chemical substances and mixtures on health and the environment and that the development of such data should be the responsibility of those who manufacture and those who process such chemical substances and mixtures."[72] Accordingly, section 4 directs EPA to require additional testing upon determining that "the manufacture, distribution in commerce, processing, use, or disposal of chemical substance or mixture … may present an unreasonable risk of injury to health or the environment," or if the chemical is produced in substantial quantities and there is a potential for a substantial quality to be released into the environment.[73]

1. CO_2 May Present an Unreasonable Risk

As described in depth in this petition, CO_2 may present an unreasonable risk to the environment. EPA interprets this to mean that there is a "substantial (i.e., more than theoretical) probability" of unreasonable risk to the environment or health.[74] The information in this petition meets the threshold for a testing rule and establishes a substantial probability that CO_2 poses an unreasonable risk to the environment, but EPA need not even make such a determination because CO_2 is produced in such large volumes that it clearly meets the criterion of exposure of substantial quantities being released into the environment.

2. Substantial Quantities of CO_2 Are Released into the Environment

It is undeniable that substantial qualities of CO_2 are released into the environment. EPA established a threshold value of one million pounds for a release of a chemical to be substantial. *TSCA Section 4(a)(1)(B) Final Statement of Policy; Criteria for Evaluating Substantial*

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[71] This could be structured similar to the sponsorship format used in TSCA's High Production Volume (HPV) Program.
[72] 15 U.S.C. § 2601(b)(1).
[73] 15 U.S.C. § 2603 (a)(1)(A), (B)(i).
[74] *Chemical Mfrs. Ass'n v. EPA*, 859 F.2d 977, 988 (D.C. Cir. 1988).

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Production, Substantial Release, and Substantial or Significant Human Exposure, 58 Fed. Reg. 28736, 28746 (May 14, 1993). According to the IPCC:

> From 1750 to 2011, CO_2 emissions from fossil fuel combustion and cement production have released 375 [345 to 405] GtC to the atmosphere, while deforestation and other land use change are estimated to have released 180 [100 to 260] GtC. This results in cumulative anthropogenic emissions of 555 [470 to 640] GtC.

(IPCC 2013, Summary for Policymakers).

In 2012, a total of 9.7 gigatonnes of CO_2 were released into the atmosphere from fossil fuel combustion and cement production (Global Carbon Project 2013). These emissions are expected to increase to 9.9 gigatonnes in 2013 (*Id.*). The United States contributed 14% of CO_2 emissions to the atmosphere (*Id.*). Models estimate that between 2003 and 2012, the oceans absorbed 27% of CO_2 from the atmosphere (*Id.*). Over the next millennium, the oceans will absorb 90% of anthropogenic CO_2 (Kleypas et al. 2006).

Therefore, the threshold of substantial release is exceeded by more than a million times over.

3. Recommendations for Testing

EPA should consider a test rule to fill the information gaps needed to make a determination of whether CO_2 presents an unreasonable risk of injury to the environment. Some recommendations for consideration include:

- Testing CO_2 reduction strategies. For example, research and development for emissions reduction strategies that include alternative practices, conservation, alternative fuels. Testing CO_2 sequestration and capture approaches, and assessing attainable CO_2 emissions reductions for industries with significant CO_2 emissions.
- Conducting a vulnerability assessment for marine and coastal species and ecosystems. Determining atmospheric CO_2 levels necessary to conserve marine ecosystems from dangerous ocean acidification. Emissions scenarios are important for informing policy approaches to acidification.
- Forecasting species' responses to ocean acidification using modeling tools to predict range shifts, demographic and population trends, and physiological responses across taxonomic groups using a range of climate models, emissions scenarios, and management timelines (25, 50, 100 years). Identify wildlife species and ecosystems imperiled by ocean acidification by evaluating range shift models and population viability models run under future ocean acidification levels. Recommend conservation actions, including protected status, for species that are most at risk. Protect species across their range since populations are likely to have different adaptations to local oceanic conditions.
- Determining the economic values of ecosystems that are at risk from ocean acidification and the costs of reducing CO_2 emissions to preserve those ecosystems.

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Additionally, EPA can use guidance on research needs based on existing research plans. There are a number of sources recommending research and data needs (National Research Council 2013; Washington State Blue Ribbon Panel 2012; National Research Council 2010).

According to TSCA, developing the data is "the responsibility of those who manufacture and those who process such chemical substances and mixtures."[75] For example, responsibility could be apportioned based on the historical carbon emissions from the EPA Greenhouse Gas Emission Inventory together with current emissions. Typically for test rules with multiple responsible parties consortiums are set up to comply.[76] Here, for example, utilities, cement and lime manufacturers, waste incinerators, and other large producers of CO_2 should be responsible for developing unbiased, independent data.

While this may seem like a complicated undertaking, EPA has successfully completed more complex test rules. For example, from 1998 through the present, the agency used three sets of regulatory test rules under TSCA to collect chemical data for almost 3,000 high production volume (HPV) chemicals, including over 10,000 individual studies with data from domestic and foreign producers.[77]

EPA must develop test rules under TSCA section 4 for research and data development focused on information essential for making a definitive TSCA section 6 finding. These would include risk, benefit and cost information.

D. Inadequacy of Existing CO_2 Reduction Strategies

Petitioners are aware that the Agency has recently planned and initiated several emission reduction actions aimed at slowing the rate at which carbon emissions are increasing. However, these actions by themselves, while laudable, will not stabilize atmospheric CO_2 at a level which will prevent widespread harm from ocean acidification.

1. Global Greenhouse Gas Emissions Are Increasing Substantially

The atmospheric concentration of CO_2 reached 400 parts per million (ppm) for the first time in human history in May, 2013, compared to the pre-industrial concentration of ~280 ppm (Scripps Institution of Oceanography 2013). The current CO_2 concentration has not been exceeded during the past 800,000 years and likely not during the past 15 to 20 million years (Denman et al. 2007; Tripati et al. 2009). Atmospheric CO_2 emissions have risen particularly rapidly since the 2000s (Raupach et al. 2007; Friedlingstein et al. 2010). The global fossil fuel CO_2 emissions growth rate was 1.0% per year in the 1990s compared with 3.1% per year since 2000, and this growth rate has largely tracked or exceeded the most fossil-fuel-intensive emissions scenarios projected by the IPCC (A1FI and RCP 8.5) since 2000 (Raupach et al. 2007, Peters et al. 2012). The CO_2 emissions growth rate fell slightly in 2009 due largely to the global financial and economic

[75] 15 U.S.C. § 2601
[76] 15 U.S.C. § 2602 (b)(3)(A)
[77] EPA, High Production Volume (HPV) Challenge; http://www.epa.gov/chemrtk/index.htm (last accessed June 28, 2015).

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crisis; however, the decrease was less than half of what was expected and was short-lived (Fiedlingstein et al. 2010). In 2014 and 2015, global CO_2 concentrations exceeded 400ppm.[78]

2. U.S. Measures to Reduce Greenhouse Gas Emissions Are Insufficient

EPA has taken some initial steps toward curbing greenhouse pollution under the Act. In 2009, the agency issued a formal finding that greenhouse pollution endangers public health and welfare and moved to limit emissions from passenger cars and trucks. The EPA also acknowledged that major new or modified "stationary" sources of greenhouse pollution, like power plants and factories, must obtain permits and control their emissions before beginning construction. However, it narrowed the scope of this requirement considerably under its so-called "tailoring rule," which initially limits the permitting program to only a few hundred very large sources of greenhouse gases, letting a huge number of smaller — but still significant — sources off the hook.

While existing domestic laws including the Clean Air Act, Energy Policy and Conservation Act, Clean Water Act, Endangered Species Act and others provide authority to executive branch agencies to require greenhouse gas emissions reductions from virtually all major sources in the United States, these agencies are either failing to implement or only partially implementing these laws for greenhouse gases. The landmark 2014 pact with China to reduce greenhouse gas emissions is significant, but there is little to ensure it is enforced and implemented. According to the plan, United States will reduce CO_2 emissions 26 to 28% below 2005 levels by 2025.

Proposed power plant rules also fail to do enough to cut CO_2 pollution. Using the Clean Air Act, the president aims to reduce existing power plant emissions 30 percent below 2005 levels (or about 7.7 percent below 1990 levels, the base year for the international climate treaty) by 2030. But international scientists warned years ago that developed countries like the United States must reduce their emissions 25 percent to 40 percent below 1990 levels by 2020 to avoid tipping the scales further toward a climate catastrophe. Likewise, the recently announced plans to limit power plant emissions (Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units) focuses on emission reduction. Power plants are responsible for about a third of our carbon emissions, and the rule is designed to reduce those emissions by almost a third by 2030. This would result in a 10% decrease in 15 years. Stabilizing atmospheric concentration to prevent further acidification of the oceans would require about an 80% decrease in all emissions. Clearly this is a good first step, but by itself inadequate to address acidification.

EPA has issued a rulemaking regulating greenhouse gas emissions from automobiles that will reduce greenhouse emissions emitted per vehicle mile traveled by passenger vehicles in the future. But because the improvements are modest and more vehicles are projected to drive more miles in the future, the rule will not reduce emissions from this sector overall but will only slow the rate of increase.[79] Meanwhile, even the government concedes that "these reductions in emissions are not sufficient by themselves to reduce total HD vehicle emissions below their 2005

[78] NOAA, Trends in Atmospheric Carbon Dioxide, http://www.esrl.noaa.gov/gmd/ccgg/trends/
[79] EPA, Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule, 75 Fed. Reg. 25324 (May 7, 2010).

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levels by 2020."[80] This means that the vehicle rule is far from achieving emissions goals agreed to by the U.S. in the Copenhagen Accord, which aim to keep global warming below 2˚C.

The EPA has also to date issued only a single proposed rule under the new source pollution standard program for stationary sources of pollution, for electric generating units (power plants). While there is enormous potential to reduce emissions through this program overall and through the power plants rule in particular, the EPA has instead proposed a weak and flawed rule that it admits will not reduce emissions from these sources between now and 2020 compared to what would be expected without the rule.[81] Indeed, in the rulemaking the EPA conceded that new power plant rule on greenhouse gas emissions "will not have direct impact on U.S. emissions of greenhouse gases under expected economic conditions."[82]

While full implementation of our flagship environmental laws, particularly the Clean Air Act, would provide an effective and comprehensive greenhouse gas reduction strategy, due to their non-implementation, existing domestic regulatory mechanisms must be considered inadequate to protect marine species from climate change and ocean acidification.

3. International Measures to Reduce Greenhouse Gas Emissions Are Inadequate

International initiatives are also currently inadequate to effectively address climate change. The United Nations Framework Convention on Climate Change, negotiated in 1992 at Rio de Janeiro, Brazil, provides the forum for the international negotiations. In the Framework Convention, signed and ratified by the United States, the world agreed to take the actions necessary to avoid dangerous climate change. Parties to the Convention also agreed as a matter of fairness that the world's rich, developed countries, having caused the vast majority of emissions responsible for the problem, would take the lead in solving it. It was not until the 1997 meeting in Kyoto, Japan, that the first concrete, legally binding agreement for reducing emissions was signed: the Kyoto Protocol. The Protocol requires the world's richest countries to reduce emissions an average of 5 percent below 1990 levels by 2012, while developing nations also take steps to reduce emissions without being subject to binding emissions targets as they continue to raise their standard of living. The United States has been a major barrier to progress in the international negotiations. After the Clinton administration extracted many concessions from the rest of the world in exchange for the United States signing on in Kyoto, the Senate rejected the equity principles behind the Convention, saying the United States should not agree to reduce its own emissions unless all other countries — regardless of their responsibility or ability — were similarly bound. Citing the same excuses, President George W. Bush repudiated the Kyoto Protocol entirely. Thus the United States is the only industrialized country in the world that has yet to ratify the Kyoto Protocol. The United States negotiating team under both the George W. Bush and the Obama administrations has pursued two primary objectives in the international talks: to refuse any legally binding emissions reduction commitments until all other

[80] NHTSA, Medium- and Heavy-Duty Fuel Efficiency Improvement Program – Final Environmental Impact Statement (June 2011).
[81] EPA, Standards of Performance for Greenhouse Gas Emissions for New Stationary Sources: Electric Utility Generating Units, 77 Fed. Reg. 22392, 22430-33 (April 13, 2012).
[82] *Id.* at 22401.

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countries— but particularly China and India — do so, and to push back the date for a new agreement. Not surprisingly, the United States had failed to meet its (never ratified) Kyoto pledge to reduce emissions to 7.2% below 1990 levels by 2012; to the contrary, U.S. emissions have increased by 10.5% since 1990 (EPA 2012).

Moreover, the Kyoto Protocol's first commitment period only sets targets for action through 2012, and there is still no binding international agreement governing greenhouse gas emissions in the years beyond 2012. While the 2009 U.N. Climate Change Conference in Copenhagen called on countries to hold the increase in global temperature below 2°C (an inadequate target for avoiding dangerous climate change), the non-binding "Copenhagen Accord" that emerged from the conference, and the subsequent "Cancún Accords" of 2010 and "Durban Platform" of 2011 failed to enact binding regulations that limit emissions to reach this goal.[83] Even if countries were to meet their Copenhagen and Cancún pledges, analyses have found that collective national pledges to cut greenhouse gas emissions are inadequate to achieve the 2°C target, and instead suggest emission scenarios leading to 2.5°C to 5°C warming (Rogelj et al. 2010; UNEP 2011; UNEP 2010). As of July 2013, many governments were not implementing the policies needed to meet their inadequate 2020 emission reduction pledges, making it more difficult to keep global temperature rise to 2°C and likely leading to a temperature rise of at least 3.5°C (USGCRP 2013). As noted in the NMFS Management Report, the U.S. has yet to issue regulations to limit greenhouse gas emissions in accordance with its pledge under the Copenhagen Accord (NMFS 2012).

CONCLUSION

In conclusion, this petition requires EPA to make a determination whether CO_2 poses an unreasonable risk to the environment therefore requiring regulation under section 6 of TSCA. In an extensive review of the literature on the impact of ocean acidification on marine fauna and ecosystem processes, the authors found that while additional research is called for, sufficient information exists to state with certainty that deleterious impacts on some marine species are unavoidable, and that substantial alteration of marine ecosystems is likely over the next century. (Fabry et al. 2008). If, nonetheless, EPA determines that the information is insufficient to make such a finding it must develop testing rules pursuant to TSCA section 4.

[83] The non-legally binding Copenhagen Accord of 2009 and Cancún Accords of 2010 recognize the objective of limiting warming to 2°C above pre-industrial temperatures, but do not enact binding regulations to achieve this goal (http://cancun.unfccc.int/cancun-agreements/main-objectives-of-the-agreements/#c33; unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf). According to the Durban Platform, developed and developing nations agreed to a process to develop a "new protocol, another legal instrument, or agreed outcome with legal force that will be applicable to all Parties to the UN climate convention"; this legal instrument must be developed as of 2015 and will not take effect until 2020 (unfccc.int/resource/docs/2011/cop17/eng/l10.pdf).

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BEFORE THE ENVIRONMENTAL PROTECTION AGENCY

PETITION FOR RULEMAKING PURSUANT TO SECTION 21 OF THE TOXIC SUBSTANCES CONTROL ACT, 15 U.S.C. § 2620, CONCERNING THE REGULATION OF CARBON DIOXIDE

Credit: NOAA

CENTER FOR BIOLOGICAL DIVERSITY

DONN J. VIVIANI, PhD

PETITIONERS

June 30, 2015

NOTICE OF PETITION

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The Center for Biological Diversity ("Center") is a non-profit, public interest environmental organization dedicated to the protection of native species and their habitats through science, policy and environmental law. The Center has over 800,000 members and online activists throughout the United States and around the world. The Center's Oceans Program and its supporters are specifically concerned with the conservation of marine species, the preservation of ocean ecosystems and the effective implementation of U.S. environmental laws, including the Toxic Substances Control Act. The Center submits this petition on its own behalf and on behalf of its members and staff with an interest in protecting the marine environment.

Donn J. Viviani, PhD, is a retired U.S. Environmental Protection Agency scientist. He was the Director of the Climate Policy Assessment Division in the Office of Policy, Economics and Innovation. He also served as Chairman of the Great Lakes Water Board's Toxic Substances Committee and as a member of the Science Coordinating Committee for the International Joint Commission for the Great Lakes. Dr. Viviani enjoys the ocean and submits this petition, in part, so his grandchildren will be able to enjoy it as well. Dr. Viviani also submits a supplement to the petition, under his signature only, and respectively requests that it be considered.

ACTION REQUESTED

Pursuant to section 21 of the Toxic Substances Control Act ("TSCA" or the "Act"), 15 U.S.C. § 2620, and section 553(e) of the Administrative Procedure Act ("APA"), 5 U.S.C. § 553(e), the Center for Biological Diversity and Donn J. Viviani (collectively, "Petitioners") hereby petition the Administrator of the U.S. Environmental Protection Agency ("EPA") to promulgate regulations protecting public health and the environment from the serious harms associated with anthropogenic emissions of carbon dioxide, including ocean acidification. Specifically, Petitioners request that EPA adopt a rule under section 6 of the Act, 15 U.S.C. § 2605, requiring manufacturers and processors to mitigate these emissions.

This petition sets in motion a specific process, placing definite response requirements on EPA. Specifically, TSCA stipulates that the agency "*shall* either grant or deny the petition" within 90 days following its receipt, "promptly commenc[ing] an appropriate [rulemaking]

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proceeding" if such action is warranted. 15 U.S.C. § 2620(b)(3) (emphasis added). Conversely, should EPA deny this petition, the agency must publish the reasons for denial in the Federal Register. 15 U.S.C. § 2620(b)(3); *see also* 5 U.S.C. § 555(e) ("Prompt notice shall be given of the denial in whole or in part of a written application, petition, or other request of an interested person made in connection with any agency proceeding."). Pursuant to 15 U.S.C. § 2620(b)(4), petitioners may file suit in federal district court to challenge an adverse or untimely determination. *See also* 5 U.S.C. §§ 702, 706.

As described in this petition, anthropogenic emissions of carbon dioxide satisfy the standard for regulation set forth at 15 U.S.C. § 2605. For example, EPA has acknowledged that these emissions have the potential to alter ocean chemistry, thus imperiling important marine ecosystems and presenting an unreasonable risk of injury to the environment. Accordingly, the agency must promptly commence the proposed rulemaking to reduce and mitigate these harms. In the event that EPA concludes that there are insufficient data and experience upon which to determine or predict the effects of carbon dioxide emissions, we alternatively request that the agency adopt a rule under section 4 of the Act, 15 U.S.C. § 2603, requiring manufacturers and processors responsible for the generation of carbon dioxide to undertake testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Dated this 30th day of June 2015.

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INTRODUCTION

Ocean acidification — caused by carbon dioxide ("CO_2") emissions — is a severe threat to the marine environment and the health of people who depend on oceans and coasts. Because of the unreasonable risk that CO_2 poses to the environment and human health, this petition seeks rulemaking under the Toxic Substances Control Act ("TSCA") to regulate CO_2 from cradle to grave.

About 28% of CO_2 emissions from power generation, cement production, industry, and other sources are absorbed by the ocean. These CO_2 emissions cause seawater to become more acidic and corrosive to sea life. Anthropogenic CO_2 emissions have increased the acidity of the oceans on average by 30%, and by the end of the century scientists predict that the oceans will become 150-170% more acidic.

While the most dangerous consequences of CO_2 on our oceans are still to come, harmful impacts on the environment are already well-documented.

- Billions of oyster larvae have perished in the Pacific Northwest due to ocean acidification;
- 53% of pteropods, plankton that form the base of the marine food web, along the West Coast have severely dissolved shells because of the corrosive nearshore conditions; and
- Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%.

These are just some of the harmful environmental impacts of ocean acidification caused by CO_2 emissions. Anthropogenic CO_2 emissions are contributing to increasingly corrosive conditions for marine animals, and will continue to grow more severe absent actions to promptly reduce CO_2 pollution in the atmosphere.

TSCA was enacted in part to address the threat of ozone depletion caused by chlorofuorocarbon (CFC) emissions. And here again TSCA regulation is needed where airborne emissions are causing damage to our environment — this time threatening ocean ecosystems, fish and shellfish industries, and communities that depend on oceans and coral reefs.

Petitioners specifically request that EPA take the following actions:

1. **Make a determination under TSCA § 6 that CO_2 presents an unreasonable risk of injury to health or the environment; and**
2. **Initiate rulemaking to control CO_2; or**
3. **If EPA finds data inadequate to make a §6 determination then EPA must initiate rulemaking for testing under TSCA § 4.**

This petition presents scientific evidence that establishes that CO_2 presents an unreasonable risk of injury to the environment, and therefore EPA must take action under TSCA section 6.

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I. The Toxic Substances Control Act

Congress enacted TSCA, 15 U.S.C. §§ 2601 *et seq.*, "to assure that … innovation and commerce in … chemical substances and mixtures do not present an unreasonable risk of injury to health or the environment."[1] Accordingly, lawmakers required those responsible for the manufacture and processing of these compounds to develop "adequate data" describing their effects, and authorized EPA to devise and implement reasonable controls to prevent the risk of injury to health or the environment.[2]

Section 6 of TSCA mandates that EPA "shall" regulate a chemical substance for which

> there is a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance or mixture, or that any combination of such activities, presents or will present an unreasonable risk of injury to health or the environment.[3]

Permissible regulations include requirements prohibiting or "limiting the amount of such substance … which may be manufactured, processed, or distributed in commerce."[4] EPA can also require processors "to give public notice of such risk [of injury], and . . . to replace or repurchase such substance . . . to adequately protect health or the environment."[5] In assessing risk, EPA must consider:

> (A) the effects of such substance or mixture on health and the magnitude of the exposure of human beings to such substance or mixture,
> (B) the effects of such substance or mixture on the environment and the magnitude of the exposure of the environment to such substance or mixture,
> (C) the benefits of such substance or mixture for various uses and the availability of substitutes for such uses, and
> (D) the reasonably ascertainable economic consequences of the rule, after consideration of the effect on the national economy, small business, technological innovation, the environment, and public health.[6]

Thus, if there is a reasonable basis to conclude that a proposed rule is necessary to protect the environment, then EPA must grant a petition for rulemaking and initiate rulemaking procedures. Factual certainty is not required; instead, the agency may "base its action on scientific theories, consideration of projections from available data, modeling using reasonable assumptions, and extrapolations from limited data."[7] Even if EPA determines that another federal law "could

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[1] 15 U.S.C. § 2601(b)(3) (2012). Within the meaning of TSCA, the term "chemical substance" includes "any organic or inorganic substance of a particular molecular identity." *Id.* § 2602(2).
[2] *Id.* § 2601(b)(1) & (2).
[3] *Id.* § 2605(a) (emphasis added).
[4] *Id.* § 2605(a)(1)(B).
[5] *Id.* § 2605(b)(2)(B).
[6] *Id.* § 2605(c)(1). E.
[7] Lead Fishing Sinkers; Response to Citizens' Petition and Proposed Ban, 59 Fed. Reg. 11,122, 11,138 (Mar. 9, 1994) (*citing* H.R. Rep. No. 1341, 9th Cong., 2d Sess. 32 (1976)).

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[sufficiently] eliminate[] or reduce[]" the risk associated with a particular chemical substance, the agency may elect to regulate the substance under TSCA, provided that a "comparison of the estimated costs" and "relative efficiency" reveals that such action promotes the public interest.[8]

In the event that EPA lacks adequate data and experience upon which to determine the health and environmental risks associated with a particular chemical substance, the agency "*shall* by rule require that testing be conducted on such substance."[9] Specifically, Section 4 of the Act authorizes EPA to compel manufacturers and processors to evaluate the safety of substances that "may present an unreasonable risk of injury to health or the environment" or that "[are] or will be produced in substantial quantities" and, thus, "may reasonably be anticipated to enter the environment in substantial quantities" or result in "significant or substantial human exposure."[10] TSCA provides for testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Over forty years ago, the Council on Environmental Quality warned of the "high priority need" for a new legal authority capable of ensuring the safe use of toxic chemicals.[11] Despite TSCA's powerful potential, however, EPA has accomplished very little under the Act. This petition presents substantial scientific evidence demonstrating that anthropogenic emissions of CO_2 pose an unreasonable risk to human and environmental health. Indeed, studies show that significant and potentially irreversible harm has already occurred. As the Council recognized decades ago, "[w]e should no longer be limited to repairing [this] damage after it has been done; nor should we continue to allow the entire population or the entire environment to be used as a laboratory." Instead, EPA must take prompt action to reduce and mitigate the anthropogenic production of CO_2.

II. EPA Must Issue a Rule to Regulate or Require Tests for CO_2 Causing Ocean Acidification

CO_2 presents an unreasonable risk of injury to the environment because its exposure to the ocean changes seawater chemistry with harmful impacts on marine life and ecosystems. Substantial evidence supports this conclusion and is discussed in this petition. Accordingly, this petition seeks a rulemaking to regulate CO_2 under TSCA.

This petition requires EPA to make a determination under TSCA section 6 if the injury to the environment and health from CO_2 is unreasonable. Alternately, if the Agency demonstrates that the existing science is insufficient to make a determination under TSCA section 6, EPA must initiate test rules under TSCA section 4 to develop the missing information needed to determine if the TSCA section 6 trigger is met and how best to mitigate the harm.

A. TSCA Authorizes EPA to Act on CO_2

To enable the achievement of TSCA's ambitious objectives, Congress broadly defined EPA's jurisdiction under the Act. As described above, TSCA explicitly directs EPA to initiate

[8] *Id.*
[9] *Id.* § 2603 (emphasis added).
[10] *Id.*
[11] Council on Envtl. Quality, Toxic Substances at v (April 1971).

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rulemaking upon finding that "the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance" threatens public health or the environment.[12] TSCA then authorizes the regulation of "chemical substances" that are "in commerce," a test met by CO_2. Indeed, CO_2 is already on the TSCA inventory as a "chemical in commerce."[13] CO_2 necessarily qualifies as a "chemical substance," a category that includes "any organic or inorganic substance of a particular molecular identity."[14] Moreover, the anthropogenic emissions at issue are in commerce; federal courts have previously concluded that air emissions[15] and "incidental byproducts of industrial chemical processes" are within the scope of EPA's authority under the Act.[16] Existing scientific evidence demonstrates that the anthropogenic production of CO_2 has already damaged marine ecosystems and endangered vulnerable portions of the human population. For the reasons described below, EPA must promptly reduce and mitigate these harms.

1. CO_2 Is a Chemical Substance

First, carbon dioxide is a "chemical substance" falling within the scope of the Act. The Act defines "chemical substance" as "any organic or inorganic substance of a particular molecular identity, including any combination of such substances occurring in whole or in part as a result of a chemical reaction or occurring in nature and (ii) any element or uncombined radical."[17]. CO_2 meets this definition. CO_2 is a chemical substance that occurs both in nature and as a result of a chemical reaction. It consists of a carbon atom bonded to two oxygen atoms:

$$O=C=O$$

It is identified by molecular formula CO_2 and by CAS number 124-38-9.

2. CO_2 Is in Commerce

Second, CO_2 is in commerce, and it is already on the TSCA inventory (CAS 124-38-9) with "chemical in commerce" as the stated reason for regulation.[18] Under TSCA's statutory text, "commerce" is defined as "trade, traffic, transportation, or other commerce . . . between a place in a State and any place outside of such state, or . . . which affects trade, traffic, transportation, or commerce."[19] CO_2 is primarily produced as a byproduct from the combustion of fossil fuels; according to the EPA, CO_2 emissions account for 77% of greenhouse gas emissions worldwide.[20]

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[12] *Id.* §§ 2605(a), 2603(a)(1)(A)(i), 2506(a). Although TSCA does not define "disposal," other federal environmental laws explain that this term encompasses "the discharge, deposit, injection, dumping, spilling, leaking, or placing of any solid waste or hazardous waste into or on any land or water so that such solid waste or hazardous waste or any constituent thereof may enter the environment or be emitted into the air or discharged into any waters, including ground waters." 42 U.S.C. §§ 6903(3), 9601(29).
[13] EPA, Substance Registry at http://1.usa.gov/1IBS1w6 (last accessed June 28, 2015).
[14] 15 U.S.C. § 2602(2). This definition excludes specific compounds already subject to federal control, such as pesticides, tobacco products, nuclear materials and food, drugs and cosmetics. *Id.* § 2602(2)(B).
[15] *Citizens for a Better Env't v. Thomas*, 704 F. Supp. 149, 152 (E.D. Ill. 1989).
[16] *Envtl. Def. Fund v. Envtl. Prot. Agency*, 636 F.2d 1267, 1271 (D.C. Cir. 1980).
[17] 15 U.S.C. § 2602(2)(A).
[18] EPA, Substance Registry at http://1.usa.gov/1IBS1w6.
[19] 15 U.S.C. § 2602(3).
[20] EPA, Global Greenhouse Gas Emissions Data, http://www.epa.gov/climatechange/ghgemissions/global.html (last updated June 21, 2013; last accessed June 28, 2015).

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The most voluminous sources of greenhouse gas emissions are energy suppliers,[21] industry,[22] land use and forestry,[23] agriculture,[24] transportation,[25] commercial and residential buildings,[26] and waste and wastewater.[27] All of these emitters produce CO_2 as a byproduct of their ordinary processes.

TSCA's statutory and regulatory text support the proposition that CO_2 emitted as a byproduct of industrial processes can be regulated under TSCA because CO_2 in this context is manufactured, meaning "produce[d] . . . with the purpose of obtaining an immediate or eventual commercial advantage."[28] All of the industries listed above which emit CO_2 are performed to obtain an immediate or eventual commercial advantage, as all of these industries are commercial and part of a competitive market. Therefore, incidental production of CO_2 is manufactured or produced "for a commercial purpose," and is found "in commerce" pursuant to TSCA regulations.

Accordingly, CO_2 emissions fit the regulatory definition of a chemical substance produced for a commercial purpose. This is bolstered by the broad definition of "commerce" in the TSCA statute; at the very least, CO_2 emissions "affect" trade, traffic, transportation, and commerce.

TSCA's purpose and regulatory text support the regulation of chemical substances that are an incidental byproduct, and indeed EPA has regulated chemical byproducts under TSCA before. For example, PCBs are regulated under TSCA even when they are only incidentally produced as a byproduct of industrial processes.[29] EPA regulates PCB "byproducts" for which there are no separate commercial intents, and TSCA regulates inadvertently vented PCB emissions.[30] Moreover, EPA's authority under TSCA broadly defines what it regulates under "disposal" of PCBs to include intentional and accidental disposal.[31] EPA has also previously prohibited wastes from chemical manufacturing under TSCA.[32]

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[21] Which emit greenhouse gases through "[t]he burning of coal, natural gas, and oil for electricity and heat." *Id.*

[22] Which emit greenhouse gases through "fossil fuels burned on-site at facilities for energy" and "chemical, metallurgical, and mineral transformation processes not associated with energy consumption." *Id.*

[23] Which emit "carbon dioxide . . . from deforestation, land clearing for agriculture, and fires or decay of peat soils." *Id.*

[24] "Greenhouse emissions from agriculture mostly come from the management of agricultural soils, livestock, rice production, and biomass burning." *Id.*

[25] Which emit greenhouse gases through "fossil fuels burned for road, rail, air, and marine transportation." *Id.*

[26] Which emit greenhouse gases from "on-site energy generation and burning fuels or heat in buildings or cooking in homes." *Id.*

[27] Which emit carbon dioxide through the "incineration of some waste products that were made with fossil fuels, such as plastics and synthetic textiles." *Id.*

[28] 40 C.F.R. § 710.3; 40 C.F.R. § 704.3 ("Manufacture for commercial purposes also applies to substances that are produced coincidentally during the manufacture, processing, use, or disposal of another substance or mixture, including both byproducts that are separated from that other substance or mixture and impurities that remain in that substance or mixture. Such byproducts and impurities may, or may not, in themselves have commercial value. They are nonetheless produced for the purpose of obtaining a commercial advantage since they are part of the manufacture of a chemical product for a commercial purpose.").

[29] 44 Fed. Reg. 31525 (May 31, 1979); 40 C.F.R. § 761.

[30] *See, e.g.,* 40 C.F.R. Part 761.

[31] 40 C.F.R. § 761.3.

[32] 45 Fed. Reg. 592 (March 11, 1980);40 C.F.R. § 775 (1980) (prohibiting disposal of 2,3,7,8-tetracholorodibenzo-p-dioxin (TCDD) a manufacturing waste).

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Further, CO_2 emissions are in commerce as they are traded, bought, and sold as carbon offsets. CO_2 is also produced for commerical purposes including for uses in fertilizer, beverage carbonation, dry ice, refrigeration, pressurization, fire extinguishment, and packaging.

B. EPA Should Initiate Rulemaking to Control CO_2 under TSCA

Petitioners request that EPA make finding that CO_2 presents or will present an unreasonable risk of injury to the environment or health. TSCA requires that EPA "shall" initiate rulemaking upon finding "a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use or disposal of a chemical substance of mixture … presents or will present an unreasonable risk of injury to health or the environment."[33]

The information and supporting documents provided in this petition indicate that CO_2 is already causing injury to the environment due to ocean acidification. The scientific evidence further supports that the injury to the environment and health will grow more severe as CO_2 pollution continues. EPA cannot deny that CO_2 is harming the environment. Indeed, EPA acknowledges that ocean acidification poses risk:

> Ocean acidification, like Climate change is primarily caused by increasing carbon dioxide (CO_2) concentrations in the atmosphere. As a result of absorbing large quantities of human made CO_2 emissions the ocean chemistry is changing, which is likely to negatively affect important marine ecosystems and species including coral reefs, shellfish, and fisheries.

(Environmental Protection Agency 2010).

EPA must find that such injury is an unreasonable risk.[34] While Congress did not define the phrase "unreasonable risk," EPA has interpreted relevant legislative history to require that the agency:

> balance the benefits derived from risk reduction against the social and economic costs incurred, taking into account such factors as the extent and magnitude of risk posed; the societal consequences of removing or restricting use of products; availability and potential hazards of substitutes; and impacts on industry, employment, and international trade.[35]

No specific factual determination is necessary to establish "unreasonable risk." For example, even under the stricter standard of 15 U.S.C. § 2606, EPA need not present evidence of actual injury before obtaining emergency injunctive relief to control "immanently hazardous chemical substance[s] or mixture[s]."[36] For the reasons discussed below, application of the agency's balancing test supports the additional regulation of CO_2.

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[33] 15 U.S.C. § 2605(a).
[34] *Id.*
[35] EPA, Guidance for Petitioning the Environmental Protection Agency Under Section 21 of the Toxic Substances Control Act, 50 Fed. Reg. 46,825 (Nov. 13, 1985).
[36] *See* H.R. Conf. Rep. No. 94-1679 78 (1976).

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According to scientific experts: "Reducing CO_2 emissions is the only way to minimise [sic] long-term, large-scale risks" (IBGP et al. 2013).

1. CO_2 Pollution Presents an Unreasonable Risk of Injury to the Environment

There is clear consensus among leading national and international scientific bodies that anthropogenic CO_2 causes changes in ocean chemistry that harm the marine environment. The Intergovernmental Panel on Climate Change ("IPCC") determined that human sources of CO_2 have caused a significant decline in surface ocean pH (Rhein et al. 2013), and over 90 national academies of sciences, including the United States', have signed a statement that ocean acidification will "cause grave harm to important marine ecosystems as CO_2 concentrations reach 450 ppm and above" (Interacademy Panel 2009). The Interacademy Panel concluded that CO_2 has increased ocean acidity with "potentially profound consequences for marine plants and animals" including severe threats to coral reefs, polar ecosystems, and a likely reduction in marine food supplies (*Id.*). The National Research Council also acknowledges that "existing data support a growing consensus in the research community that most documented responses to acidification reflect impairment of physiological capacity or performance" for marine life with likely substantial socioeconomic impacts (National Research Council 2013). The U.S. National Climate Assessment concluded that ocean acidification will alter marine ecosystems in dramatic ways including threatening coral reef habitats and causing reduced growth and survival of shellfish in all regions (Doney et al. 2014).

EPA acknowledges that "ocean acidification presents a suite of environmental changes that would likely negatively affect ocean ecosystems, fisheries, and other marine resources." 75 Fed. Reg. 13538 (Mar. 22, 2010). EPA previously concluded that greenhouse gases, including CO_2, endanger public health and the environment in part because of ocean acidification.[37]

There is no doubt that CO_2 pollution is changing ocean chemistry and harming the marine environment. Unabated, there will be severe and detrimental impacts on marine ecosystems, the economy, and public health. Accordingly, EPA must find that CO_2 poses an unreasonable risk to the environment and health.

a. CO_2 Causes Irreversible Ocean Acidification

Ocean acidification is a major threat to the marine environment. The oceans have absorbed CO_2 emitted into the atmosphere from power plants, manufacturing, cement production, and land use changes. Between 1750 and 2011, human activities have released 375 gigatons of carbon into the atmosphere, and approximately half of that has been absorbed by the oceans (Rhein et al. 2013). Each day about 22 million metric tons of CO_2 is taken up by the oceans (Feely et al. 2008). This uptake of CO_2 is changing ocean chemistry, causing the oceans to become more acidic. Since the industrial revolution surface ocean pH has declined by 0.11 units on average, corresponding with

[37] EPA, Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act 80 (Dec. 7, 2009).

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a 30% increase in acidity (Orr et al. 2005; Caldeira & Wickett 2005).[38] If emissions continue unabated, ocean acidity will increase up to 170% by the end of the century (IBGP et al. 2013).

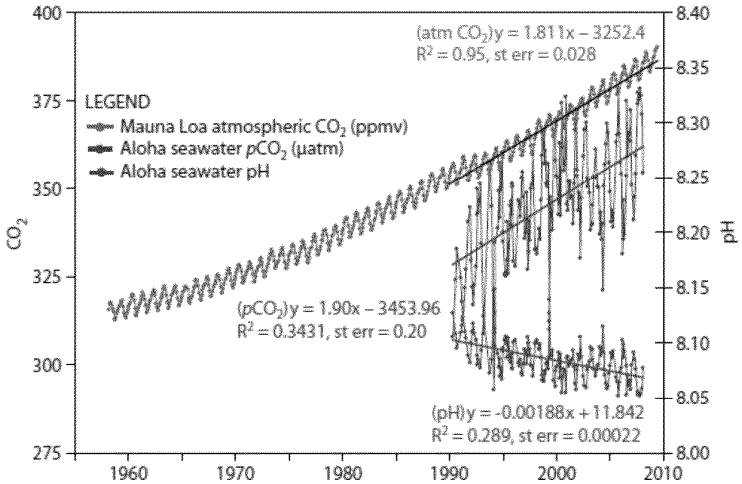

Figure 1. Time series of atmospheric CO 2 at Mauna Loa (ppmv) and surface ocean pH and pCO2 (µatm) at Ocean Station Aloha in the subtropical North Pacific Ocean (see inset map). Note that the increase in oceanic CO 2 over the period of observations is consistent with the atmospheric increase within the statistical limits of the measurements. (Feely et al. 2009).

Anthropogenic ocean acidification exceeds the trend in natural variability significantly, up to 30 times in some regions (Friedrich et al. 2012). The rate of change in ocean acidity is unprecedented in the past 300 million years, a period that includes four mass extinctions (Honisch et al. 2012; Zeebe 2012). The seawater chemistry change is an order of magnitude faster than what occurred 55 million years ago during Paleocene-Eocene Thermal Maximum, which is considered to be the closest analogue to the present, and during that period 96% of marine species went extinct (*Id.*). The current changes in seawater chemistry are irreversible on human timescales (Royal Society 2005).

CO_2's impact on ocean chemistry is fundamentally altering the marine environment with negative impacts on marine species, habitats and ecosystems.

i. What Is Ocean Acidification

When the ocean absorbs CO_2 from the atmosphere it changes ocean chemistry. CO_2 that is absorbed by seawater reacts to form carbonic acid, which dissociates to form bicarbonate and releases hydrogen ions. This reaction reduces the amount of carbonate ions and decreases pH. The oceans store a significant amount of the CO_2 pollution from human activities (Royal Society 2005). While this has provided society with an important service of buffering against climate change impacts, it comes at a cost to the marine environment.

[38] Because the pH scale is logarithmic a small decrease is a significant change in acidity; for example, a decrease of 0.1 pH is an approximate 30 percent increase in acidity.

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Globally, surface water pH has declined 0.11 units on average between 1750 and 1994 (Sabine et al. 2004). Long-term monitoring has documented the impact of increasing atmospheric CO_2 on declining seawater pH in the Pacific and Atlantic Oceans (*see* Figure 2). Results from time-series stations in the North Atlantic and North Pacific show a decrease of about 0.002 pH per year (Rhein et al. 2013).

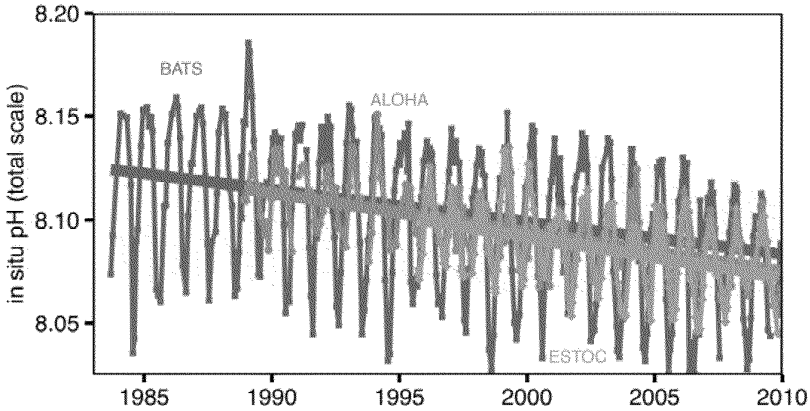

Figure 2. Long-term trends of surface seawater pH at three subtropical ocean time series in the North Atlantic and North Pacific Oceans, including (a) Bermuda Atlantic Time-series Study (BATS, 31°40'N, 64°10'W; green) and Hydrostation S (32°10', 64°30'W) from 1983 to present (updated from Bates, 2007); (b) Hawaii Ocean Time-series (HOT) at Station ALOHA (A Long-term Oligotrophic Habitat Assessment; 22°45'N, 158°00'W; orange) from 1988 to present (updated from Dore et al., 2009) and (c) European Station for Time series in the Ocean (ESTOC, 29°10'N, 15°30'W; blue) from 1994 to present (updated from González-Dávila et al., 2010). Atmospheric pCO2 (black) from the Mauna Loa Observatory Hawaii is shown in the top panel. Lines show linear fits to the data, whereas Table 3.2 give results for harmonic fits to the data (updated from Orr, 2011).(Rhein et al. 2013)

Ocean acidification not only makes the oceans more acidic, but it also reduces the amount of carbonate ions available for animals to build the shells and skeletons they need to survive. Carbonate is an important constituent of seawater because many organisms form their shells and skeletons by complexing calcium and carbonate. Waters that are supersaturated with aragonite are generally good for shell-building, while undersaturated waters (<1.0 Ω_{ar}) are corrosive to some marine animals. Corals require supersaturated waters above 3.3 Ω_{ar} (Meissner et al. 2012). Globally, there has been a decrease of about -0.4 Ω_{ar} (Gruber et al. 2012). The aragonite saturation state has declined 16% since the Industrial Revolution due, in large part, to anthropogenic CO_2 (Feely et al. 2012a; Ishii et al. 2011). Modeling of the oceans' aragonite saturation predicts that by the end of the century up to 75% of ocean volume could be undersaturated with respect to aragonite (Joos et al. 2011).

ii. Observed and Predicted Acidification

CO_2 has already had measurable impacts on seawater chemistry. Some regions, such as those with upwelling systems or high latitudes, are especially vulnerable to ocean acidification.

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1. Pacific Coast

The West Coast is already experiencing adverse impacts of ocean acidification. As early as 2008, a survey off the coasts of Washington, Oregon, and California revealed that this region is already experiencing corrosive waters not expected until mid-century (See figure 3) (Feely 2008). Researchers found seawater undersaturated with respect to aragonite upwelling onto large portions of the continental shelf, reaching shallow depths of 40 to 120 meters (*Id.*). According to the study, the waters were last at the surface approximately 50 years ago when atmospheric CO_2 concentrations were much lower (Feely et al. 2008). Feely et al. report that in the Pacific Ocean there has been a decrease of the saturation state of surface seawater with respect to aragonite and calcite as well as an upward shoaling of the saturation horizon by about 1-2 meters per year on average, due in large part to anthropogenic CO_2 (R. A. Feely, Sabine, et al. 2012). As a result, marine organisms in surface waters, in the water column, and on the sea floor along the West Coast of the United States are already being exposed to corrosive water during the upwelling season.

Modeling of the California Current System demonstrates that the area is rapidly approaching year-round undersaturation with respect to aragonite and it is departing significantly from natural variability (Hauri et al. 2013). Time series monitoring shows that the aragonite saturation state along the California coast is much lower than would be expected in the North Pacific (Harris, DeGrandpre et al. 2013). Surface Ω_{ar} values ranged between 0.66 and 3.9 compared to an estimated pre-industrial range of 1.0 to 4.7. While some areas, like Puget Sound, already exhibit undersaturated conditions every year (Feely, Klinger, et al. 2012; Reum et al. 2014), scientists predict that most shallow shelf areas along the West Coast will become undersaturated with respect to aragonite within the next 20-30 years (Capone & Hutchins 2013; Gruber et al. 2012).

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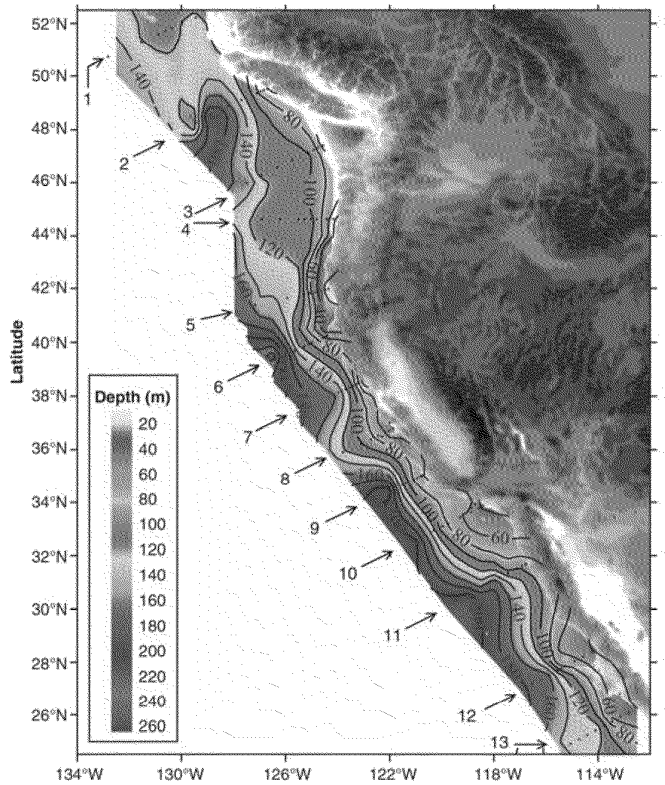

Figure 3. Distribution of the depths of the undersaturated water (aragonite saturation < 1.0; pH < 7.75) on the continental shelf of western North America from Queen Charlotte Sound, Canada, to San Gregorio Baja California Sur,Mexico. On transect line 5, the corrosive water reaches all the way to the surface in the inshore waters near the coast. The black dots represent station locations (Feely et al. 2008).

2. *Alaskan Waters*

High latitude waters are the "bellwether" of ocean acidification because these will be the first ocean regions to become persistently undersaturated with respect to aragonite as a result of greenhouse gas pollution (Fabry et al. 2009; Steinacher et al. 2009). High-latitude waters have naturally lower carbonate ion concentrations and saturation states due to a combination of cold temperatures which increase the solubility of CO_2 and ocean mixing patterns (Fabry et al. 2009; Mathis et al. 2011a). As early as 2016, 10% of Arctic surface waters are expected to be undersaturated with respect to aragonite for at least one month per year (Steinacher et al. 2009).

Recent observations of calcium carbonate saturation states in the North Pacific and Bering Sea have found that full water column undersaturation of calcium carbonate due to ocean acidification is already prevalent. Mathis et al. (2011a) reported that extensive areas of bottom waters over the Bering Sea shelf are becoming undersaturated with respect to aragonite for at least several months (July to September), and some areas of bottom water were already observed to be undersaturated with respect to calcite (Fabry et al. 2009, Mathis et al. 2011a).

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Scientists predict that polar waters will be corrosive to shellbuilding animals within decades (IBGP et al. 2013). A 2015 study of observations in the Chukchi and Beaufort Seas in the Arctic indicates that within 15 years waters will become so corrosive that it will be difficult for marine animals to build and maintain their shells (Mathis et al. 2015). The highly productive fisheries of Alaska are in some of the most rapidly changing seawater conditions (Mathis et al. 2014).

3. Sub-tropical Waters

Subtropical waters have experienced declining saturation states due to ocean acidification. Within decades, scientists believe that ocean acidification will impair coral growth (IBGP et al. 2013). Models show that by the end of the century, most coral reef areas will no longer have aragonite saturation states that are optimal for coral growth. A 10-year study of the Caribbean region found a strong regional decrease in aragonite saturation state between 1996-2006, from 4.05 to 3.9, resulting from CO_2 (Gledhill et al. 2008). Modeling predicts that under various emissions scenarios the coral reefs in the Caribbean will be thermally and chemically stressed between now and 2030 (Meissner et al. 2012). Even under the most optimistic scenario, 98% of reefs will be stressed by 2050 (*Id.*). In the Pacific subtropical ocean near Hawaii, there are nearly 20 years of time-series measurements of significant decreasing seawater pH that match the ocean's uptake of atmospheric CO_2 (Dore et al. 2009)

4. Atlantic Coast

Even ocean waters not at high latitude, in upwelling systems, or containing coral reefs ecosystems are, or will soon be, exhibiting signs of ocean acidification. Observations of East Coast waters during all seasons show that while they remain supersaturated with respect to aragonite, by the end of this century, saturation states of aragonite and calcite will decrease by 20–40%, with the lowest Ωar dropping to 1.3 in some seasons (Jiang et al. 2010). A survey of the Atlantic Coast showed that waters in the Northeast and particularly the Gulf of Maine are the most susceptible to ocean acidification (Wang 2013).

iii. CO_2 Kills and Injures Marine Life

High-CO_2 waters seriously harm marine wildlife and the entire ocean ecosystem. When CO_2 concentrations in seawater increase, the availability of carbonate ions decreases, making it more difficult for marine organisms to form, build, and maintain the calcium carbonate shells and skeletons required for their survival. As seawater becomes more corrosive, it can kill fish eggs and inhibit the development of, and essentially dissolve, the shells of small crustaceans, baby shellfish, and other tiny creatures at the base of the food web (Fabry 2008). Ocean acidification also harms and stresses fish, squid, and other animals that do not build shells (*Id.*). Not only does ocean acidification directly threaten various types of marine animals, it also has implications for the broader marine environment and food web.

The harmful effects of ocean acidification have already begun to occur. For example, ocean acidification has caused:

- A massive die-off of oysters in the Pacific Northwest (Barton et al. 2012; R. a. Feely, Sabine, et al. 2012; Washington State Blue Ribbon Panel 2012);

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- Declines in abundance and size of the California mussel, blue mussel and goose barnacle in tidepools correlated with a severely declining pH (Wootton et al. 2008);
- Sluggish growth of corals in the Caribbean and Great Barrier Reef (De'ath et al. 2009; De'ath et al. 2012; Gledhill et al. 2008); and
- Shells of plankton to dissolve off the California Coast and thinner and weaker shells of plankton in the Southern Ocean (Bednarsek 2014; Moy et al. 2009).

In a meta-analysis of over 400 experiments examining the impacts of ocean acidification on marine organisms, Kroeker et al. (2013) found the biological effects to be generally large and negative. This analysis was restricted to experiments with pH manipulations of less than 0.5 units, in order to reflect the predicted level of ocean acidification by the end of the century (IPCC 2007). By limiting the analysis to small variations in pH, this study shows that within the foreseeable future ocean acidification will have "profound repercussions for marine organisms" (Kroeker et al. 2010). While the negative effect of ocean acidification was most pronounced for calcification and survival (27% reductions in both responses), the study also revealed significant negative effects on growth and reproduction (11 to 19%, respectively). In addition, abundance was reduced by 15%. The strength of this analysis suggests that the patterns highlighted in this study are a robust representation of the current literature on ocean acidification.

While most of the worst consequences of ocean acidification are predicted for the future, scientists have already observed damage from CO_2 in the oceans. Additionally, the impacts of ocean acidification can affect the entire marine food web by altering habitat, prey availability, and species interactions.

b. High-CO_2 Waters Injure the Growth, Survival, Fitness, and Reproduction of Marine Animals

The primary known harm of CO_2 in the oceans is that it impairs the growth and survival of animals that build shells. Because ocean acidification reduces the availability of carbonate ions that marine animals use to calcify their shells and skeletons, CO_2 reduces the ability of these animals to build their protective structures (Doney et al. 2009). Acidified waters can also damage and dissolve shells.

These negative effects have been observed in the ocean as well as documented in laboratory studies. Corals, coralline algae, plankton, mollusks, and other shellfish exposed to future levels of ocean acidification have all experienced problems (Kleypas & Yates 2009; Kuffner et al. 2007; Barton et al. 2012; Talmage & Gobler 2011; Talmage & Gobler 2009; Orr et al. 2005; Riebesell et al. 2000).

i. Molluscs, Echinoderms, and Crustaceans

High CO_2 waters are lethal to shellfish. Since 2005, waters off the coast of Washington and Oregon have been killing oysters and other molluscs. Shellfish hatcheries in Washington and Oregon reported massive mortalities of oyster larvae (Washington State Blue Ribbon Panel 2012).Wild oysters also failed to reproduce in Willapa Bay, Washington (*Id.*). Scientists have definitively linked oyster production failures to high-CO_2 ocean waters that were used to raise larvae (Barton et al. 2012).

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In response to reported shellfish hatchery problems in Oregon, Barton et al. reported the results of their observations from the Whiskey Creek Hatchery on Netarts Bay in the summer of 2009 (Barton et al. 2012). Unlike previous laboratory experiments, this study analyzed calcifying organism responses in the ambient-water CO_2 chemistry of Oregon's coastal waters. Larval production and mid-stage growth (~120 um to ~150 um) of the oyster, *Crassostrea gigas*, were both significantly negatively correlated with the chemistry of waters in which larval oysters were spawned and reared for the first 48 hours of life. Although the impact of the exposure was not immediate, the delayed reaction caused a significant decline in growth for mid-sized oyster larvae and reduced overall production. The findings corroborate other laboratory studies that show that many marine species, especially at the larval stage, are adversely affected by ocean acidification.

Scientific studies have demonstrated that even modest pH declines affect the sensitive and vulnerable early developmental stages of organisms because these life histories have specific environmental needs (Kurihara 2008) (*see* Figure 10, below, showing negative effects from low pH treatments). A number of studies have found a delay in development or less development, degraded shells, decreased rate of metamorphosis, shell thickness, and loss of hinge integrity (Ross et al. 2011a). The resulting reduced larval size can reduce the feeding efficiency of larvae, and smaller larvae are more susceptible to starvation because they encounter comparatively less food (Kurihara & Shirayama 2004). Sub-lethal effects of elevated acidity can severely alter the composition and fitness of larvae, and given the high mortality rates of larvae in the water column and during the transition to benthic settler, small perturbations to larvae potentially may have large alterations to settlement dynamics, post-settlement mortality, recruitment, and ultimately adult populations (Ross et al. 2011).

Watson et al. (2009) exposed one day-old oyster larvae to a range of pH conditions, from 7.6 to 8.1, for 10 days and showed significant decline in the survival and growth of young larvae at lower pH. Waldbusser et al. (2010), in a study on the Chesapeake Bay, showed that even modest changes in pH present conditions that are corrosive to shells and have physiological impacts on adult and larval oysters. Biocalcification declined significantly with a reduction of 0.2 pH units, making juvenile bivalves more susceptible to predation and other mortality factors (*Id.*).

Negative effects have been seen on the metamorphosis, size, and survival of larval hard clams (*Mercenaria mercenaria*), bay scallops (*Argopecten irradians*), and Eastern oysters (*Crassostrea virginica*) at levels of CO_2 predicted to occur in the 21st century (Talmage & Gobler 2011). At 650 ppm, or an approximate drop of 0.3-0.4 from pre-industrial values, both *M. mercenaria* and *A. irrandians* larvae exhibited dramatic declines (over 50%) in survivorship as well as significantly delayed matamorphosis and significantly smaller size. *C. virginica* also experienced lowered growth and delayed metamorphosis at this level, an indicator that current and future increases in CO_2 populations may deplete or alter the composition of shellfish populations in coastal ecosystems (*Id.*).

The Olympia oyster, *Ostrea lurida*, a foundation species in estuaries along the Pacific coast, exhibits clear decline in larval growth and settlement as levels of CO_2 affect seawater pH. (Hettinger et al. 2012). Oysters in this experiment were raised at three levels of seawater pH,

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including a control (8.0) and two additional levels (7.9 and 7.8). Larvae reared under pH 7.8 exhibited a 15% decrease in larval shell growth rate, and a 7% decrease in shell area at settlement, compared to larvae reared under control conditions. Impacts were even more pronounced a week after settlement, with juveniles that had been reared as larvae under reduced pH exhibiting a 41% decrease in shell growth rate.

Oysters on the Atlantic coast also experience the ill effects of ocean acidification. Dickinson et al. (2012) found negative effects on juvenile eastern oysters after exposure to water with a 0.2 pH change. Exposure of the oysters to elevated acidity led to a significant increase in mortality, reduction of tissue energy stores and negative soft tissue growth, indicating energy deficiency. Under ocean acidification conditions, thermal tolerance is impaired in oyster larvae, leading to reduced development, size and increased abnormality (Ross et al. 2011; Parker et al. 2010). Similar results have been found in red abalone, with thermal tolerance impaired at pH 7.87 compared to control (pH 8.05) (Zippay and Hoffman 2010).

In studies with edible mussel (*Mytilus edulis*) and Pacific oyster (*Crassostrea gigas*) researchers found a strong decline of calcification under ocean acidification conditions (Gazeau et al. 2007). Based upon these results, researchers concluded that mussel and oyster calcification may decrease by 25% and 10%, respectively, by the end of the century." (*Id.*). Oysters and mussels also exhibit development abnormalities when exposed to acidification (Kurihara 2008). When oyster eggs were reared under pH 7.8, they showed malformations of their shell, and when reared under pH 7.4, more than 70% of the larvae were either completely non-shelled, or only partially shelled, and only 4% of CO_2 treated embryos developed into normal larvae by 48 hours after fertilization, in contrast to about 70% successful development in control embryos.

The shrimp *Palaemon pacificus* displayed variable responses at different developmental stages, pH and length of exposure (Kurihara 2008). Following long term (30 weeks) exposure of adults to pH 7.89 and 7.64, survival and egg production in early developmental stages decreased in both treatments. Findlay et al. (2010) found a slower rate of development of embryos in the common intertidal northern hemisphere barnacle *Semibalanus balanoides* with an estimated 19 days delay in reaching 50% hatching stage at pH 7.7. Other amphipods have exhibited metabolic changes in response to acidification levels greater than what is allowed under the federal criterion (Hauton et al. 2009).

Echinoderms exhibit delayed and asymmetrical development when exposed to acidified conditions. In the absence of adequate adaptation or acclimation, lowered pH levels will have a range of sub-lethal effects on sea urchins, brittlestar and seastar larvae from a range of geographical regions (Ross et al. 2011). Larvae of the ecological keystone brittlestar, *Ophiothrix fragilis*, either were abnormal, had altered skeletal proportions, or asymmetry during skeletogenesis, and there was a delay in development at pH levels of 7.9, or approximately 0.3 units below current surface levels (Gutowska et al. 2009). Other experiments on brittlestar in low pH waters resulted in dramatic results; acidification of 0.2 units induced 100% larval mortality within an eight day period. Control larvae showed 70% survival over the same period. Because the calcite skeleton of the larval brittlestar aids key functions such as feeding and vertical migration, and defense against predators, abnormal development of the skeleton will have drastic consequences for fitness. The developmental abnormalities may be exacerbated by temperature

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increases predicted for the end of the century; some scientists suggest that this may result in the disappearance of echinoderms from the surface oceans within the next 50-100 years (Ross et al. 2011a).

Reproductive success is compromised by ocean acidification. The fertilization rate of sea urchins decreases with increasing CO_2 concentrations (8.1 to 6.8 pH) (Kurihara 2008). In another sea urchin experiment utilizing six CO_2 concentrations, with a pH between 8.01 (control) and 6.83, cleavage rate, developmental speed, and larval morphology all declined with increased CO_2 concentration (Kurihara & Shirayama 2004). At a 0.2 change from control, effects could be seen on the morphology and development of the larvae, and these effects became more pronounced with greater pH changes (*Id.*) (*see* Figure 4, below). The authors concluded that "all the effects of raised CO_2 concentration observed in this study would have a negative impact on the survival of sea urchin embryos in their early life history." A recent study showed that sea urchin sperm flagellar motility was significantly reduced when seawater pH decreased by .3 units, from 8.0 to 7.7 (Suwa et al. 2010). As discussed above, decreased flagellar motility has severe consequences for fertilization and subsequent population dynamics; if sperm lose their ability to find eggs, the population size will necessarily diminish.

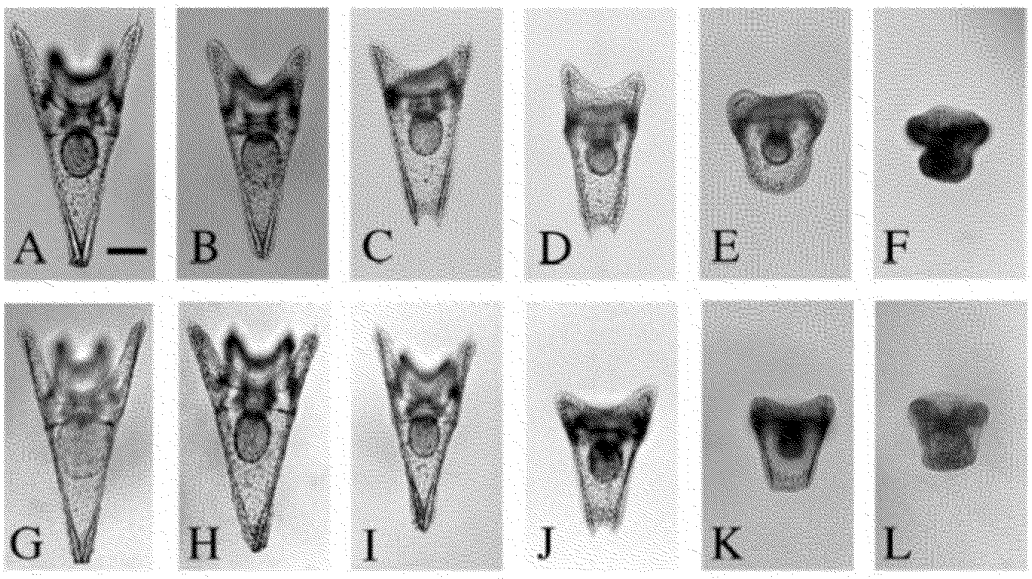

Fig. 6. *Hemicentrotus pulcherrimus*. Morphology of 4-armed pluteus larvae cultured for 3 d in (A–F) CO_2-seawater and (G–L) HCl-seawater. (A & G) control (pH 8.0); (B & H) +500 ppm (pH 7.8); (C & I) +1000 ppm (pH 7.6); (D & J) +2000 ppm (pH 7.4); (E & K) +5000 ppm (pH 7.0); (F & L) +10 000 ppm (pH 6.8). Scale bar = 50 µm

Figure 4. Declining development of sea urchin larvae exposed to acidified waters (Kurihara & Shirayama 2004).

Even moderate increases in atmospheric CO_2 and ensuing acidification adversely affect the growth of both gastropods and sea urchins (Shirayama & Thornton 2005). Before the end of this century, atmospheric CO_2 is likely to increase by more than 200 ppm, decreasing the pH of the ocean by approximately 0.3 units from pre-industrial levels. Two species of sea urchin as well as the gastropod *Strombus luhanus* were exposed for six months to waters with this level of elevated CO_2, and all three species exhibited similar consequences. Increased CO_2 negatively affected growth rate, calcification, shell height and body mass, and metabolic activity

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(Shirayama & Thornton 2005). The developing embryos of the gastropod and intertidal snail *Littorina obtusata* also demonstrate slower overall development time, altered embryonic movement, and modification of shell shape in hatchlings while exposed to acidified waters (pH 7.6) (Ellis et al. 2009).

Arnold et al. (2009) investigated the effect of ocean acidification on lobsters and found that indirect disruption of calcification and carapace mass may adversely affect the competitive fitness and recruitment success of larval lobsters with serious consequences for population dynamics and marine ecosystem function

Reduced metabolism is expected to impair predator-prey interactions, as well as have consequences for growth, reproduction, and survival. Metabolic suppression has previously been reported to occur in a variety of adult marine invertebrates, including crabs, squid, worms, bivalves, pteropods and amphipods (Albright 2011). Slowed metabolism is generally achieved by halting energy-expensive processes, such as protein synthesis, and therefore may lead to reductions in growth and reproductive potential (*Id.*). The blue mussel *Mytilus edulis* has strong physiological mechanisms by which it is able to protect body tissues against short-term exposure to acidified seawater, but these come at an energetic cost, and will result in reduced growth during long term exposures (Bibby et al. 2008). Consequently, the predicted long-term changes to sea water are likely to have a significant effect on the health and survival of blue mussel populations (*Id.*). Mussel beds are a dominant coastal habitat and provide food and structure for a diverse array of species in an otherwise physically stressful environment; any decline in their population structure will lead to a reduction in appropriate habitat for a myriad of other species.

In summary, acidified waters impact the development, growth, and reproductive success of a suite of echinoderms, crustaceans, and molluscs. A growing body of information is becoming available on the effecting of declining pH on these organisms and their ecosystems. The results of these studies are clear; as pH falls even 0.2 units from pre-industrial values, these organisms will struggle to survive in their increasingly acidic environment.

ii. Corals

Coral reef ecosystems, which are estimated to harbor one-third of marine species and which support the livelihoods of a half billion people, are particularly threatened by ocean acidification. Some corals are already experiencing reduced calcification (De'ath et al. 2009; Cooper et al. 2008; Bates et al. 2010; Gledhill et al. 2008). Due to the ocean acidification and warming, reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations of 450 ppm (Veron et al. 2009; Bijma et al. 2013). Prominent coral scientists have called for reducing atmospheric CO_2 to less than 350 ppm to protect coral reefs from collapse (Veron et al. 2009, Frieler et al. 2012). Coral reefs cannot exist below 7.8 pH units (Fabricius et al. 2011), and the threshold for coral growth is 3.3 Ω_{ar} (Meissner et al. 2012).

Ricke et al. (2013) analyzed aragonite saturation state (Ω_{ar}) surrounding reefs in CMIP5 simulations under several representative concentration pathway (RCP) scenarios (Ricke et al. 2013). The study found that in preindustrial times, 99.9% of reefs adjacent to open ocean in the CMIP5 ensemble were located in regions with $\Omega a > 3.5$. Accordingly, the study used $\Omega a = 3.5$ as

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an upper bound viability threshold for corals, while also examining thresholds of $\Omega a = 3.25$ and 3. Under a business-as-usual scenario (RCP 8.5), every coral reef considered was projected to be surrounded by water with $\Omega_{ar} < 3$ by the end of the 21st century and the reefs' long-term fate was independent of their specific saturation threshold. Under scenarios with significant CO_2 emissions abatement, the Ω_{ar} threshold for reefs was critical to projecting their fate. The study concluded that the "results indicate that to maintain a majority of reefs surrounded by waters with $\Omega_{ar} > 3{:}5$ to the end of the century, very aggressive reductions in emissions are required."

Corals are among the ecosystems most threatened by ocean acidification. To date, most scientific investigations into the effects of ocean acidification on coral reefs have been related to the reefs' unique ability to produce voluminous amounts of calcium carbonate (Kleypas & Yates 2009). The persistence of carbonate structures on coral reefs is essential in providing habitats for a large number of species and maintaining the extraordinary biodiversity associated with these ecosystems. As a consequence of ocean acidification, the ability of marine calcifiers to produce calcium carbonate will decrease, resulting in a transition from a condition of net accretion to one of net erosion, with drastic consequences for the role and function of these ecosystems (Kleypas & Yates 2009).

Coral reefs are predicted to drastically lower their calcification rates in the near future, and historical records show that calcification rates have already fallen relative to pre-industrial values. According to scientists, the main reef building organisms will calcify up to 50% less relative to pre-industrial rates by the middle of this century (*Id.*). A drop of approximately 60% coral reef calcification is projected for the end of the century, when pH is predicted to fall 0.5 units below pre-industrial values (Caldeira & Archer 2007). Many studies suggest calcification rates could be reduced between 20-60% at 560ppm, or 7.9 pH, and that a reduction of this magnitude would fundamentally alter reef structure and function (Convention on Biological Diversity 2009). According to the model of Silverman et al. (2009), developed from field observations from more than 9,000 reef locations, all coral reefs are expected to reduce calcification by more than 80% relative to their pre-industrial rate at 560 ppm (0.3 pH change), and at this point "all coral reefs will cease to grow and start to dissolve." The Interacademy Panel on International Issues concurs; "at current emission rates models suggest that all coral reefs and polar ecosystems will be severely affected by 2050 or potentially even earlier."

In a meta-analysis on coral calcification responses to ocean acidification, the coral calcification declined by a mean of 15% per unit decrease in aragonite saturation state ($2 < \Omega < 4$) (Chan and Connolly 2013). On current emission trends, calcification will decline 22% on average for corals by the end of the century (*Id.*). This falls to the lower range of responses that have been predicted by ocean acidification researchers and described above, which the authors believe reflects variation in the calcification responses of different corals.

Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%, (Caldeira & Archer 2007), and data from the Great Barrier Reef indicates a 14% decline in calcification rates between 1990 and 2005 (De'ath et al. 2009). Other studies in the Great Barrier reef indicate a decline of approximately 21%, and analysis of coral growth records confirm that this decline is unprecedented in recent centuries (Cooper et al. 2008). A model based on field samples shows that calcification of coral reefs in French

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Polynesia declined 15% between the pre-industrial period and 1992, and that rates will decline 40% by 2050, when CO_2 levels reach 560 ppm (pH 7.9) (Anthony et al. 2011). Near Bermuda, historical records show that coral skeletal density has decreased 33%, and coral calcification rates have declined by 52% as a result of changes in seawater carbonate chemistry (Bates et al. 2010). These observed changes have occurred even before a 0.2 unit decline in ocean pH; as atmospheric CO_2 continues to rise and lower pH values, calcification rates will maintain their precipitous decline.

Ocean acidification acts in concert with ocean warming and coral bleaching in furthering coral reef decline (Anlauf et al. 2011) (observing a 3% reduction in acidification with a 0.2 decline in pH, and a 30% decline when acidification is coupled with 1° C warming). While natural variability in the annual cycle and interannual variability may account for some of the observed change in coral growth rates, scientists are "virtually certain" that anthropogenic trends already exceed natural variability (Friedrich et al. 2012). Studies projecting the combined impacts of ocean acidification and ocean warming on corals predict that coral erosion will exceed calcification rates at atmospheric CO_2 concentrations of 450 to 500 ppm, (Hoegh-Guldberg et al. 2007), and all coral reefs will begin dissolve at CO_2 concentrations of 560 ppm (Silverman et al. 2009). These figures correspond to a 0.2 and 0.3 unit drop in pH, respectively, as compared to pre-industrial values. Van Hooidonk et al. (2014) presented updated global projections for threats to coral reefs from ocean warming and ocean acidification based on ensembles of IPCC AR5 climate models using the Representative Concentration Pathways (RCPs). For all tropical reef locations, the study projected absolute and percentage changes in aragonite saturation state (Ω_{ar}) for the period between 2006 and the onset of annual severe bleaching.

In the Caribbean, a recent study concluded that "coral reef communities are likely to be essentially gone from substantial parts of the Southeast Caribbean by the year 2035" (Buddemeier et al. 2011). The Great Barrier Reef has lost 50% of its coral cover since 1985 as a result of the combined effects of ocean acidification, global warming, coral bleaching, coral predation by starfish, and cyclone damage (De'ath et al. 2012). In short, due to the synergistic impacts of ocean acidification, mass bleaching, and local impacts, coral reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations 450 ppm, or pH 8.0, a level that is expected before mid-century (Veron et al. 2009).

Many experimental studies show declining calcification rates and other ill effects when corals are exposed to acidified waters. Decreases in calcification rates across a suite of benthic species and calcifying systems range from 3 to 60% for a doubling in pCO_2, which corresponds to a 0.3 reduction in pH (Abbasi & Abbasi 2011). The average response of corals is a 30% decline in calcification in response to a doubling in pCO_2 (*Id.*). In a study of an assemblage of corals exposed to conditions designed to mimic the change that may be experienced in the next 50-100 years (pH decline of 0.22 to 0.28 units), calcification rates declined between 44% and 80%.

The coral *Acropora palmata* (listed as threatened under the Endangered Species Act), once the dominant reef building coral in the Caribbean, experiences impaired fertilization, settlement, and growth with increasing pCO_2 (Albright et al. 2010). The cumulative impact of ocean acidification on fertilization and settlement success is an estimated 52% and 73% reduction in the number of larval settlers on the reef under pCO_2 conditions projected for the middle and end

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of this century, respectively (0.2 and 0.5 decline in pH) (*Id.*). After only 8 days of high CO_2 conditions (pH 7.75), *Acropora* experiences a statistically significant (18%) reduction in calcification rate (Murubini et al. 2003). Furthermore, there 22 coral species listed as threatened under the Endangered Species Act primarily because of threats from ocean warming, acidification and disease. The rule proposing listing for the corals found that ocean acidification was one of the highest priority threats for corals:

> Ocean acidification has the potential to cause substantial reduction in coral calcification and reef cementation. Further, ocean acidification adversely affects adult growth rates and fecundity, fertilization, pelagic planula settlement, polyp development, and juvenile growth.

77 Fed. Reg. at 73230 (Dec. 7, 2012). In other words, ocean acidification is driving the extinction of corals and the destruction of coral reef ecosystems.

Experimental studies evaluating the effects of ocean acidification on early life history stages of corals generally conclude that primary polyp growth is hindered by increasing acidity (Albright et al. 2010, Cohen & Holcomb 2009). Renegar and Riegl (2005) showed a significant decrease in the growth rate of *Acropora cervicornis* larvae at pH levels 0.3-0.5 units below control. Larvae of the common Atlantic golf ball coral, *Favia fragum*, shows significant delays in both the initiation of calcification and subsequent growth of the primary corallite in acidic waters (8.17 – 7.54 pH) (Cohen & Holcomb 2009). Visible changes in the skeletal development were observed in all non-control treatments, and in the most acidic waters skeletal development was 75% less than the control.

Acidification also affects cold water corals. Cold water corals have a worldwide but patchy distribution, and are often found in areas with highly productive fisheries (De Mol et al. 2002; Kenyon et al. 2003). Overall, more than two-thirds of all known coral species are cold water corals (Roberts & Hirshfield 2012; Cairns 2007). Recent exploration and research that has begun to search for, map, and observe cold water corals has found that these organisms are fragile, long-lived, slow-growing, very sensitive to physical or environmental disturbance and adapted for a specific environmental niche (McDonough & Puglise 2003). Alaskan waters are already showing widespread evidence of ocean acidification as a result of greenhouse gas emissions (Mathis et al. 2011a). By 2100, 70% of cold-water corals will be exposed to corrosive waters (Convention on Biological Diversity 2009). Conditions in waters typically inhabited by cold-water corals are even less favorable for calcification than those experienced by warm water corals; this may cause cold-water corals to be affected earlier and more strongly by CO_2-related ocean acidification than their warm water counterparts (Abbasi & Abbasi 2011).

The vulnerable early developmental and reproductive stages of cold water corals may be especially strongly impacted (Kurihara 2008; Dupont & Thorndyke 2009; Kroeker et al. 2010). In an experiment on the cold-water coral *Lophelia pertusa*, lowering the pH by 0.3 units relative to the ambient level resulted in calcification being reduced by 56% (Maier et al. 2009). Lower pH reduced calcification more in fast growing, young polyps (59% reduction) than in older polyps (40% reduction). Thus, corals' larvae and young corals are significantly more susceptible to ocean acidification than adults, and will likely show a higher degree of reduced calcification

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and growth with reduced pH, making young and larval corals less likely to survive to maturity as the ocean continues to absorb anthropogenic CO_2 and as climate change progresses.

In addition to reduced calcification rates, the strength of cementation may also be reduced in waters with a lower pH, promoting higher rates of physical and bio-erosion (Manzello et al. 2008). Once coral reefs experience lowered calcification and poor cementation, erosion and reef flattening can result, which severely reduced the structural heterogeneity of reefs and lowers its potential to support biodiversity. An important new study of reef bioerosion determined that the combined effects of lower calcification with increased bioerosion can significantly degrade coral reefs (Wissshak et al. 2012). In the study, a common bioeroding sponge in the Great Barrier Reef was observed on massive Porites. The sponge was more effective at bioerosion of the corals at high CO_2, ranging from 17% increase from present day levels to 61% increase at the highest CO_2 treatment. The researchers describe the important role of balancing the antagonistic processes of calcification and bioerosion in a reef for a healthy coral ecosystem, and predict detrimental consequences under ocean acidification as calcification declines and bioerosion increases.

Bioerosion may result in a loss of change in fish assemblages, lower densities of commercially important species, and lower rates of larval fish recruitment (Feary et al. 2007). Weaker reef calcification and cementation also increases the potential for reef damage as storm frequency and intensity increases with continued global warning, leading to further reef degradation (*Id.*). In a study looking at the impacts of storm damage and ocean acidification, researchers concluded that table coral populations are vulnerable to collapse (Madin et al. 2012). In the Indo-Pacific, table corals provide an important role in the reef ecosystem by creating reef structure and sheltering other reef species. They are also particularly vulnerable to ocean acidification, thermal stress, bleaching, disease and stress from storm waves. The table corals will become more vulnerable to storm waves as ocean acidification reduces calcification and increases bioerosion, therefore weakening their cementation and structure. Madin et al. (2012) found that a coral colony was four times more likely to be dislodged by a storm wave by the end of the century ocean acidification levels. Because of this vulnerability, the results showed that table corals are prone to large and rapid declines in coral cover.

Numerous biological responses independent of calcification are also negatively impacted by ocean acidification. Corals in acidifying waters are likely to be in a nutritionally or energetically stressed state and thus less likely to initiate reproduction, or successfully reproduce, due to negative impacts of ocean acidification on all stages of the reproductive cycle (Maier et al. 2009; McCulloch et al. 2012). Sperm flagellar motility also declines in response to decreasing pH. If sperm lose their ability to find eggs in the vast extent of the sea, the life of marine organisms is potentially limited. Sperm flagellar motility, which is indispensable for fertilization, is regulated by an elevation of intracellular sperm pH (Morita et al. 2010). While 69% of *Acropora* sperm were motile at pH 8.0, 46% were motile at pH 7.8, and fewer than 20% at pH 7.7 (*Id.*). Additionally, the physiological costs associated with reproduction are more likely to result in the demise of the organism due to the compounding stressors from ocean acidification and climate change (Wood et al. 2008, Cohen & Holcomb 2009). Significant reductions in metabolism have been observed for coral larvae following exposure to waters with a 0.2 decline in pH, levels projected to occur by the middle of this century (Albright & Langdon 2011).

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Albright et al. (2010) concluded that with increased CO_2 concentrations to those projected to occur in this century (560 atm to 800 atm, or a 0.3 to 0.5 decline in pH from pre-industrial values), the fertilization success of the tropical reef-building coral *Acropora palmata* decreased by 12-13%, settlement success reduced 45-69%, and linear extension was significantly reduced. The compounding effect of these impacts translated to 52-73% reduction in the number of larval settlers on the reef. Albright et al. (2010) predicted that the net impact on recruitment would actually be greater than that given that the depressed post-settlement growth is likely to result in elevated rates of post-settlement mortality. This corroborates other studies showing negative impacts on early-stage tropical corals.

Albright and Langdon (2011) tested the effects of ocean acidification on sexual recruitment of tropical corals. Larval metabolism was depressed by 27% at acidification levels expected by mid-century (0.3 pH reduction) and 63% at end-of-century acidification levels (0.4-0.5 pH reduction). Settlement was also reduced 42-45% and 55-60% at the mid and end-of-century levels respectively, relative to controls (Albright & Langdon 2011). Another study of larvae of tropical corals showed that short-term or long term exposure of larvae to ocean acidification decreased their metamorphosis (Suwa et al. 2010). This means that even when larval survivorship is unchanged, the success of recruiting new corals could be inhibited by ocean acidification (*Id.*).

Additionally, under conditions of acidification planktonic larvae lose their preference for settlement on the optimal crustose coralline algae communities (Doropoulos et al. 2012). Crustose coralline algae in turn, will experience a lower recruitment rate as marine waters become more acidic. Crustose coralline algae, a red calcifying algae, is of key importance in coral reef ecosystems, stabilizing reef structures and providing an important food source for benthic organisms (Convention on Biological Diversity 2009). Crustose coralline algae form a major calcifying component of the marine benthos from polar to tropical regions and are considered to influence the settlement of coral recruits. With a mean pH change of 0.26 between control and treatment, Kuffner et al. (2007) found that crustose coralline algae growth rates declined by 40%, and recruitment rate and percentage cover decreased by 78% and 92%, respectively.

In sum, reproduction is critical to maintaining a healthy coral reef population, and the long-term impacts of ocean acidification on reproduction, especially on larval settlement and growth, may significantly reduce the corals' ability to recover or maintain a population in the face of human caused disturbances and anthropogenic CO_2 emissions. This would result in a lack of reproductive capacity, genetic bottlenecks, and population collapse (Dupont et al. 2010; Ross et al. 2011).

As the world's oceans become more acidic and less saturated with carbonate minerals, corals are expected to build weaker skeletons and experience slower growth rates, which will make it more difficult for corals to retain competitive advantage over other marine organisms (Guinotte et al. 2006). As coral skeletons weaken, they will become increasingly at risk of storm damage and bioerosion, which will reduce the structural complexity of the reef system, reducing habitat quality and diversity alongside the loss of coastal protection functions (Hoegh-Guldberg et al. 2007). At greater than 550 ppm, coral reef ecosystems will be reduced to "crumbling

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frameworks." (*Id.*). Extensive studies have demonstrated that small changes in ocean chemistry will cause a suite of negative impacts, from reduced calcification rates to lowered reproductive success.

iii. Plankton

Plankton, which comprise the basis of the marine food web, are among the calcifying organisms adversely affected by ocean acidification. Changes to calcifying zooplankton, such as pteropods and foraminfera, have the potential to affect the ecological and tropic dynamics which govern the exchange of energy and cycling of nutrients throughout the marine food web (Gattuso & Hansson 2011). For example, the shelled pteropod, *Limacina helicina*, an Arctic pelagic mollusc, is a food source for higher predators such as fishes, whales and birds that are particularly important in high latitude areas. *L. helicina* makes up about 60 percent of the pink salmon diet (Comeau et al. 2012). A decline of pteropod population would likely cause dramatic changes to various pelagic ecosystems, and impact the commercially important salmon fishery; a 10% decrease in pteropods can lead to a 20% reduction in pink salmon body weight (Aydin 2005).

Pteropods form integral components of food webs, and are considered an overall indicator of ecosystem health (Orr et al. 2005). Studies have shown that pteropods exposed to a pH value predicted for the end of this century exhibited a 28% decrease in calcification (Comeau et al. 2009). Experiments on *L. helicina* showed that changes from 8.05 pH to 7.89 pH (Δ -0.16 units) cased shell dissolution and cracks appeared at 7.76pH, and linear extension of the shell decreased as a function of declining pH (Comeau et al. 2012). Samples show dissolution already happening in areas that have low aragonite saturation states. A sampling study off the coasts of California, Oregon, and Washington showed average to severe dissolution of *L. helicina* for 53% of onshore individuals and 24% of offshore individuals (Bednarsek 2014). A sampling study in 2008 of the Southern Ocean found severe dissolution of *L. helicina* in Ω_{ara} 1.0 (Bednarsek 2012). Another study found shell weights of one form of Antarctic species declined 35% from 1997-2006 (Roberts unpublished).

Ample studies corroborate that high CO_2 waters dissolve the shells of *L. helicina* and reduce calcification rates. Comeau et al. (2010) noted decreased calcification for *L. helicina* with decrease in aragonite saturation. Lishka (2012) looked at overwintering *L. helicina* and L. retroversa in the Arctic and noted that they do not calcify in the winter, and they are subject to dissolution under high CO_2 conditions. Bednarsek (2012) looked at *L. helicina* and *Clio pyramidata* from the Southern Ocean under different aragonite saturation states and recorded dissolution stages.

Modeling by Comeau et al. (2012) shows that by the end of the century *Limacina helicina* will not be able to calcify over much of the Arctic because of aragonite undersaturation—prediction may be conservative because it did not account for shell dissolution. Commentary suggests that as waters warm these pteropods will be trapped in acidified conditions and will "disappear entirely by the end of the century." Modeling suggests that waters in the California Current will be undersaturated year-round by 2050 (Gruber 2012). Modeling of the Arctic suggests that by mid-century the Bering Sea will be persistently undersaturated with respect to aragonite (Mathis 2011). An analysis of survey measurements in 2005-2006 and 1991-1992 demonstrated a

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shoaling of the aragonite saturation state in waters off Alaska (Feely et al. 2012). In the North Pacific the aragonite saturation state shoaled to depths less than 200 m between 40˚N and 50˚N (*Id.*). On average, the calcite saturation horizon in the Pacific shoaled about 1 m/yr from 1991 to 2006 (*Id.*).

Other species of plankton are also harmed by CO_2. Another pteropod, *Clio pyramidata,* kept in aragonite undersaturated waters began to dissolve within two days (Orr et al. 2005). Some coccolithophorids are also susceptible to ocean acidification. Studies showed that CO_2 related changes to seawater caused reduced calcification, resulting in malformed and incomplete shells. Calcification of cocolithophorids declined 15-44%, and their shells were malformed as pH changed up to about 0.3 units (Riebesell et al. 2000). Coccolithophorids are globally distributed and bloom in massive areas affecting the optical properties of the ocean, reflecting light from the earth, and play a major role in the ocean carbon cycle. Elevated CO_2 concentrations also reduce the shell mass of foraminifera (Kleypas et al. 2006). Modern shell weights of foraminifera in the Southern Ocean are 30–35% lower than those from preindustrial sediments, which is consistent with reduced calcification induced by ocean acidification (Moy et al. 2009).

iv. Cephlopods and Fish

The negative physiological effects of ocean acidification are not confined to invertebrates. For example, the gametes, embryos, and larvae of vertebrates such as fish are vulnerable to changes in ocean chemistry and have shown impairments in their homing and predator/prey detection capabilities.

Changes in the ocean's CO_2 concentration result in accumulation of CO_2 in the tissues and fluids of fish and other marine animals, called hypercapnia, and increased acidity in the body fluids, called acidosis. These impacts can cause a variety of problems for marine animals, including difficulties with acid-base regulation, calcification, growth, respiration, energy turnover, predation response, and mode of metabolism (Pörtner et al. 2005; Pörtner et al. 2004). Studies have shown adverse impacts in squid and fish, among other animals (Rosa & Seibel 2008; Ishimatsu et al. 2004; Pörtner et al. 2004). For example, when exposed to acidification, orange clownfish suffer a type of brain malfunction that interferes with their homing abilities and makes them 5-9 times more likely to swim toward a predator (Munday et al. 2009; Simpson et al. 2011; Ferrari et al. 2011).

Laboratory experiments have shown that ocean acidification at levels expected to occur within this century impairs larval orange clownfish and damselfish sensory abilities and behavior, making it more difficult for them to locate suitable settlement sites on reef habitat and avoid predators. Specifically, ocean acidification disrupts smell, hearing, and behavior of larval orange clownfish, (Munday et al. 2009; Nilsson et al. 2012), making larval clownfish attracted to odors from predators and unfavorable habitat (Munday et al. 2010; Dickson et al. 2010). Olfactory cues that prompted avoidance or neutral behavior in controls (pH 8.15) stimulated strong preference behavior in larvae raised at pH 7.8, in addition to significant reduction in response to usually positive preferences. Ocean acidification also impairs the hearing capacity of larval clownfish, which is predicted to have negative effects on settlement success and survival (Simpson et al. 2011).

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Similarly, research on six damselfish species found that ocean acidification impairs larval damselfish smell, vision, learning, behavior, and brain function, leading to higher risk of mortality. For example, in acidified waters, larval damselfish (1) become attracted to predator odors and display much riskier behaviors, making them more prone to predation; two species suffered a five-fold to nine-fold increase in predation rate at CO_2 levels of 700 to 850 ppm, or 0.3 pH units below control (Munday et al. 2009; Ferrari et al. 2011); (2) cannot discriminate between habitat olfactory cues, making it more difficult to locate appropriate settlement habitat (Devine et al. 2011); (3) settle on the reef during dangerous times—the full moon rather than new moon—when they are more vulnerable to predation (Devine et al. 2011); (4) fail to visually recognize or evade important predator species; (5) cannot learn to respond appropriately to a common predator by watching other fish react or by smelling injured fish, unlike fish under normal conditions (*Id.*); and (6) suffer disruption of an important neurotransmitter which is thought to result in the sensory and behavioral impairment observed in acidified conditions (Nilsson et al. 2012).

An animal's ability to transport oxygen is reduced by pH changes (Pörtner 2005). Water breathing animals have a limited capacity to compensate for changes in the acidity (Haugan 2006). For example, fish that take up oxygen and respire CO_2 through their gills are vulnerable because decreased pH can affect the respiratory gas exchange (Royal Society 2005). Changes in metabolic rate are caused by the changes in pH, carbonates, and CO_2 in marine animals (Haugan 2006).

Squid, for example, show a very high sensitivity to pH because of their energy intensive manner of swimming (Royal Society 2005). Because of their energy demand, even under a moderate 0.15 pH change squid have reduced capacity to carry oxygen and higher CO_2 pressures are likely to be lethal (Pörtner 2004). Even species more tolerant to pH changes experience decreased metabolism from increased CO_2 in the water (Pörtner 2004). For example, as much as 50% mortality was observed in copepods after only six days of exposure to waters with a pH level 0.2 units below the control (Pörtner 2005). Reducing pH by 0.3 pH cased a 31% decline in metabolic rate and a 45% decrease in activity level for the jumbo squid, an important predator in the Easter Pacific (Rosa & Seibel 2008).

In fish, pH also affects circulation. Fishexposed to high concentrations of CO_2 in seawater experience cardiac failure and increased mortality (Ishimatsu 2004). At lower concentrations sublethal effects can be expected that can seriously compromise the fitness of fish. Juvenile and larval stages of fish were found to be even more vulnerable (Ishimatsu 2004).

In sum, ocean acidification can have many adverse effects on marine animals that can reduce their fitness and survival (Royal Society 2005). Many marine animals have low thresholds for long-term CO_2 exposure (Pörtner 2005).

c. Other Environmental Impacts of Ocean Acidification

i. Increased Toxicity of Harmful Algal Blooms and Sediments

Ocean acidification may already be increasing the toxicity of harmful algal blooms known as "red tides." These toxic red tides poison shellfish, marine mammals, fish, and even cause

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paralytic shellfish poisoning in people. High CO_2 levels in seawater magnify the toxins of harmful algae. (Fu et al. 2012; Avery O Tatters et al. 2013; Tatters et al. 2012; Avery O. Tatters et al. 2013). Studies of the genus *Pseudo-nitzscia* show that the toxicity of diatoms which produce a neurotoxin increases significantly under ocean acidification conditions. A -0.5pH change caused toxin production in the diatoms to increase 4.2-fold and a -0.3pH unit change increased the toxicity 2.5-fold (Tatters et al. 2012). Many studies on the effects of ocean acidification and algal blooms have been conducted at CO_2 levels that are already occurring in California, and the increase in the toxicity of harmful algal blooms in Southern California (and resulting mass mortalities of fish and marine mammals) may be due, in part, to acidified waters (*Id.*) However, these studies suggest that the damage will become much worse.

Additionally, research shows that under conditions of ocean acidification sediments become more toxic (Roberts, Birchenough et al. 2013). Ocean acidification makes sediment-bound metals more available and thus more toxic for aquatic life (*Id.*) For example, ocean acidification increases the toxicity of copper (Campbell & Mangan 2014).

ii. Noise Pollution Increases in Low pH Waters

Ocean acidification can also decrease the sound absorption of seawater, causing sounds to travel further with potential impacts on marine mammals and other marine life sensitive to the sounds of vessel traffic, seismic surveys, and other noise pollution (Hester et al. 2008). Sound travels 10-15 percent further with a change of 0.1 pH, and it is predicted to increase about 40 percent by mid-century (Hester et al. 2008). Additionally, a decline of 0.3 pH units causes a 40 percent decrease in the sound absorption of surface seawater and sound may travel 70 percent farther, further affecting sensitive marine mammals (Brewer et al. 2009).

d. Ocean Acidification's Ecosystem Impacts

While the full implications of elevated CO_2 on marine ecosystems are not well-documented, there is high confidence that there will be negative ecosystem consequences from ocean acidification. The exact changes are difficult to predict, but some of the anticipated impacts include loss of diversity, loss of abundance of calcifying species, shifting prey and predator interactions, and loss of suitable habitat.

New mesocosm studies have sought to understand some of the potential ecosystem impacts of CO_2. Studies of biodiversity near underwater volcanic vents demonstrate reduced richness in high-CO_2 waters. For example, coral species diversity declined by about 39% between low and high-CO_2 sites, with the reefs shifting from complex communities to a coral reef dominated by massive Porites. Most importantly, the researchers found that coral reef development ceases at 7.7 pH, and they concluded that a pH decline below 7.8 would be "catastrophic for coral reefs" (Fabricius et al. 2011). Scientists also observed that in high-CO_2 waters the loss of complex coral reef habitat resulted in a loss of diversity of reef-associated species such as crustaceans and crinoids (Fabricius et al. 2014). Looking at the macroinvertebrates, the density declined 48% between control and high-CO_2 areas and taxa diversity declined by 77% (*Id.*).

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Loss of species diversity associated with ocean acidification can also result from changes in competitive interactions. A study of a rocky reef near volcanic vents documented that macro algae outcompeted calcareous species in low-pH waters (Kroeker et al. 2012). The researchers explained that under the high-CO_2 conditions the calcifying species grew more slowly while the seaweed took hold and that grazing of seaweed was depressed (*Id.*). In another study, while the areas near volcanic vents lacked scleractinian corals and had low abundance of sea urchins and coralline algae, invasive algal species benefited from the acidified conditions (Hall-Spencer et al. 2008).

Research on the diversity the intertidal community in the Pacific Northwest documented a shift from a ecosystem dominated by calcifying animals to one with non-calcifying organisms as pH declined. Researchers documented declines in abundance and size of the California mussel, blue mussel, and goose barnacle in tidepools on the Olympic Coast in Washington (Wootton et al. 2008). They found that in years with low pH waters the calcifying animals were replaced by non-calcifying organisms (*Id.*).

The synergistic impacts of ocean acidification and warming are also potentially severe. Ocean acidification may induce a negative climate feedback that may increase temperature rise. Mesocosm studies found that ocean acidification may amplify global warming through decreasing biogenic production of the marine sulfur component dimethylsulphide which can impact cloud albedo (Six 2013). Ocean acidification therefore may also contribute to climate change impacts on the environment.

2. Risk Reduction Costs and Benefits

EPA must make a determination whether the risk of ocean acidification is unreasonable and this constitutes a balancing of costs and benefits. While it is EPA's burden to conduct this analysis, petitioners present some limited data on (1) the socio-economic costs of CO_2 pollution in light of ocean acidification, (2) the feasibility of controls on CO_2 pollution, and (3) the social cost of carbon including the costs of delaying action to reduce and mitigate CO_2 pollution.

a. Socioeconomic Costs of Ocean Acidification

The release of CO_2 into the environment is already having social and economic impact, and these impacts are predicted to become even more concerning. Primary economic concerns are from the loss of fisheries and coral reefs. Ocean acidification also poses food security and nutrition risks.

U.N. Convention on Biological Diversity estimated costs on the predicted damage of ocean acidification and predicts that the oceans will lose more than $1 trillion in value annually from ocean acidification (Convention on Biological Diversity 2014). CO_2 related ocean warming and acidification will threaten marine food resources by disrupting marine communities, promoting harmful algal blooms and the spread of some diseases, and increasing contaminants in fish and shellfish (Tirado et al. 2010).

The United Nations Environment Programme reported that ocean acidification's impact on marine organisms is a threat to food security (UNEP 2010). The report documents that ocean

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acidification is measurable and increasing, which poses a threat to fisheries resources and the billions of people that have a marine-based diet (United Nations Environment Programme 2010). Seafood has been shown to prevent hundreds of thousands of premature deaths, as well as significantly reduce infant morbidity; a decline of seafood availability will decrease these benefits. Some populations, including subsistence fishing populations and poor communities, depend on seafood and mortality and morbidity can result from the loss of these food sources (Mozaffarian 2006). For example, 95% of Alaskan households do some sort of subsistence fishing, and 17% of the state's population, 120,000 people, depend on subsistence fishing (Mathis et al. 2014). Many subsistence fishers also have cultural ties threatened by ocean acidification. Accordingly, CO_2 can result in social and environmental justice concerns that must also be assessed and weighed (Convention on Biological Diversity 2014).

Not only will ocean acidification affect global food webs and ecosystems, it will have a direct effect on the global economy. The U.S. economy is very dependent on the health of the ocean. In 2009, the ocean economy contributed over $223 billion annually to the U.S. gross domestic product and provided more than 2.6 million jobs (NOAA, http://oceanservice.noaa.gov/facts/oceaneconomy.html). Cooley and Doney (2009) estimate that if just a 10-25% decrease in United States mollusk harvests from 2007 were to occur today, $75-187 million in direct revenue would be lost each year henceforth, with a net loss of $1.7-10 billion through mid-century, when pH levels are approximately 0.3 units below pre-industrial values. In Washington State alone, the seafood industry generates $1.7 billion for gross state product and employs 42,000 people (Washington State Blue Ribbon Panel 2012). Already, shellfish hatchery failures in Washington have caused an economic stir and caused some hatcheries to relocate. Alaska's commercial fishing industry is valued at over $4 billion a year, and supports 90,000 jobs—recreational fishing and fishing tourism add even more value. Meanwhile, Alaska is ranked among the most vulnerable areas to acidification.

Tropical coral reefs provide ecosystem services, such as habitat and nursery functions for commercial and recreational fisheries and coastal protection. As reefs decline in acidified waters, there will be an ecological shift to a new ecosystem state dominated by less commercially valuable species. In 2009, Brander et al. estimated the annual economic damage of ocean acidification-induced coral reef loss to escalate rapidly over time, reaching $870 billion by 2100 (Brander et al. 2009a). In 2014, Brander et al. increased the anticipated loss of ecosystem services from corals to be $1000 billion (UNEP 2014). Shoreline protection offered by coral reefs and the services it provides by preventing loss of life, property damage and erosion are also reduced by CO_2 emissions.

Lane et al. (2014) modeled three major U.S. locations for shallow water reefs -- South Florida, Puerto Rico, and Hawaii – to project future reef cover and the economic values generated by coral reefs for a greenhouse gas emissions mitigation scenario that represents international implementation of policies to reduce global emissions (resulting in a CO_2 concentration of 427 ppm in 2100), compared to a business as usual greenhouse gas emissions scenario resulting in a CO_2 concentration of 785 ppm in 2100. The study estimated that reducing emissions would result in an "avoided loss" in Hawaii of approximately $10.6 billion in recreational use values compared to business as usual. Reducing emissions was projected to provide fewer economic benefits in Puerto Rico and South Florida, where sea-surface temperatures are already close to

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bleaching thresholds and coral cover is projected to drop well below 5% cover under both scenarios by 2050, and below 1% cover under both scenarios by 2100 (Lane et al. 2014).

As discussed previously, the toxicity of harmful algal blooms increases under conditions of ocean acidification. These toxins not only poison marine mammals, but also cause paralytic shellfish poisoning in people. Scientists hypothesize that some of the increases red tides off the coast of Southern California may be related to ocean acidification, though this has yet to be confirmed. In turn, harmful algal blooms cost the United States approximately $82 million each year from impacts to fisheries, public health, management, and lost recreational opportunities (Hoagland and Scatasta 2006).

A recent study estimated that the damage our oceans will face from emissions-related problems will amount to $428 billion a year by 2050 and nearly $2 trillion per year by the century's end (Noone et al. 2012).

> Acidification impacts processes so fundamental to the overall structure and function of marine ecosystems that any significant changes could have far-reaching consequences for the oceans of the future and the millions of people that depend on its food and other resources for their livelihoods.

(Doney et al. 2009). There is also a significant cost to delaying action. According to a recent report by the Council of Economic Advisers, delaying the implementation of policies to mitigate climate change could significantly increase economic damages, in addition to worsening environmental harm.[39]

While there are still large unknowns on the biological consequences of ocean acidification, the science we have is clear: from shellfish to corals, and from pteropods to fish, our marine resources are threatened by the acidification of our ocean waters.

b. Risk Reduction Methods

There are several ways to reduce risk from CO_2. EPA should use a suite of tools to reduce emissions, sequester CO_2, mitigate harms, and promote alternatives. Under TSCA EPA has authority to:[40]

- prohibit or limit the amount of production or distribution of a substance in commerce;
- prohibit or limit the production or distribution of a substance for a particular use;
- limit the volume or concentration of the chemical produced;
- prohibit or regulate the manner or method of commercial use;
- require warning labels and/or instructions on containers or products;
- require notification of the risk of injury to distributors and, to the extent possible, consumers;

[39] Executive Office of the President of the United States, The Cost of Delaying Action to Stem Climate Change at 1 (July 2014).
[40] 15 U.S.C. § 260.

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- require record-keeping by producers;
- specify disposal methods; and
- require replacement or repurchase of products already distributed.

EPA also may impose any of these requirements in combination or for a specific geographical region. [41] Specifically, the agency must impose controls sufficient "to protect adequately against such risk using the least burdensome requirement."[42]

There is evidence that many industries could employ existing technology to achieve meaningful emissions reductions affordably. EPA's own data demonstrate that lower pollution rates are readily achievable for many industrial sources of CO_2. For example, the agency has identified dozens of "control measures and energy efficiency options that are currently available for pulp and paper mill processes," ranging from technological upgrades to improved equipment maintenance.[43] Similarly, EPA has compiled more than a decade of reports on "cost-effective" control strategies and other approaches available to reduce cement plant CO_2 emissions, "includ[ing], for example, energy efficiency measures, reductions in cement clinker content, and raw materials substitution."[44]

Although cost-effective strategies to reduce CO_2 emissions are available, existing controls have not reduced CO_2 emissions sufficiently to protect against environmental harm. For example, most natural gas power plants have *never* exceeded the agency's recently proposed emissions limit, thus indicating that existing and newly constructed facilities could easily satisfy a more stringent standard.[45] Because energy-related CO_2 pollution accounts for more than eighty percent of U.S. greenhouse gas production, readily achievable reductions in this sector would significantly benefit the environment.[46] Similarly, the pulp and paper industry ranks among the largest consumers of energy,[47] and emitted nearly 58 million metric tons of CO_2 equivalent gases in 2004.[48] Moreover, market incentives and regulatory controls are effective in increasing the rate of innovation for technologies that can reduce CO_2 emissions.

If a chemical presenting an unreasonable risk to health and the environment has already been distributed, EPA may prescribe procedures by which relevant manufacturers and purchasers must replace or repurchase that chemical.[49] In the present situation, we urge the agency to exercise its

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[41] *Id.*
[42] 15 U.S.C. § 2605(a).
[43] *See* EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 11 (2010).
[44] EPA, National Emission Standards for Hazardous Air Pollutants From the Portland Cement Manufacturing Industry and Standards of Performance for Portland Cement Plants, 75 Fed. Reg. 54,970, 54,997 (Sep. 9, 2010).
[45] Ctr. for Biological Diversity, Comments on Standards of Performance for Greenhouse Gas Emissions from New Stationary Sources: Electric Utility Generating Units (Proposed Rule) Docket No. EPA-HQ-OAR-2013-0495 at 13-14 (May 9, 2014).
[46] U.S. Dept. of State, U.S. Climate Action Report at 16 (2010).
[47] *See* U.S. Energy Information Administration, First Use of Energy for All Purposes (Fuel and Nonfuel), 2010 (Mar. 2013), http://www.eia.gov/consumption/manufacturing/data/2010/#r1.
[48] EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 7 (2010).
[49] 15 U.S.C. § 2605(a)(7)(C).

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authority to remediate existing harm by requiring that responsible parties mitigate past CO_2 emissions.

There are numerous approaches to mitigating and sequestering CO_2 emissions that EPA must evaluate. Effective land use and agricultural practices can significantly reduce carbon emissions and sequester CO_2. Federal programs aimed at consumers can reduce CO_2 emissions. For example, EPA's Energy Star program has prevented 1.8 billion tons of greenhouse gas emissions by providing information that helps customers select energy efficient devices. Sequestration of CO_2 in products, infrastructure, and waste management are among numerous methods that could be cost-effective to mitigate CO_2 pollution.

c. Social Costs of Carbon

In any analysis of the cost and benefits of reducing CO_2 pollution, the costs of failing to address the problem of global warming should be included. Most efforts to quantify the social costs of carbon underestimate the real-world costs of CO_2 pollution. Nevertheless, EPA may not ignore these costs.

Global emissions must be less than 1000 Gt of CO_2 between 2000 and 2050 to avoid dangerous climate change, which scientists have recommended that this means maintaining temperature change below 2° C.[50] This means keeping atmospheric CO_2 to 450 ppm, a threshold below which experts also use for ocean acidification (Veron et al. 2009; Silverman et al. 2009; Interacademy Panel 2009; McNeil & Matear 2008; Sea et al. 2007). For example, coral scientists predict that at 450 ppm, reef-building will be severely diminished or will cease altogether (Veron et al. 2009). But the global community has already used a substantial portion of this CO_2 budget, emitting 305 Gt of CO_2 between 2000 and 2008 alone.[51] As a result, the years between now and 2020 have been dubbed the "critical decade."[52] Because carbon emissions must peak soon and decline thereafter, the sooner emissions peak, the less severe the subsequent annual reductions will need to be;[53] correspondingly, if emissions are not sufficiently curbed in this decade, avoiding catastrophic damages will require much more drastic, disruptive and costly measures and may no longer be possible at all. Nonetheless, if action is taken immediately, it is both technologically and economically feasible to reduce emissions by 2020 and lay the groundwork for future emissions reductions.[54]

Every year that the world delays its efforts to reach sustainable levels of greenhouse gas emissions represents a lost opportunity of tremendous economic significance. McKinsey & Company estimated in 2009 that for every year of delay, 1.8 Gt of potential CO_2 abatement is foregone.[55] This delay, and the accompanying Gts of lost CO_2 abatement, has a price tag, as the

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[50] Australia Department of Climate Change and Energy Efficiency, The Critical Decade: Climate Science, Risks and Responses at 53 (May 2011), *available at* http://www.scribd.com/doc/56043375/The-Critical-Decade-Climate-Change-Commision-Report.
[51] *Id.*
[52] *Id.*
[53] UNEP, The Emissions Gap Report at 14 (Nov. 2010), *available at* http://www.unep.org/publications/ebooks/emissionsgapreport/; for a discussion of economic implications of these facts, *see infra.*
[54] *Id.* at 23.
[55] McKinsey & Company, Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve at 16 (2009), *available at* www.worldwildlife.org/climate/WWWFBinaryitem11334.pdf.

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damage caused by CO_2 emissions accelerate while the cumulative amount of greenhouse gases in the atmosphere rises, both because of the increasingly dire damages wrought by rising temperatures and other greenhouse gas effects, *and* because of the delay factor itself. If governments delay mitigation in the present, the emissions reduction curve in future years necessarily becomes much steeper, requiring much more drastic and costly emission reduction mechanisms with tremendous economy-wide disruptions, just to "catch up" with the lost opportunities from prior years to reach a sustainable emissions trajectory—or risk undergoing unsustainable climatic extremes.

Economists have sought to quantify the costs of waiting to embark upon an emissions reduction path. In 2007, researchers used the DICE model[56] to estimate the cost of delaying mitigation for a given period of time and then switching to an optimal abatement trajectory. According to their findings, the global cost of ten years of delay, relative to starting on an optimal trajectory in the present, ranges from hundreds of billions to several trillion dollars.[57] For instance, this study estimates that it would cost somewhere between $200 and $400 billion dollars to delay action for ten years and then embark upon a mitigation strategy that would result in stabilization at 3 °C (a level now universally understood to far exceed the dangerous). The cost of delaying mitigation soars into the trillions of dollars as the delay continues, until it ultimately becomes impossible to achieve a certain level of temperature stabilization. According to this study, more than thirty years' delay of changing the current course would make it impossible – no matter what the expense – to stabilize temperature rises at 2° C above pre-industrial levels.

EPA and other federal agencies have been using the social cost of carbon to estimate the climate benefits of rulemakings since it was first developed by a dozen agencies (including USDA, CEQ and EPA) and published by the Interagency Working Group in 2010.[58] The social cost of carbon, usually expressed as a dollar-per-ton figure, provides an estimate of the economic damages associated with an increase in CO_2 emissions, conventionally one metric ton, in a given year. The dollar figure can also represent the value of damages avoided for emission reductions achieved by federal rulemakings. The social cost of carbon is designed to provide a comprehensive estimate of climate change damages, including, but not limited to, changes in net agricultural productivity, human health, and property damages from increased flood risk. However, given current modeling and data limitations, even EPA has conceded that that the social cost of carbon protocol is likely a conservative estimate because it does not yet account for all important damages.[59] Nevertheless, the protocol is designed for use in regulatory processes like this one. In 2013 the Federal Interagency Working Group increased its estimates of the social cost of carbon, using the same 3% annual discount rate, by 50%.[60] The 2013 estimates are 50% higher for emissions in 2010, with greater percentage increases in subsequent years. Yet, even these social

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[56] DICE stands for the Dynamic Integrated Climate and Economy model developed by William Nordhaus in 1990.
[57] Keller, K. et al., The Regrets of Procrastination in Climate Policy, Environmental Research Letters (2007), *available at* iopscience.iop.org/1748-9326/2/2/024004/.
[58] EPA, The Social Cost of Carbon, http://www.epa.gov/climatechange/EPAactivities/economics/scc.html (last accessed June 28, 2015).
[59] *Id.*
[60] Interagency Working Group on Social Cost of Carbon, United States Government, Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 (Nov. 2013) at 3, available at http://www.whitehouse.gov/sites/default/files/omb/assets/inforeg/technical-updatesocial-cost-of-carbon-for-regulator-impact-analysis.pdf.

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cost of carbon figures significantly underestimate the true social cost of carbon, possibly by several orders of magnitude.

Economists have noted that the social cost of carbon is far greater than the $21 per ton of CO_2 assumed by interagency protocol in 2010 and greater than the 2013 revision.[61] There are several inadequacies that make the values too conservative. Foremost, the models fail to evaluate ocean acidification—to the contrary the models consider the ocean a sink for CO_2. The FUND model used in the Working Group's analysis wholly excludes consideration of climate-induced catastrophic events. But the Working Group weighs the values generated by each of the three models equally, even though the FUND model's values is significantly lower[62] than the others, and consequently pulls down the final value of the social cost of carbon. The potential for catastrophic climate events, and the increasing likelihood that tipping points will be reached even sooner than anticipated, are increasingly serious risks, however, and, despite the associated uncertainties, must be fully represented in any evaluation of the social cost of carbon. Instead, the Working Group employed a risk-neutral approach, clearly inappropriate in light of the vast majority of scientific studies. Also, the models used fail to account fully or even partially for certain highly complex aspects of climate change, including the possibility of interrelations between different sectors and accelerating damage feedback loops, non-CO_2 emissions,[63] and social and political instability. Moreover, the valuation techniques and discount rates used to reach these values are inherently problematic and fail to represent the full value of all losses from climate change, in significant part because some cannot be reduced to monetary terms.

Other evaluations of the social cost of carbon attempt to account for these omitted factors. The Stern Review, in particular, reaches a SCC of $85/ton of CO_2 (in 2000 dollars).[64] For comparison purposes with a Working Group value of $21 in 2005 dollars, this amount is equivalent to

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[61] F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon (2010) (the social cost of carbon could be over $800 per ton of CO2 equivalent; F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon, in Economics, vol. 6 (Apr. 4, 2012) (reaching similar conclusions), available online at http://www.economics-ejournal.org/economics/journalarticles/2012-10 (last visited June 27, 2014); P. Epstein et al., Full cost accounting for the life cycle of coal, Ann. N.Y. Acad. Sci. (2011) (estimating the social cost of coal at between $10 and $100 per ton of CO2 equivalent); L. Johnson & C. Hope, The social cost of carbon in U.S. regulatory impact analyses: an introduction and critique, J. Envtl. Stud. & Sci. (Sept. 9, 2012) (finding a social cost of a ton of CO2 emissions to be 2.6 to over 12 times larger than the Interagency Working Group's central estimate of $21 per ton of CO2) available online athttp://link.springer.com/article/10.1007%2Fs13412-012-0087-7 (last visited June 27, 2014) E. Stanton et al., Comments on the 2013 Technical Update of the Social Cost of Carbon, January 27, 2014.

[62] Interagency Working Group on the Social Cost of Carbon, Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, at 16-A-11, Fig. 16-A-4.2, *available at* http://www.rff.org/Publications/WPC/Pages/Estimating-the-Social-Cost-of-Carbon-for-Regulatory-Impact-Analysis.aspx.

[63] For instance, the estimated social cost of methane and SF_6, are, respectively, $105/tonne and $200,000/tonne. *See* Intergovernmental Panel on Climate Change, Climate Change 2007 Synthesis Report 822, *available at* http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html. For a critical analysis of the Working Group's assumptions, *see also* Ackerman, F. and Stanton, E. A., The Social Cost of Carbon A Report for the Economics for Equity and the Environment Network (April 1, 2010), *available at* http://www.e3network.org/papers/SocialCostOfCarbon_SEI_20100401.pdf.

[64] Nicholas Stern, Stern Review on the Economics of Climate Change Part III: The Economics of Stabilisation at 287 (2006), *available at* http://webarchive.nationalarchives.gov.uk/+/http:/www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm.

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$96.25/ton in 2005. The Stern Review uses the PAGE model, which explicitly models for the risk of catastrophic climate change.[65] In contrast with the Working Group, the Stern Review uses a mean temperature increase of 3.9 °C for its baseline scenario (consistent with the Third IPCC Report) and a 4.3 °C increase for its higher climate scenario. The resulting higher value of the social cost of carbon is thus very likely to be a closer approximation of the real cost of CO_2.

Meanwhile, the costs of reducing CO_2 emissions are well worth taking prompt action. The "central estimates of the annual costs of achieving stabilisation between 500 and 550ppm CO_2 are around 1% of global GDP, if we start to take strong action now. [...] It would already be very difficult and costly to aim to stabilise at 450ppm CO_2e. If we delay, the opportunity to stabilise at 500-550ppm CO_2e may slip away.'"(Stern 2006). Likewise, the benefits of addressing CO_2 for ocean acidification also have the ancillary effect of slowing global warming and preventing costs associated with climate change.

The recently proposed rule to reducing power plant CO_2 emissions calculates both costs and benefits—notably the benefits far exceed the costs. The recently proposed rules for reducing power plant carbon emissions, calculates both costs and benefits for a more modest reduction. EPA projects that the annual compliance cost will be $4.3 to $5.5 billion (in 2011 dollars, depending on discount rate) in 2020 and $5.5 billion (for a 5% discount rate) in 2030.[66] The total combined climate benefits and health co-benefits are estimated to be $15.6 to $88 billion in 2020 and $32.3 to $151 billion in 2030 (depending on discount rate and the options chosen).[67] The insurance industry also is well aware of the potential costs of failing to address CO2 emissions and its associated effects, including: "[h]urricanes and other flooding events … [h]ealth issues associated with heat waves… more airborne allergens, rising temperatures, greater humidity, more wildfires, and more dust and particulate pollution may considerably exacerbate upper respiratory disease (rhinitis, conjunctivitis, sinusitis, asthma) and cardiovascular disease."[68] A European insurance company estimates losses from extreme climate change events of 37% within a decade, over $1 trillion under bad circumstances.[69] The increasing frequency and severity of storms in the U.S. has caused damages to increase 60-fold from 1950s to the 1990s.[70]

Petitioners ask that action to mitigate ocean acidification under TSCA be initiated, either through TSCA section 6 (e.g., requiring "repurchasing" relief using sequestration, emission reductions, etc.), or through section 4 in order to determine the need for action under section 6 and the most effective mitigation strategies. In any case, petitioners suggest that costs be apportioned among

[65] According to the Working Group itself, DICE "offers the best insight into the SCC if the world were to experience catastrophic climate change." *See* Working Group, *supra* note 62, at 16-A-35.
[66] EPA, Regulatory Impact Analysis Technical Document EPA-452/R-14-002 (June 2014).
[67] *Id.*
[68] National Association of Insurance Commissioners, The Potential Impact of Climate Change on Insurance Regulation at 10 (2008).
[69] See e.g. Allianz, Climate Change and the Financial Sector: An Action Plan; Evan Mills, Responding to Climate Change: The Insurance Industry Perspective.
[70] Mills, E. Insurance in a Climate of Change, Science 308: 1040 (2005).

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CO_2 emission contributors according to the cumulative CO_2 emission inventory information EPA has collected.[71]

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In summary, the weight of the scientific information on ocean acidification is sufficient to make a determination that CO_2 poses an unreasonable risk, to the extent that EPA declines to find the data adequate, then EPA must develop a test rule under TSCA section 4 as described below.

C. Alternatively, EPA Must Require Testing to Develop Adequate Data

EPA must make a determination as to whether adequate data exist to evaluate the environmental and health effects of CO_2. There is well-established scientific information on the risk of CO_2 on the environment, but if EPA determines that the data are insufficient then it must develop a testing rule.

In enacting TSCA, Congress declared that "adequate data should be developed with respect to the effect of chemical substances and mixtures on health and the environment and that the development of such data should be the responsibility of those who manufacture and those who process such chemical substances and mixtures."[72] Accordingly, section 4 directs EPA to require additional testing upon determining that "the manufacture, distribution in commerce, processing, use, or disposal of chemical substance or mixture … may present an unreasonable risk of injury to health or the environment," or if the chemical is produced in substantial quantities and there is a potential for a substantial quality to be released into the environment.[73]

1. CO_2 May Present an Unreasonable Risk

As described in depth in this petition, CO_2 may present an unreasonable risk to the environment. EPA interprets this to mean that there is a "substantial (i.e., more than theoretical) probability" of unreasonable risk to the environment or health.[74] The information in this petition meets the threshold for a testing rule and establishes a substantial probability that CO_2 poses an unreasonable risk to the environment, but EPA need not even make such a determination because CO_2 is produced in such large volumes that it clearly meets the criterion of exposure of substantial quantities being released into the environment.

2. Substantial Quantities of CO_2 Are Released into the Environment

It is undeniable that substantial qualities of CO_2 are released into the environment. EPA established a threshold value of one million pounds for a release of a chemical to be substantial. *TSCA Section 4(a)(1)(B) Final Statement of Policy; Criteria for Evaluating Substantial*

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[71] This could be structured similar to the sponsorship format used in TSCA's High Production Volume (HPV) Program.
[72] 15 U.S.C. § 2601(b)(1).
[73] 15 U.S.C. § 2603 (a)(1)(A), (B)(i).
[74] *Chemical Mfrs. Ass'n v. EPA*, 859 F.2d 977, 988 (D.C. Cir. 1988).

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Production, Substantial Release, and Substantial or Significant Human Exposure, 58 Fed. Reg. 28736, 28746 (May 14, 1993). According to the IPCC:

> From 1750 to 2011, CO_2 emissions from fossil fuel combustion and cement production have released 375 [345 to 405] GtC to the atmosphere, while deforestation and other land use change are estimated to have released 180 [100 to 260] GtC. This results in cumulative anthropogenic emissions of 555 [470 to 640] GtC.

(IPCC 2013, Summary for Policymakers).

In 2012, a total of 9.7 gigatonnes of CO_2 were released into the atmosphere from fossil fuel combustion and cement production (Global Carbon Project 2013). These emissions are expected to increase to 9.9 gigatonnes in 2013 (*Id.*). The United States contributed 14% of CO_2 emissions to the atmosphere (*Id.*). Models estimate that between 2003 and 2012, the oceans absorbed 27% of CO_2 from the atmosphere (*Id.*). Over the next millennium, the oceans will absorb 90% of anthropogenic CO_2 (Kleypas et al. 2006).

Therefore, the threshold of substantial release is exceeded by more than a million times over.

3. Recommendations for Testing

EPA should consider a test rule to fill the information gaps needed to make a determination of whether CO_2 presents an unreasonable risk of injury to the environment. Some recommendations for consideration include:

- Testing CO_2 reduction strategies. For example, research and development for emissions reduction strategies that include alternative practices, conservation, alternative fuels. Testing CO_2 sequestration and capture approaches, and assessing attainable CO_2 emissions reductions for industries with significant CO_2 emissions.
- Conducting a vulnerability assessment for marine and coastal species and ecosystems. Determining atmospheric CO_2 levels necessary to conserve marine ecosystems from dangerous ocean acidification. Emissions scenarios are important for informing policy approaches to acidification.
- Forecasting species' responses to ocean acidification using modeling tools to predict range shifts, demographic and population trends, and physiological responses across taxonomic groups using a range of climate models, emissions scenarios, and management timelines (25, 50, 100 years). Identify wildlife species and ecosystems imperiled by ocean acidification by evaluating range shift models and population viability models run under future ocean acidification levels. Recommend conservation actions, including protected status, for species that are most at risk. Protect species across their range since populations are likely to have different adaptations to local oceanic conditions.
- Determining the economic values of ecosystems that are at risk from ocean acidification and the costs of reducing CO_2 emissions to preserve those ecosystems.

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Additionally, EPA can use guidance on research needs based on existing research plans. There are a number of sources recommending research and data needs (National Research Council 2013; Washington State Blue Ribbon Panel 2012; National Research Council 2010).

According to TSCA, developing the data is "the responsibility of those who manufacture and those who process such chemical substances and mixtures."[75] For example, responsibility could be apportioned based on the historical carbon emissions from the EPA Greenhouse Gas Emission Inventory together with current emissions. Typically for test rules with multiple responsible parties consortiums are set up to comply.[76] Here, for example, utilities, cement and lime manufacturers, waste incinerators, and other large producers of CO_2 should be responsible for developing unbiased, independent data.

While this may seem like a complicated undertaking, EPA has successfully completed more complex test rules. For example, from 1998 through the present, the agency used three sets of regulatory test rules under TSCA to collect chemical data for almost 3,000 high production volume (HPV) chemicals, including over 10,000 individual studies with data from domestic and foreign producers.[77]

EPA must develop test rules under TSCA section 4 for research and data development focused on information essential for making a definitive TSCA section 6 finding. These would include risk, benefit and cost information.

D. Inadequacy of Existing CO_2 Reduction Strategies

Petitioners are aware that the Agency has recently planned and initiated several emission reduction actions aimed at slowing the rate at which carbon emissions are increasing. However, these actions by themselves, while laudable, will not stabilize atmospheric CO_2 at a level which will prevent widespread harm from ocean acidification.

1. Global Greenhouse Gas Emissions Are Increasing Substantially

The atmospheric concentration of CO_2 reached 400 parts per million (ppm) for the first time in human history in May, 2013, compared to the pre-industrial concentration of ~280 ppm (Scripps Institution of Oceanography 2013). The current CO_2 concentration has not been exceeded during the past 800,000 years and likely not during the past 15 to 20 million years (Denman et al. 2007; Tripati et al. 2009). Atmospheric CO_2 emissions have risen particularly rapidly since the 2000s (Raupach et al. 2007; Friedlingstein et al. 2010). The global fossil fuel CO_2 emissions growth rate was 1.0% per year in the 1990s compared with 3.1% per year since 2000, and this growth rate has largely tracked or exceeded the most fossil-fuel-intensive emissions scenarios projected by the IPCC (A1FI and RCP 8.5) since 2000 (Raupach et al. 2007, Peters et al. 2012). The CO_2 emissions growth rate fell slightly in 2009 due largely to the global financial and economic

[75] 15 U.S.C. § 2601
[76] 15 U.S.C. § 2602 (b)(3)(A)
[77] EPA, High Production Volume (HPV) Challenge; http://www.epa.gov/chemrtk/index.htm (last accessed June 28, 2015).

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crisis; however, the decrease was less than half of what was expected and was short-lived (Fiedlingstein et al. 2010). In 2014 and 2015, global CO_2 concentrations exceeded 400ppm.[78]

2. U.S. Measures to Reduce Greenhouse Gas Emissions Are Insufficient

EPA has taken some initial steps toward curbing greenhouse pollution under the Act. In 2009, the agency issued a formal finding that greenhouse pollution endangers public health and welfare and moved to limit emissions from passenger cars and trucks. The EPA also acknowledged that major new or modified "stationary" sources of greenhouse pollution, like power plants and factories, must obtain permits and control their emissions before beginning construction. However, it narrowed the scope of this requirement considerably under its so-called "tailoring rule," which initially limits the permitting program to only a few hundred very large sources of greenhouse gases, letting a huge number of smaller — but still significant — sources off the hook.

While existing domestic laws including the Clean Air Act, Energy Policy and Conservation Act, Clean Water Act, Endangered Species Act and others provide authority to executive branch agencies to require greenhouse gas emissions reductions from virtually all major sources in the United States, these agencies are either failing to implement or only partially implementing these laws for greenhouse gases. The landmark 2014 pact with China to reduce greenhouse gas emissions is significant, but there is little to ensure it is enforced and implemented. According to the plan, United States will reduce CO_2 emissions 26 to 28% below 2005 levels by 2025.

Proposed power plant rules also fail to do enough to cut CO_2 pollution. Using the Clean Air Act, the president aims to reduce existing power plant emissions 30 percent below 2005 levels (or about 7.7 percent below 1990 levels, the base year for the international climate treaty) by 2030. But international scientists warned years ago that developed countries like the United States must reduce their emissions 25 percent to 40 percent below 1990 levels by 2020 to avoid tipping the scales further toward a climate catastrophe. Likewise, the recently announced plans to limit power plant emissions (Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units) focuses on emission reduction. Power plants are responsible for about a third of our carbon emissions, and the rule is designed to reduce those emissions by almost a third by 2030. This would result in a 10% decrease in 15 years. Stabilizing atmospheric concentration to prevent further acidification of the oceans would require about an 80% decrease in all emissions. Clearly this is a good first step, but by itself inadequate to address acidification.

EPA has issued a rulemaking regulating greenhouse gas emissions from automobiles that will reduce greenhouse emissions emitted per vehicle mile traveled by passenger vehicles in the future. But because the improvements are modest and more vehicles are projected to drive more miles in the future, the rule will not reduce emissions from this sector overall but will only slow the rate of increase.[79] Meanwhile, even the government concedes that "these reductions in emissions are not sufficient by themselves to reduce total HD vehicle emissions below their 2005

[78] NOAA, Trends in Atmospheric Carbon Dioxide, http://www.esrl.noaa.gov/gmd/ccgg/trends/
[79] EPA, Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule, 75 Fed. Reg. 25324 (May 7, 2010).

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levels by 2020."[80] This means that the vehicle rule is far from achieving emissions goals agreed to by the U.S. in the Copenhagen Accord, which aim to keep global warming below 2˚C.

The EPA has also to date issued only a single proposed rule under the new source pollution standard program for stationary sources of pollution, for electric generating units (power plants). While there is enormous potential to reduce emissions through this program overall and through the power plants rule in particular, the EPA has instead proposed a weak and flawed rule that it admits will not reduce emissions from these sources between now and 2020 compared to what would be expected without the rule.[81] Indeed, in the rulemaking the EPA conceded that new power plant rule on greenhouse gas emissions "will not have direct impact on U.S. emissions of greenhouse gases under expected economic conditions."[82]

While full implementation of our flagship environmental laws, particularly the Clean Air Act, would provide an effective and comprehensive greenhouse gas reduction strategy, due to their non-implementation, existing domestic regulatory mechanisms must be considered inadequate to protect marine species from climate change and ocean acidification.

3. International Measures to Reduce Greenhouse Gas Emissions Are Inadequate

International initiatives are also currently inadequate to effectively address climate change. The United Nations Framework Convention on Climate Change, negotiated in 1992 at Rio de Janeiro, Brazil, provides the forum for the international negotiations. In the Framework Convention, signed and ratified by the United States, the world agreed to take the actions necessary to avoid dangerous climate change. Parties to the Convention also agreed as a matter of fairness that the world's rich, developed countries, having caused the vast majority of emissions responsible for the problem, would take the lead in solving it. It was not until the 1997 meeting in Kyoto, Japan, that the first concrete, legally binding agreement for reducing emissions was signed: the Kyoto Protocol. The Protocol requires the world's richest countries to reduce emissions an average of 5 percent below 1990 levels by 2012, while developing nations also take steps to reduce emissions without being subject to binding emissions targets as they continue to raise their standard of living. The United States has been a major barrier to progress in the international negotiations. After the Clinton administration extracted many concessions from the rest of the world in exchange for the United States signing on in Kyoto, the Senate rejected the equity principles behind the Convention, saying the United States should not agree to reduce its own emissions unless all other countries — regardless of their responsibility or ability — were similarly bound. Citing the same excuses, President George W. Bush repudiated the Kyoto Protocol entirely. Thus the United States is the only industrialized country in the world that has yet to ratify the Kyoto Protocol. The United States negotiating team under both the George W. Bush and the Obama administrations has pursued two primary objectives in the international talks: to refuse any legally binding emissions reduction commitments until all other

[80] NHTSA, Medium- and Heavy-Duty Fuel Efficiency Improvement Program – Final Environmental Impact Statement (June 2011).
[81] EPA, Standards of Performance for Greenhouse Gas Emissions for New Stationary Sources: Electric Utility Generating Units, 77 Fed. Reg. 22392, 22430-33 (April 13, 2012).
[82] *Id.* at 22401.

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countries— but particularly China and India — do so, and to push back the date for a new agreement. Not surprisingly, the United States had failed to meet its (never ratified) Kyoto pledge to reduce emissions to 7.2% below 1990 levels by 2012; to the contrary, U.S. emissions have increased by 10.5% since 1990 (EPA 2012).

Moreover, the Kyoto Protocol's first commitment period only sets targets for action through 2012, and there is still no binding international agreement governing greenhouse gas emissions in the years beyond 2012. While the 2009 U.N. Climate Change Conference in Copenhagen called on countries to hold the increase in global temperature below 2□C (an inadequate target for avoiding dangerous climate change), the non-binding "Copenhagen Accord" that emerged from the conference, and the subsequent "Cancún Accords" of 2010 and "Durban Platform" of 2011 failed to enact binding regulations that limit emissions to reach this goal.[83] Even if countries were to meet their Copenhagen and Cancún pledges, analyses have found that collective national pledges to cut greenhouse gas emissions are inadequate to achieve the 2°C target, and instead suggest emission scenarios leading to 2.5□C to 5□C warming (Rogelj et al. 2010; UNEP 2011; UNEP 2010). As of July 2013, many governments were not implementing the policies needed to meet their inadequate 2020 emission reduction pledges, making it more difficult to keep global temperature rise to 2□C and likely leading to a temperature rise of at least 3.5□C (USGCRP 2013). As noted in the NMFS Management Report, the U.S. has yet to issue regulations to limit greenhouse gas emissions in accordance with its pledge under the Copenhagen Accord (NMFS 2012).

CONCLUSION

In conclusion, this petition requires EPA to make a determination whether CO_2 poses an unreasonable risk to the environment therefore requiring regulation under section 6 of TSCA. In an extensive review of the literature on the impact of ocean acidification on marine fauna and ecosystem processes, the authors found that while additional research is called for, sufficient information exists to state with certainty that deleterious impacts on some marine species are unavoidable, and that substantial alteration of marine ecosystems is likely over the next century. (Fabry et al. 2008). If, nonetheless, EPA determines that the information is insufficient to make such a finding it must develop testing rules pursuant to TSCA section 4.

[83] The non-legally binding Copenhagen Accord of 2009 and Cancún Accords of 2010 recognize the objective of limiting warming to 2°C above pre-industrial temperatures, but do not enact binding regulations to achieve this goal (http://cancun.unfccc.int/cancun-agreements/main-objectives-of-the-agreements/#c33; unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf). According to the Durban Platform, developed and developing nations agreed to a process to develop a "new protocol, another legal instrument, or agreed outcome with legal force that will be applicable to all Parties to the UN climate convention"; this legal instrument must be developed as of 2015 and will not take effect until 2020 (unfccc.int/resource/docs/2011/cop17/eng/l10.pdf).

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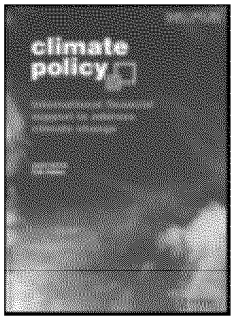

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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climate policy

B research article

Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Benefit–cost analysis can serve as an informative input into the policy-making process, but only to the degree it characterizes the major impacts of the regulation under consideration. Recently, the US, amongst other nations, has begun to use estimates of the social cost of CO_2 (SC-CO_2) to develop analyses that more fully capture the climate change impacts of GHG abatement. The SC-CO_2 represents the aggregate willingness to pay to avoid the damages associated with an additional tonne of CO_2 emissions. In comparison, the social costs of non-CO_2 GHGs have received little attention from researchers and policy analysts, despite their non-negligible climate impact. This article addresses this issue by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. By extending existing integrated assessment models, it is possible to develop a set of social cost estimates for these gases that are consistent with the SC-CO_2 estimates currently in use by the US federal government.

Policy relevance

Within the benefit–cost analyses that inform the design of major regulations, all Federal agencies within the US Government (USG) use a set of agreed upon SC-CO_2 estimates to value the impact of CO_2 emissions changes. However, the value of changes in non-CO_2 GHG emissions has not been included in USG policy analysis to date. This article addresses that omission by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. These new estimates are designed to be compatible with the USG SC-CO_2 estimates currently in use and may therefore be directly applied to value emissions changes for these non-CO_2 gases within the benefit–cost analyses used to evaluate future policies.

Keywords: integrated assessment; non-CO_2 GHGs; social cost of carbon

1. Introduction

The social cost of CO_2 (SC-CO_2) is a measure of the monetary value of the damages occurring both within and outside economic markets as the result of an additional unit of CO_2 emissions. Specifically, it represents society's aggregate willingness to pay to prevent future impacts that occur when one additional unit of CO_2 is emitted into the atmosphere in a particular year. Estimates of SC-CO_2

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therefore provide a way to value changes in CO_2 emissions in benefit–cost analyses (BCAs) of policy alternatives. Without an estimate of the SC-CO_2, the benefits of mitigating the climate change impacts from CO_2 emissions would implicitly be valued at zero in BCAs, thereby significantly weakening the information provided by such analyses. Since 2009, the US Federal Government (USG) has used a set of agreed-upon SC-CO_2 estimates in the BCAs used to evaluate major regulations that impact CO_2 emissions (USG, 2010), including over 30 regulatory actions to date. The USG SC-CO_2 estimates are also increasingly being used in analysis and discussions outside the USG (e.g. by states, regional organizations, other nations, international organizations, NGOs, and academic researchers)[1] and have even figured in several recent public hearings and court cases (e.g. Keohane, 2010a, 2010b).

Although CO_2 is the primary anthropogenic GHG, other GHGs such as methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are also important contributors to climate change. The combined effect of all GHGs accumulated in the atmosphere is to increase the Earth's radiative forcing, which is the amount of energy from the Sun that is trapped in the Earth's atmosphere and therefore acts to warm the planet and change the climate. In 2011, the atmospheric CO_2 concentration contributed 64% of overall radiative forcing, while CH_4 and N_2O accounted for approximately 23% (Myhre et al., 2013). Non-CO_2 GHGs, notably CH_4 and N_2O, therefore contribute significantly to the negative impacts on human well-being from climate change. Furthermore, several recent studies have shown that consideration of non-CO_2 GHGs, particularly CH_4 and N_2O, is important for the design of cost-effective climate policy (Reilly et al., 1999; Tol, Heintz, & Lammers, 2003; Weyant, De La Chesnaye, & Blenford, 2006).

The monetary value of changes in emissions of non-CO_2 GHGs has not been included in USG policy analysis to date. This shortcoming prevents the development of accurate and comprehensive assessments of potential regulatory alternatives by the USG and others that rely on the USG SC-CO_2 estimates (Kopp & Mignone 2012; Marten & Newbold, 2012). For example, fossil fuels (e.g. coal and natural gas) have different compositions of GHG emissions across gases when considering the entire process of extraction, production, transmission, and combustion. Thus, if a regulation is anticipated to cause an industry to substitute between fuels, analysts may be providing inadequate information to decision makers and the public about its benefits if only the welfare implications of direct CO_2 emissions are considered while ignoring changes in CH_4 and other GHG emissions (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2011).

A key reason for the value of non-CO_2 GHG emissions impacts not being included in USG analyses so far is that existing estimates of the social cost of non-CO_2 GHGs presented in the literature are inconsistent with USG SC-CO_2 modelling assumptions. For example, the recent US Environmental Protection Agency BCA of new pollution standards for the oil and natural gas industry concluded that, because they are not consistent with the USG SC-CO_2, 'the methane climate benefit estimates available in the current literature are not acceptable to use to value the methane reductions finalized in this rulemaking' (USEPA, 2012). This article seeks to address that gap by developing a new set of social cost estimates for CH_4 and N_2O (SC-CH_4 and SC-N_2O, respectively) that are fully consistent with the modelling assumptions underlying the current USG SC-CO_2 estimates. This article also develops an approach to extending the models used by the USG to generate estimates of the social cost of additional GHGs that are consistent with the latest USG estimates of the SC-CO_2.

It is important to note at the outset that by restricting attention to the derivation of social cost estimates consistent with the USG SC-CO_2 estimates, any limitations that apply to inputs and modelling

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assumptions underlying the USG SC-CO_2 estimates (e.g. Arrow et al., 2013; Kopp & Mignone 2012; Marten, 2011; O'Neil, 2010; Warren, Mastrandrea, Hope, & Hof, 2010) also apply to the SC-CH_4 and SC-N_2O estimates derived here. Thus, while it is anticipated that the USG will continue to improve the models and data it uses to estimate the SC-CO_2, this article focuses on the more immediate task of developing a set of consistent estimates for the social cost of other GHG emissions so that they need not be implicitly assigned a value of zero in USG policy analyses.

The remainder of the article is organized as follows. Section 2 presents an overview of the USG SC-CO_2 estimation approach and how it compares to the existing literature on the social cost of non-CO_2 GHGs, including a discussion of some of the critiques of the approach. Section 3 presents the approach for estimating the SC-CH_4 and SC-N_2O in a manner consistent with the USG SC-CO_2 estimates. Section 4 presents the results and a comparison of the relative social costs to the previous literature and the global warming potential (GWP)-based metric that is often used as an approximation in the absence of direct estimates, and Section 5 provides concluding remarks.

2. Background

In 2009–2010 the USG formed an interagency working group to develop a set of SC-CO_2 estimates for use by all Executive Branch agencies to value marginal changes in CO_2 emissions in regulatory impact analyses (USG, 2010). The goal of this exercise was to improve the accuracy and consistency with which agencies value marginal changes in CO_2 emissions. Before the release of these estimates, CO_2 emissions changes were valued in some but not all regulatory analyses, and the SC-CO_2 estimates used by different agencies varied substantially. The USG recently updated their estimates for the SC-CO_2 by employing new versions of the three underlying integrated assessment models (IAMs), but leaving the original estimation approach and underlying assumptions unchanged (USG, 2013). This section provides a brief overview of the estimation approach and assumptions used by the USG for estimating SC-CO_2, describes some critiques of the approach by other researchers, and discusses the existing literature on the social cost of non-CO_2 GHGs.

2.1. USG SC-CO_2 estimation approach

To estimate the SC-CO_2 the USG used three IAMs that couple simplified models of atmospheric gas cycles and climate systems with highly aggregate models of the global economy and human behaviour to capture the effects that GHG emissions, through their effect on the climate, have on human welfare. Within IAMs, the modelling that guides the transition from emissions into climate impacts is based on scientific assessments, while the mapping of climate impacts into changes in human welfare is based on economic research that has studied the effect of climate on various market and non-market sectors. Nordhaus and Boyer (2000) provide a very informative and detailed description of how such models are developed.[2]

The three models used by the USG are those that feature most prominently in the published social cost of carbon literature: the Dynamic Integrated Climate and Economy (DICE) (Nordhaus, 2008; Nordhaus & Boyer, 2000), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2006b, 2008), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff, Hepburn, & Tol, 2009; Tol, 2002a, 2002b, 2009) models. The USG chose to use the IAMs'

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climate system submodels and the functions that map climate change into economic damages as implemented by the model developers, but adopted a common set of input assumptions for equilibrium climate sensitivity, discount rates, global population, economic output, and GHG emissions projections. The remainder of this section provides a brief description of these common assumptions and the steps used to calculate the SC-CO_2 estimates. Interested readers can find more details in the USG's 2010 technical support document (USG, 2010).

2.1.1. Reference socio-economic-emissions scenarios

The USG selected five scenarios of economic output, population, and GHG emissions projections using results from the 2009 Stanford Energy Modeling Forum exercise number 22 (EMF-22). Four of the scenarios are based on baseline runs from global economic models (MERGE, MESSAGE, MiniCAM, and IMAGE) and span a range of emissions projections and plausible outcomes for future population and economic output absent significant global action to address climate change. These scenarios allowed for internally consistent forecasts of economic output, population, and emissions for the years 2000–2100. The fifth scenario used by the USG is based on the average of the 550 ppm CO_2e stabilization runs for each of the four models from which baseline scenarios were selected to represent potential action by the rest of the world absent US action. Across the five scenarios, atmospheric CO_2 concentrations in 2100 ranged from approximately 450 to 890 ppm (550–1130 ppm in CO_2e). Over the time horizon, the forecasts of the average growth rate for global per capita economic output ranged from 1.5% to 2.0% per year, and the average global population growth rate ranged from 0.4% to 0.5% per year. To run the IAMs through the year 2300, the USG extrapolated the selected EMF scenarios using the following assumptions: starting in 2100 the population growth rate declines linearly to zero in 2200; starting in 2100 the growth rate of economic output per capita declines linearly to zero in 2300; for all years after 2100 the growth rate of the carbon intensity of the global economy (CO_2 emissions/economic output) remains constant at its 2090–2100 average; starting in 2100 net land-use CO_2 emissions decline linearly to zero in 2200; and for all years beyond 2100 non-CO_2 radiative forcing anomalies remain constant at their 2100 levels.

Several limitations of the simplifying assumptions underlying the USG approach to scenario development have been discussed by other researchers. O'Neil (2010) pointed out that the selected EMF scenarios do not reflect the full range of outcomes that appear in other studies in the literature, and Kopp and Mignone (2012) suggested that the selected scenarios may effectively over-sample the peaks of the distributions. As for the extrapolations, while running the models out for multi-century time horizons is not necessary for relatively short-lived GHGs like CH_4, it is important for understanding the impacts of long lived GHGs such as CO_2 and N_2O that will affect human welfare well beyond 2100. As emphasized by O'Neil (2010) and Kopp and Mignone (2012), the state of the world beyond 2100 is highly uncertain and the scenario extrapolation approach taken by the USG represents only one of many possibilities. Furthermore, the extrapolations for each component of the scenarios (economic output, population, emissions) are separate and nothing ensures internal consistency within the scenarios past 2100. As shown by Marten and Newbold (2012), the temporal decomposition of damages for a perturbation of CO_2 and N_2O are relatively similar in shape and therefore the general findings of studies that explore the sensitivity of the SC-CO_2 to these assumptions should also be applicable to the SC-N_2O.

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2.1.2. Equilibrium climate sensitivity

In reduced-form IAMs, the speed and magnitude of temperature change for a given emissions projection are influenced largely by the 'equilibrium climate sensitivity' (ECS) parameter. The ECS represents the long-term global average temperature response to a level of radiative forcing associated with a sustained doubling of atmospheric CO_2 concentration (around 550 ppm). To represent the uncertainty in the responsiveness of the climate system to changing atmospheric conditions, the USG used a probability distribution for the ECS parameter of the form suggested by Roe and Baker (2007). The USG calibrated the parameters of the probability distribution to have a median equal to 3 8C, two-thirds probability that the ECS lies between 2 and 4.5 8C, which was intended to be consistent with the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) consensus statement about the ECS (Meehl et al., 2007). The distribution was truncated from above at 10 8C. This specification of the ECS distribution is retained to maintain consistency with the USG estimates of the SC-CO_2, but it is noted that the recently released AR5 by the IPCC has revisited the equilibrium climate sensitivity and revised the range downwards to 1.5–4.5 8C and no longer provides a most likely value (Collins et al., 2013). The ultimate effect of updating the ECS distribution to be consistent with the IPCC AR5 findings will depend heavily on the central tendency selected for the distribution.

2.1.3. Discount rates

Because the damages from an additional tonne of CO_2 emissions occur over many decades, the discount rate, which reflects the tradeoff between present and future consumption, plays a critical role in estimating the SC-CO_2. In light of disagreement in the literature regarding the appropriate discount rate to use in this context and uncertainty about future conditions that impact the discount rate, the USG used three constant discount rates intended to span a plausible range: 2.5%, 3%, and 5% per year. It is worth noting that the debate regarding not only the appropriate discount rate but also its time path is ongoing (Arrow et al., 2013; Dasgupta, 2008). While the appropriate value for the discount rate will presumably remain an area of active debate for some time to come, there appears to be agreement that the use of a constant discount rate over long time horizons with uncertain changes in the consumption per capita growth is not theoretically consistent. This article uses the same three constant discount rates as the USG estimation process, but in Appendix C results are reported from a series of sensitivity analyses using a Ramsey discounting approach. Similar to Marten and Newbold (2012), it is found that applying Ramsey discounting using plausible values for the components of the consumption discount rate gives a range of social cost estimates that is broadly consistent with the range of results obtained using the constant discount rates.

2.1.4. Calculating the SC-CO_2

The process to estimate the SC-CO_2 for emissions in year t has four steps. First, each model is used to forecast monetized impacts associated with the baseline path of emissions, economic output, and population. Second, each model is re-run with an additional unit of CO_2 emissions in year t to forecast monetized impacts for all years beyond t along this perturbed path of emissions. Third, the marginal damages in each year are calculated as the difference between the monetized impacts forecast in steps 1 and 2. Finally, the resulting path of marginal damages is discounted and summed to calculate

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the present value of the marginal damages in the year when the additional unit of emissions used to perturb the model is emitted.

The USG repeated this process with each model, discount rate, and socio-economic-emissions scenario for each decade between 2010 and 2050. Because the ECS parameter is modelled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run represents a distribution over the SC-CO_2 in each year. These distributions were estimated using 10,000 simulations in each model run. Therefore, the exercise produced 45 separate distributions of the SC-CO_2 for a given emissions year, based on the three models, three discount rates, and five socio-economic-emissions scenarios considered. To provide a range of estimates that reflects this uncertainty but still emphasizes the central tendency, the distributions from each of the models and scenarios were equally weighted and combined to produce three separate probability distributions for the SC-CO_2 in a given year, one for each assumed discount rate. Four SC-CO_2 estimates were selected from these three probability distributions to reflect the global damages caused by one tonne of CO_2 emissions. Three estimates are based on the average SC-CO_2 across the three models and five socio-economic-emissions scenarios for the 5%, 3%, and 2.5% discount rates, respectively. The fourth value is the 95th percentile of the SC-CO_2 distribution at the 3% discount rate, and was chosen to represent potential higher-than-expected impacts from anthropogenic GHG emissions.

2.2. Existing estimates of the social cost of non-CO_2 GHG emissions

A significant limitation of the aforementioned USG interagency process is that the social costs of non-CO_2 GHG emissions were not estimated. Therefore, as an alternative to applying direct estimates for the social costs of non-CO_2 GHG emissions in the primary BCA, several recent USG regulatory analyses have approximated the benefits of non-CO_2 GHG emissions reductions in sensitivity analyses by transforming the non-CO_2 GHG emissions to 'CO_2-equivalents' using estimates of the GWP for the GHG in question and then using the USG SC-CO_2 for valuation (e.g. US EPA, 2012, 2013).

Gas comparison metrics, such as the GWP, have been designed to measure the impact of different GHGs relative to CO_2, where the point of comparison along the pathway from emissions to monetized damages (depicted in Figure 1) may differ across measures. The GWP, in particular, is designed to measure the additional radiative forcing (i.e. the amount of energy absorbed by atmospheric concentrations of GHGs) from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years). The GWP and other gas-comparison metrics are problematic as an SC-CO_2 scalar in BCA, as the remaining linkages in the pathway depicted in Figure 1 are complex and non-linear. Marten and Newbold (2012) demonstrate that using the GWP to adjust SC-CO_2 estimates to capture the impact of non-CO_2 gases provides a significant improvement over the implicit assumption that they are zero when such benefits are left unquantified, but may still underestimate mitigation benefits. Alternative gas comparison metrics that compare GHGs at different points in the chain of

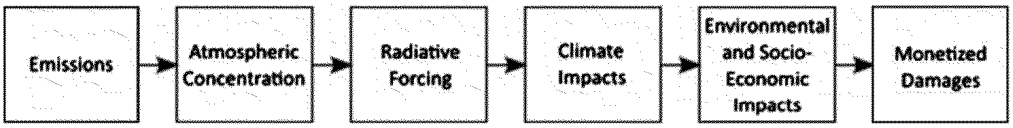

Figure 1 Path from GHG emissions to monetized damages

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causation (e.g. global temperature change potential (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005), peak commitment temperature (Smith et al., 2012), temperature proxy index (Tanaka, O'Neill, Rokityanskiy, Obersteiner, & Tol, 2009)) have also been shown to be imperfect substitutes for direct estimates.

Several researchers have directly estimated the social cost of non-CO_2 GHG emissions using IAMs, although the number of such estimates is small compared to the large number of SC-CO_2 estimates available in the literature. Among these previous direct estimates there is considerable variation in the model versions and input assumptions used. See Table 1 for a summary of the 11 non-CO_2 studies published to date.

As shown in Table 1, the estimates cover emissions years from 1990 to 2050, although the specific perturbation year is not stated in all studies. The studies also cover a wide range of constant and variable discount rate specifications and consider a range of baseline socio-economic and emissions scenarios that have been developed over the last 20 years. Finally, some studies in the literature have chosen not to report the social cost estimates directly. Instead, they opt to report only the 'global damage potential', which is a ratio of the social cost of gas X to the SC-CO_2. Normalizing the SC-CH_4 or

TABLE 1 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Model	Time horizon	Discount rate	Emissions year	Scenario[a]	Climate sensitivity
Reilly and Richards (1993)	N/A	140 years	2, 5, 8%	1990	N/A	N/A
Fankhauser (1994)	N/A	230 years	Ramsey	1991–2030	IS92[b]	N/A
Kandlikar (1995)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Kandlikar (1996)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Hammitt et al. (1996)	N/A	2200	1, 3, 5%	1995–2015	IS92a,c,e	1.5, 2,5, 4.5 8C
Tol (1999)	FUND 1.6	2100	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Tol et al. (2003)	FUND 1.7	2200	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Hope (2005)	PAGE95	2200	Ramsey	2000	SRES A2	Probabilistic, mode of 3 8C
Hope (2006a)	PAGE2002	2200	Ramsey	2001	SRES A2	Probabilistic, mean of 3 8C
Waldhoff et al. (2011)	FUND 3.5	3000	Ramsey	2010–2019	FUND, SRES A1B, A2, B1, B2	2, 3, 4.5 8C
Marten and Newbold (2012)	DICE2007 w/ MAGICC	2300	Ramsey, 2.5, 3, 5%	2010–2050	EMF-22 MiniCAM Base	Probabilistic,median of 3 8C

[a]IS90 scenarios are based on the IPCC First Assessment Report (IPCC, 1990); IS92 scenarios are based on the IPCC Supplementary Report (IPCC, 1992); SRES scenarios are based on the IPCC Special Report on Emissions (IPCC, 2000); the FUND scenario is the default scenario in the FUND model; EMF-22 scenarios are based on results from Stanford's Energy Modeling Forum's 22nd exercise (Clarke et al., 2009).[b]The particular IS92 scenario used was not specified.

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SC-N_2O estimate using the SC-CO_2, in part, controls for differences in the modelling to allow for a better comparison with other estimates in the literature.

Fankhauser (1994) was one of the first to develop estimates of the average SC-CH_4 and SC-N_2O for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt, Jain, Adams, and Wuebbles (1996) also developed estimates of SC-CH_4 and SC-N_2O for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006a) developed estimates for the SC-CH_4 in 2000 using the FUND and PAGE models, respectively. Waldhoff, Anthoff, Rose, and Tol (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal CO_2, CH_4, N_2O, and SF_6 emissions for the average year in the 2010 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios from the IPCC special report on emissions (IPCC, 2000) in addition to the default FUND scenario. In Section 4, the specific results of these previous studies are discussed with a comparison to the estimates obtained in the present study.

The above-mentioned previous studies provide a basic understanding of the relative social costs of different GHGs but do not provide sufficient information about how this relationship changes over time. Marten and Newbold (2012) used an IAM that couples the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) with economic components of the 2007 version of William Nordhaus' DICE model to directly estimate the social cost of marginal CO_2, CH_4, and N_2O emissions. They estimated the annual social costs for the years 2010–2050 along a single socio-economic-emissions pathway given uncertainty about the equilibrium climate sensitivity parameter. An advantage of their approach is that through the use of a more detailed, yet still relatively simple, climate model their results are not affected by over-simplification of temperature response or atmospheric chemistry, which have been shown to have non-negligible effects on the estimates of social costs (Marten, 2011; Warren et al., 2010).

The work of Marten and Newbold (2012) uses many of the assumptions used by the USG in its estimation of SC-CO_2, including discount rates, the equilibrium climate sensitivity distribution, and post-2100 socio-economic and emissions extrapolations. However, they focus on only one of the three models and one of the five socio-economic-emissions scenarios used by the USG. Furthermore, they use a different climate sub-model, which leads their estimate of the SC-CO_2 to be different from the USG estimate, even for the same IAM and scenario combination. Therefore, although these studies, including Marten and Newbold (2012), have increased our understanding about the relative social costs of GHG emissions, they have not provided a set of estimates that are entirely consistent with the USG SC-CO_2 estimates. In Section 4, the estimates derived in this article are compared with those of Marten and Newbold (2012) to more clearly demonstrate the similarities and differences in the two sets of estimates for SC-CH_4 and SC-N_2O.

3. Estimating the social cost of non-CO_2 GHGs consistent with USG SC-CO_2

The primary obstacle in estimating the social cost of non-CO_2 GHG emissions in a manner consistent with the USG SC-CO_2 estimates is that not all of the IAMs used include explicit representations of the non-CO_2 gases of interest. This section describes the degree to which non-CO_2 GHGs are currently

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represented in the default versions of DICE, PAGE, and FUND, and then discusses how they are amended to estimate the social cost of these gases.

3.1. Representation of non-CO_2 GHGs in DICE, PAGE, and FUND

The FUND model explicitly considers CH_4, N_2O, and SF_6 in addition to CO_2. The model uses one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels. For CH_4 and N_2O, FUND estimates the additional radiative forcing imposed by the atmospheric buildup of these gases using the simplified expressions presented in Chapter 6 of the IPCC's Third Assessment Report (TAR) (Ramaswamy et al., 2001). FUND also augments the TAR expression for the additional radiative forcing from CH_4 to account for the influences of stratospheric water vapour and tropospheric ozone changes. Because FUND uses CH_4 and N_2O emissions as inputs and internally computes their impact on the climate system, it is possible to directly estimate the social cost of those gases without modifying the model.

In the DICE model, the only GHG that is explicitly represented is CO_2; an exogenous radiative forcing projection is used to account for the impact of all other gases on the climate. To develop an exogenous radiative forcing pathway consistent with the emissions scenarios used to estimate the SC-CO_2, the USG decomposed the default DICE exogenous radiative forcing vector into CH_4, N_2O, F-gases, aerosols, and other residual forcing components. The USG then replaced the radiative forcing attributed to CH_4, N_2O, and F-gases with estimates associated with the EMF-22 scenarios. As non-CO_2 emissions are not a direct input into DICE, it is not possible to simply perturb the emissions projection and re-run the model to obtain a forecast of additional damages.

The 2002 version of the PAGE model, which was used by the USG in developing its first set of estimates (USG, 2010), includes an atmospheric model for CH_4 and SF_6, but represents the effects of other non-CO_2 GHGs in an exogenous radiative forcing projection. Presumably to simplify the process and maintain consistency with DICE, the USG did not use PAGE's internal CH_4 component. Instead, the same exogenous radiative forcing projection was used for the effect of CH_4, N_2O, and F-gas emissions as was used for DICE. Since then, a N_2O component has been added to the PAGE model, although in the recent 2013 SC-CO_2 update the USG maintained the approach of using the same single exogenous forcing projection as was applied to DICE (USG, 2013). Therefore PAGE, as implemented by the USG, faces the same limitations as DICE with respect to estimating the social costs of marginal non-CO_2 emissions that are consistent with the USG SC-CO_2 estimates. For these reasons, computing estimates for the social cost of non-CO_2 gases in DICE and PAGE requires either replacing the climate component of these models with a more complete representation, as was done with DICE by Marten and Newbold (2012), or deriving an estimate of the path of additional radiative forcing that would result from a perturbation of the gas in question. This article uses the latter approach for DICE and PAGE, as the former would represent a substantial change to the underlying IAMs and would have implications for the SC-CO_2 estimates, making this work inconsistent with the USG SC-CO_2 estimates currently used in regulatory analysis.

3.2. Estimating the social cost of non-CO_2 GHGs in DICE and PAGE

The process used in this article to estimate the social cost of non-CO_2 GHGs in DICE and PAGE as implemented by the USG requires first generating a forecast of the additional radiative forcing

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associated with a perturbation of a non-CO_2 gas's emissions in a single year, and then adding this radiative forcing perturbation to each model's exogenous radiative forcing projection. To determine the additional radiative forcing associated with the emission perturbation, there is a need to model the change in atmospheric concentration and the radiative forcing associated with the additional concentration. For both CH_4 and N_2O, a simple one-box atmospheric gas cycle model with a constant decay rate is used to estimate the atmospheric concentration of each gas based on its assumed emissions. The use of a one-box gas cycle for CH_4 and N_2O with constant decay follows the approach used by the IPCC to compute GWPs (Forster et al., 2007) and the FUND model (Anthoff & Tol, 2013). In both the baseline and the perturbed case, the contribution of the gas to the global radiative forcing anomaly is determined by the forcing relationships presented in the IPCC TAR (Ramaswamy et al., 2001), which were not updated by the IPCC in AR4. The incremental radiative forcing is defined by the difference between the baseline forcing path and the emissions path that includes a one tonne perturbation in a given year. Next, the path of additional radiative forcing is added to the stream of exogenous radiative forcing in each IAM to estimate the climate damages in the perturbed scenario. These damages are then compared to the baseline damages to determine the social cost of gas X (SC-X). Specifically, the process is as follows:

1. Run the IAM as described in the SC-CO_2 technical support document (USG, 2010) to estimate baseline damages.
2. Estimate the baseline atmospheric concentration for gas X.
3. Estimate the baseline radiative forcing contribution of gas X.
4. Perturb the stream of gas X emissions by one tonne in year t.
5. Estimate atmospheric concentration for gas X in the perturbed scenario.
6. Estimate the radiative forcing contribution of gas X in the perturbed scenario.
7. Compute the incremental radiative forcing as the difference between the results of steps 3 and 6.
8. Add the additional radiative forcing from step 7 to the exogenous radiative forcing path used in the IAM in step 1.
9. Re-run the IAM to compute the damages along the perturbed emissions path.
10. Compute the social cost of gas X for emission year t as the present value of the difference in damages estimated in steps 1 and 9.

Two practical issues associated with implementation are worth noting. First, while the SC-X estimates are associated with a one tonne perturbation, to avoid computational rounding error a 1 Mt perturbation is used and then the resulting change in damages is scaled to get the average effect per tonne. Experiments conducted by Griffiths et al. (2012) to assess the applicability of the SC-CO_2 to non-marginal emission changes show that the average per tonne SC-CO_2 estimate is relatively constant over large differences in perturbation size. Additional experiments in the context of this article found that alternative perturbation sizes do not significantly change the average one tonne social cost estimate. Second, the additional radiative forcing due to the emissions perturbation is computed based on an annual time step, but because DICE and PAGE use longer time steps the average radiative forcing over the time step is added to the model's exogenous radiative forcing vectors.

The remainder of this section describes the procedure for modelling the incremental radiative forcing of a perturbation for CH_4 and N_2O, and explores the sensitivity of these projections to

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two issues. First, it evaluates whether the simple one-box gas cycle model with a constant decay rate produces a close approximation to the forecasts of future atmospheric CH_4 and N_2O concentrations based on a more sophisticated climate model. Second, it explores the sensitivity of the results to the method used for extrapolating non-CO_2 emissions from 2100 to 2300. This is important, because the USG did not specify a particular set of emissions pathways for each constituent gas, instead assuming only that non-CO_2 radiative forcing remains constant past 2100. Such a situation could arise from a myriad of possible individual gas projections and the USG did not specify which it was assuming.

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3.3. Methane

A simple one-box atmospheric gas cycle model for methane specifies the concentration in year t, $C_t^{CH_4}$ [ppb], such that

$$C_t^{CH_4} = C_{t-1}^{CH_4} + d_{CH_4}(C_{pre}^{CH_4} - C_{t-1}^{CH_4}) + g_{CH_4}E_{t-1}^{CH_4}, \tag{1}$$

where d_{CH_4} defines the rate of decay, $C_{pre}^{CH_4}$ [ppb] is the pre-industrial atmospheric concentration, and g_{CH_4} [ppb/Mt] converts emissions, $E_{t-1}^{CH_4}$ [Mt], from mass to atmospheric volume. The mass to volume conversion factor is g_{CH_4} ¼ 0.3597 ppb/Mt and $C_{pre}^{CH_4}$ ¼ 700 ppb, following the IPCC TAR. The rate of decay is set to d_{CH_4} ¼ 1/12 following the IPCC AR4 stated CH_4 lifetime of 12 years. The iteration begins in the year 2006 using the emissions from the EMF-22 scenario (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used so that $C_{2005}^{CH_4}$ ¼ 1774 ppb.

The contribution of atmospheric methane to global radiative forcing, denoted $Q_t^{CH_4}$, is defined using the relationship in Table 6.2 of the IPCC TAR:

$$Q_t^{CH_4} = f\ 0.036\ \left(C_t^{CH_4} - C_{pre}^{CH_4}\right) - \left[f(C_t^{CH_4}, C_{pre}^{N_2O}) - (C_{pre}^{CH_4}, C_{pre}^{N_2O})\right], \tag{2}$$

where $C_{pre}^{N_2O}$ [ppb] is the pre-industrial atmospheric concentration of nitrous oxide and

$$f(C^{CH_4}, C^{N_2O}) = 0.47 \ln\left[1 + 2.01 \times 10^{-5}(C^{CH_4}C^{N_2O})\right]^{0.75} + 5.31 \times 10^{-15}C^{CH_4}(C^{CH_4}C^{N_2O})^{1.52}. \tag{3}$$

The function in expression (3) accounts for the overlapping absorption bands of CH_4 and N_2O, thereby reducing their effective absorption. Parameter f is used to proxy for indirect effects of CH_4 that include the enhancement of stratospheric water vapour and tropospheric ozone changes. Following the IPCC AR4, an enhancement effect of 40% (25% from tropospheric ozone change and 15% for stratospheric water vapour enhancement) is used, such that f ¼ 1.4. The pre-industrial concentration of N_2O is set consistent with the IPCC TAR, such that $C_{pre}^{N_2O}$ ¼ 270 ppb.

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A key simplification in this approach is the constant decay rate used in the atmospheric gas cycle model. As discussed by IPCC Working Group I in Chapter 4 of the TAR, the lifetime of methane emissions in the atmosphere depends on temperature and the concentrations of CO, NOx, and other VOCs in the atmosphere (Ehhalt et al., 2001). Sensitivity analysis is used to understand the potential implications of ignoring these interactions by comparing the incremental atmospheric concentration projected by the simple model described above to the analogous projection from the climate model MAGICC,[3] which, while still relatively simple, incorporates these interactions between the lifetime of CH_4 in the atmosphere and the other gases and climate variables. This exercise uses CH_4 emissions from the EMF-22 MiniCAM reference scenario and considers a one tonne perturbation of CH_4 in 2015. It is noted that these results are robust across alternative emissions levels.[4]

Figure 2(a) presents the projected average decadal increment to atmospheric concentrations using both the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. At the time of the perturbation (2015), the inter-annual time step of MAGICC allows for an uptake of the additional emissions into the atmosphere, whereas the strict annual time step of the simple model causes a year to pass before the change is registered. After the initial year, the models originally differ by around 15%. This difference falls to under 10% within the first decade, with the faster effective growth in the simple model causing its additional concentration to eventually fall below that of MAGICC.

The difference in the incremental radiative forcing from the perturbation between the simple model and MAGICC is also of importance. Although MAGICC relies on similar equations to derive the radiative forcing of atmospheric CH_4 concentrations, it differs in the way it handles indirect effects of CH_4 on tropospheric ozone and stratospheric water vapour, in addition to including other temperature-related feedbacks. Figure 2(b) presents the average additional radiative forcing per decade attributed to the 2015 CH_4 perturbation in both models. The average increase in radiative forcing over the decade is considered because this is the input required by DICE due to its ten-year time step and therefore a more relevant comparison (PAGE requires a similar multi-year average). When considering the average additional radiative forcing over the decade, the initial difference in concentration between MAGICC and the simple model has a minimal effect and the difference in radiative forcing between the two models is less than 2% over the first two decades. However, this difference grows to –18% over the subsequent two decades. This escalation in the difference is in part due to the use of a constant decay rate in the simple model, whereas MAGICC takes into account the growing atmospheric concentrations of other gases and increasing atmospheric temperature, which increase the lifetime of atmospheric CH_4.

To understand the effect that this difference would have on an estimate of the SC-CH_4, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of CH_4, as computed using both the simple model and MAGICC, is added to the exogenous forcing projection. As above, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 2 presents the results of this experiment. In line with the results comparing the radiative forcing perturbations above, the two approaches produce similar social cost estimates for emissions in 2015, where additional analysis has shown these results to hold with PAGE as well. The impact of assuming a constant decay rate is greater further out into the future, due to the projected increase in the atmospheric concentration of other relevant gases and atmospheric temperature that are accounted for in MAGICC, and the social cost

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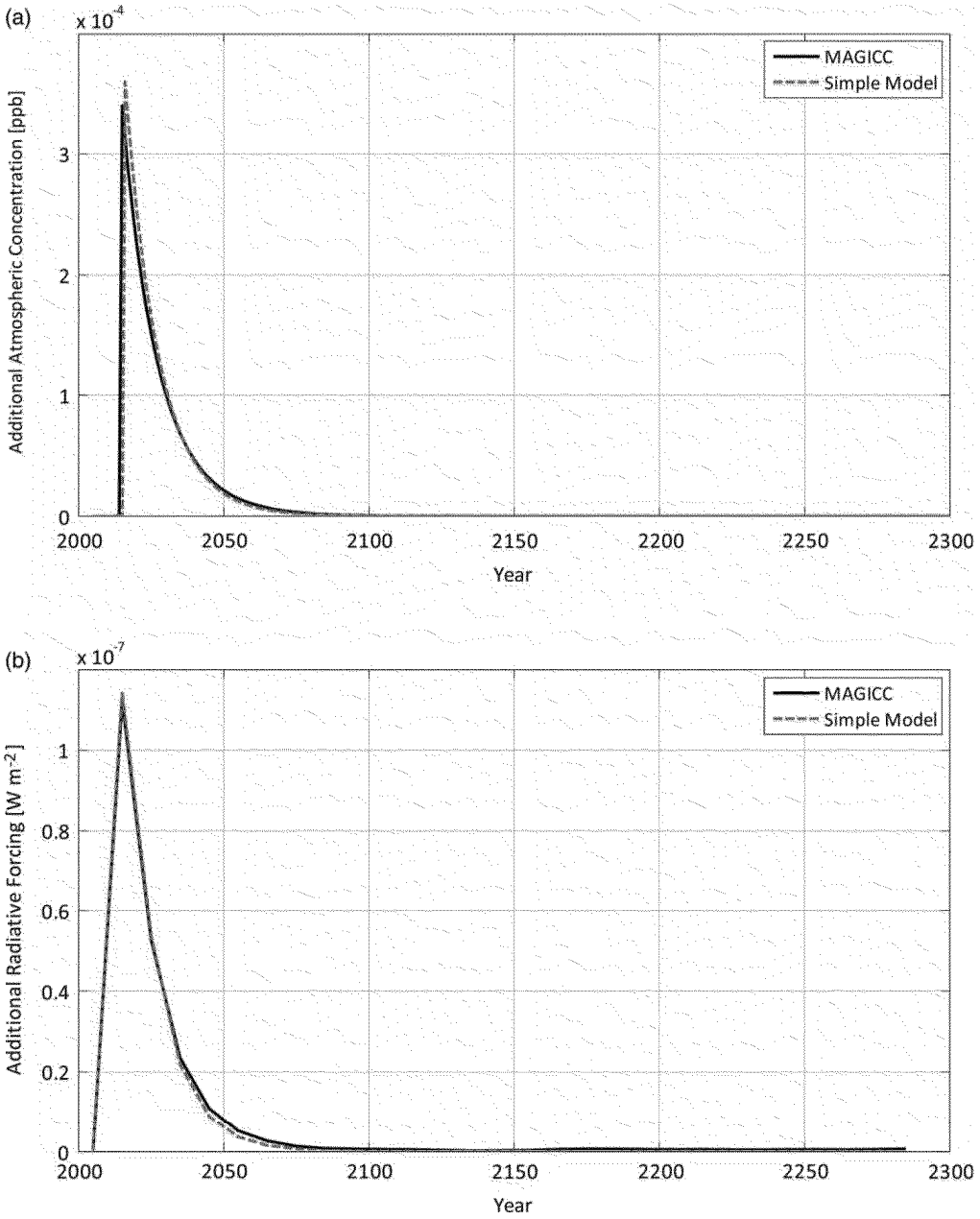

Figure 2 Effects of perturbation in 2015 CH_4 emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

estimates begin to diverge for later emissions years. For the same reason, the two approaches will show greater differences for lower discount rates that give increased weight to future time periods. While over-simplification of the climate system can, in some circumstances, have significant effects on

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TABLE 2 Effect of CH_4 gas cycle model on SC-CH_4 (2007$ per tonne CH_4): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	1135	1183	2 4%
	3.0%	822	851	2 3%
	5.0%	349	354	2 2%
2045	2.5%	2490	2707	2 8%
	3.0%	1933	2084	2 7%
	5.0%	956	1006	2 5%

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social cost estimates (e.g. Marten 2011), the near-term differences based on this simplification seem relatively small considering the precision of such social cost estimates.

3.4. Nitrous oxide

The simple one-box atmospheric gas cycle model for N_2O takes a similar form to the model used for CH_4, such that the concentration of nitrous oxide in year t, $C_t^{N_2O}$ [ppb], is specified as

$$C_t^{N_2O} = C_{t-1}^{N_2O} + d_{N_2O}(C_{pre}^{N_2O} - C_{t-1}^{N_2O}) + g_{N_2O}E_{t-1}^{N_2O}, \tag{4}$$

where d_{N_2O} is the rate of decay, and g_{N_2O} [ppb N_2O/Mt N] converts emissions, $E_{t-1}^{N_2O}$ [Mt N], from mass to atmospheric volume. Following the IPCC AR4, the mass to volume conversion factor is g_{N_2O} ¼ 0.2079 ppb N_2O/Mt N and the rate of decay is d_{N_2O} ¼ 1/114 based on a 114-year lifetime. As with CH_4, the iteration begins in the year 2006 using the emissions from the EMF-22 scenarios (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used, such that $C_{2005}^{N_2O}$ ¼ 319 ppb.

The contribution of atmospheric N_2O to global radiative forcing, denoted $Q_t^{N_2O}$, is defined using the relationship in Table 6.2 of the IPCC TAR, such that

$$Q_t^{CH_4} = 0.12 \left[C_t^{N_2O} - C_{pre}^{N_2O} - [f(C_{pre}^{CH_4}, C_t^{N_2O}) - f(C_{pre}^{CH_4}, C_{pre}^{N_2O})] \right], \tag{5}$$

where $f(C^{CH_4}, C^{N_2O})$ is defined in expression (3).

As with CH_4, a key simplifying assumption is the constant decay rate used in the simple gas cycle model (and potentially the time it takes the gas to become well mixed within the atmosphere). As discussed in the IPCC TAR, the decay rate of N_2O will depend on the atmospheric concentration of N_2O and so will not be constant in reality. To examine the extent to which this impacts the results of the simple model, an analogous set of experiments as conducted for CH_4 were performed. Given future

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N_2O emissions based on the EMF-22 MiniCAM reference scenario, a one tonne N_2O perturbation in 2015 is considered. Figure 3(a) shows the projected atmospheric concentration increase from the perturbation using the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. This comparison illustrates that the simple model tracks the output of MAGICC well for the entire 300-year time horizon. Outside the initial perturbation year, the two projections do not differ by more than 2% within the first century, with the largest difference occurring in the perturbation year, for the same reasons as with CH_4.

Figure 3(b) presents the estimates of average additional radiative forcing per decade as a result of the N_2O perturbation using both models. The additional radiative forcing from the N_2O perturbation in the one-box model is forecast to be slightly lower (7%) in the first decade compared to MAGICC. Subsequently, the difference is within 2% through to 2300.

As with CH_4, to assess the effect that this difference would have on the SC-N_2O, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of N_2O computed using both the simple model and MAGICC is added to the exogenous forcing projection. As before, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 3 presents the results of this experiment. As the comparisons of the projected radiative forcing perturbations would suggest, the difference between the social cost estimates for the two approaches is relatively small. In contrast to the case of CH_4, here an increase in the discount rate increases rather than decreases the divergence between the estimates due to the greater weight being placed on the earlier years when the radiative forcing perturbations have a slightly higher degree of divergence.

3.5. Effect of post-2100 non-CO_2 radiative forcing assumptions

The EMF-22 socio-economic-emissions scenarios used by the USG include years only up to 2100, while the USG ran the IAMs out to 2300. Therefore, additional assumptions were required to extrapolate the scenarios beyond 2100. For the purposes of this study, the most important of these assumptions is that non-CO_2 radiative forcing will remain constant at its 2100 level until 2300. Such a broad assumption was sufficient for the purposes of the USG in estimating the SC-CO_2. However, estimating the social cost of non-CO_2 GHGs requires explicit projections of baseline emissions of non-CO_2 gases in order to correctly determine the effect of the perturbation. The USG's broad assumption regarding the extrapolation of non-CO_2 gases is therefore problematic as constant non-CO_2 radiative forcing post 2100 may occur in an infinite number of ways. For instance, one way to achieve this outcome is to assume that emissions of each non-CO_2 gas falls to a level equal to its respective rate of decay in 2100. This assumption would keep atmospheric concentrations, and in turn radiative forcing, constant. Based on the simple gas cycle models laid out in the earlier sections this implies that, for gas X,

$$E_t^X = \frac{-d_X(C_{pre}^X - C_{2100}^X)}{g_X} \forall t \ . \ 2100. \tag{6}$$

To put this assumption into context, the solid lines in Figure 4(a) and (b) present the emissions paths for CH_4 and N_2O, respectively, under the MiniCAM EMF-22 reference scenario extrapolated using

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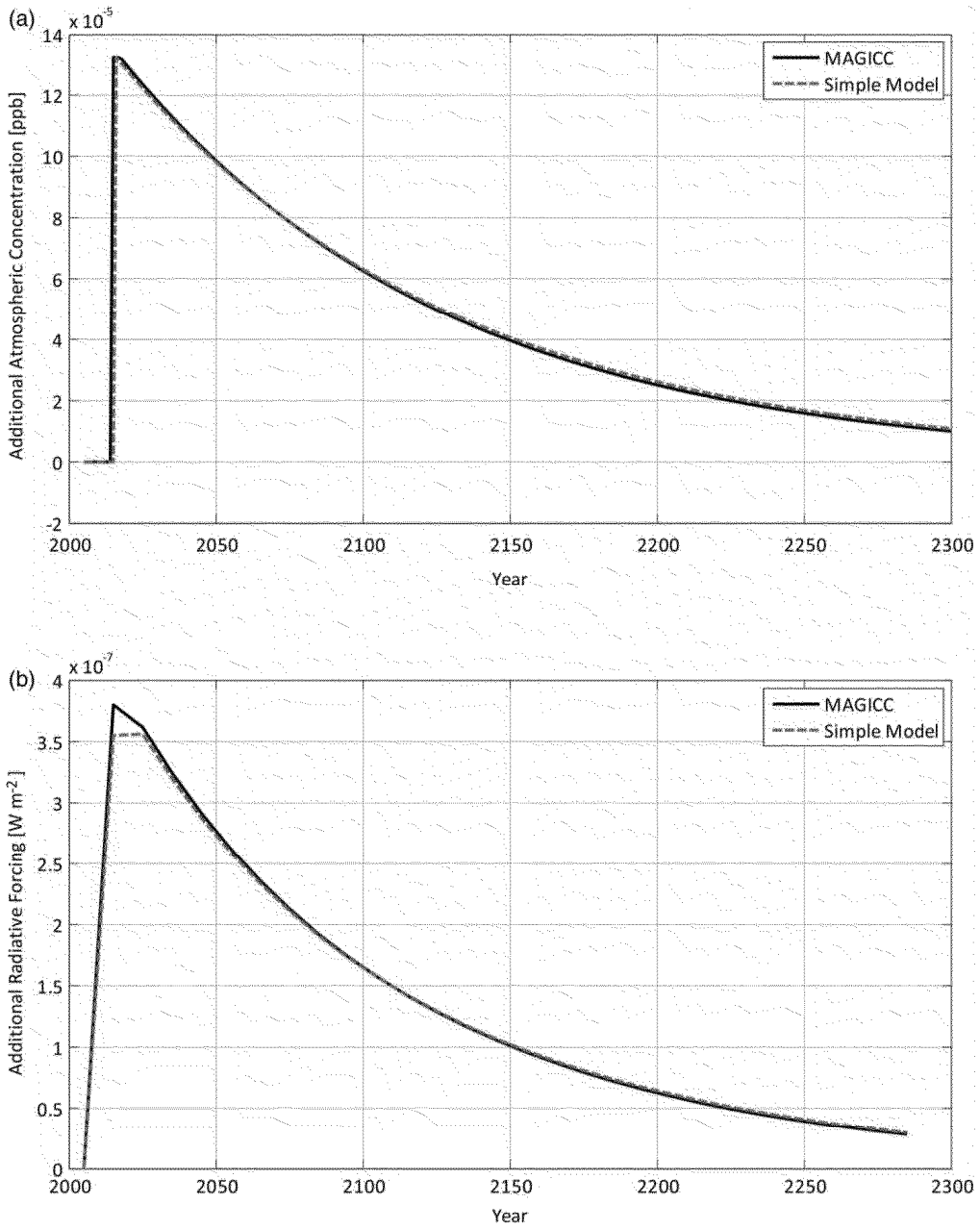

Figure 3 Effects of perturbation in 2015 N_2O emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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TABLE 3 Effect of climate model on SC-N_2O (2007$ per tonne N_2O): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	19,689	19,819	2 1%
	3.0%	12,390	12,525	2 1%
	5.0%	3,346	3,419	2 2%
2045	2.5%	36,968	37,358	2 1%
	3.0%	25,030	25,427	2 2%
	5.0%	8,280	8,528	2 3%

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expression (6), while the dashed lines show two alternative extrapolation approaches, one where emissions are held constant at their 2100 level and one that assumes emissions intensity (emissions/economic output) continues to decline at the same rate forecast by the EMF-22 scenario in 2090–2100 (dotted line). This latter alternative is analogous to the USG assumption regarding industrial CO_2 emissions. The two alternatives will not result in the radiative forcing contribution of gas X remaining constant post-2100, but do not in themselves violate the assumption that overall non-CO_2 radiative forcing remains constant. Noteworthy is the fact that the assumption in (6) is almost analogous to keeping CH_4 emissions constant at their 2100 levels, whereas for N_2O the assumption requires a sudden decrease in emissions of over 35%.

While Figure 4 illustrates that these three extrapolation approaches can lead to vastly different projections for emissions after 2100, the relevant comparison is how these assumptions affect the additional radiative forcing from a perturbation of the gas and in turn the SC-X estimates. Figure 5(a–d) present the additional radiative forcing resulting from a one tonne perturbation based on the simple model presented in Sections 3.1 and 3.2. Figure 5(a) and (b) demonstrates the difference for a perturbation in 2015, whereas Figure 5(c) and (d) represents perturbations in 2045. For CH_4, the cumulative radiative forcing from the projection over the time horizon differs by less than 0.001%, even for a

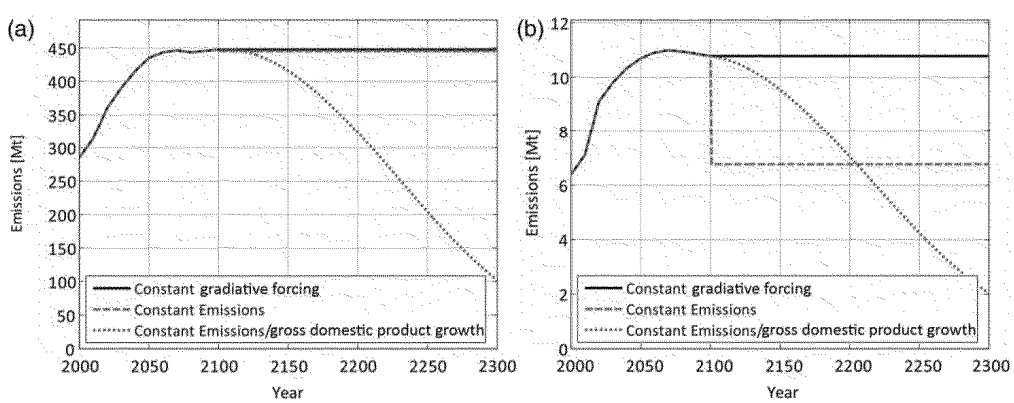

Figure 4 EMF-22 MiniCAM extended emissions scenario: (a) CH_4 emissions; (b) N_2O emissions

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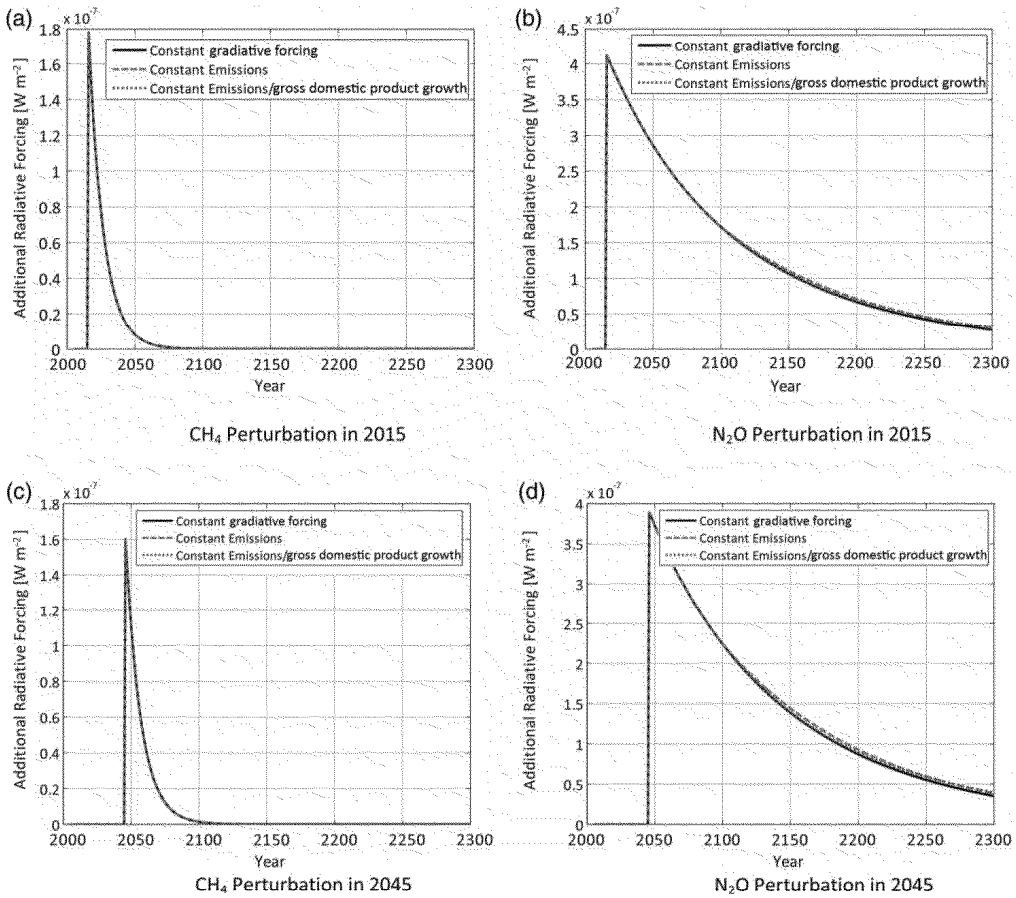

Figure 5 Effect of extrapolation approach on radiative forcing perturbation from simple model: (a) CH_4 perturbation in 2015; (b) N_2O perturbation in 2015; (c) CH_4 perturbation in 2045; (d) N_2O perturbation in 2045

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perturbation in 2045. Accordingly, the relevant annual difference is smaller even than one-thousandth of a percent. This result occurs because of the short atmospheric lifetime of the gas, which renders assumptions regarding CH_4 emissions after 2100 unimportant for near-term perturbations. Post-2100 emissions will have a larger effect in the case of N_2O, which has a much longer atmospheric residence time. However, even for a perturbation in 2045, the difference in cumulative additional radiative forcing is less than 2.5% across the extrapolation assumptions.

To examine the impact of these assumptions on SC-CH_4 and SC-N_2O, an experiment was conducted using the DICE model based on the EMF-22 MiniCAM socio-economic-emissions scenario. The results of this experiment are presented in Table 4 for the perturbation year 2045 (noting that the extrapolation method will have greater impact on future emissions years). As may be seen, the relatively short atmospheric lifetime of CH_4 leads to a situation in which post-2100 assumptions do not affect SC-CH_4 estimates, even in 2045. For the longer-lived gas N_2O, in emission year 2045, where the effect of the post-2100 extrapolation approach would be largest, the difference across the three

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TABLE 4 Effect of post-2100 extrapolation on the 2045 SC-X (2007$ per tonne): DICE2010, MiniCAM

Gas	Discount rate	Constant RF	Constant emissions	Constant emissions intensity growth
CH_4	2.5%	2,490	2,490	2,490
	3.0%	1,933	1,933	1,933
	5.0%	956	956	956
N_2O	2.5%	36,968	36,588	36,662
	3.0%	25,030	24,837	24,868
	5.0%	8,280	8,261	8,263

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assumptions is less than 1% and the projections are equivalent to two significant digits. Therefore, in the remainder of this article, non-CO_2 emissions are extrapolated past 2100 using expression (6) to ensure that the gas-specific contribution to overall radiative forcing remains constant in the simple model. While additional study may lead to improvements of long-term forecasts of CH_4 and N_2O emissions and possible correlations, compared to the paths in Figure 5(a), the very minimal effect of such assumptions on the social cost estimates suggests the impact of such efforts would be minimal in this context.

4. Results

For FUND, the social cost of non-CO_2 GHGs is estimated by perturbing the paths of emissions directly, while for DICE and PAGE the approach presented in Section 3 is used. In both cases, all additional assumptions made by the USG are applied, including the five EMF-22 socio-economic-emissions scenarios, the Roe and Baker (2007) distribution for the equilibrium climate sensitivity, and constant discount rates of 2.5%, 3.0%, and 5.0%. Following the USG, the estimates for the expected social cost are averaged across scenarios and models, with each model and scenario given equal weight. Estimates are not combined across discount rates, and a fourth estimate is included representing the 95th percentile when using the 3.0% discount rate. By using the same assumptions and procedures as the USG, estimates of the SC-CO_2 derived in this article are identical to the values used in US Federal rule making. Specifically, these estimates are equivalent to the recent 2013 update of the USG SC-CO_2, which revised the original 2010 USG upwards based on new versions of the IAMs used. The non-CO_2 results, as well as the USG SC-CO_2 estimates, are presented in Table 5 for emissions years 2020 and 2050.[5] Results for additional years, and the results of sensitivity analyses using Ramsey discounting, may be found in Appendix B and C, respectively.

As expected, considering their higher radiative efficacy, the social costs associated with a tonne of CH_4 and N_2O emissions are substantially higher than for CO_2. The values are higher at lower discount rates, although the impact of the discount rate is lower for CH_4 given its relatively short lifetime. Similar to CO_2, the social cost estimates for CH_4 and N_2O increase over time as the climate and economic systems become more stressed, although the growth rate of the social cost estimate may differ between the gases, as discussed in the following.

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TABLE 5 SC-X (2007$ per tonne)

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CO_2	12	43	64	128
	CH_4	550	1,200	1,600	3,200
	N_2O	4,800	15,000	22,000	41,000
2050	CO_2	26	71	97	220
	CH_4	1,400	2,500	3,100	6,900
	N_2O	11,000	27,000	38,000	74,000

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To better understand how the social costs of CH_4 and N_2O compare to CO_2, Table 6 presents the global damage potentials corresponding to the social cost estimates from Table 5. (The disaggregated results, by model and scenario, for 2020 are provided in Appendix B.) As explained in Section 2, the global damage potential for gas X is the ratio of SC-X to SC-CO_2, and therefore by construction captures all the important linkages between emissions and monetized climate change damages (to the degree they are captured by the IAMs) directly within the gas comparison metric. As noted by Frankhauser (1994), this is preferred to the commonly used GWP gas comparison metric, which only measures the additional radiative forcing from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years) and ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages.

The global damage potential of CH_4 decreases with the discount rate due to the relatively shorter atmospheric lifetime. This difference in atmospheric lifetime leads to a situation where lowering the discount rate has a greater impact on the SC-CO_2 than the SC-CH_4. This finding is robust across the models. The estimates in Table 6 also present the same result for N_2O in the aggregate case, although this characteristic is not consistent across the models or the previous literature. Based on the disaggregated results (presented in Appendix B), the results from the DICE model suggests the global damage potential for N_2O increases with lower discount rates due to a lower effective decay rate over the relevant time horizon for N_2O than CO_2. This result is consistent with previous findings by Marten and Newbold (2012). However, for FUND the opposite is seen to hold. Waldhoff et al. (2011) show that this result is primarily due to the inclusion of increased production in the agriculture and forestry sectors from CO_2 fertilization effects. At lower discount rates these benefits place a greater downward

TABLE 6 Global damage potential

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CH_4	46	29	25	25
	N_2O	397	359	353	317
2050	CH_4	52	36	32	31
	N_2O	414	388	387	338

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impact on the SC-CO_2, thereby lowering the global damage potential. If one were to remove those impacts from the FUND model the global damage potential for N_2O becomes relatively insensitive to the discount rate. One would expect the role of the discount rate in determining the global damage potential in PAGE to be the same as in DICE, but the results suggest that this is not the case. It seems most likely that this is because the PAGE model has only ten time steps to cover the entire time horizon, which results in very large, up to 100-year, time steps further out in time. As noted in Section 3, the additional radiative forcing from the N_2O perturbation is implemented as the average across the model's time steps. It seems that PAGE does not average radiative forcing over the time step for CO_2, which causes the global damage potential for N_2O to decrease with the discount rate. It is not clear if this result would hold if the size of the time steps in the model were reduced.

A comparison across models further highlights the importance of CO_2 fertilization impacts on the global damage potential. CO_2 emissions, and the resulting increase in atmospheric concentration, have the potential to increase yields in the agriculture and forestry sector. This characteristic is not shared by other GHG emissions. Accordingly, the FUND model, which explicitly captures this effect, exerts downward pressure on the SC-CO_2 that is not present for the SC-CH_4 and SC-N_2O, allowing for the possibility of substantially higher global damage potential estimates. The results based on the FUND model presented in this article exhibit this effect; however, the CO_2 fertilization effect is not explicitly modelled in DICE and PAGE and therefore they are found to produce lower estimates of the global damage potential. For example, using the 3% discount rate, the global damage potential for CH_4 as estimated by FUND ranges between 58 and 88 depending on the scenario, whereas it ranges from 19 to 28 for DICE and PAGE. As the DICE and PAGE models only consider two natural system impacts, temperature and sea level, if they do implicitly include potential CO_2 fertilization benefits, they are included by using the temperature anomaly as a proxy for the increasing atmospheric CO_2 concentration. Fertilization benefits would therefore be allowed to falsely accrue to perturbations of other GHG emissions besides CO_2. It is not clear the degree to which these models try to incorporate CO_2 fertilization effects and therefore the degree to which this issue is of concern.

Finally, the results in this article show that the 100-year GWP (25 for CH_4 and 298 for N_2O; Forster et al., 2007) probably provides an underestimate of the global damage potential of each gas, a finding consistent with previous studies by Marten and Newbold (2012) and Waldhoff et al. (2011). Unlike the GWP as calculated by the IPCC, the global damage potential will be dependent upon the year of the emissions perturbations, so the degree of underestimation varies by year. For CH_4, the global damage potential in Table 6 is 0–84% higher than the GWP in 2020, increasing to 24–108% in 2050. For N_2O, the global damage potential is 6–33% higher than the GWP in 2020, increasing to 13–39% in 2050. While inaccurate, using the GWP to convert emissions reductions into CO_2 equivalents that can be valued with the SC-CO_2 would probably provide a conservative estimate for the abatement benefits.

For the comparison above, the GWP estimates presented in the AR4 by the IPCC (Forster et al., 2007) were used to maintain consistency with the assumptions regarding the direct and indirect effect of CH_4 and N_2O concentrations within the modelling. The recent AR5 by the IPCC (Myhre et al., 2013) has increased the estimate of the indirect effects of CH_4, which gives a higher 100-year GWP for CH_4 of 28. A reduction in their estimate of the radiative efficacy of N_2O has decreased its 100-year GWP to 265. It is likely that updated modelling of the social cost estimates based on similar assumptions would maintain the finding that the GWP is an underestimate of the global damage potential.

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4.1. Comparison with previous estimates

For comparison, Table 7 presents the social cost estimates, when available, and the global damage potential estimates for CH_4 and N_2O from three recent studies in the literature whose features are more up to date and therefore more directly comparable with this study: Hope (2006a), Waldhoff et al. (2011), and Marten and Newbold (2012). A direct comparison to the longer list of studies presented in Table 1 is more difficult as they are based on models and socio-economic and emissions scenarios that were developed up to 20 years ago in a rapidly evolving field.

The social cost estimates presented in Table 5 are higher than the estimates in Hope (2006a) and Waldhoff et al. (2011) for CH_4, and in the range of Waldhoff et al. (2011) for N_2O. This result holds whether the comparison is made with the aggregate results in Table 5 or the disaggregated model-specific results. One reason for the significant difference in the SC-CH_4 estimates is that the earlier studies rely on older model versions (PAGE2002 and FUND3.5), neither of which include the indirect effects of CH_4 emissions on radiative forcing, but are included within this analysis. As noted in Section 3.3 the indirect effects of CH_4 are modelled as a 40% increase in its effective radiative forcing. The result of this change alone would likely be a greater than 40% increase in the SC-CH_4 due to the nonlinear damage functions. Furthermore, the assumptions regarding preference parameters in the main cases of Hope (2006a) and Waldhoff et al. (2011) lead to effective discount rates that are significantly higher than 3%. Other differences in input assumptions (e.g. equilibrium climate sensitivity, socio-economic emissions scenario) will also lead to differences, although these are likely to be of second-order importance given the relative similarity in the assumptions.

However, the results in Table 5 averaged across the combinations of the three models and five scenarios are relatively similar to those of Marten and Newbold (2012), which focused on a single scenario

TABLE 7 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Discount Rate	Emissions Year	Social cost (2007$/tonne X)[a]		Global damage potential (SC-X/SC-CO_2)	
			SC-CH_4	SC-N_2O	CH_4	N_2O
Hope (2006a)	Ramsey	2001	125	–	20	–
Waldhoff et al. (2011)[b]	Ramsey	2010–2019	265	7,616	26	738
			–	–	8–221	383–3,503
Marten and Newbold (2012)	2.5%	2020	1,500	26,000	23	403
		2050	3,500	50,000	32	444
	3%	2020	1,100	17,000	27	400
		2050	2,900	34,000	36	439
	5%	2020	550	4,900	42	380
		2050	1,500	12,000	53	415

[a]All values are discounted to the year of the emissions perturbation.
[b]The first row presents the base case and the second row presents the range found from sensitivity analysis (over socio-economic scenario, climate sensitivity, pure rate of time preference, climate sensitivity and CO_2 fertilization).

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and model. This result is in part based on the fact that both sets of results include the indirect effects of CH_4, use the same discount rates and equilibrium climate sensitivity distribution, and relatively similar scenarios. The estimates in this study are slightly higher for the SC-CH_4 and slightly lower for the SC-N_2O compared to Marten and Newbold (2012). Of particular interest is the specific comparison of this article's estimates based on DICE 2010 and the MiniCAM scenario to those of Marten and Newbold (2012) using the same scenario, discount rates, and equilibrium climate sensitivity but an the older 2007 version of the DICE model and a more complete climate sub-model. In this case, estimates for both the SC-CH_4 and SC-N_2O (presented in Appendix B) are notably lower. The myriad of differences between the model vintages and climate sub-models make it difficult to assess which differences are most important for explaining this relationship.

As previously noted, the global damage potential may provide a better value with which to compare across studies that estimate the social cost of non-CO_2 GHG emissions, as it helps to control for some of the underlying differences in assumptions across studies. For example, the global damage potential is far less sensitive to the discount rate used than the SC-X values themselves. However, the global damage potential does not address the lack of indirect CH_4 effects, as may be seen in the lower estimates of Hope (2006a) and Waldhoff et al. (2011). In these cases the exclusion of the 40% additional increase in radiative forcing from the indirect effects of the CH_4 perturbation explains the majority of the difference. In comparison to Marten and Newbold (2012), the results presented in Table 6 are relatively similar for CH_4 in both the aggregate and disaggregated results. For N_2O, similar results are found in the DICE estimates, but notable differences are found in how the aggregate results respond to the discount rate, due to the differences in this relationship between the models as noted above.

5. Concluding remarks

This article presents a simple and transparent approach to estimating the social cost of CH_4 (SC-CH_4) and N_2O (SC-N_2O) in a manner that is consistent with estimates of the social cost of CO_2 (SC-CO_2) already in use in benefit–cost analysis (BCA) for US Federal regulations. This approach is used to estimate the SC-CH_4 and SC-N_2O for the period 2010–2050. These directly modelled estimates are found to be larger than approximations of the social costs of these gases based on the application of common physical gas comparison metrics, such as global warming potentials (GWPs), to the SC-CO_2. This result generalizes the empirical findings of Marten and Newbold (2012) that using a GWP-based approximation approach will likely offer a conservative estimate of the social cost of non-CO_2 GHGs.

The social costs associated with emissions of non-CO_2 GHGs are substantial and should be included within the BCAs used to assess the overall welfare implications of policy alternatives. For example, by not including monetized values of the benefits from reducing CH_4 and N_2O emissions, the BCA for recent standards regulating the fuel efficiency and GHG emissions of light duty vehicles implicitly assigned them a value of zero (US EPA, 2010). However, the results of this article suggest that those reductions have benefits of US$85–493 million (2007$) for CH_4 and $1.5–12 million (2007$) for N_2O in the year 2020 alone. Failing to account for such impacts could limit the ability of the analysis to serve as a transparent and informative input into the decision-making process about the relative benefits and costs of regulatory alternatives. That said, by restricting the article to a derivation of social cost estimates consistent with the USG SC-CO_2 estimates, the myriad issues related to

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whether those estimates can themselves be improved are set aside.[6] Any limitations that apply to the USG SC-CO_2 estimates therefore also apply to the SC-CH_4 and SC-N_2O estimates derived here.

Supplemental data

Supplemental data for this article can be accessed 10.1080/14693062.2014.912981.

Notes

1. Examples include Minnesota's draft methodology for setting the value of a tariff to compensate solar panel owners for the surplus power they deliver to utilities (http://www.eenews.net/stories/1059992297, http://mn.gov/commerce/energy/images/DRAFT-MN-VOS-Methodology-111913.pdf), the Northwest Power and Conservation Council's symposium supporting the development of the 7th Power Plan (http://www.nwcouncil.org/energy/powerplan/7/symposiums/greenhouse/agenda), BCA of Canada's Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations (http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html), analysis of climate change projects at the Inter-American Development Bank (correspondence with Patrick Doyle, Senior Climate and Energy Officer, Structured and Corporate Finance Department), the International Monetary Fund's recent Energy Subsidy Reform report (http://www.imf.org/external/np/pp/eng/2013/012813.pdf), and Parry and Strand (2012).
2. An alternative approach for estimating the social cost of GHG emissions could be based on stated preference (SP) surveys designed to elicit respondents' maximum willingness-to-pay for various levels of GHG emission reductions (e.g. Longo, Markandya, & Petrucci, 2008; Soliño, 2010). This approach would not suffer from the difficulties associated with creating and parameterizing a numerical integrated assessment model. However, it would suffer from its own set of difficulties, including well-known general limitations that affect all SP studies including the potential for 'hypothetical bias' (e.g. Carson, 2012; Hausman, 2012; Kling, Phaneuf, & Zhao, 2012), plus difficulties that may be specific to this application stemming from the generally limited knowledge base regarding the potential climatic, biophysical, and especially economic impacts of GHG emissions on current and far future generations that most respondents will bring to the survey.
3. The fork of MAGICC version 5.3 included in Pacific Northwest National Laboratory's open source model GCAM version 2 (Calvin et al., 2009) is used without carbon cycle feedbacks and, unless otherwise specified, an equilibrium climate sensitivity of 3 8C. We note that sensitivity analysis found the general results of this side analysis to be robust to other values of the equilibrium climate sensitivity.
4. The EMF-22 scenario is extended past 2100 assuming that emissions stay constant at the 2100 level. This assumption is revisited later in this article.
5. The PAGE 2009 model restricts the user to representing the entire time horizon, in this case out to 2300, with only ten time steps. This leads to the unrealistic situation in a small number of simulations where the marginal unit of emissions can cause 'catastrophic' climate impacts to occur one period earlier, which could be 100 years earlier in some cases. We consider these occurrences to be a limitation of the model and drop them from the overall distribution of estimates. Appendix A contains further details about this issue.
6. In addition to the critiques previously cited, we point the interested reader to the work of Marten et al. (2013) and Oppenheimer (2013) for a review of literature that considers potential improvements in the assessment and valuation of climate change impacts.

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BEFORE THE ENVIRONMENTAL PROTECTION AGENCY

PETITION FOR RULEMAKING PURSUANT TO SECTION 21 OF THE TOXIC SUBSTANCES CONTROL ACT, 15 U.S.C. § 2620, CONCERNING THE REGULATION OF CARBON DIOXIDE

Credit: NOAA

CENTER FOR BIOLOGICAL DIVERSITY

DONN J. VIVIANI, PhD

PETITIONERS

June 30, 2015

NOTICE OF PETITION

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The Center for Biological Diversity ("Center") is a non-profit, public interest environmental organization dedicated to the protection of native species and their habitats through science, policy and environmental law. The Center has over 800,000 members and online activists throughout the United States and around the world. The Center's Oceans Program and its supporters are specifically concerned with the conservation of marine species, the preservation of ocean ecosystems and the effective implementation of U.S. environmental laws, including the Toxic Substances Control Act. The Center submits this petition on its own behalf and on behalf of its members and staff with an interest in protecting the marine environment.

Donn J. Viviani, PhD, is a retired U.S. Environmental Protection Agency scientist. He was the Director of the Climate Policy Assessment Division in the Office of Policy, Economics and Innovation. He also served as Chairman of the Great Lakes Water Board's Toxic Substances Committee and as a member of the Science Coordinating Committee for the International Joint Commission for the Great Lakes. Dr. Viviani enjoys the ocean and submits this petition, in part, so his grandchildren will be able to enjoy it as well. Dr. Viviani also submits a supplement to the petition, under his signature only, and respectively requests that it be considered.

ACTION REQUESTED

Pursuant to section 21 of the Toxic Substances Control Act ("TSCA" or the "Act"), 15 U.S.C. § 2620, and section 553(e) of the Administrative Procedure Act ("APA"), 5 U.S.C. § 553(e), the Center for Biological Diversity and Donn J. Viviani (collectively, "Petitioners") hereby petition the Administrator of the U.S. Environmental Protection Agency ("EPA") to promulgate regulations protecting public health and the environment from the serious harms associated with anthropogenic emissions of carbon dioxide, including ocean acidification. Specifically, Petitioners request that EPA adopt a rule under section 6 of the Act, 15 U.S.C. § 2605, requiring manufacturers and processors to mitigate these emissions.

This petition sets in motion a specific process, placing definite response requirements on EPA. Specifically, TSCA stipulates that the agency "*shall* either grant or deny the petition" within 90 days following its receipt, "promptly commenc[ing] an appropriate [rulemaking]

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proceeding" if such action is warranted. 15 U.S.C. § 2620(b)(3) (emphasis added). Conversely, should EPA deny this petition, the agency must publish the reasons for denial in the Federal Register. 15 U.S.C. § 2620(b)(3); *see also* 5 U.S.C. § 555(e) ("Prompt notice shall be given of the denial in whole or in part of a written application, petition, or other request of an interested person made in connection with any agency proceeding."). Pursuant to 15 U.S.C. § 2620(b)(4), petitioners may file suit in federal district court to challenge an adverse or untimely determination. *See also* 5 U.S.C. §§ 702, 706.

As described in this petition, anthropogenic emissions of carbon dioxide satisfy the standard for regulation set forth at 15 U.S.C. § 2605. For example, EPA has acknowledged that these emissions have the potential to alter ocean chemistry, thus imperiling important marine ecosystems and presenting an unreasonable risk of injury to the environment. Accordingly, the agency must promptly commence the proposed rulemaking to reduce and mitigate these harms. In the event that EPA concludes that there are insufficient data and experience upon which to determine or predict the effects of carbon dioxide emissions, we alternatively request that the agency adopt a rule under section 4 of the Act, 15 U.S.C. § 2603, requiring manufacturers and processors responsible for the generation of carbon dioxide to undertake testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Dated this 30th day of June 2015.

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INTRODUCTION

Ocean acidification — caused by carbon dioxide ("CO_2") emissions — is a severe threat to the marine environment and the health of people who depend on oceans and coasts. Because of the unreasonable risk that CO_2 poses to the environment and human health, this petition seeks rulemaking under the Toxic Substances Control Act ("TSCA") to regulate CO_2 from cradle to grave.

About 28% of CO_2 emissions from power generation, cement production, industry, and other sources are absorbed by the ocean. These CO_2 emissions cause seawater to become more acidic and corrosive to sea life. Anthropogenic CO_2 emissions have increased the acidity of the oceans on average by 30%, and by the end of the century scientists predict that the oceans will become 150-170% more acidic.

While the most dangerous consequences of CO_2 on our oceans are still to come, harmful impacts on the environment are already well-documented.

- Billions of oyster larvae have perished in the Pacific Northwest due to ocean acidification;
- 53% of pteropods, plankton that form the base of the marine food web, along the West Coast have severely dissolved shells because of the corrosive nearshore conditions; and
- Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%.

These are just some of the harmful environmental impacts of ocean acidification caused by CO_2 emissions. Anthropogenic CO_2 emissions are contributing to increasingly corrosive conditions for marine animals, and will continue to grow more severe absent actions to promptly reduce CO_2 pollution in the atmosphere.

TSCA was enacted in part to address the threat of ozone depletion caused by chlorofuorocarbon (CFC) emissions. And here again TSCA regulation is needed where airborne emissions are causing damage to our environment — this time threatening ocean ecosystems, fish and shellfish industries, and communities that depend on oceans and coral reefs.

Petitioners specifically request that EPA take the following actions:

1. **Make a determination under TSCA § 6 that CO_2 presents an unreasonable risk of injury to health or the environment; and**
2. **Initiate rulemaking to control CO_2; or**
3. **If EPA finds data inadequate to make a §6 determination then EPA must initiate rulemaking for testing under TSCA § 4.**

This petition presents scientific evidence that establishes that CO_2 presents an unreasonable risk of injury to the environment, and therefore EPA must take action under TSCA section 6.

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I. The Toxic Substances Control Act

Congress enacted TSCA, 15 U.S.C. §§ 2601 *et seq.*, "to assure that … innovation and commerce in … chemical substances and mixtures do not present an unreasonable risk of injury to health or the environment."[1] Accordingly, lawmakers required those responsible for the manufacture and processing of these compounds to develop "adequate data" describing their effects, and authorized EPA to devise and implement reasonable controls to prevent the risk of injury to health or the environment.[2]

Section 6 of TSCA mandates that EPA "shall" regulate a chemical substance for which

> there is a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance or mixture, or that any combination of such activities, presents or will present an unreasonable risk of injury to health or the environment.[3]

Permissible regulations include requirements prohibiting or "limiting the amount of such substance … which may be manufactured, processed, or distributed in commerce."[4] EPA can also require processors "to give public notice of such risk [of injury], and . . . to replace or repurchase such substance . . . to adequately protect health or the environment."[5] In assessing risk, EPA must consider:

> (A) the effects of such substance or mixture on health and the magnitude of the exposure of human beings to such substance or mixture,
> (B) the effects of such substance or mixture on the environment and the magnitude of the exposure of the environment to such substance or mixture,
> (C) the benefits of such substance or mixture for various uses and the availability of substitutes for such uses, and
> (D) the reasonably ascertainable economic consequences of the rule, after consideration of the effect on the national economy, small business, technological innovation, the environment, and public health.[6]

Thus, if there is a reasonable basis to conclude that a proposed rule is necessary to protect the environment, then EPA must grant a petition for rulemaking and initiate rulemaking procedures. Factual certainty is not required; instead, the agency may "base its action on scientific theories, consideration of projections from available data, modeling using reasonable assumptions, and extrapolations from limited data."[7] Even if EPA determines that another federal law "could

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[1] 15 U.S.C. § 2601(b)(3) (2012). Within the meaning of TSCA, the term "chemical substance" includes "any organic or inorganic substance of a particular molecular identity." *Id.* § 2602(2).
[2] *Id.* § 2601(b)(1) & (2).
[3] *Id.* § 2605(a) (emphasis added).
[4] *Id.* § 2605(a)(1)(B).
[5] *Id.* § 2605(b)(2)(B).
[6] *Id.* § 2605(c)(1). E.
[7] Lead Fishing Sinkers; Response to Citizens' Petition and Proposed Ban, 59 Fed. Reg. 11,122, 11,138 (Mar. 9, 1994) (*citing* H.R. Rep. No. 1341, 9th Cong., 2d Sess. 32 (1976)).

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[sufficiently] eliminate[] or reduce[]" the risk associated with a particular chemical substance, the agency may elect to regulate the substance under TSCA, provided that a "comparison of the estimated costs" and "relative efficiency" reveals that such action promotes the public interest.[8]

In the event that EPA lacks adequate data and experience upon which to determine the health and environmental risks associated with a particular chemical substance, the agency "*shall* by rule require that testing be conducted on such substance."[9] Specifically, Section 4 of the Act authorizes EPA to compel manufacturers and processors to evaluate the safety of substances that "may present an unreasonable risk of injury to health or the environment" or that "[are] or will be produced in substantial quantities" and, thus, "may reasonably be anticipated to enter the environment in substantial quantities" or result in "significant or substantial human exposure."[10] TSCA provides for testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Over forty years ago, the Council on Environmental Quality warned of the "high priority need" for a new legal authority capable of ensuring the safe use of toxic chemicals.[11] Despite TSCA's powerful potential, however, EPA has accomplished very little under the Act. This petition presents substantial scientific evidence demonstrating that anthropogenic emissions of CO_2 pose an unreasonable risk to human and environmental health. Indeed, studies show that significant and potentially irreversible harm has already occurred. As the Council recognized decades ago, "[w]e should no longer be limited to repairing [this] damage after it has been done; nor should we continue to allow the entire population or the entire environment to be used as a laboratory." Instead, EPA must take prompt action to reduce and mitigate the anthropogenic production of CO_2.

II. EPA Must Issue a Rule to Regulate or Require Tests for CO_2 Causing Ocean Acidification

CO_2 presents an unreasonable risk of injury to the environment because its exposure to the ocean changes seawater chemistry with harmful impacts on marine life and ecosystems. Substantial evidence supports this conclusion and is discussed in this petition. Accordingly, this petition seeks a rulemaking to regulate CO_2 under TSCA.

This petition requires EPA to make a determination under TSCA section 6 if the injury to the environment and health from CO_2 is unreasonable. Alternately, if the Agency demonstrates that the existing science is insufficient to make a determination under TSCA section 6, EPA must initiate test rules under TSCA section 4 to develop the missing information needed to determine if the TSCA section 6 trigger is met and how best to mitigate the harm.

A. TSCA Authorizes EPA to Act on CO_2

To enable the achievement of TSCA's ambitious objectives, Congress broadly defined EPA's jurisdiction under the Act. As described above, TSCA explicitly directs EPA to initiate

[8] *Id.*
[9] *Id.* § 2603 (emphasis added).
[10] *Id.*
[11] Council on Envtl. Quality, Toxic Substances at v (April 1971).

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rulemaking upon finding that "the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance" threatens public health or the environment.[12] TSCA then authorizes the regulation of "chemical substances" that are "in commerce," a test met by CO_2. Indeed, CO_2 is already on the TSCA inventory as a "chemical in commerce."[13] CO_2 necessarily qualifies as a "chemical substance," a category that includes "any organic or inorganic substance of a particular molecular identity."[14] Moreover, the anthropogenic emissions at issue are in commerce; federal courts have previously concluded that air emissions[15] and "incidental byproducts of industrial chemical processes" are within the scope of EPA's authority under the Act.[16] Existing scientific evidence demonstrates that the anthropogenic production of CO_2 has already damaged marine ecosystems and endangered vulnerable portions of the human population. For the reasons described below, EPA must promptly reduce and mitigate these harms.

1. CO_2 Is a Chemical Substance

First, carbon dioxide is a "chemical substance" falling within the scope of the Act. The Act defines "chemical substance" as "any organic or inorganic substance of a particular molecular identity, including any combination of such substances occurring in whole or in part as a result of a chemical reaction or occurring in nature and (ii) any element or uncombined radical."[17]. CO_2 meets this definition. CO_2 is a chemical substance that occurs both in nature and as a result of a chemical reaction. It consists of a carbon atom bonded to two oxygen atoms:

$$O=C=O$$

It is identified by molecular formula CO_2 and by CAS number 124-38-9.

2. CO_2 Is in Commerce

Second, CO_2 is in commerce, and it is already on the TSCA inventory (CAS 124-38-9) with "chemical in commerce" as the stated reason for regulation.[18] Under TSCA's statutory text, "commerce" is defined as "trade, traffic, transportation, or other commerce . . . between a place in a State and any place outside of such state, or . . . which affects trade, traffic, transportation, or commerce."[19] CO_2 is primarily produced as a byproduct from the combustion of fossil fuels; according to the EPA, CO_2 emissions account for 77% of greenhouse gas emissions worldwide.[20]

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[12] *Id.* §§ 2605(a), 2603(a)(1)(A)(i), 2506(a). Although TSCA does not define "disposal," other federal environmental laws explain that this term encompasses "the discharge, deposit, injection, dumping, spilling, leaking, or placing of any solid waste or hazardous waste into or on any land or water so that such solid waste or hazardous waste or any constituent thereof may enter the environment or be emitted into the air or discharged into any waters, including ground waters." 42 U.S.C. §§ 6903(3), 9601(29).
[13] EPA, Substance Registry at http://1.usa.gov/1IBS1w6 (last accessed June 28, 2015).
[14] 15 U.S.C. § 2602(2). This definition excludes specific compounds already subject to federal control, such as pesticides, tobacco products, nuclear materials and food, drugs and cosmetics. *Id.* § 2602(2)(B).
[15] *Citizens for a Better Env't v. Thomas*, 704 F. Supp. 149, 152 (E.D. Ill. 1989).
[16] *Envtl. Def. Fund v. Envtl. Prot. Agency*, 636 F.2d 1267, 1271 (D.C. Cir. 1980).
[17] 15 U.S.C. § 2602(2)(A).
[18] EPA, Substance Registry at http://1.usa.gov/1IBS1w6.
[19] 15 U.S.C. § 2602(3).
[20] EPA, Global Greenhouse Gas Emissions Data, http://www.epa.gov/climatechange/ghgemissions/global.html (last updated June 21, 2013; last accessed June 28, 2015).

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The most voluminous sources of greenhouse gas emissions are energy suppliers,[21] industry,[22] land use and forestry,[23] agriculture,[24] transportation,[25] commercial and residential buildings,[26] and waste and wastewater.[27] All of these emitters produce CO_2 as a byproduct of their ordinary processes.

TSCA's statutory and regulatory text support the proposition that CO_2 emitted as a byproduct of industrial processes can be regulated under TSCA because CO_2 in this context is manufactured, meaning "produce[d] . . . with the purpose of obtaining an immediate or eventual commercial advantage."[28] All of the industries listed above which emit CO_2 are performed to obtain an immediate or eventual commercial advantage, as all of these industries are commercial and part of a competitive market. Therefore, incidental production of CO_2 is manufactured or produced "for a commercial purpose," and is found "in commerce" pursuant to TSCA regulations.

Accordingly, CO_2 emissions fit the regulatory definition of a chemical substance produced for a commercial purpose. This is bolstered by the broad definition of "commerce" in the TSCA statute; at the very least, CO_2 emissions "affect" trade, traffic, transportation, and commerce.

TSCA's purpose and regulatory text support the regulation of chemical substances that are an incidental byproduct, and indeed EPA has regulated chemical byproducts under TSCA before. For example, PCBs are regulated under TSCA even when they are only incidentally produced as a byproduct of industrial processes.[29] EPA regulates PCB "byproducts" for which there are no separate commercial intents, and TSCA regulates inadvertently vented PCB emissions.[30] Moreover, EPA's authority under TSCA broadly defines what it regulates under "disposal" of PCBs to include intentional and accidental disposal.[31] EPA has also previously prohibited wastes from chemical manufacturing under TSCA.[32]

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[21] Which emit greenhouse gases through "[t]he burning of coal, natural gas, and oil for electricity and heat." *Id.*

[22] Which emit greenhouse gases through "fossil fuels burned on-site at facilities for energy" and "chemical, metallurgical, and mineral transformation processes not associated with energy consumption." *Id.*

[23] Which emit "carbon dioxide . . . from deforestation, land clearing for agriculture, and fires or decay of peat soils." *Id.*

[24] "Greenhouse emissions from agriculture mostly come from the management of agricultural soils, livestock, rice production, and biomass burning." *Id.*

[25] Which emit greenhouse gases through "fossil fuels burned for road, rail, air, and marine transportation." *Id.*

[26] Which emit greenhouse gases from "on-site energy generation and burning fuels or heat in buildings or cooking in homes." *Id.*

[27] Which emit carbon dioxide through the "incineration of some waste products that were made with fossil fuels, such as plastics and synthetic textiles." *Id.*

[28] 40 C.F.R. § 710.3; 40 C.F.R. § 704.3 ("Manufacture for commercial purposes also applies to substances that are produced coincidentally during the manufacture, processing, use, or disposal of another substance or mixture, including both byproducts that are separated from that other substance or mixture and impurities that remain in that substance or mixture. Such byproducts and impurities may, or may not, in themselves have commercial value. They are nonetheless produced for the purpose of obtaining a commercial advantage since they are part of the manufacture of a chemical product for a commercial purpose.").

[29] 44 Fed. Reg. 31525 (May 31, 1979); 40 C.F.R. § 761.

[30] *See, e.g.,* 40 C.F.R. Part 761.

[31] 40 C.F.R. § 761.3.

[32] 45 Fed. Reg. 592 (March 11, 1980);40 C.F.R. § 775 (1980) (prohibiting disposal of 2,3,7,8-tetracholorodibenzo-p-dioxin (TCDD) a manufacturing waste).

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Further, CO_2 emissions are in commerce as they are traded, bought, and sold as carbon offsets. CO_2 is also produced for commerical purposes including for uses in fertilizer, beverage carbonation, dry ice, refrigeration, pressurization, fire extinguishment, and packaging.

B. EPA Should Initiate Rulemaking to Control CO_2 under TSCA

Petitioners request that EPA make finding that CO_2 presents or will present an unreasonable risk of injury to the environment or health. TSCA requires that EPA "shall" initiate rulemaking upon finding "a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use or disposal of a chemical substance of mixture … presents or will present an unreasonable risk of injury to health or the environment."[33]

The information and supporting documents provided in this petition indicate that CO_2 is already causing injury to the environment due to ocean acidification. The scientific evidence further supports that the injury to the environment and health will grow more severe as CO_2 pollution continues. EPA cannot deny that CO_2 is harming the environment. Indeed, EPA acknowledges that ocean acidification poses risk:

> Ocean acidification, like Climate change is primarily caused by increasing carbon dioxide (CO_2) concentrations in the atmosphere. As a result of absorbing large quantities of human made CO_2 emissions the ocean chemistry is changing, which is likely to negatively affect important marine ecosystems and species including coral reefs, shellfish, and fisheries.

(Environmental Protection Agency 2010).

EPA must find that such injury is an unreasonable risk.[34] While Congress did not define the phrase "unreasonable risk," EPA has interpreted relevant legislative history to require that the agency:

> balance the benefits derived from risk reduction against the social and economic costs incurred, taking into account such factors as the extent and magnitude of risk posed; the societal consequences of removing or restricting use of products; availability and potential hazards of substitutes; and impacts on industry, employment, and international trade.[35]

No specific factual determination is necessary to establish "unreasonable risk." For example, even under the stricter standard of 15 U.S.C. § 2606, EPA need not present evidence of actual injury before obtaining emergency injunctive relief to control "immanently hazardous chemical substance[s] or mixture[s]."[36] For the reasons discussed below, application of the agency's balancing test supports the additional regulation of CO_2.

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[33] 15 U.S.C. § 2605(a).
[34] *Id.*
[35] EPA, Guidance for Petitioning the Environmental Protection Agency Under Section 21 of the Toxic Substances Control Act, 50 Fed. Reg. 46,825 (Nov. 13, 1985).
[36] *See* H.R. Conf. Rep. No. 94-1679 78 (1976).

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According to scientific experts: "Reducing CO_2 emissions is the only way to minimise [sic] long-term, large-scale risks" (IBGP et al. 2013).

1. CO_2 Pollution Presents an Unreasonable Risk of Injury to the Environment

There is clear consensus among leading national and international scientific bodies that anthropogenic CO_2 causes changes in ocean chemistry that harm the marine environment. The Intergovernmental Panel on Climate Change ("IPCC") determined that human sources of CO_2 have caused a significant decline in surface ocean pH (Rhein et al. 2013), and over 90 national academies of sciences, including the United States', have signed a statement that ocean acidification will "cause grave harm to important marine ecosystems as CO_2 concentrations reach 450 ppm and above" (Interacademy Panel 2009). The Interacademy Panel concluded that CO_2 has increased ocean acidity with "potentially profound consequences for marine plants and animals" including severe threats to coral reefs, polar ecosystems, and a likely reduction in marine food supplies (*Id.*). The National Research Council also acknowledges that "existing data support a growing consensus in the research community that most documented responses to acidification reflect impairment of physiological capacity or performance" for marine life with likely substantial socioeconomic impacts (National Research Council 2013). The U.S. National Climate Assessment concluded that ocean acidification will alter marine ecosystems in dramatic ways including threatening coral reef habitats and causing reduced growth and survival of shellfish in all regions (Doney et al. 2014).

EPA acknowledges that "ocean acidification presents a suite of environmental changes that would likely negatively affect ocean ecosystems, fisheries, and other marine resources." 75 Fed. Reg. 13538 (Mar. 22, 2010). EPA previously concluded that greenhouse gases, including CO_2, endanger public health and the environment in part because of ocean acidification.[37]

There is no doubt that CO_2 pollution is changing ocean chemistry and harming the marine environment. Unabated, there will be severe and detrimental impacts on marine ecosystems, the economy, and public health. Accordingly, EPA must find that CO_2 poses an unreasonable risk to the environment and health.

a. CO_2 Causes Irreversible Ocean Acidification

Ocean acidification is a major threat to the marine environment. The oceans have absorbed CO_2 emitted into the atmosphere from power plants, manufacturing, cement production, and land use changes. Between 1750 and 2011, human activities have released 375 gigatons of carbon into the atmosphere, and approximately half of that has been absorbed by the oceans (Rhein et al. 2013). Each day about 22 million metric tons of CO_2 is taken up by the oceans (Feely et al. 2008). This uptake of CO_2 is changing ocean chemistry, causing the oceans to become more acidic. Since the industrial revolution surface ocean pH has declined by 0.11 units on average, corresponding with

[37] EPA, Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act 80 (Dec. 7, 2009).

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a 30% increase in acidity (Orr et al. 2005; Caldeira & Wickett 2005).[38] If emissions continue unabated, ocean acidity will increase up to 170% by the end of the century (IBGP et al. 2013).

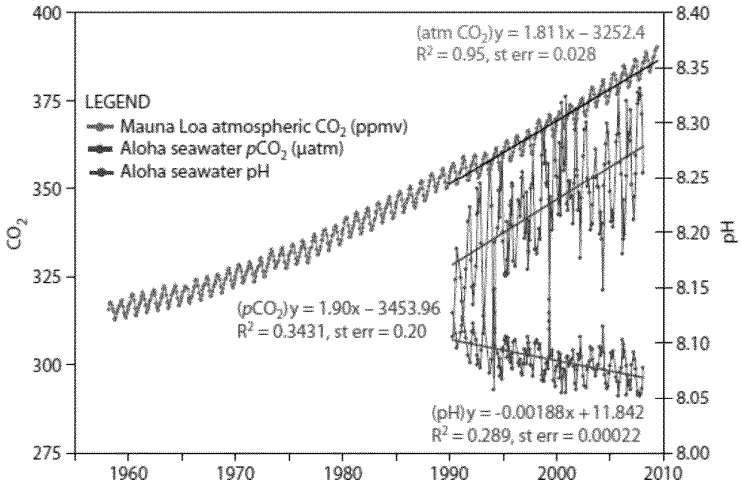

Figure 1. Time series of atmospheric CO 2 at Mauna Loa (ppmv) and surface ocean pH and pCO2 (µatm) at Ocean Station Aloha in the subtropical North Pacific Ocean (see inset map). Note that the increase in oceanic CO 2 over the period of observations is consistent with the atmospheric increase within the statistical limits of the measurements. (Feely et al. 2009).

Anthropogenic ocean acidification exceeds the trend in natural variability significantly, up to 30 times in some regions (Friedrich et al. 2012). The rate of change in ocean acidity is unprecedented in the past 300 million years, a period that includes four mass extinctions (Honisch et al. 2012; Zeebe 2012). The seawater chemistry change is an order of magnitude faster than what occurred 55 million years ago during Paleocene-Eocene Thermal Maximum, which is considered to be the closest analogue to the present, and during that period 96% of marine species went extinct (*Id.*). The current changes in seawater chemistry are irreversible on human timescales (Royal Society 2005).

CO_2's impact on ocean chemistry is fundamentally altering the marine environment with negative impacts on marine species, habitats and ecosystems.

i. What Is Ocean Acidification

When the ocean absorbs CO_2 from the atmosphere it changes ocean chemistry. CO_2 that is absorbed by seawater reacts to form carbonic acid, which dissociates to form bicarbonate and releases hydrogen ions. This reaction reduces the amount of carbonate ions and decreases pH. The oceans store a significant amount of the CO_2 pollution from human activities (Royal Society 2005). While this has provided society with an important service of buffering against climate change impacts, it comes at a cost to the marine environment.

[38] Because the pH scale is logarithmic a small decrease is a significant change in acidity; for example, a decrease of 0.1 pH is an approximate 30 percent increase in acidity.

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Globally, surface water pH has declined 0.11 units on average between 1750 and 1994 (Sabine et al. 2004). Long-term monitoring has documented the impact of increasing atmospheric CO_2 on declining seawater pH in the Pacific and Atlantic Oceans (*see* Figure 2). Results from time-series stations in the North Atlantic and North Pacific show a decrease of about 0.002 pH per year (Rhein et al. 2013).

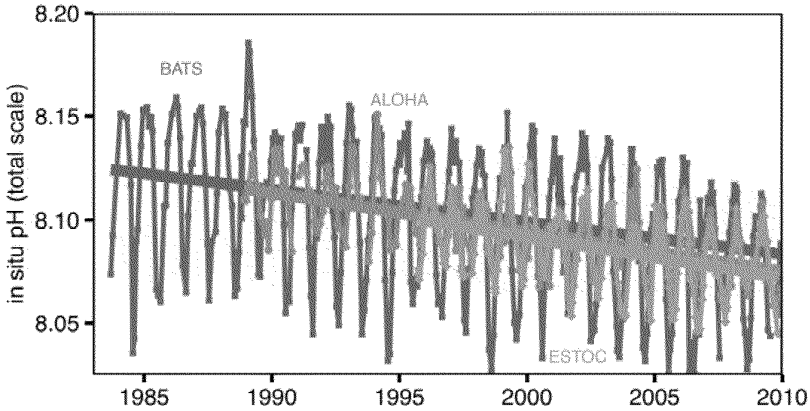

Figure 2. Long-term trends of surface seawater pH at three subtropical ocean time series in the North Atlantic and North Pacific Oceans, including (a) Bermuda Atlantic Time-series Study (BATS, 31°40'N, 64°10'W; green) and Hydrostation S (32°10', 64°30'W) from 1983 to present (updated from Bates, 2007); (b) Hawaii Ocean Time-series (HOT) at Station ALOHA (A Long-term Oligotrophic Habitat Assessment; 22°45'N, 158°00'W; orange) from 1988 to present (updated from Dore et al., 2009) and (c) European Station for Time series in the Ocean (ESTOC, 29°10'N, 15°30'W; blue) from 1994 to present (updated from González-Dávila et al., 2010). Atmospheric pCO2 (black) from the Mauna Loa Observatory Hawaii is shown in the top panel. Lines show linear fits to the data, whereas Table 3.2 give results for harmonic fits to the data (updated from Orr, 2011).(Rhein et al. 2013)

Ocean acidification not only makes the oceans more acidic, but it also reduces the amount of carbonate ions available for animals to build the shells and skeletons they need to survive. Carbonate is an important constituent of seawater because many organisms form their shells and skeletons by complexing calcium and carbonate. Waters that are supersaturated with aragonite are generally good for shell-building, while undersaturated waters (<1.0 Ω_{ar}) are corrosive to some marine animals. Corals require supersaturated waters above 3.3 Ω_{ar} (Meissner et al. 2012). Globally, there has been a decrease of about -0.4 Ω_{ar} (Gruber et al. 2012). The aragonite saturation state has declined 16% since the Industrial Revolution due, in large part, to anthropogenic CO_2 (Feely et al. 2012a; Ishii et al. 2011). Modeling of the oceans' aragonite saturation predicts that by the end of the century up to 75% of ocean volume could be undersaturated with respect to aragonite (Joos et al. 2011).

ii. Observed and Predicted Acidification

CO_2 has already had measurable impacts on seawater chemistry. Some regions, such as those with upwelling systems or high latitudes, are especially vulnerable to ocean acidification.

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1. Pacific Coast

The West Coast is already experiencing adverse impacts of ocean acidification. As early as 2008, a survey off the coasts of Washington, Oregon, and California revealed that this region is already experiencing corrosive waters not expected until mid-century (See figure 3) (Feely 2008). Researchers found seawater undersaturated with respect to aragonite upwelling onto large portions of the continental shelf, reaching shallow depths of 40 to 120 meters (*Id.*). According to the study, the waters were last at the surface approximately 50 years ago when atmospheric CO_2 concentrations were much lower (Feely et al. 2008). Feely et al. report that in the Pacific Ocean there has been a decrease of the saturation state of surface seawater with respect to aragonite and calcite as well as an upward shoaling of the saturation horizon by about 1-2 meters per year on average, due in large part to anthropogenic CO_2 (R. A. Feely, Sabine, et al. 2012). As a result, marine organisms in surface waters, in the water column, and on the sea floor along the West Coast of the United States are already being exposed to corrosive water during the upwelling season.

Modeling of the California Current System demonstrates that the area is rapidly approaching year-round undersaturation with respect to aragonite and it is departing significantly from natural variability (Hauri et al. 2013). Time series monitoring shows that the aragonite saturation state along the California coast is much lower than would be expected in the North Pacific (Harris, DeGrandpre et al. 2013). Surface Ω_{ar} values ranged between 0.66 and 3.9 compared to an estimated pre-industrial range of 1.0 to 4.7. While some areas, like Puget Sound, already exhibit undersaturated conditions every year (Feely, Klinger, et al. 2012; Reum et al. 2014), scientists predict that most shallow shelf areas along the West Coast will become undersaturated with respect to aragonite within the next 20-30 years (Capone & Hutchins 2013; Gruber et al. 2012).

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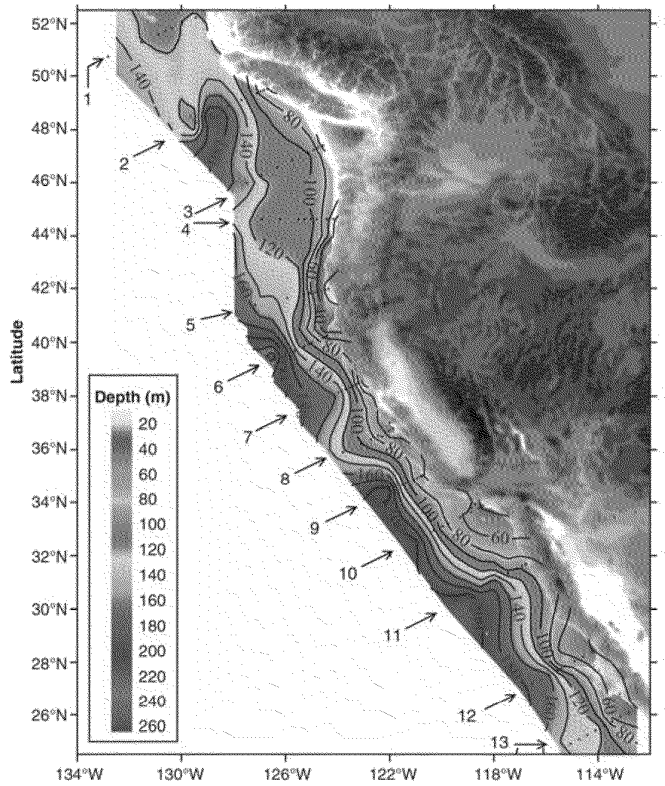

Figure 3. Distribution of the depths of the undersaturated water (aragonite saturation < 1.0; pH < 7.75) on the continental shelf of western North America from Queen Charlotte Sound, Canada, to San Gregorio Baja California Sur,Mexico. On transect line 5, the corrosive water reaches all the way to the surface in the inshore waters near the coast. The black dots represent station locations (Feely et al. 2008).

2. *Alaskan Waters*

High latitude waters are the "bellwether" of ocean acidification because these will be the first ocean regions to become persistently undersaturated with respect to aragonite as a result of greenhouse gas pollution (Fabry et al. 2009; Steinacher et al. 2009). High-latitude waters have naturally lower carbonate ion concentrations and saturation states due to a combination of cold temperatures which increase the solubility of CO_2 and ocean mixing patterns (Fabry et al. 2009; Mathis et al. 2011a). As early as 2016, 10% of Arctic surface waters are expected to be undersaturated with respect to aragonite for at least one month per year (Steinacher et al. 2009).

Recent observations of calcium carbonate saturation states in the North Pacific and Bering Sea have found that full water column undersaturation of calcium carbonate due to ocean acidification is already prevalent. Mathis et al. (2011a) reported that extensive areas of bottom waters over the Bering Sea shelf are becoming undersaturated with respect to aragonite for at least several months (July to September), and some areas of bottom water were already observed to be undersaturated with respect to calcite (Fabry et al. 2009, Mathis et al. 2011a).

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Scientists predict that polar waters will be corrosive to shellbuilding animals within decades (IBGP et al. 2013). A 2015 study of observations in the Chukchi and Beaufort Seas in the Arctic indicates that within 15 years waters will become so corrosive that it will be difficult for marine animals to build and maintain their shells (Mathis et al. 2015). The highly productive fisheries of Alaska are in some of the most rapidly changing seawater conditions (Mathis et al. 2014).

3. Sub-tropical Waters

Subtropical waters have experienced declining saturation states due to ocean acidification. Within decades, scientists believe that ocean acidification will impair coral growth (IBGP et al. 2013). Models show that by the end of the century, most coral reef areas will no longer have aragonite saturation states that are optimal for coral growth. A 10-year study of the Caribbean region found a strong regional decrease in aragonite saturation state between 1996-2006, from 4.05 to 3.9, resulting from CO_2 (Gledhill et al. 2008). Modeling predicts that under various emissions scenarios the coral reefs in the Caribbean will be thermally and chemically stressed between now and 2030 (Meissner et al. 2012). Even under the most optimistic scenario, 98% of reefs will be stressed by 2050 (*Id.*). In the Pacific subtropical ocean near Hawaii, there are nearly 20 years of time-series measurements of significant decreasing seawater pH that match the ocean's uptake of atmospheric CO_2 (Dore et al. 2009)

4. Atlantic Coast

Even ocean waters not at high latitude, in upwelling systems, or containing coral reefs ecosystems are, or will soon be, exhibiting signs of ocean acidification. Observations of East Coast waters during all seasons show that while they remain supersaturated with respect to aragonite, by the end of this century, saturation states of aragonite and calcite will decrease by 20–40%, with the lowest Ωar dropping to 1.3 in some seasons (Jiang et al. 2010). A survey of the Atlantic Coast showed that waters in the Northeast and particularly the Gulf of Maine are the most susceptible to ocean acidification (Wang 2013).

iii. CO_2 Kills and Injures Marine Life

High-CO_2 waters seriously harm marine wildlife and the entire ocean ecosystem. When CO_2 concentrations in seawater increase, the availability of carbonate ions decreases, making it more difficult for marine organisms to form, build, and maintain the calcium carbonate shells and skeletons required for their survival. As seawater becomes more corrosive, it can kill fish eggs and inhibit the development of, and essentially dissolve, the shells of small crustaceans, baby shellfish, and other tiny creatures at the base of the food web (Fabry 2008). Ocean acidification also harms and stresses fish, squid, and other animals that do not build shells (*Id.*). Not only does ocean acidification directly threaten various types of marine animals, it also has implications for the broader marine environment and food web.

The harmful effects of ocean acidification have already begun to occur. For example, ocean acidification has caused:

- A massive die-off of oysters in the Pacific Northwest (Barton et al. 2012; R. a. Feely, Sabine, et al. 2012; Washington State Blue Ribbon Panel 2012);

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- Declines in abundance and size of the California mussel, blue mussel and goose barnacle in tidepools correlated with a severely declining pH (Wootton et al. 2008);
- Sluggish growth of corals in the Caribbean and Great Barrier Reef (De'ath et al. 2009; De'ath et al. 2012; Gledhill et al. 2008); and
- Shells of plankton to dissolve off the California Coast and thinner and weaker shells of plankton in the Southern Ocean (Bednarsek 2014; Moy et al. 2009).

In a meta-analysis of over 400 experiments examining the impacts of ocean acidification on marine organisms, Kroeker et al. (2013) found the biological effects to be generally large and negative. This analysis was restricted to experiments with pH manipulations of less than 0.5 units, in order to reflect the predicted level of ocean acidification by the end of the century (IPCC 2007). By limiting the analysis to small variations in pH, this study shows that within the foreseeable future ocean acidification will have "profound repercussions for marine organisms" (Kroeker et al. 2010). While the negative effect of ocean acidification was most pronounced for calcification and survival (27% reductions in both responses), the study also revealed significant negative effects on growth and reproduction (11 to 19%, respectively). In addition, abundance was reduced by 15%. The strength of this analysis suggests that the patterns highlighted in this study are a robust representation of the current literature on ocean acidification.

While most of the worst consequences of ocean acidification are predicted for the future, scientists have already observed damage from CO_2 in the oceans. Additionally, the impacts of ocean acidification can affect the entire marine food web by altering habitat, prey availability, and species interactions.

b. High-CO_2 Waters Injure the Growth, Survival, Fitness, and Reproduction of Marine Animals

The primary known harm of CO_2 in the oceans is that it impairs the growth and survival of animals that build shells. Because ocean acidification reduces the availability of carbonate ions that marine animals use to calcify their shells and skeletons, CO_2 reduces the ability of these animals to build their protective structures (Doney et al. 2009). Acidified waters can also damage and dissolve shells.

These negative effects have been observed in the ocean as well as documented in laboratory studies. Corals, coralline algae, plankton, mollusks, and other shellfish exposed to future levels of ocean acidification have all experienced problems (Kleypas & Yates 2009; Kuffner et al. 2007; Barton et al. 2012; Talmage & Gobler 2011; Talmage & Gobler 2009; Orr et al. 2005; Riebesell et al. 2000).

i. Molluscs, Echinoderms, and Crustaceans

High CO_2 waters are lethal to shellfish. Since 2005, waters off the coast of Washington and Oregon have been killing oysters and other molluscs. Shellfish hatcheries in Washington and Oregon reported massive mortalities of oyster larvae (Washington State Blue Ribbon Panel 2012).Wild oysters also failed to reproduce in Willapa Bay, Washington (*Id.*). Scientists have definitively linked oyster production failures to high-CO_2 ocean waters that were used to raise larvae (Barton et al. 2012).

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In response to reported shellfish hatchery problems in Oregon, Barton et al. reported the results of their observations from the Whiskey Creek Hatchery on Netarts Bay in the summer of 2009 (Barton et al. 2012). Unlike previous laboratory experiments, this study analyzed calcifying organism responses in the ambient-water CO_2 chemistry of Oregon's coastal waters. Larval production and mid-stage growth (~120 um to ~150 um) of the oyster, *Crassostrea gigas*, were both significantly negatively correlated with the chemistry of waters in which larval oysters were spawned and reared for the first 48 hours of life. Although the impact of the exposure was not immediate, the delayed reaction caused a significant decline in growth for mid-sized oyster larvae and reduced overall production. The findings corroborate other laboratory studies that show that many marine species, especially at the larval stage, are adversely affected by ocean acidification.

Scientific studies have demonstrated that even modest pH declines affect the sensitive and vulnerable early developmental stages of organisms because these life histories have specific environmental needs (Kurihara 2008) (*see* Figure 10, below, showing negative effects from low pH treatments). A number of studies have found a delay in development or less development, degraded shells, decreased rate of metamorphosis, shell thickness, and loss of hinge integrity (Ross et al. 2011a). The resulting reduced larval size can reduce the feeding efficiency of larvae, and smaller larvae are more susceptible to starvation because they encounter comparatively less food (Kurihara & Shirayama 2004). Sub-lethal effects of elevated acidity can severely alter the composition and fitness of larvae, and given the high mortality rates of larvae in the water column and during the transition to benthic settler, small perturbations to larvae potentially may have large alterations to settlement dynamics, post-settlement mortality, recruitment, and ultimately adult populations (Ross et al. 2011).

Watson et al. (2009) exposed one day-old oyster larvae to a range of pH conditions, from 7.6 to 8.1, for 10 days and showed significant decline in the survival and growth of young larvae at lower pH. Waldbusser et al. (2010), in a study on the Chesapeake Bay, showed that even modest changes in pH present conditions that are corrosive to shells and have physiological impacts on adult and larval oysters. Biocalcification declined significantly with a reduction of 0.2 pH units, making juvenile bivalves more susceptible to predation and other mortality factors (*Id.*).

Negative effects have been seen on the metamorphosis, size, and survival of larval hard clams (*Mercenaria mercenaria*), bay scallops (*Argopecten irradians*), and Eastern oysters (*Crassostrea virginica*) at levels of CO_2 predicted to occur in the 21st century (Talmage & Gobler 2011). At 650 ppm, or an approximate drop of 0.3-0.4 from pre-industrial values, both *M. mercenaria* and *A. irrandians* larvae exhibited dramatic declines (over 50%) in survivorship as well as significantly delayed matamorphosis and significantly smaller size. *C. virginica* also experienced lowered growth and delayed metamorphosis at this level, an indicator that current and future increases in CO_2 populations may deplete or alter the composition of shellfish populations in coastal ecosystems (*Id.*).

The Olympia oyster, *Ostrea lurida*, a foundation species in estuaries along the Pacific coast, exhibits clear decline in larval growth and settlement as levels of CO_2 affect seawater pH. (Hettinger et al. 2012). Oysters in this experiment were raised at three levels of seawater pH,

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including a control (8.0) and two additional levels (7.9 and 7.8). Larvae reared under pH 7.8 exhibited a 15% decrease in larval shell growth rate, and a 7% decrease in shell area at settlement, compared to larvae reared under control conditions. Impacts were even more pronounced a week after settlement, with juveniles that had been reared as larvae under reduced pH exhibiting a 41% decrease in shell growth rate.

Oysters on the Atlantic coast also experience the ill effects of ocean acidification. Dickinson et al. (2012) found negative effects on juvenile eastern oysters after exposure to water with a 0.2 pH change. Exposure of the oysters to elevated acidity led to a significant increase in mortality, reduction of tissue energy stores and negative soft tissue growth, indicating energy deficiency. Under ocean acidification conditions, thermal tolerance is impaired in oyster larvae, leading to reduced development, size and increased abnormality (Ross et al. 2011; Parker et al. 2010). Similar results have been found in red abalone, with thermal tolerance impaired at pH 7.87 compared to control (pH 8.05) (Zippay and Hoffman 2010).

In studies with edible mussel (*Mytilus edulis*) and Pacific oyster (*Crassostrea gigas*) researchers found a strong decline of calcification under ocean acidification conditions (Gazeau et al. 2007). Based upon these results, researchers concluded that mussel and oyster calcification may decrease by 25% and 10%, respectively, by the end of the century." (*Id.*). Oysters and mussels also exhibit development abnormalities when exposed to acidification (Kurihara 2008). When oyster eggs were reared under pH 7.8, they showed malformations of their shell, and when reared under pH 7.4, more than 70% of the larvae were either completely non-shelled, or only partially shelled, and only 4% of CO_2 treated embryos developed into normal larvae by 48 hours after fertilization, in contrast to about 70% successful development in control embryos.

The shrimp *Palaemon pacificus* displayed variable responses at different developmental stages, pH and length of exposure (Kurihara 2008). Following long term (30 weeks) exposure of adults to pH 7.89 and 7.64, survival and egg production in early developmental stages decreased in both treatments. Findlay et al. (2010) found a slower rate of development of embryos in the common intertidal northern hemisphere barnacle *Semibalanus balanoides* with an estimated 19 days delay in reaching 50% hatching stage at pH 7.7. Other amphipods have exhibited metabolic changes in response to acidification levels greater than what is allowed under the federal criterion (Hauton et al. 2009).

Echinoderms exhibit delayed and asymmetrical development when exposed to acidified conditions. In the absence of adequate adaptation or acclimation, lowered pH levels will have a range of sub-lethal effects on sea urchins, brittlestar and seastar larvae from a range of geographical regions (Ross et al. 2011). Larvae of the ecological keystone brittlestar, *Ophiothrix fragilis*, either were abnormal, had altered skeletal proportions, or asymmetry during skeletogenesis, and there was a delay in development at pH levels of 7.9, or approximately 0.3 units below current surface levels (Gutowska et al. 2009). Other experiments on brittlestar in low pH waters resulted in dramatic results; acidification of 0.2 units induced 100% larval mortality within an eight day period. Control larvae showed 70% survival over the same period. Because the calcite skeleton of the larval brittlestar aids key functions such as feeding and vertical migration, and defense against predators, abnormal development of the skeleton will have drastic consequences for fitness. The developmental abnormalities may be exacerbated by temperature

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increases predicted for the end of the century; some scientists suggest that this may result in the disappearance of echinoderms from the surface oceans within the next 50-100 years (Ross et al. 2011a).

Reproductive success is compromised by ocean acidification. The fertilization rate of sea urchins decreases with increasing CO_2 concentrations (8.1 to 6.8 pH) (Kurihara 2008). In another sea urchin experiment utilizing six CO_2 concentrations, with a pH between 8.01 (control) and 6.83, cleavage rate, developmental speed, and larval morphology all declined with increased CO_2 concentration (Kurihara & Shirayama 2004). At a 0.2 change from control, effects could be seen on the morphology and development of the larvae, and these effects became more pronounced with greater pH changes (*Id.*) (*see* Figure 4, below). The authors concluded that "all the effects of raised CO_2 concentration observed in this study would have a negative impact on the survival of sea urchin embryos in their early life history." A recent study showed that sea urchin sperm flagellar motility was significantly reduced when seawater pH decreased by .3 units, from 8.0 to 7.7 (Suwa et al. 2010). As discussed above, decreased flagellar motility has severe consequences for fertilization and subsequent population dynamics; if sperm lose their ability to find eggs, the population size will necessarily diminish.

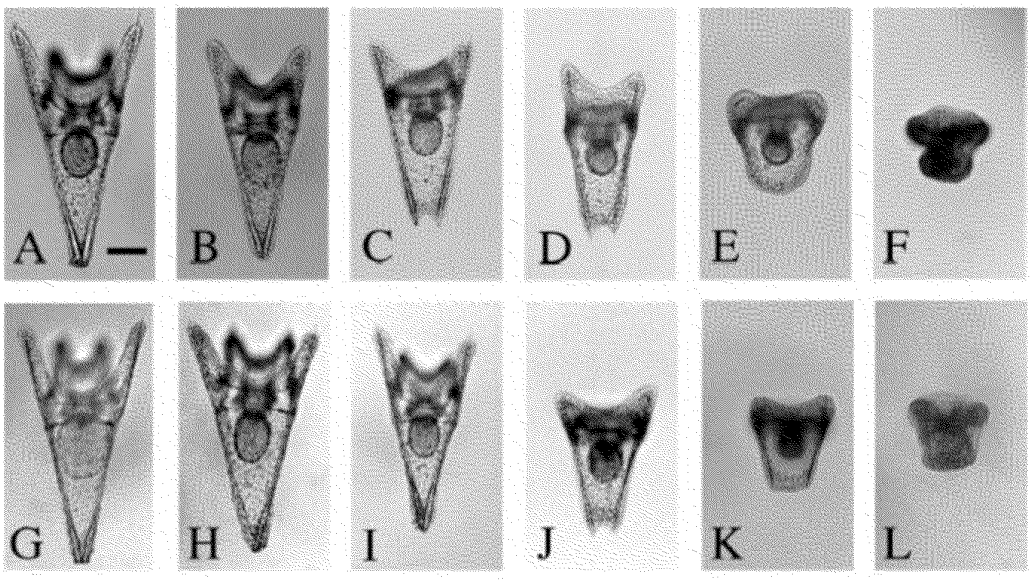

Fig. 6. *Hemicentrotus pulcherrimus*. Morphology of 4-armed pluteus larvae cultured for 3 d in (A–F) CO_2-seawater and (G–L) HCl-seawater. (A & G) control (pH 8.0); (B & H) +500 ppm (pH 7.8); (C & I) +1000 ppm (pH 7.6); (D & J) +2000 ppm (pH 7.4); (E & K) +5000 ppm (pH 7.0); (F & L) +10 000 ppm (pH 6.8). Scale bar = 50 µm

Figure 4. Declining development of sea urchin larvae exposed to acidified waters (Kurihara & Shirayama 2004).

Even moderate increases in atmospheric CO_2 and ensuing acidification adversely affect the growth of both gastropods and sea urchins (Shirayama & Thornton 2005). Before the end of this century, atmospheric CO_2 is likely to increase by more than 200 ppm, decreasing the pH of the ocean by approximately 0.3 units from pre-industrial levels. Two species of sea urchin as well as the gastropod *Strombus luhanus* were exposed for six months to waters with this level of elevated CO_2, and all three species exhibited similar consequences. Increased CO_2 negatively affected growth rate, calcification, shell height and body mass, and metabolic activity

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(Shirayama & Thornton 2005). The developing embryos of the gastropod and intertidal snail *Littorina obtusata* also demonstrate slower overall development time, altered embryonic movement, and modification of shell shape in hatchlings while exposed to acidified waters (pH 7.6) (Ellis et al. 2009).

Arnold et al. (2009) investigated the effect of ocean acidification on lobsters and found that indirect disruption of calcification and carapace mass may adversely affect the competitive fitness and recruitment success of larval lobsters with serious consequences for population dynamics and marine ecosystem function

Reduced metabolism is expected to impair predator-prey interactions, as well as have consequences for growth, reproduction, and survival. Metabolic suppression has previously been reported to occur in a variety of adult marine invertebrates, including crabs, squid, worms, bivalves, pteropods and amphipods (Albright 2011). Slowed metabolism is generally achieved by halting energy-expensive processes, such as protein synthesis, and therefore may lead to reductions in growth and reproductive potential (*Id.*). The blue mussel *Mytilus edulis* has strong physiological mechanisms by which it is able to protect body tissues against short-term exposure to acidified seawater, but these come at an energetic cost, and will result in reduced growth during long term exposures (Bibby et al. 2008). Consequently, the predicted long-term changes to sea water are likely to have a significant effect on the health and survival of blue mussel populations (*Id.*). Mussel beds are a dominant coastal habitat and provide food and structure for a diverse array of species in an otherwise physically stressful environment; any decline in their population structure will lead to a reduction in appropriate habitat for a myriad of other species.

In summary, acidified waters impact the development, growth, and reproductive success of a suite of echinoderms, crustaceans, and molluscs. A growing body of information is becoming available on the effecting of declining pH on these organisms and their ecosystems. The results of these studies are clear; as pH falls even 0.2 units from pre-industrial values, these organisms will struggle to survive in their increasingly acidic environment.

ii. Corals

Coral reef ecosystems, which are estimated to harbor one-third of marine species and which support the livelihoods of a half billion people, are particularly threatened by ocean acidification. Some corals are already experiencing reduced calcification (De'ath et al. 2009; Cooper et al. 2008; Bates et al. 2010; Gledhill et al. 2008). Due to the ocean acidification and warming, reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations of 450 ppm (Veron et al. 2009; Bijma et al. 2013). Prominent coral scientists have called for reducing atmospheric CO_2 to less than 350 ppm to protect coral reefs from collapse (Veron et al. 2009, Frieler et al. 2012). Coral reefs cannot exist below 7.8 pH units (Fabricius et al. 2011), and the threshold for coral growth is 3.3 Ω_{ar} (Meissner et al. 2012).

Ricke et al. (2013) analyzed aragonite saturation state (Ω_{ar}) surrounding reefs in CMIP5 simulations under several representative concentration pathway (RCP) scenarios (Ricke et al. 2013). The study found that in preindustrial times, 99.9% of reefs adjacent to open ocean in the CMIP5 ensemble were located in regions with $\Omega a > 3.5$. Accordingly, the study used $\Omega a = 3.5$ as

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an upper bound viability threshold for corals, while also examining thresholds of $\Omega a = 3.25$ and 3. Under a business-as-usual scenario (RCP 8.5), every coral reef considered was projected to be surrounded by water with $\Omega_{ar} < 3$ by the end of the 21st century and the reefs' long-term fate was independent of their specific saturation threshold. Under scenarios with significant CO_2 emissions abatement, the Ω_{ar} threshold for reefs was critical to projecting their fate. The study concluded that the "results indicate that to maintain a majority of reefs surrounded by waters with $\Omega_{ar} > 3{:}5$ to the end of the century, very aggressive reductions in emissions are required."

Corals are among the ecosystems most threatened by ocean acidification. To date, most scientific investigations into the effects of ocean acidification on coral reefs have been related to the reefs' unique ability to produce voluminous amounts of calcium carbonate (Kleypas & Yates 2009). The persistence of carbonate structures on coral reefs is essential in providing habitats for a large number of species and maintaining the extraordinary biodiversity associated with these ecosystems. As a consequence of ocean acidification, the ability of marine calcifiers to produce calcium carbonate will decrease, resulting in a transition from a condition of net accretion to one of net erosion, with drastic consequences for the role and function of these ecosystems (Kleypas & Yates 2009).

Coral reefs are predicted to drastically lower their calcification rates in the near future, and historical records show that calcification rates have already fallen relative to pre-industrial values. According to scientists, the main reef building organisms will calcify up to 50% less relative to pre-industrial rates by the middle of this century (*Id.*). A drop of approximately 60% coral reef calcification is projected for the end of the century, when pH is predicted to fall 0.5 units below pre-industrial values (Caldeira & Archer 2007). Many studies suggest calcification rates could be reduced between 20-60% at 560ppm, or 7.9 pH, and that a reduction of this magnitude would fundamentally alter reef structure and function (Convention on Biological Diversity 2009). According to the model of Silverman et al. (2009), developed from field observations from more than 9,000 reef locations, all coral reefs are expected to reduce calcification by more than 80% relative to their pre-industrial rate at 560 ppm (0.3 pH change), and at this point "all coral reefs will cease to grow and start to dissolve." The Interacademy Panel on International Issues concurs; "at current emission rates models suggest that all coral reefs and polar ecosystems will be severely affected by 2050 or potentially even earlier."

In a meta-analysis on coral calcification responses to ocean acidification, the coral calcification declined by a mean of 15% per unit decrease in aragonite saturation state ($2 < \Omega < 4$) (Chan and Connolly 2013). On current emission trends, calcification will decline 22% on average for corals by the end of the century (*Id.*). This falls to the lower range of responses that have been predicted by ocean acidification researchers and described above, which the authors believe reflects variation in the calcification responses of different corals.

Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%, (Caldeira & Archer 2007), and data from the Great Barrier Reef indicates a 14% decline in calcification rates between 1990 and 2005 (De'ath et al. 2009). Other studies in the Great Barrier reef indicate a decline of approximately 21%, and analysis of coral growth records confirm that this decline is unprecedented in recent centuries (Cooper et al. 2008). A model based on field samples shows that calcification of coral reefs in French

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Polynesia declined 15% between the pre-industrial period and 1992, and that rates will decline 40% by 2050, when CO_2 levels reach 560 ppm (pH 7.9) (Anthony et al. 2011). Near Bermuda, historical records show that coral skeletal density has decreased 33%, and coral calcification rates have declined by 52% as a result of changes in seawater carbonate chemistry (Bates et al. 2010). These observed changes have occurred even before a 0.2 unit decline in ocean pH; as atmospheric CO_2 continues to rise and lower pH values, calcification rates will maintain their precipitous decline.

Ocean acidification acts in concert with ocean warming and coral bleaching in furthering coral reef decline (Anlauf et al. 2011) (observing a 3% reduction in acidification with a 0.2 decline in pH, and a 30% decline when acidification is coupled with 1° C warming). While natural variability in the annual cycle and interannual variability may account for some of the observed change in coral growth rates, scientists are "virtually certain" that anthropogenic trends already exceed natural variability (Friedrich et al. 2012). Studies projecting the combined impacts of ocean acidification and ocean warming on corals predict that coral erosion will exceed calcification rates at atmospheric CO_2 concentrations of 450 to 500 ppm, (Hoegh-Guldberg et al. 2007), and all coral reefs will begin dissolve at CO_2 concentrations of 560 ppm (Silverman et al. 2009). These figures correspond to a 0.2 and 0.3 unit drop in pH, respectively, as compared to pre-industrial values. Van Hooidonk et al. (2014) presented updated global projections for threats to coral reefs from ocean warming and ocean acidification based on ensembles of IPCC AR5 climate models using the Representative Concentration Pathways (RCPs). For all tropical reef locations, the study projected absolute and percentage changes in aragonite saturation state (Ω_{ar}) for the period between 2006 and the onset of annual severe bleaching.

In the Caribbean, a recent study concluded that "coral reef communities are likely to be essentially gone from substantial parts of the Southeast Caribbean by the year 2035" (Buddemeier et al. 2011). The Great Barrier Reef has lost 50% of its coral cover since 1985 as a result of the combined effects of ocean acidification, global warming, coral bleaching, coral predation by starfish, and cyclone damage (De'ath et al. 2012). In short, due to the synergistic impacts of ocean acidification, mass bleaching, and local impacts, coral reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations 450 ppm, or pH 8.0, a level that is expected before mid-century (Veron et al. 2009).

Many experimental studies show declining calcification rates and other ill effects when corals are exposed to acidified waters. Decreases in calcification rates across a suite of benthic species and calcifying systems range from 3 to 60% for a doubling in pCO_2, which corresponds to a 0.3 reduction in pH (Abbasi & Abbasi 2011). The average response of corals is a 30% decline in calcification in response to a doubling in pCO_2 (*Id.*). In a study of an assemblage of corals exposed to conditions designed to mimic the change that may be experienced in the next 50-100 years (pH decline of 0.22 to 0.28 units), calcification rates declined between 44% and 80%.

The coral *Acropora palmata* (listed as threatened under the Endangered Species Act), once the dominant reef building coral in the Caribbean, experiences impaired fertilization, settlement, and growth with increasing pCO_2 (Albright et al. 2010). The cumulative impact of ocean acidification on fertilization and settlement success is an estimated 52% and 73% reduction in the number of larval settlers on the reef under pCO_2 conditions projected for the middle and end

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of this century, respectively (0.2 and 0.5 decline in pH) (*Id.*). After only 8 days of high CO_2 conditions (pH 7.75), *Acropora* experiences a statistically significant (18%) reduction in calcification rate (Murubini et al. 2003). Furthermore, there 22 coral species listed as threatened under the Endangered Species Act primarily because of threats from ocean warming, acidification and disease. The rule proposing listing for the corals found that ocean acidification was one of the highest priority threats for corals:

> Ocean acidification has the potential to cause substantial reduction in coral calcification and reef cementation. Further, ocean acidification adversely affects adult growth rates and fecundity, fertilization, pelagic planula settlement, polyp development, and juvenile growth.

77 Fed. Reg. at 73230 (Dec. 7, 2012). In other words, ocean acidification is driving the extinction of corals and the destruction of coral reef ecosystems.

Experimental studies evaluating the effects of ocean acidification on early life history stages of corals generally conclude that primary polyp growth is hindered by increasing acidity (Albright et al. 2010, Cohen & Holcomb 2009). Renegar and Riegl (2005) showed a significant decrease in the growth rate of *Acropora cervicornis* larvae at pH levels 0.3-0.5 units below control. Larvae of the common Atlantic golf ball coral, *Favia fragum*, shows significant delays in both the initiation of calcification and subsequent growth of the primary corallite in acidic waters (8.17 – 7.54 pH) (Cohen & Holcomb 2009). Visible changes in the skeletal development were observed in all non-control treatments, and in the most acidic waters skeletal development was 75% less than the control.

Acidification also affects cold water corals. Cold water corals have a worldwide but patchy distribution, and are often found in areas with highly productive fisheries (De Mol et al. 2002; Kenyon et al. 2003). Overall, more than two-thirds of all known coral species are cold water corals (Roberts & Hirshfield 2012; Cairns 2007). Recent exploration and research that has begun to search for, map, and observe cold water corals has found that these organisms are fragile, long-lived, slow-growing, very sensitive to physical or environmental disturbance and adapted for a specific environmental niche (McDonough & Puglise 2003). Alaskan waters are already showing widespread evidence of ocean acidification as a result of greenhouse gas emissions (Mathis et al. 2011a). By 2100, 70% of cold-water corals will be exposed to corrosive waters (Convention on Biological Diversity 2009). Conditions in waters typically inhabited by cold-water corals are even less favorable for calcification than those experienced by warm water corals; this may cause cold-water corals to be affected earlier and more strongly by CO_2-related ocean acidification than their warm water counterparts (Abbasi & Abbasi 2011).

The vulnerable early developmental and reproductive stages of cold water corals may be especially strongly impacted (Kurihara 2008; Dupont & Thorndyke 2009; Kroeker et al. 2010). In an experiment on the cold-water coral *Lophelia pertusa*, lowering the pH by 0.3 units relative to the ambient level resulted in calcification being reduced by 56% (Maier et al. 2009). Lower pH reduced calcification more in fast growing, young polyps (59% reduction) than in older polyps (40% reduction). Thus, corals' larvae and young corals are significantly more susceptible to ocean acidification than adults, and will likely show a higher degree of reduced calcification

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and growth with reduced pH, making young and larval corals less likely to survive to maturity as the ocean continues to absorb anthropogenic CO_2 and as climate change progresses.

In addition to reduced calcification rates, the strength of cementation may also be reduced in waters with a lower pH, promoting higher rates of physical and bio-erosion (Manzello et al. 2008). Once coral reefs experience lowered calcification and poor cementation, erosion and reef flattening can result, which severely reduced the structural heterogeneity of reefs and lowers its potential to support biodiversity. An important new study of reef bioerosion determined that the combined effects of lower calcification with increased bioerosion can significantly degrade coral reefs (Wissshak et al. 2012). In the study, a common bioeroding sponge in the Great Barrier Reef was observed on massive Porites. The sponge was more effective at bioerosion of the corals at high CO_2, ranging from 17% increase from present day levels to 61% increase at the highest CO_2 treatment. The researchers describe the important role of balancing the antagonistic processes of calcification and bioerosion in a reef for a healthy coral ecosystem, and predict detrimental consequences under ocean acidification as calcification declines and bioerosion increases.

Bioerosion may result in a loss of change in fish assemblages, lower densities of commercially important species, and lower rates of larval fish recruitment (Feary et al. 2007). Weaker reef calcification and cementation also increases the potential for reef damage as storm frequency and intensity increases with continued global warning, leading to further reef degradation (*Id.*). In a study looking at the impacts of storm damage and ocean acidification, researchers concluded that table coral populations are vulnerable to collapse (Madin et al. 2012). In the Indo-Pacific, table corals provide an important role in the reef ecosystem by creating reef structure and sheltering other reef species. They are also particularly vulnerable to ocean acidification, thermal stress, bleaching, disease and stress from storm waves. The table corals will become more vulnerable to storm waves as ocean acidification reduces calcification and increases bioerosion, therefore weakening their cementation and structure. Madin et al. (2012) found that a coral colony was four times more likely to be dislodged by a storm wave by the end of the century ocean acidification levels. Because of this vulnerability, the results showed that table corals are prone to large and rapid declines in coral cover.

Numerous biological responses independent of calcification are also negatively impacted by ocean acidification. Corals in acidifying waters are likely to be in a nutritionally or energetically stressed state and thus less likely to initiate reproduction, or successfully reproduce, due to negative impacts of ocean acidification on all stages of the reproductive cycle (Maier et al. 2009; McCulloch et al. 2012). Sperm flagellar motility also declines in response to decreasing pH. If sperm lose their ability to find eggs in the vast extent of the sea, the life of marine organisms is potentially limited. Sperm flagellar motility, which is indispensable for fertilization, is regulated by an elevation of intracellular sperm pH (Morita et al. 2010). While 69% of *Acropora* sperm were motile at pH 8.0, 46% were motile at pH 7.8, and fewer than 20% at pH 7.7 (*Id.*). Additionally, the physiological costs associated with reproduction are more likely to result in the demise of the organism due to the compounding stressors from ocean acidification and climate change (Wood et al. 2008, Cohen & Holcomb 2009). Significant reductions in metabolism have been observed for coral larvae following exposure to waters with a 0.2 decline in pH, levels projected to occur by the middle of this century (Albright & Langdon 2011).

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Albright et al. (2010) concluded that with increased CO_2 concentrations to those projected to occur in this century (560 atm to 800 atm, or a 0.3 to 0.5 decline in pH from pre-industrial values), the fertilization success of the tropical reef-building coral *Acropora palmata* decreased by 12-13%, settlement success reduced 45-69%, and linear extension was significantly reduced. The compounding effect of these impacts translated to 52-73% reduction in the number of larval settlers on the reef. Albright et al. (2010) predicted that the net impact on recruitment would actually be greater than that given that the depressed post-settlement growth is likely to result in elevated rates of post-settlement mortality. This corroborates other studies showing negative impacts on early-stage tropical corals.

Albright and Langdon (2011) tested the effects of ocean acidification on sexual recruitment of tropical corals. Larval metabolism was depressed by 27% at acidification levels expected by mid-century (0.3 pH reduction) and 63% at end-of-century acidification levels (0.4-0.5 pH reduction). Settlement was also reduced 42-45% and 55-60% at the mid and end-of-century levels respectively, relative to controls (Albright & Langdon 2011). Another study of larvae of tropical corals showed that short-term or long term exposure of larvae to ocean acidification decreased their metamorphosis (Suwa et al. 2010). This means that even when larval survivorship is unchanged, the success of recruiting new corals could be inhibited by ocean acidification (*Id.*).

Additionally, under conditions of acidification planktonic larvae lose their preference for settlement on the optimal crustose coralline algae communities (Doropoulos et al. 2012). Crustose coralline algae in turn, will experience a lower recruitment rate as marine waters become more acidic. Crustose coralline algae, a red calcifying algae, is of key importance in coral reef ecosystems, stabilizing reef structures and providing an important food source for benthic organisms (Convention on Biological Diversity 2009). Crustose coralline algae form a major calcifying component of the marine benthos from polar to tropical regions and are considered to influence the settlement of coral recruits. With a mean pH change of 0.26 between control and treatment, Kuffner et al. (2007) found that crustose coralline algae growth rates declined by 40%, and recruitment rate and percentage cover decreased by 78% and 92%, respectively.

In sum, reproduction is critical to maintaining a healthy coral reef population, and the long-term impacts of ocean acidification on reproduction, especially on larval settlement and growth, may significantly reduce the corals' ability to recover or maintain a population in the face of human caused disturbances and anthropogenic CO_2 emissions. This would result in a lack of reproductive capacity, genetic bottlenecks, and population collapse (Dupont et al. 2010; Ross et al. 2011).

As the world's oceans become more acidic and less saturated with carbonate minerals, corals are expected to build weaker skeletons and experience slower growth rates, which will make it more difficult for corals to retain competitive advantage over other marine organisms (Guinotte et al. 2006). As coral skeletons weaken, they will become increasingly at risk of storm damage and bioerosion, which will reduce the structural complexity of the reef system, reducing habitat quality and diversity alongside the loss of coastal protection functions (Hoegh-Guldberg et al. 2007). At greater than 550 ppm, coral reef ecosystems will be reduced to "crumbling

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frameworks." (*Id.*). Extensive studies have demonstrated that small changes in ocean chemistry will cause a suite of negative impacts, from reduced calcification rates to lowered reproductive success.

iii. Plankton

Plankton, which comprise the basis of the marine food web, are among the calcifying organisms adversely affected by ocean acidification. Changes to calcifying zooplankton, such as pteropods and foraminfera, have the potential to affect the ecological and tropic dynamics which govern the exchange of energy and cycling of nutrients throughout the marine food web (Gattuso & Hansson 2011). For example, the shelled pteropod, *Limacina helicina*, an Arctic pelagic mollusc, is a food source for higher predators such as fishes, whales and birds that are particularly important in high latitude areas. *L. helicina* makes up about 60 percent of the pink salmon diet (Comeau et al. 2012). A decline of pteropod population would likely cause dramatic changes to various pelagic ecosystems, and impact the commercially important salmon fishery; a 10% decrease in pteropods can lead to a 20% reduction in pink salmon body weight (Aydin 2005).

Pteropods form integral components of food webs, and are considered an overall indicator of ecosystem health (Orr et al. 2005). Studies have shown that pteropods exposed to a pH value predicted for the end of this century exhibited a 28% decrease in calcification (Comeau et al. 2009). Experiments on *L. helicina* showed that changes from 8.05 pH to 7.89 pH (Δ -0.16 units) cased shell dissolution and cracks appeared at 7.76pH, and linear extension of the shell decreased as a function of declining pH (Comeau et al. 2012). Samples show dissolution already happening in areas that have low aragonite saturation states. A sampling study off the coasts of California, Oregon, and Washington showed average to severe dissolution of *L. helicina* for 53% of onshore individuals and 24% of offshore individuals (Bednarsek 2014). A sampling study in 2008 of the Southern Ocean found severe dissolution of *L. helicina* in Ω_{ara} 1.0 (Bednarsek 2012). Another study found shell weights of one form of Antarctic species declined 35% from 1997-2006 (Roberts unpublished).

Ample studies corroborate that high CO_2 waters dissolve the shells of *L. helicina* and reduce calcification rates. Comeau et al. (2010) noted decreased calcification for *L. helicina* with decrease in aragonite saturation. Lishka (2012) looked at overwintering *L. helicina* and L. retroversa in the Arctic and noted that they do not calcify in the winter, and they are subject to dissolution under high CO_2 conditions. Bednarsek (2012) looked at *L. helicina* and *Clio pyramidata* from the Southern Ocean under different aragonite saturation states and recorded dissolution stages.

Modeling by Comeau et al. (2012) shows that by the end of the century *Limacina helicina* will not be able to calcify over much of the Arctic because of aragonite undersaturation—prediction may be conservative because it did not account for shell dissolution. Commentary suggests that as waters warm these pteropods will be trapped in acidified conditions and will "disappear entirely by the end of the century." Modeling suggests that waters in the California Current will be undersaturated year-round by 2050 (Gruber 2012). Modeling of the Arctic suggests that by mid-century the Bering Sea will be persistently undersaturated with respect to aragonite (Mathis 2011). An analysis of survey measurements in 2005-2006 and 1991-1992 demonstrated a

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shoaling of the aragonite saturation state in waters off Alaska (Feely et al. 2012). In the North Pacific the aragonite saturation state shoaled to depths less than 200 m between 40˚N and 50˚N (*Id.*). On average, the calcite saturation horizon in the Pacific shoaled about 1 m/yr from 1991 to 2006 (*Id.*).

Other species of plankton are also harmed by CO_2. Another pteropod, *Clio pyramidata,* kept in aragonite undersaturated waters began to dissolve within two days (Orr et al. 2005). Some coccolithophorids are also susceptible to ocean acidification. Studies showed that CO_2 related changes to seawater caused reduced calcification, resulting in malformed and incomplete shells. Calcification of cocolithophorids declined 15-44%, and their shells were malformed as pH changed up to about 0.3 units (Riebesell et al. 2000). Coccolithophorids are globally distributed and bloom in massive areas affecting the optical properties of the ocean, reflecting light from the earth, and play a major role in the ocean carbon cycle. Elevated CO_2 concentrations also reduce the shell mass of foraminifera (Kleypas et al. 2006). Modern shell weights of foraminifera in the Southern Ocean are 30–35% lower than those from preindustrial sediments, which is consistent with reduced calcification induced by ocean acidification (Moy et al. 2009).

iv. Cephlopods and Fish

The negative physiological effects of ocean acidification are not confined to invertebrates. For example, the gametes, embryos, and larvae of vertebrates such as fish are vulnerable to changes in ocean chemistry and have shown impairments in their homing and predator/prey detection capabilities.

Changes in the ocean's CO_2 concentration result in accumulation of CO_2 in the tissues and fluids of fish and other marine animals, called hypercapnia, and increased acidity in the body fluids, called acidosis. These impacts can cause a variety of problems for marine animals, including difficulties with acid-base regulation, calcification, growth, respiration, energy turnover, predation response, and mode of metabolism (Pörtner et al. 2005; Pörtner et al. 2004). Studies have shown adverse impacts in squid and fish, among other animals (Rosa & Seibel 2008; Ishimatsu et al. 2004; Pörtner et al. 2004). For example, when exposed to acidification, orange clownfish suffer a type of brain malfunction that interferes with their homing abilities and makes them 5-9 times more likely to swim toward a predator (Munday et al. 2009; Simpson et al. 2011; Ferrari et al. 2011).

Laboratory experiments have shown that ocean acidification at levels expected to occur within this century impairs larval orange clownfish and damselfish sensory abilities and behavior, making it more difficult for them to locate suitable settlement sites on reef habitat and avoid predators. Specifically, ocean acidification disrupts smell, hearing, and behavior of larval orange clownfish, (Munday et al. 2009; Nilsson et al. 2012), making larval clownfish attracted to odors from predators and unfavorable habitat (Munday et al. 2010; Dickson et al. 2010). Olfactory cues that prompted avoidance or neutral behavior in controls (pH 8.15) stimulated strong preference behavior in larvae raised at pH 7.8, in addition to significant reduction in response to usually positive preferences. Ocean acidification also impairs the hearing capacity of larval clownfish, which is predicted to have negative effects on settlement success and survival (Simpson et al. 2011).

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Similarly, research on six damselfish species found that ocean acidification impairs larval damselfish smell, vision, learning, behavior, and brain function, leading to higher risk of mortality. For example, in acidified waters, larval damselfish (1) become attracted to predator odors and display much riskier behaviors, making them more prone to predation; two species suffered a five-fold to nine-fold increase in predation rate at CO_2 levels of 700 to 850 ppm, or 0.3 pH units below control (Munday et al. 2009; Ferrari et al. 2011); (2) cannot discriminate between habitat olfactory cues, making it more difficult to locate appropriate settlement habitat (Devine et al. 2011); (3) settle on the reef during dangerous times—the full moon rather than new moon—when they are more vulnerable to predation (Devine et al. 2011); (4) fail to visually recognize or evade important predator species; (5) cannot learn to respond appropriately to a common predator by watching other fish react or by smelling injured fish, unlike fish under normal conditions (*Id.*); and (6) suffer disruption of an important neurotransmitter which is thought to result in the sensory and behavioral impairment observed in acidified conditions (Nilsson et al. 2012).

An animal's ability to transport oxygen is reduced by pH changes (Pörtner 2005). Water breathing animals have a limited capacity to compensate for changes in the acidity (Haugan 2006). For example, fish that take up oxygen and respire CO_2 through their gills are vulnerable because decreased pH can affect the respiratory gas exchange (Royal Society 2005). Changes in metabolic rate are caused by the changes in pH, carbonates, and CO_2 in marine animals (Haugan 2006).

Squid, for example, show a very high sensitivity to pH because of their energy intensive manner of swimming (Royal Society 2005). Because of their energy demand, even under a moderate 0.15 pH change squid have reduced capacity to carry oxygen and higher CO_2 pressures are likely to be lethal (Pörtner 2004). Even species more tolerant to pH changes experience decreased metabolism from increased CO_2 in the water (Pörtner 2004). For example, as much as 50% mortality was observed in copepods after only six days of exposure to waters with a pH level 0.2 units below the control (Pörtner 2005). Reducing pH by 0.3 pH cased a 31% decline in metabolic rate and a 45% decrease in activity level for the jumbo squid, an important predator in the Easter Pacific (Rosa & Seibel 2008).

In fish, pH also affects circulation. Fishexposed to high concentrations of CO_2 in seawater experience cardiac failure and increased mortality (Ishimatsu 2004). At lower concentrations sublethal effects can be expected that can seriously compromise the fitness of fish. Juvenile and larval stages of fish were found to be even more vulnerable (Ishimatsu 2004).

In sum, ocean acidification can have many adverse effects on marine animals that can reduce their fitness and survival (Royal Society 2005). Many marine animals have low thresholds for long-term CO_2 exposure (Pörtner 2005).

c. Other Environmental Impacts of Ocean Acidification

i. Increased Toxicity of Harmful Algal Blooms and Sediments

Ocean acidification may already be increasing the toxicity of harmful algal blooms known as "red tides." These toxic red tides poison shellfish, marine mammals, fish, and even cause

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paralytic shellfish poisoning in people. High CO_2 levels in seawater magnify the toxins of harmful algae. (Fu et al. 2012; Avery O Tatters et al. 2013; Tatters et al. 2012; Avery O. Tatters et al. 2013). Studies of the genus *Pseudo-nitzscia* show that the toxicity of diatoms which produce a neurotoxin increases significantly under ocean acidification conditions. A -0.5pH change caused toxin production in the diatoms to increase 4.2-fold and a -0.3pH unit change increased the toxicity 2.5-fold (Tatters et al. 2012). Many studies on the effects of ocean acidification and algal blooms have been conducted at CO_2 levels that are already occurring in California, and the increase in the toxicity of harmful algal blooms in Southern California (and resulting mass mortalities of fish and marine mammals) may be due, in part, to acidified waters (*Id.*) However, these studies suggest that the damage will become much worse.

Additionally, research shows that under conditions of ocean acidification sediments become more toxic (Roberts, Birchenough et al. 2013). Ocean acidification makes sediment-bound metals more available and thus more toxic for aquatic life (*Id.*) For example, ocean acidification increases the toxicity of copper (Campbell & Mangan 2014).

ii. Noise Pollution Increases in Low pH Waters

Ocean acidification can also decrease the sound absorption of seawater, causing sounds to travel further with potential impacts on marine mammals and other marine life sensitive to the sounds of vessel traffic, seismic surveys, and other noise pollution (Hester et al. 2008). Sound travels 10-15 percent further with a change of 0.1 pH, and it is predicted to increase about 40 percent by mid-century (Hester et al. 2008). Additionally, a decline of 0.3 pH units causes a 40 percent decrease in the sound absorption of surface seawater and sound may travel 70 percent farther, further affecting sensitive marine mammals (Brewer et al. 2009).

d. Ocean Acidification's Ecosystem Impacts

While the full implications of elevated CO_2 on marine ecosystems are not well-documented, there is high confidence that there will be negative ecosystem consequences from ocean acidification. The exact changes are difficult to predict, but some of the anticipated impacts include loss of diversity, loss of abundance of calcifying species, shifting prey and predator interactions, and loss of suitable habitat.

New mesocosm studies have sought to understand some of the potential ecosystem impacts of CO_2. Studies of biodiversity near underwater volcanic vents demonstrate reduced richness in high-CO_2 waters. For example, coral species diversity declined by about 39% between low and high-CO_2 sites, with the reefs shifting from complex communities to a coral reef dominated by massive Porites. Most importantly, the researchers found that coral reef development ceases at 7.7 pH, and they concluded that a pH decline below 7.8 would be "catastrophic for coral reefs" (Fabricius et al. 2011). Scientists also observed that in high-CO_2 waters the loss of complex coral reef habitat resulted in a loss of diversity of reef-associated species such as crustaceans and crinoids (Fabricius et al. 2014). Looking at the macroinvertebrates, the density declined 48% between control and high-CO_2 areas and taxa diversity declined by 77% (*Id.*).

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Loss of species diversity associated with ocean acidification can also result from changes in competitive interactions. A study of a rocky reef near volcanic vents documented that macro algae outcompeted calcareous species in low-pH waters (Kroeker et al. 2012). The researchers explained that under the high-CO_2 conditions the calcifying species grew more slowly while the seaweed took hold and that grazing of seaweed was depressed (*Id.*). In another study, while the areas near volcanic vents lacked scleractinian corals and had low abundance of sea urchins and coralline algae, invasive algal species benefited from the acidified conditions (Hall-Spencer et al. 2008).

Research on the diversity the intertidal community in the Pacific Northwest documented a shift from a ecosystem dominated by calcifying animals to one with non-calcifying organisms as pH declined. Researchers documented declines in abundance and size of the California mussel, blue mussel, and goose barnacle in tidepools on the Olympic Coast in Washington (Wootton et al. 2008). They found that in years with low pH waters the calcifying animals were replaced by non-calcifying organisms (*Id.*).

The synergistic impacts of ocean acidification and warming are also potentially severe. Ocean acidification may induce a negative climate feedback that may increase temperature rise. Mesocosm studies found that ocean acidification may amplify global warming through decreasing biogenic production of the marine sulfur component dimethylsulphide which can impact cloud albedo (Six 2013). Ocean acidification therefore may also contribute to climate change impacts on the environment.

2. Risk Reduction Costs and Benefits

EPA must make a determination whether the risk of ocean acidification is unreasonable and this constitutes a balancing of costs and benefits. While it is EPA's burden to conduct this analysis, petitioners present some limited data on (1) the socio-economic costs of CO_2 pollution in light of ocean acidification, (2) the feasibility of controls on CO_2 pollution, and (3) the social cost of carbon including the costs of delaying action to reduce and mitigate CO_2 pollution.

a. Socioeconomic Costs of Ocean Acidification

The release of CO_2 into the environment is already having social and economic impact, and these impacts are predicted to become even more concerning. Primary economic concerns are from the loss of fisheries and coral reefs. Ocean acidification also poses food security and nutrition risks.

U.N. Convention on Biological Diversity estimated costs on the predicted damage of ocean acidification and predicts that the oceans will lose more than $1 trillion in value annually from ocean acidification (Convention on Biological Diversity 2014). CO_2 related ocean warming and acidification will threaten marine food resources by disrupting marine communities, promoting harmful algal blooms and the spread of some diseases, and increasing contaminants in fish and shellfish (Tirado et al. 2010).

The United Nations Environment Programme reported that ocean acidification's impact on marine organisms is a threat to food security (UNEP 2010). The report documents that ocean

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acidification is measurable and increasing, which poses a threat to fisheries resources and the billions of people that have a marine-based diet (United Nations Environment Programme 2010). Seafood has been shown to prevent hundreds of thousands of premature deaths, as well as significantly reduce infant morbidity; a decline of seafood availability will decrease these benefits. Some populations, including subsistence fishing populations and poor communities, depend on seafood and mortality and morbidity can result from the loss of these food sources (Mozaffarian 2006). For example, 95% of Alaskan households do some sort of subsistence fishing, and 17% of the state's population, 120,000 people, depend on subsistence fishing (Mathis et al. 2014). Many subsistence fishers also have cultural ties threatened by ocean acidification. Accordingly, CO_2 can result in social and environmental justice concerns that must also be assessed and weighed (Convention on Biological Diversity 2014).

Not only will ocean acidification affect global food webs and ecosystems, it will have a direct effect on the global economy. The U.S. economy is very dependent on the health of the ocean. In 2009, the ocean economy contributed over $223 billion annually to the U.S. gross domestic product and provided more than 2.6 million jobs (NOAA, http://oceanservice.noaa.gov/facts/oceaneconomy.html). Cooley and Doney (2009) estimate that if just a 10-25% decrease in United States mollusk harvests from 2007 were to occur today, $75-187 million in direct revenue would be lost each year henceforth, with a net loss of $1.7-10 billion through mid-century, when pH levels are approximately 0.3 units below pre-industrial values. In Washington State alone, the seafood industry generates $1.7 billion for gross state product and employs 42,000 people (Washington State Blue Ribbon Panel 2012). Already, shellfish hatchery failures in Washington have caused an economic stir and caused some hatcheries to relocate. Alaska's commercial fishing industry is valued at over $4 billion a year, and supports 90,000 jobs—recreational fishing and fishing tourism add even more value. Meanwhile, Alaska is ranked among the most vulnerable areas to acidification.

Tropical coral reefs provide ecosystem services, such as habitat and nursery functions for commercial and recreational fisheries and coastal protection. As reefs decline in acidified waters, there will be an ecological shift to a new ecosystem state dominated by less commercially valuable species. In 2009, Brander et al. estimated the annual economic damage of ocean acidification-induced coral reef loss to escalate rapidly over time, reaching $870 billion by 2100 (Brander et al. 2009a). In 2014, Brander et al. increased the anticipated loss of ecosystem services from corals to be $1000 billion (UNEP 2014). Shoreline protection offered by coral reefs and the services it provides by preventing loss of life, property damage and erosion are also reduced by CO_2 emissions.

Lane et al. (2014) modeled three major U.S. locations for shallow water reefs -- South Florida, Puerto Rico, and Hawaii – to project future reef cover and the economic values generated by coral reefs for a greenhouse gas emissions mitigation scenario that represents international implementation of policies to reduce global emissions (resulting in a CO_2 concentration of 427 ppm in 2100), compared to a business as usual greenhouse gas emissions scenario resulting in a CO_2 concentration of 785 ppm in 2100. The study estimated that reducing emissions would result in an "avoided loss" in Hawaii of approximately $10.6 billion in recreational use values compared to business as usual. Reducing emissions was projected to provide fewer economic benefits in Puerto Rico and South Florida, where sea-surface temperatures are already close to

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bleaching thresholds and coral cover is projected to drop well below 5% cover under both scenarios by 2050, and below 1% cover under both scenarios by 2100 (Lane et al. 2014).

As discussed previously, the toxicity of harmful algal blooms increases under conditions of ocean acidification. These toxins not only poison marine mammals, but also cause paralytic shellfish poisoning in people. Scientists hypothesize that some of the increases red tides off the coast of Southern California may be related to ocean acidification, though this has yet to be confirmed. In turn, harmful algal blooms cost the United States approximately $82 million each year from impacts to fisheries, public health, management, and lost recreational opportunities (Hoagland and Scatasta 2006).

A recent study estimated that the damage our oceans will face from emissions-related problems will amount to $428 billion a year by 2050 and nearly $2 trillion per year by the century's end (Noone et al. 2012).

> Acidification impacts processes so fundamental to the overall structure and function of marine ecosystems that any significant changes could have far-reaching consequences for the oceans of the future and the millions of people that depend on its food and other resources for their livelihoods.

(Doney et al. 2009). There is also a significant cost to delaying action. According to a recent report by the Council of Economic Advisers, delaying the implementation of policies to mitigate climate change could significantly increase economic damages, in addition to worsening environmental harm.[39]

While there are still large unknowns on the biological consequences of ocean acidification, the science we have is clear: from shellfish to corals, and from pteropods to fish, our marine resources are threatened by the acidification of our ocean waters.

b. Risk Reduction Methods

There are several ways to reduce risk from CO_2. EPA should use a suite of tools to reduce emissions, sequester CO_2, mitigate harms, and promote alternatives. Under TSCA EPA has authority to:[40]

- prohibit or limit the amount of production or distribution of a substance in commerce;
- prohibit or limit the production or distribution of a substance for a particular use;
- limit the volume or concentration of the chemical produced;
- prohibit or regulate the manner or method of commercial use;
- require warning labels and/or instructions on containers or products;
- require notification of the risk of injury to distributors and, to the extent possible, consumers;

[39] Executive Office of the President of the United States, The Cost of Delaying Action to Stem Climate Change at 1 (July 2014).
[40] 15 U.S.C. § 260.

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- require record-keeping by producers;
- specify disposal methods; and
- require replacement or repurchase of products already distributed.

EPA also may impose any of these requirements in combination or for a specific geographical region. [41] Specifically, the agency must impose controls sufficient "to protect adequately against such risk using the least burdensome requirement."[42]

There is evidence that many industries could employ existing technology to achieve meaningful emissions reductions affordably. EPA's own data demonstrate that lower pollution rates are readily achievable for many industrial sources of CO_2. For example, the agency has identified dozens of "control measures and energy efficiency options that are currently available for pulp and paper mill processes," ranging from technological upgrades to improved equipment maintenance.[43] Similarly, EPA has compiled more than a decade of reports on "cost-effective" control strategies and other approaches available to reduce cement plant CO_2 emissions, "includ[ing], for example, energy efficiency measures, reductions in cement clinker content, and raw materials substitution."[44]

Although cost-effective strategies to reduce CO_2 emissions are available, existing controls have not reduced CO_2 emissions sufficiently to protect against environmental harm. For example, most natural gas power plants have *never* exceeded the agency's recently proposed emissions limit, thus indicating that existing and newly constructed facilities could easily satisfy a more stringent standard.[45] Because energy-related CO_2 pollution accounts for more than eighty percent of U.S. greenhouse gas production, readily achievable reductions in this sector would significantly benefit the environment.[46] Similarly, the pulp and paper industry ranks among the largest consumers of energy,[47] and emitted nearly 58 million metric tons of CO_2 equivalent gases in 2004.[48] Moreover, market incentives and regulatory controls are effective in increasing the rate of innovation for technologies that can reduce CO_2 emissions.

If a chemical presenting an unreasonable risk to health and the environment has already been distributed, EPA may prescribe procedures by which relevant manufacturers and purchasers must replace or repurchase that chemical.[49] In the present situation, we urge the agency to exercise its

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[41] *Id.*
[42] 15 U.S.C. § 2605(a).
[43] *See* EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 11 (2010).
[44] EPA, National Emission Standards for Hazardous Air Pollutants From the Portland Cement Manufacturing Industry and Standards of Performance for Portland Cement Plants, 75 Fed. Reg. 54,970, 54,997 (Sep. 9, 2010).
[45] Ctr. for Biological Diversity, Comments on Standards of Performance for Greenhouse Gas Emissions from New Stationary Sources: Electric Utility Generating Units (Proposed Rule) Docket No. EPA-HQ-OAR-2013-0495 at 13-14 (May 9, 2014).
[46] U.S. Dept. of State, U.S. Climate Action Report at 16 (2010).
[47] *See* U.S. Energy Information Administration, First Use of Energy for All Purposes (Fuel and Nonfuel), 2010 (Mar. 2013), http://www.eia.gov/consumption/manufacturing/data/2010/#r1.
[48] EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 7 (2010).
[49] 15 U.S.C. § 2605(a)(7)(C).

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authority to remediate existing harm by requiring that responsible parties mitigate past CO_2 emissions.

There are numerous approaches to mitigating and sequestering CO_2 emissions that EPA must evaluate. Effective land use and agricultural practices can significantly reduce carbon emissions and sequester CO_2. Federal programs aimed at consumers can reduce CO_2 emissions. For example, EPA's Energy Star program has prevented 1.8 billion tons of greenhouse gas emissions by providing information that helps customers select energy efficient devices. Sequestration of CO_2 in products, infrastructure, and waste management are among numerous methods that could be cost-effective to mitigate CO_2 pollution.

c. Social Costs of Carbon

In any analysis of the cost and benefits of reducing CO_2 pollution, the costs of failing to address the problem of global warming should be included. Most efforts to quantify the social costs of carbon underestimate the real-world costs of CO_2 pollution. Nevertheless, EPA may not ignore these costs.

Global emissions must be less than 1000 Gt of CO_2 between 2000 and 2050 to avoid dangerous climate change, which scientists have recommended that this means maintaining temperature change below 2° C.[50] This means keeping atmospheric CO_2 to 450 ppm, a threshold below which experts also use for ocean acidification (Veron et al. 2009; Silverman et al. 2009; Interacademy Panel 2009; McNeil & Matear 2008; Sea et al. 2007). For example, coral scientists predict that at 450 ppm, reef-building will be severely diminished or will cease altogether (Veron et al. 2009). But the global community has already used a substantial portion of this CO_2 budget, emitting 305 Gt of CO_2 between 2000 and 2008 alone.[51] As a result, the years between now and 2020 have been dubbed the "critical decade."[52] Because carbon emissions must peak soon and decline thereafter, the sooner emissions peak, the less severe the subsequent annual reductions will need to be;[53] correspondingly, if emissions are not sufficiently curbed in this decade, avoiding catastrophic damages will require much more drastic, disruptive and costly measures and may no longer be possible at all. Nonetheless, if action is taken immediately, it is both technologically and economically feasible to reduce emissions by 2020 and lay the groundwork for future emissions reductions.[54]

Every year that the world delays its efforts to reach sustainable levels of greenhouse gas emissions represents a lost opportunity of tremendous economic significance. McKinsey & Company estimated in 2009 that for every year of delay, 1.8 Gt of potential CO_2 abatement is foregone.[55] This delay, and the accompanying Gts of lost CO_2 abatement, has a price tag, as the

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[50] Australia Department of Climate Change and Energy Efficiency, The Critical Decade: Climate Science, Risks and Responses at 53 (May 2011), *available at* http://www.scribd.com/doc/56043375/The-Critical-Decade-Climate-Change-Commision-Report.
[51] *Id.*
[52] *Id.*
[53] UNEP, The Emissions Gap Report at 14 (Nov. 2010), *available at* http://www.unep.org/publications/ebooks/emissionsgapreport/; for a discussion of economic implications of these facts, *see infra.*
[54] *Id.* at 23.
[55] McKinsey & Company, Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve at 16 (2009), *available at* www.worldwildlife.org/climate/WWWFBinaryitem11334.pdf.

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damage caused by CO_2 emissions accelerate while the cumulative amount of greenhouse gases in the atmosphere rises, both because of the increasingly dire damages wrought by rising temperatures and other greenhouse gas effects, *and* because of the delay factor itself. If governments delay mitigation in the present, the emissions reduction curve in future years necessarily becomes much steeper, requiring much more drastic and costly emission reduction mechanisms with tremendous economy-wide disruptions, just to "catch up" with the lost opportunities from prior years to reach a sustainable emissions trajectory—or risk undergoing unsustainable climatic extremes.

Economists have sought to quantify the costs of waiting to embark upon an emissions reduction path. In 2007, researchers used the DICE model[56] to estimate the cost of delaying mitigation for a given period of time and then switching to an optimal abatement trajectory. According to their findings, the global cost of ten years of delay, relative to starting on an optimal trajectory in the present, ranges from hundreds of billions to several trillion dollars.[57] For instance, this study estimates that it would cost somewhere between $200 and $400 billion dollars to delay action for ten years and then embark upon a mitigation strategy that would result in stabilization at 3 °C (a level now universally understood to far exceed the dangerous). The cost of delaying mitigation soars into the trillions of dollars as the delay continues, until it ultimately becomes impossible to achieve a certain level of temperature stabilization. According to this study, more than thirty years' delay of changing the current course would make it impossible – no matter what the expense – to stabilize temperature rises at 2° C above pre-industrial levels.

EPA and other federal agencies have been using the social cost of carbon to estimate the climate benefits of rulemakings since it was first developed by a dozen agencies (including USDA, CEQ and EPA) and published by the Interagency Working Group in 2010.[58] The social cost of carbon, usually expressed as a dollar-per-ton figure, provides an estimate of the economic damages associated with an increase in CO_2 emissions, conventionally one metric ton, in a given year. The dollar figure can also represent the value of damages avoided for emission reductions achieved by federal rulemakings. The social cost of carbon is designed to provide a comprehensive estimate of climate change damages, including, but not limited to, changes in net agricultural productivity, human health, and property damages from increased flood risk. However, given current modeling and data limitations, even EPA has conceded that that the social cost of carbon protocol is likely a conservative estimate because it does not yet account for all important damages.[59] Nevertheless, the protocol is designed for use in regulatory processes like this one. In 2013 the Federal Interagency Working Group increased its estimates of the social cost of carbon, using the same 3% annual discount rate, by 50%.[60] The 2013 estimates are 50% higher for emissions in 2010, with greater percentage increases in subsequent years. Yet, even these social

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[56] DICE stands for the Dynamic Integrated Climate and Economy model developed by William Nordhaus in 1990.
[57] Keller, K. et al., The Regrets of Procrastination in Climate Policy, Environmental Research Letters (2007), *available at* iopscience.iop.org/1748-9326/2/2/024004/.
[58] EPA, The Social Cost of Carbon, http://www.epa.gov/climatechange/EPAactivities/economics/scc.html (last accessed June 28, 2015).
[59] *Id.*
[60] Interagency Working Group on Social Cost of Carbon, United States Government, Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 (Nov. 2013) at 3, available at http://www.whitehouse.gov/sites/default/files/omb/assets/inforeg/technical-updatesocial-cost-of-carbon-for-regulator-impact-analysis.pdf.

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cost of carbon figures significantly underestimate the true social cost of carbon, possibly by several orders of magnitude.

Economists have noted that the social cost of carbon is far greater than the $21 per ton of CO_2 assumed by interagency protocol in 2010 and greater than the 2013 revision.[61] There are several inadequacies that make the values too conservative. Foremost, the models fail to evaluate ocean acidification—to the contrary the models consider the ocean a sink for CO_2. The FUND model used in the Working Group's analysis wholly excludes consideration of climate-induced catastrophic events. But the Working Group weighs the values generated by each of the three models equally, even though the FUND model's values is significantly lower[62] than the others, and consequently pulls down the final value of the social cost of carbon. The potential for catastrophic climate events, and the increasing likelihood that tipping points will be reached even sooner than anticipated, are increasingly serious risks, however, and, despite the associated uncertainties, must be fully represented in any evaluation of the social cost of carbon. Instead, the Working Group employed a risk-neutral approach, clearly inappropriate in light of the vast majority of scientific studies. Also, the models used fail to account fully or even partially for certain highly complex aspects of climate change, including the possibility of interrelations between different sectors and accelerating damage feedback loops, non-CO_2 emissions,[63] and social and political instability. Moreover, the valuation techniques and discount rates used to reach these values are inherently problematic and fail to represent the full value of all losses from climate change, in significant part because some cannot be reduced to monetary terms.

Other evaluations of the social cost of carbon attempt to account for these omitted factors. The Stern Review, in particular, reaches a SCC of $85/ton of CO_2 (in 2000 dollars).[64] For comparison purposes with a Working Group value of $21 in 2005 dollars, this amount is equivalent to

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[61] F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon (2010) (the social cost of carbon could be over $800 per ton of CO2 equivalent; F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon, in Economics, vol. 6 (Apr. 4, 2012) (reaching similar conclusions), available online at http://www.economics-ejournal.org/economics/journalarticles/2012-10 (last visited June 27, 2014); P. Epstein et al., Full cost accounting for the life cycle of coal, Ann. N.Y. Acad. Sci. (2011) (estimating the social cost of coal at between $10 and $100 per ton of CO2 equivalent); L. Johnson & C. Hope, The social cost of carbon in U.S. regulatory impact analyses: an introduction and critique, J. Envtl. Stud. & Sci. (Sept. 9, 2012) (finding a social cost of a ton of CO2 emissions to be 2.6 to over 12 times larger than the Interagency Working Group's central estimate of $21 per ton of CO2) available online athttp://link.springer.com/article/10.1007%2Fs13412-012-0087-7 (last visited June 27, 2014) E. Stanton et al., Comments on the 2013 Technical Update of the Social Cost of Carbon, January 27, 2014.

[62] Interagency Working Group on the Social Cost of Carbon, Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, at 16-A-11, Fig. 16-A-4.2, *available at* http://www.rff.org/Publications/WPC/Pages/Estimating-the-Social-Cost-of-Carbon-for-Regulatory-Impact-Analysis.aspx.

[63] For instance, the estimated social cost of methane and SF_6, are, respectively, $105/tonne and $200,000/tonne. *See* Intergovernmental Panel on Climate Change, Climate Change 2007 Synthesis Report 822, *available at* http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html. For a critical analysis of the Working Group's assumptions, *see also* Ackerman, F. and Stanton, E. A., The Social Cost of Carbon A Report for the Economics for Equity and the Environment Network (April 1, 2010), *available at* http://www.e3network.org/papers/SocialCostOfCarbon_SEI_20100401.pdf.

[64] Nicholas Stern, Stern Review on the Economics of Climate Change Part III: The Economics of Stabilisation at 287 (2006), *available at* http://webarchive.nationalarchives.gov.uk/+/http:/www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm.

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$96.25/ton in 2005. The Stern Review uses the PAGE model, which explicitly models for the risk of catastrophic climate change.[65] In contrast with the Working Group, the Stern Review uses a mean temperature increase of 3.9 °C for its baseline scenario (consistent with the Third IPCC Report) and a 4.3 °C increase for its higher climate scenario. The resulting higher value of the social cost of carbon is thus very likely to be a closer approximation of the real cost of CO_2.

Meanwhile, the costs of reducing CO_2 emissions are well worth taking prompt action. The "central estimates of the annual costs of achieving stabilisation between 500 and 550ppm CO_2 are around 1% of global GDP, if we start to take strong action now. [...] It would already be very difficult and costly to aim to stabilise at 450ppm CO_2e. If we delay, the opportunity to stabilise at 500-550ppm CO_2e may slip away.'"(Stern 2006). Likewise, the benefits of addressing CO_2 for ocean acidification also have the ancillary effect of slowing global warming and preventing costs associated with climate change.

The recently proposed rule to reducing power plant CO_2 emissions calculates both costs and benefits—notably the benefits far exceed the costs. The recently proposed rules for reducing power plant carbon emissions, calculates both costs and benefits for a more modest reduction. EPA projects that the annual compliance cost will be $4.3 to $5.5 billion (in 2011 dollars, depending on discount rate) in 2020 and $5.5 billion (for a 5% discount rate) in 2030.[66] The total combined climate benefits and health co-benefits are estimated to be $15.6 to $88 billion in 2020 and $32.3 to $151 billion in 2030 (depending on discount rate and the options chosen).[67] The insurance industry also is well aware of the potential costs of failing to address CO2 emissions and its associated effects, including: "[h]urricanes and other flooding events … [h]ealth issues associated with heat waves… more airborne allergens, rising temperatures, greater humidity, more wildfires, and more dust and particulate pollution may considerably exacerbate upper respiratory disease (rhinitis, conjunctivitis, sinusitis, asthma) and cardiovascular disease."[68] A European insurance company estimates losses from extreme climate change events of 37% within a decade, over $1 trillion under bad circumstances.[69] The increasing frequency and severity of storms in the U.S. has caused damages to increase 60-fold from 1950s to the 1990s.[70]

Petitioners ask that action to mitigate ocean acidification under TSCA be initiated, either through TSCA section 6 (e.g., requiring "repurchasing" relief using sequestration, emission reductions, etc.), or through section 4 in order to determine the need for action under section 6 and the most effective mitigation strategies. In any case, petitioners suggest that costs be apportioned among

[65] According to the Working Group itself, DICE "offers the best insight into the SCC if the world were to experience catastrophic climate change." *See* Working Group, *supra* note 62, at 16-A-35.
[66] EPA, Regulatory Impact Analysis Technical Document EPA-452/R-14-002 (June 2014).
[67] *Id.*
[68] National Association of Insurance Commissioners, The Potential Impact of Climate Change on Insurance Regulation at 10 (2008).
[69] See e.g. Allianz, Climate Change and the Financial Sector: An Action Plan; Evan Mills, Responding to Climate Change: The Insurance Industry Perspective.
[70] Mills, E. Insurance in a Climate of Change, Science 308: 1040 (2005).

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CO_2 emission contributors according to the cumulative CO_2 emission inventory information EPA has collected.[71]

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In summary, the weight of the scientific information on ocean acidification is sufficient to make a determination that CO_2 poses an unreasonable risk, to the extent that EPA declines to find the data adequate, then EPA must develop a test rule under TSCA section 4 as described below.

C. Alternatively, EPA Must Require Testing to Develop Adequate Data

EPA must make a determination as to whether adequate data exist to evaluate the environmental and health effects of CO_2. There is well-established scientific information on the risk of CO_2 on the environment, but if EPA determines that the data are insufficient then it must develop a testing rule.

In enacting TSCA, Congress declared that "adequate data should be developed with respect to the effect of chemical substances and mixtures on health and the environment and that the development of such data should be the responsibility of those who manufacture and those who process such chemical substances and mixtures."[72] Accordingly, section 4 directs EPA to require additional testing upon determining that "the manufacture, distribution in commerce, processing, use, or disposal of chemical substance or mixture … may present an unreasonable risk of injury to health or the environment," or if the chemical is produced in substantial quantities and there is a potential for a substantial quality to be released into the environment.[73]

1. CO_2 May Present an Unreasonable Risk

As described in depth in this petition, CO_2 may present an unreasonable risk to the environment. EPA interprets this to mean that there is a "substantial (i.e., more than theoretical) probability" of unreasonable risk to the environment or health.[74] The information in this petition meets the threshold for a testing rule and establishes a substantial probability that CO_2 poses an unreasonable risk to the environment, but EPA need not even make such a determination because CO_2 is produced in such large volumes that it clearly meets the criterion of exposure of substantial quantities being released into the environment.

2. Substantial Quantities of CO_2 Are Released into the Environment

It is undeniable that substantial qualities of CO_2 are released into the environment. EPA established a threshold value of one million pounds for a release of a chemical to be substantial. *TSCA Section 4(a)(1)(B) Final Statement of Policy; Criteria for Evaluating Substantial*

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[71] This could be structured similar to the sponsorship format used in TSCA's High Production Volume (HPV) Program.
[72] 15 U.S.C. § 2601(b)(1).
[73] 15 U.S.C. § 2603 (a)(1)(A), (B)(i).
[74] *Chemical Mfrs. Ass'n v. EPA*, 859 F.2d 977, 988 (D.C. Cir. 1988).

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Production, Substantial Release, and Substantial or Significant Human Exposure, 58 Fed. Reg. 28736, 28746 (May 14, 1993). According to the IPCC:

> From 1750 to 2011, CO_2 emissions from fossil fuel combustion and cement production have released 375 [345 to 405] GtC to the atmosphere, while deforestation and other land use change are estimated to have released 180 [100 to 260] GtC. This results in cumulative anthropogenic emissions of 555 [470 to 640] GtC.

(IPCC 2013, Summary for Policymakers).

In 2012, a total of 9.7 gigatonnes of CO_2 were released into the atmosphere from fossil fuel combustion and cement production (Global Carbon Project 2013). These emissions are expected to increase to 9.9 gigatonnes in 2013 (*Id.*). The United States contributed 14% of CO_2 emissions to the atmosphere (*Id.*). Models estimate that between 2003 and 2012, the oceans absorbed 27% of CO_2 from the atmosphere (*Id.*). Over the next millennium, the oceans will absorb 90% of anthropogenic CO_2 (Kleypas et al. 2006).

Therefore, the threshold of substantial release is exceeded by more than a million times over.

3. Recommendations for Testing

EPA should consider a test rule to fill the information gaps needed to make a determination of whether CO_2 presents an unreasonable risk of injury to the environment. Some recommendations for consideration include:

- Testing CO_2 reduction strategies. For example, research and development for emissions reduction strategies that include alternative practices, conservation, alternative fuels. Testing CO_2 sequestration and capture approaches, and assessing attainable CO_2 emissions reductions for industries with significant CO_2 emissions.
- Conducting a vulnerability assessment for marine and coastal species and ecosystems. Determining atmospheric CO_2 levels necessary to conserve marine ecosystems from dangerous ocean acidification. Emissions scenarios are important for informing policy approaches to acidification.
- Forecasting species' responses to ocean acidification using modeling tools to predict range shifts, demographic and population trends, and physiological responses across taxonomic groups using a range of climate models, emissions scenarios, and management timelines (25, 50, 100 years). Identify wildlife species and ecosystems imperiled by ocean acidification by evaluating range shift models and population viability models run under future ocean acidification levels. Recommend conservation actions, including protected status, for species that are most at risk. Protect species across their range since populations are likely to have different adaptations to local oceanic conditions.
- Determining the economic values of ecosystems that are at risk from ocean acidification and the costs of reducing CO_2 emissions to preserve those ecosystems.

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Additionally, EPA can use guidance on research needs based on existing research plans. There are a number of sources recommending research and data needs (National Research Council 2013; Washington State Blue Ribbon Panel 2012; National Research Council 2010).

According to TSCA, developing the data is "the responsibility of those who manufacture and those who process such chemical substances and mixtures."[75] For example, responsibility could be apportioned based on the historical carbon emissions from the EPA Greenhouse Gas Emission Inventory together with current emissions. Typically for test rules with multiple responsible parties consortiums are set up to comply.[76] Here, for example, utilities, cement and lime manufacturers, waste incinerators, and other large producers of CO_2 should be responsible for developing unbiased, independent data.

While this may seem like a complicated undertaking, EPA has successfully completed more complex test rules. For example, from 1998 through the present, the agency used three sets of regulatory test rules under TSCA to collect chemical data for almost 3,000 high production volume (HPV) chemicals, including over 10,000 individual studies with data from domestic and foreign producers.[77]

EPA must develop test rules under TSCA section 4 for research and data development focused on information essential for making a definitive TSCA section 6 finding. These would include risk, benefit and cost information.

D. Inadequacy of Existing CO_2 Reduction Strategies

Petitioners are aware that the Agency has recently planned and initiated several emission reduction actions aimed at slowing the rate at which carbon emissions are increasing. However, these actions by themselves, while laudable, will not stabilize atmospheric CO_2 at a level which will prevent widespread harm from ocean acidification.

1. Global Greenhouse Gas Emissions Are Increasing Substantially

The atmospheric concentration of CO_2 reached 400 parts per million (ppm) for the first time in human history in May, 2013, compared to the pre-industrial concentration of ~280 ppm (Scripps Institution of Oceanography 2013). The current CO_2 concentration has not been exceeded during the past 800,000 years and likely not during the past 15 to 20 million years (Denman et al. 2007; Tripati et al. 2009). Atmospheric CO_2 emissions have risen particularly rapidly since the 2000s (Raupach et al. 2007; Friedlingstein et al. 2010). The global fossil fuel CO_2 emissions growth rate was 1.0% per year in the 1990s compared with 3.1% per year since 2000, and this growth rate has largely tracked or exceeded the most fossil-fuel-intensive emissions scenarios projected by the IPCC (A1FI and RCP 8.5) since 2000 (Raupach et al. 2007, Peters et al. 2012). The CO_2 emissions growth rate fell slightly in 2009 due largely to the global financial and economic

[75] 15 U.S.C. § 2601
[76] 15 U.S.C. § 2602 (b)(3)(A)
[77] EPA, High Production Volume (HPV) Challenge; http://www.epa.gov/chemrtk/index.htm (last accessed June 28, 2015).

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crisis; however, the decrease was less than half of what was expected and was short-lived (Fiedlingstein et al. 2010). In 2014 and 2015, global CO_2 concentrations exceeded 400ppm.[78]

2. U.S. Measures to Reduce Greenhouse Gas Emissions Are Insufficient

EPA has taken some initial steps toward curbing greenhouse pollution under the Act. In 2009, the agency issued a formal finding that greenhouse pollution endangers public health and welfare and moved to limit emissions from passenger cars and trucks. The EPA also acknowledged that major new or modified "stationary" sources of greenhouse pollution, like power plants and factories, must obtain permits and control their emissions before beginning construction. However, it narrowed the scope of this requirement considerably under its so-called "tailoring rule," which initially limits the permitting program to only a few hundred very large sources of greenhouse gases, letting a huge number of smaller — but still significant — sources off the hook.

While existing domestic laws including the Clean Air Act, Energy Policy and Conservation Act, Clean Water Act, Endangered Species Act and others provide authority to executive branch agencies to require greenhouse gas emissions reductions from virtually all major sources in the United States, these agencies are either failing to implement or only partially implementing these laws for greenhouse gases. The landmark 2014 pact with China to reduce greenhouse gas emissions is significant, but there is little to ensure it is enforced and implemented. According to the plan, United States will reduce CO_2 emissions 26 to 28% below 2005 levels by 2025.

Proposed power plant rules also fail to do enough to cut CO_2 pollution. Using the Clean Air Act, the president aims to reduce existing power plant emissions 30 percent below 2005 levels (or about 7.7 percent below 1990 levels, the base year for the international climate treaty) by 2030. But international scientists warned years ago that developed countries like the United States must reduce their emissions 25 percent to 40 percent below 1990 levels by 2020 to avoid tipping the scales further toward a climate catastrophe. Likewise, the recently announced plans to limit power plant emissions (Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units) focuses on emission reduction. Power plants are responsible for about a third of our carbon emissions, and the rule is designed to reduce those emissions by almost a third by 2030. This would result in a 10% decrease in 15 years. Stabilizing atmospheric concentration to prevent further acidification of the oceans would require about an 80% decrease in all emissions. Clearly this is a good first step, but by itself inadequate to address acidification.

EPA has issued a rulemaking regulating greenhouse gas emissions from automobiles that will reduce greenhouse emissions emitted per vehicle mile traveled by passenger vehicles in the future. But because the improvements are modest and more vehicles are projected to drive more miles in the future, the rule will not reduce emissions from this sector overall but will only slow the rate of increase.[79] Meanwhile, even the government concedes that "these reductions in emissions are not sufficient by themselves to reduce total HD vehicle emissions below their 2005

[78] NOAA, Trends in Atmospheric Carbon Dioxide, http://www.esrl.noaa.gov/gmd/ccgg/trends/
[79] EPA, Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule, 75 Fed. Reg. 25324 (May 7, 2010).

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levels by 2020."[80] This means that the vehicle rule is far from achieving emissions goals agreed to by the U.S. in the Copenhagen Accord, which aim to keep global warming below 2˚C.

The EPA has also to date issued only a single proposed rule under the new source pollution standard program for stationary sources of pollution, for electric generating units (power plants). While there is enormous potential to reduce emissions through this program overall and through the power plants rule in particular, the EPA has instead proposed a weak and flawed rule that it admits will not reduce emissions from these sources between now and 2020 compared to what would be expected without the rule.[81] Indeed, in the rulemaking the EPA conceded that new power plant rule on greenhouse gas emissions "will not have direct impact on U.S. emissions of greenhouse gases under expected economic conditions."[82]

While full implementation of our flagship environmental laws, particularly the Clean Air Act, would provide an effective and comprehensive greenhouse gas reduction strategy, due to their non-implementation, existing domestic regulatory mechanisms must be considered inadequate to protect marine species from climate change and ocean acidification.

3. International Measures to Reduce Greenhouse Gas Emissions Are Inadequate

International initiatives are also currently inadequate to effectively address climate change. The United Nations Framework Convention on Climate Change, negotiated in 1992 at Rio de Janeiro, Brazil, provides the forum for the international negotiations. In the Framework Convention, signed and ratified by the United States, the world agreed to take the actions necessary to avoid dangerous climate change. Parties to the Convention also agreed as a matter of fairness that the world's rich, developed countries, having caused the vast majority of emissions responsible for the problem, would take the lead in solving it. It was not until the 1997 meeting in Kyoto, Japan, that the first concrete, legally binding agreement for reducing emissions was signed: the Kyoto Protocol. The Protocol requires the world's richest countries to reduce emissions an average of 5 percent below 1990 levels by 2012, while developing nations also take steps to reduce emissions without being subject to binding emissions targets as they continue to raise their standard of living. The United States has been a major barrier to progress in the international negotiations. After the Clinton administration extracted many concessions from the rest of the world in exchange for the United States signing on in Kyoto, the Senate rejected the equity principles behind the Convention, saying the United States should not agree to reduce its own emissions unless all other countries — regardless of their responsibility or ability — were similarly bound. Citing the same excuses, President George W. Bush repudiated the Kyoto Protocol entirely. Thus the United States is the only industrialized country in the world that has yet to ratify the Kyoto Protocol. The United States negotiating team under both the George W. Bush and the Obama administrations has pursued two primary objectives in the international talks: to refuse any legally binding emissions reduction commitments until all other

[80] NHTSA, Medium- and Heavy-Duty Fuel Efficiency Improvement Program – Final Environmental Impact Statement (June 2011).
[81] EPA, Standards of Performance for Greenhouse Gas Emissions for New Stationary Sources: Electric Utility Generating Units, 77 Fed. Reg. 22392, 22430-33 (April 13, 2012).
[82] *Id.* at 22401.

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countries— but particularly China and India — do so, and to push back the date for a new agreement. Not surprisingly, the United States had failed to meet its (never ratified) Kyoto pledge to reduce emissions to 7.2% below 1990 levels by 2012; to the contrary, U.S. emissions have increased by 10.5% since 1990 (EPA 2012).

Moreover, the Kyoto Protocol's first commitment period only sets targets for action through 2012, and there is still no binding international agreement governing greenhouse gas emissions in the years beyond 2012. While the 2009 U.N. Climate Change Conference in Copenhagen called on countries to hold the increase in global temperature below 2□C (an inadequate target for avoiding dangerous climate change), the non-binding "Copenhagen Accord" that emerged from the conference, and the subsequent "Cancún Accords" of 2010 and "Durban Platform" of 2011 failed to enact binding regulations that limit emissions to reach this goal.[83] Even if countries were to meet their Copenhagen and Cancún pledges, analyses have found that collective national pledges to cut greenhouse gas emissions are inadequate to achieve the 2°C target, and instead suggest emission scenarios leading to 2.5□C to 5□C warming (Rogelj et al. 2010; UNEP 2011; UNEP 2010). As of July 2013, many governments were not implementing the policies needed to meet their inadequate 2020 emission reduction pledges, making it more difficult to keep global temperature rise to 2□C and likely leading to a temperature rise of at least 3.5□C (USGCRP 2013). As noted in the NMFS Management Report, the U.S. has yet to issue regulations to limit greenhouse gas emissions in accordance with its pledge under the Copenhagen Accord (NMFS 2012).

CONCLUSION

In conclusion, this petition requires EPA to make a determination whether CO_2 poses an unreasonable risk to the environment therefore requiring regulation under section 6 of TSCA. In an extensive review of the literature on the impact of ocean acidification on marine fauna and ecosystem processes, the authors found that while additional research is called for, sufficient information exists to state with certainty that deleterious impacts on some marine species are unavoidable, and that substantial alteration of marine ecosystems is likely over the next century. (Fabry et al. 2008). If, nonetheless, EPA determines that the information is insufficient to make such a finding it must develop testing rules pursuant to TSCA section 4.

[83] The non-legally binding Copenhagen Accord of 2009 and Cancún Accords of 2010 recognize the objective of limiting warming to 2°C above pre-industrial temperatures, but do not enact binding regulations to achieve this goal (http://cancun.unfccc.int/cancun-agreements/main-objectives-of-the-agreements/#c33; unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf). According to the Durban Platform, developed and developing nations agreed to a process to develop a "new protocol, another legal instrument, or agreed outcome with legal force that will be applicable to all Parties to the UN climate convention"; this legal instrument must be developed as of 2015 and will not take effect until 2020 (unfccc.int/resource/docs/2011/cop17/eng/l10.pdf).

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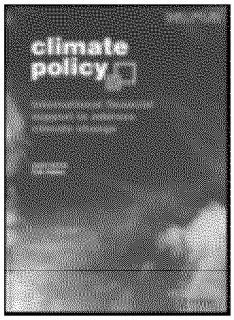

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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climate policy

B research article

Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Benefit–cost analysis can serve as an informative input into the policy-making process, but only to the degree it characterizes the major impacts of the regulation under consideration. Recently, the US, amongst other nations, has begun to use estimates of the social cost of CO_2 (SC-CO_2) to develop analyses that more fully capture the climate change impacts of GHG abatement. The SC-CO_2 represents the aggregate willingness to pay to avoid the damages associated with an additional tonne of CO_2 emissions. In comparison, the social costs of non-CO_2 GHGs have received little attention from researchers and policy analysts, despite their non-negligible climate impact. This article addresses this issue by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. By extending existing integrated assessment models, it is possible to develop a set of social cost estimates for these gases that are consistent with the SC-CO_2 estimates currently in use by the US federal government.

Policy relevance

Within the benefit–cost analyses that inform the design of major regulations, all Federal agencies within the US Government (USG) use a set of agreed upon SC-CO_2 estimates to value the impact of CO_2 emissions changes. However, the value of changes in non-CO_2 GHG emissions has not been included in USG policy analysis to date. This article addresses that omission by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. These new estimates are designed to be compatible with the USG SC-CO_2 estimates currently in use and may therefore be directly applied to value emissions changes for these non-CO_2 gases within the benefit–cost analyses used to evaluate future policies.

Keywords: integrated assessment; non-CO_2 GHGs; social cost of carbon

1. Introduction

The social cost of CO_2 (SC-CO_2) is a measure of the monetary value of the damages occurring both within and outside economic markets as the result of an additional unit of CO_2 emissions. Specifically, it represents society's aggregate willingness to pay to prevent future impacts that occur when one additional unit of CO_2 is emitted into the atmosphere in a particular year. Estimates of SC-CO_2

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therefore provide a way to value changes in CO_2 emissions in benefit–cost analyses (BCAs) of policy alternatives. Without an estimate of the SC-CO_2, the benefits of mitigating the climate change impacts from CO_2 emissions would implicitly be valued at zero in BCAs, thereby significantly weakening the information provided by such analyses. Since 2009, the US Federal Government (USG) has used a set of agreed-upon SC-CO_2 estimates in the BCAs used to evaluate major regulations that impact CO_2 emissions (USG, 2010), including over 30 regulatory actions to date. The USG SC-CO_2 estimates are also increasingly being used in analysis and discussions outside the USG (e.g. by states, regional organizations, other nations, international organizations, NGOs, and academic researchers)[1] and have even figured in several recent public hearings and court cases (e.g. Keohane, 2010a, 2010b).

Although CO_2 is the primary anthropogenic GHG, other GHGs such as methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are also important contributors to climate change. The combined effect of all GHGs accumulated in the atmosphere is to increase the Earth's radiative forcing, which is the amount of energy from the Sun that is trapped in the Earth's atmosphere and therefore acts to warm the planet and change the climate. In 2011, the atmospheric CO_2 concentration contributed 64% of overall radiative forcing, while CH_4 and N_2O accounted for approximately 23% (Myhre et al., 2013). Non-CO_2 GHGs, notably CH_4 and N_2O, therefore contribute significantly to the negative impacts on human well-being from climate change. Furthermore, several recent studies have shown that consideration of non-CO_2 GHGs, particularly CH_4 and N_2O, is important for the design of cost-effective climate policy (Reilly et al., 1999; Tol, Heintz, & Lammers, 2003; Weyant, De La Chesnaye, & Blenford, 2006).

The monetary value of changes in emissions of non-CO_2 GHGs has not been included in USG policy analysis to date. This shortcoming prevents the development of accurate and comprehensive assessments of potential regulatory alternatives by the USG and others that rely on the USG SC-CO_2 estimates (Kopp & Mignone 2012; Marten & Newbold, 2012). For example, fossil fuels (e.g. coal and natural gas) have different compositions of GHG emissions across gases when considering the entire process of extraction, production, transmission, and combustion. Thus, if a regulation is anticipated to cause an industry to substitute between fuels, analysts may be providing inadequate information to decision makers and the public about its benefits if only the welfare implications of direct CO_2 emissions are considered while ignoring changes in CH_4 and other GHG emissions (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2011).

A key reason for the value of non-CO_2 GHG emissions impacts not being included in USG analyses so far is that existing estimates of the social cost of non-CO_2 GHGs presented in the literature are inconsistent with USG SC-CO_2 modelling assumptions. For example, the recent US Environmental Protection Agency BCA of new pollution standards for the oil and natural gas industry concluded that, because they are not consistent with the USG SC-CO_2, 'the methane climate benefit estimates available in the current literature are not acceptable to use to value the methane reductions finalized in this rulemaking' (USEPA, 2012). This article seeks to address that gap by developing a new set of social cost estimates for CH_4 and N_2O (SC-CH_4 and SC-N_2O, respectively) that are fully consistent with the modelling assumptions underlying the current USG SC-CO_2 estimates. This article also develops an approach to extending the models used by the USG to generate estimates of the social cost of additional GHGs that are consistent with the latest USG estimates of the SC-CO_2.

It is important to note at the outset that by restricting attention to the derivation of social cost estimates consistent with the USG SC-CO_2 estimates, any limitations that apply to inputs and modelling

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assumptions underlying the USG SC-CO_2 estimates (e.g. Arrow et al., 2013; Kopp & Mignone 2012; Marten, 2011; O'Neil, 2010; Warren, Mastrandrea, Hope, & Hof, 2010) also apply to the SC-CH_4 and SC-N_2O estimates derived here. Thus, while it is anticipated that the USG will continue to improve the models and data it uses to estimate the SC-CO_2, this article focuses on the more immediate task of developing a set of consistent estimates for the social cost of other GHG emissions so that they need not be implicitly assigned a value of zero in USG policy analyses.

The remainder of the article is organized as follows. Section 2 presents an overview of the USG SC-CO_2 estimation approach and how it compares to the existing literature on the social cost of non-CO_2 GHGs, including a discussion of some of the critiques of the approach. Section 3 presents the approach for estimating the SC-CH_4 and SC-N_2O in a manner consistent with the USG SC-CO_2 estimates. Section 4 presents the results and a comparison of the relative social costs to the previous literature and the global warming potential (GWP)-based metric that is often used as an approximation in the absence of direct estimates, and Section 5 provides concluding remarks.

2. Background

In 2009–2010 the USG formed an interagency working group to develop a set of SC-CO_2 estimates for use by all Executive Branch agencies to value marginal changes in CO_2 emissions in regulatory impact analyses (USG, 2010). The goal of this exercise was to improve the accuracy and consistency with which agencies value marginal changes in CO_2 emissions. Before the release of these estimates, CO_2 emissions changes were valued in some but not all regulatory analyses, and the SC-CO_2 estimates used by different agencies varied substantially. The USG recently updated their estimates for the SC-CO_2 by employing new versions of the three underlying integrated assessment models (IAMs), but leaving the original estimation approach and underlying assumptions unchanged (USG, 2013). This section provides a brief overview of the estimation approach and assumptions used by the USG for estimating SC-CO_2, describes some critiques of the approach by other researchers, and discusses the existing literature on the social cost of non-CO_2 GHGs.

2.1. USG SC-CO_2 estimation approach

To estimate the SC-CO_2 the USG used three IAMs that couple simplified models of atmospheric gas cycles and climate systems with highly aggregate models of the global economy and human behaviour to capture the effects that GHG emissions, through their effect on the climate, have on human welfare. Within IAMs, the modelling that guides the transition from emissions into climate impacts is based on scientific assessments, while the mapping of climate impacts into changes in human welfare is based on economic research that has studied the effect of climate on various market and non-market sectors. Nordhaus and Boyer (2000) provide a very informative and detailed description of how such models are developed.[2]

The three models used by the USG are those that feature most prominently in the published social cost of carbon literature: the Dynamic Integrated Climate and Economy (DICE) (Nordhaus, 2008; Nordhaus & Boyer, 2000), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2006b, 2008), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff, Hepburn, & Tol, 2009; Tol, 2002a, 2002b, 2009) models. The USG chose to use the IAMs'

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climate system submodels and the functions that map climate change into economic damages as implemented by the model developers, but adopted a common set of input assumptions for equilibrium climate sensitivity, discount rates, global population, economic output, and GHG emissions projections. The remainder of this section provides a brief description of these common assumptions and the steps used to calculate the SC-CO_2 estimates. Interested readers can find more details in the USG's 2010 technical support document (USG, 2010).

2.1.1. Reference socio-economic-emissions scenarios

The USG selected five scenarios of economic output, population, and GHG emissions projections using results from the 2009 Stanford Energy Modeling Forum exercise number 22 (EMF-22). Four of the scenarios are based on baseline runs from global economic models (MERGE, MESSAGE, MiniCAM, and IMAGE) and span a range of emissions projections and plausible outcomes for future population and economic output absent significant global action to address climate change. These scenarios allowed for internally consistent forecasts of economic output, population, and emissions for the years 2000–2100. The fifth scenario used by the USG is based on the average of the 550 ppm CO_2e stabilization runs for each of the four models from which baseline scenarios were selected to represent potential action by the rest of the world absent US action. Across the five scenarios, atmospheric CO_2 concentrations in 2100 ranged from approximately 450 to 890 ppm (550–1130 ppm in CO_2e). Over the time horizon, the forecasts of the average growth rate for global per capita economic output ranged from 1.5% to 2.0% per year, and the average global population growth rate ranged from 0.4% to 0.5% per year. To run the IAMs through the year 2300, the USG extrapolated the selected EMF scenarios using the following assumptions: starting in 2100 the population growth rate declines linearly to zero in 2200; starting in 2100 the growth rate of economic output per capita declines linearly to zero in 2300; for all years after 2100 the growth rate of the carbon intensity of the global economy (CO_2 emissions/economic output) remains constant at its 2090–2100 average; starting in 2100 net land-use CO_2 emissions decline linearly to zero in 2200; and for all years beyond 2100 non-CO_2 radiative forcing anomalies remain constant at their 2100 levels.

Several limitations of the simplifying assumptions underlying the USG approach to scenario development have been discussed by other researchers. O'Neil (2010) pointed out that the selected EMF scenarios do not reflect the full range of outcomes that appear in other studies in the literature, and Kopp and Mignone (2012) suggested that the selected scenarios may effectively over-sample the peaks of the distributions. As for the extrapolations, while running the models out for multi-century time horizons is not necessary for relatively short-lived GHGs like CH_4, it is important for understanding the impacts of long lived GHGs such as CO_2 and N_2O that will affect human welfare well beyond 2100. As emphasized by O'Neil (2010) and Kopp and Mignone (2012), the state of the world beyond 2100 is highly uncertain and the scenario extrapolation approach taken by the USG represents only one of many possibilities. Furthermore, the extrapolations for each component of the scenarios (economic output, population, emissions) are separate and nothing ensures internal consistency within the scenarios past 2100. As shown by Marten and Newbold (2012), the temporal decomposition of damages for a perturbation of CO_2 and N_2O are relatively similar in shape and therefore the general findings of studies that explore the sensitivity of the SC-CO_2 to these assumptions should also be applicable to the SC-N_2O.

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2.1.2. Equilibrium climate sensitivity

In reduced-form IAMs, the speed and magnitude of temperature change for a given emissions projection are influenced largely by the 'equilibrium climate sensitivity' (ECS) parameter. The ECS represents the long-term global average temperature response to a level of radiative forcing associated with a sustained doubling of atmospheric CO_2 concentration (around 550 ppm). To represent the uncertainty in the responsiveness of the climate system to changing atmospheric conditions, the USG used a probability distribution for the ECS parameter of the form suggested by Roe and Baker (2007). The USG calibrated the parameters of the probability distribution to have a median equal to 3 8C, two-thirds probability that the ECS lies between 2 and 4.5 8C, which was intended to be consistent with the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) consensus statement about the ECS (Meehl et al., 2007). The distribution was truncated from above at 10 8C. This specification of the ECS distribution is retained to maintain consistency with the USG estimates of the SC-CO_2, but it is noted that the recently released AR5 by the IPCC has revisited the equilibrium climate sensitivity and revised the range downwards to 1.5–4.5 8C and no longer provides a most likely value (Collins et al., 2013). The ultimate effect of updating the ECS distribution to be consistent with the IPCC AR5 findings will depend heavily on the central tendency selected for the distribution.

2.1.3. Discount rates

Because the damages from an additional tonne of CO_2 emissions occur over many decades, the discount rate, which reflects the tradeoff between present and future consumption, plays a critical role in estimating the SC-CO_2. In light of disagreement in the literature regarding the appropriate discount rate to use in this context and uncertainty about future conditions that impact the discount rate, the USG used three constant discount rates intended to span a plausible range: 2.5%, 3%, and 5% per year. It is worth noting that the debate regarding not only the appropriate discount rate but also its time path is ongoing (Arrow et al., 2013; Dasgupta, 2008). While the appropriate value for the discount rate will presumably remain an area of active debate for some time to come, there appears to be agreement that the use of a constant discount rate over long time horizons with uncertain changes in the consumption per capita growth is not theoretically consistent. This article uses the same three constant discount rates as the USG estimation process, but in Appendix C results are reported from a series of sensitivity analyses using a Ramsey discounting approach. Similar to Marten and Newbold (2012), it is found that applying Ramsey discounting using plausible values for the components of the consumption discount rate gives a range of social cost estimates that is broadly consistent with the range of results obtained using the constant discount rates.

2.1.4. Calculating the SC-CO_2

The process to estimate the SC-CO_2 for emissions in year t has four steps. First, each model is used to forecast monetized impacts associated with the baseline path of emissions, economic output, and population. Second, each model is re-run with an additional unit of CO_2 emissions in year t to forecast monetized impacts for all years beyond t along this perturbed path of emissions. Third, the marginal damages in each year are calculated as the difference between the monetized impacts forecast in steps 1 and 2. Finally, the resulting path of marginal damages is discounted and summed to calculate

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the present value of the marginal damages in the year when the additional unit of emissions used to perturb the model is emitted.

The USG repeated this process with each model, discount rate, and socio-economic-emissions scenario for each decade between 2010 and 2050. Because the ECS parameter is modelled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run represents a distribution over the SC-CO_2 in each year. These distributions were estimated using 10,000 simulations in each model run. Therefore, the exercise produced 45 separate distributions of the SC-CO_2 for a given emissions year, based on the three models, three discount rates, and five socio-economic-emissions scenarios considered. To provide a range of estimates that reflects this uncertainty but still emphasizes the central tendency, the distributions from each of the models and scenarios were equally weighted and combined to produce three separate probability distributions for the SC-CO_2 in a given year, one for each assumed discount rate. Four SC-CO_2 estimates were selected from these three probability distributions to reflect the global damages caused by one tonne of CO_2 emissions. Three estimates are based on the average SC-CO_2 across the three models and five socio-economic-emissions scenarios for the 5%, 3%, and 2.5% discount rates, respectively. The fourth value is the 95th percentile of the SC-CO_2 distribution at the 3% discount rate, and was chosen to represent potential higher-than-expected impacts from anthropogenic GHG emissions.

2.2. Existing estimates of the social cost of non-CO_2 GHG emissions

A significant limitation of the aforementioned USG interagency process is that the social costs of non-CO_2 GHG emissions were not estimated. Therefore, as an alternative to applying direct estimates for the social costs of non-CO_2 GHG emissions in the primary BCA, several recent USG regulatory analyses have approximated the benefits of non-CO_2 GHG emissions reductions in sensitivity analyses by transforming the non-CO_2 GHG emissions to 'CO_2-equivalents' using estimates of the GWP for the GHG in question and then using the USG SC-CO_2 for valuation (e.g. US EPA, 2012, 2013).

Gas comparison metrics, such as the GWP, have been designed to measure the impact of different GHGs relative to CO_2, where the point of comparison along the pathway from emissions to monetized damages (depicted in Figure 1) may differ across measures. The GWP, in particular, is designed to measure the additional radiative forcing (i.e. the amount of energy absorbed by atmospheric concentrations of GHGs) from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years). The GWP and other gas-comparison metrics are problematic as an SC-CO_2 scalar in BCA, as the remaining linkages in the pathway depicted in Figure 1 are complex and non-linear. Marten and Newbold (2012) demonstrate that using the GWP to adjust SC-CO_2 estimates to capture the impact of non-CO_2 gases provides a significant improvement over the implicit assumption that they are zero when such benefits are left unquantified, but may still underestimate mitigation benefits. Alternative gas comparison metrics that compare GHGs at different points in the chain of

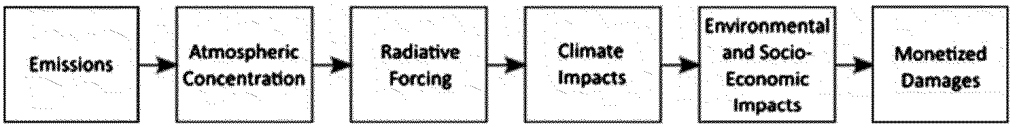

Figure 1 Path from GHG emissions to monetized damages

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causation (e.g. global temperature change potential (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005), peak commitment temperature (Smith et al., 2012), temperature proxy index (Tanaka, O'Neill, Rokityanskiy, Obersteiner, & Tol, 2009)) have also been shown to be imperfect substitutes for direct estimates.

Several researchers have directly estimated the social cost of non-CO_2 GHG emissions using IAMs, although the number of such estimates is small compared to the large number of SC-CO_2 estimates available in the literature. Among these previous direct estimates there is considerable variation in the model versions and input assumptions used. See Table 1 for a summary of the 11 non-CO_2 studies published to date.

As shown in Table 1, the estimates cover emissions years from 1990 to 2050, although the specific perturbation year is not stated in all studies. The studies also cover a wide range of constant and variable discount rate specifications and consider a range of baseline socio-economic and emissions scenarios that have been developed over the last 20 years. Finally, some studies in the literature have chosen not to report the social cost estimates directly. Instead, they opt to report only the 'global damage potential', which is a ratio of the social cost of gas X to the SC-CO_2. Normalizing the SC-CH_4 or

TABLE 1 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Model	Time horizon	Discount rate	Emissions year	Scenario[a]	Climate sensitivity
Reilly and Richards (1993)	N/A	140 years	2, 5, 8%	1990	N/A	N/A
Fankhauser (1994)	N/A	230 years	Ramsey	1991–2030	IS92[b]	N/A
Kandlikar (1995)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Kandlikar (1996)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Hammitt et al. (1996)	N/A	2200	1, 3, 5%	1995–2015	IS92a,c,e	1.5, 2,5, 4.5 8C
Tol (1999)	FUND 1.6	2100	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Tol et al. (2003)	FUND 1.7	2200	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Hope (2005)	PAGE95	2200	Ramsey	2000	SRES A2	Probabilistic, mode of 3 8C
Hope (2006a)	PAGE2002	2200	Ramsey	2001	SRES A2	Probabilistic, mean of 3 8C
Waldhoff et al. (2011)	FUND 3.5	3000	Ramsey	2010–2019	FUND, SRES A1B, A2, B1, B2	2, 3, 4.5 8C
Marten and Newbold (2012)	DICE2007 w/ MAGICC	2300	Ramsey, 2.5, 3, 5%	2010–2050	EMF-22 MiniCAM Base	Probabilistic,median of 3 8C

[a]IS90 scenarios are based on the IPCC First Assessment Report (IPCC, 1990); IS92 scenarios are based on the IPCC Supplementary Report (IPCC, 1992); SRES scenarios are based on the IPCC Special Report on Emissions (IPCC, 2000); the FUND scenario is the default scenario in the FUND model; EMF-22 scenarios are based on results from Stanford's Energy Modeling Forum's 22nd exercise (Clarke et al., 2009).[b]The particular IS92 scenario used was not specified.

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SC-N_2O estimate using the SC-CO_2, in part, controls for differences in the modelling to allow for a better comparison with other estimates in the literature.

Fankhauser (1994) was one of the first to develop estimates of the average SC-CH_4 and SC-N_2O for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt, Jain, Adams, and Wuebbles (1996) also developed estimates of SC-CH_4 and SC-N_2O for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006a) developed estimates for the SC-CH_4 in 2000 using the FUND and PAGE models, respectively. Waldhoff, Anthoff, Rose, and Tol (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal CO_2, CH_4, N_2O, and SF_6 emissions for the average year in the 2010 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios from the IPCC special report on emissions (IPCC, 2000) in addition to the default FUND scenario. In Section 4, the specific results of these previous studies are discussed with a comparison to the estimates obtained in the present study.

The above-mentioned previous studies provide a basic understanding of the relative social costs of different GHGs but do not provide sufficient information about how this relationship changes over time. Marten and Newbold (2012) used an IAM that couples the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) with economic components of the 2007 version of William Nordhaus' DICE model to directly estimate the social cost of marginal CO_2, CH_4, and N_2O emissions. They estimated the annual social costs for the years 2010–2050 along a single socio-economic-emissions pathway given uncertainty about the equilibrium climate sensitivity parameter. An advantage of their approach is that through the use of a more detailed, yet still relatively simple, climate model their results are not affected by over-simplification of temperature response or atmospheric chemistry, which have been shown to have non-negligible effects on the estimates of social costs (Marten, 2011; Warren et al., 2010).

The work of Marten and Newbold (2012) uses many of the assumptions used by the USG in its estimation of SC-CO_2, including discount rates, the equilibrium climate sensitivity distribution, and post-2100 socio-economic and emissions extrapolations. However, they focus on only one of the three models and one of the five socio-economic-emissions scenarios used by the USG. Furthermore, they use a different climate sub-model, which leads their estimate of the SC-CO_2 to be different from the USG estimate, even for the same IAM and scenario combination. Therefore, although these studies, including Marten and Newbold (2012), have increased our understanding about the relative social costs of GHG emissions, they have not provided a set of estimates that are entirely consistent with the USG SC-CO_2 estimates. In Section 4, the estimates derived in this article are compared with those of Marten and Newbold (2012) to more clearly demonstrate the similarities and differences in the two sets of estimates for SC-CH_4 and SC-N_2O.

3. Estimating the social cost of non-CO_2 GHGs consistent with USG SC-CO_2

The primary obstacle in estimating the social cost of non-CO_2 GHG emissions in a manner consistent with the USG SC-CO_2 estimates is that not all of the IAMs used include explicit representations of the non-CO_2 gases of interest. This section describes the degree to which non-CO_2 GHGs are currently

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represented in the default versions of DICE, PAGE, and FUND, and then discusses how they are amended to estimate the social cost of these gases.

3.1. Representation of non-CO_2 GHGs in DICE, PAGE, and FUND

The FUND model explicitly considers CH_4, N_2O, and SF_6 in addition to CO_2. The model uses one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels. For CH_4 and N_2O, FUND estimates the additional radiative forcing imposed by the atmospheric buildup of these gases using the simplified expressions presented in Chapter 6 of the IPCC's Third Assessment Report (TAR) (Ramaswamy et al., 2001). FUND also augments the TAR expression for the additional radiative forcing from CH_4 to account for the influences of stratospheric water vapour and tropospheric ozone changes. Because FUND uses CH_4 and N_2O emissions as inputs and internally computes their impact on the climate system, it is possible to directly estimate the social cost of those gases without modifying the model.

In the DICE model, the only GHG that is explicitly represented is CO_2; an exogenous radiative forcing projection is used to account for the impact of all other gases on the climate. To develop an exogenous radiative forcing pathway consistent with the emissions scenarios used to estimate the SC-CO_2, the USG decomposed the default DICE exogenous radiative forcing vector into CH_4, N_2O, F-gases, aerosols, and other residual forcing components. The USG then replaced the radiative forcing attributed to CH_4, N_2O, and F-gases with estimates associated with the EMF-22 scenarios. As non-CO_2 emissions are not a direct input into DICE, it is not possible to simply perturb the emissions projection and re-run the model to obtain a forecast of additional damages.

The 2002 version of the PAGE model, which was used by the USG in developing its first set of estimates (USG, 2010), includes an atmospheric model for CH_4 and SF_6, but represents the effects of other non-CO_2 GHGs in an exogenous radiative forcing projection. Presumably to simplify the process and maintain consistency with DICE, the USG did not use PAGE's internal CH_4 component. Instead, the same exogenous radiative forcing projection was used for the effect of CH_4, N_2O, and F-gas emissions as was used for DICE. Since then, a N_2O component has been added to the PAGE model, although in the recent 2013 SC-CO_2 update the USG maintained the approach of using the same single exogenous forcing projection as was applied to DICE (USG, 2013). Therefore PAGE, as implemented by the USG, faces the same limitations as DICE with respect to estimating the social costs of marginal non-CO_2 emissions that are consistent with the USG SC-CO_2 estimates. For these reasons, computing estimates for the social cost of non-CO_2 gases in DICE and PAGE requires either replacing the climate component of these models with a more complete representation, as was done with DICE by Marten and Newbold (2012), or deriving an estimate of the path of additional radiative forcing that would result from a perturbation of the gas in question. This article uses the latter approach for DICE and PAGE, as the former would represent a substantial change to the underlying IAMs and would have implications for the SC-CO_2 estimates, making this work inconsistent with the USG SC-CO_2 estimates currently used in regulatory analysis.

3.2. Estimating the social cost of non-CO_2 GHGs in DICE and PAGE

The process used in this article to estimate the social cost of non-CO_2 GHGs in DICE and PAGE as implemented by the USG requires first generating a forecast of the additional radiative forcing

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associated with a perturbation of a non-CO_2 gas's emissions in a single year, and then adding this radiative forcing perturbation to each model's exogenous radiative forcing projection. To determine the additional radiative forcing associated with the emission perturbation, there is a need to model the change in atmospheric concentration and the radiative forcing associated with the additional concentration. For both CH_4 and N_2O, a simple one-box atmospheric gas cycle model with a constant decay rate is used to estimate the atmospheric concentration of each gas based on its assumed emissions. The use of a one-box gas cycle for CH_4 and N_2O with constant decay follows the approach used by the IPCC to compute GWPs (Forster et al., 2007) and the FUND model (Anthoff & Tol, 2013). In both the baseline and the perturbed case, the contribution of the gas to the global radiative forcing anomaly is determined by the forcing relationships presented in the IPCC TAR (Ramaswamy et al., 2001), which were not updated by the IPCC in AR4. The incremental radiative forcing is defined by the difference between the baseline forcing path and the emissions path that includes a one tonne perturbation in a given year. Next, the path of additional radiative forcing is added to the stream of exogenous radiative forcing in each IAM to estimate the climate damages in the perturbed scenario. These damages are then compared to the baseline damages to determine the social cost of gas X (SC-X). Specifically, the process is as follows:

1. Run the IAM as described in the SC-CO_2 technical support document (USG, 2010) to estimate baseline damages.
2. Estimate the baseline atmospheric concentration for gas X.
3. Estimate the baseline radiative forcing contribution of gas X.
4. Perturb the stream of gas X emissions by one tonne in year t.
5. Estimate atmospheric concentration for gas X in the perturbed scenario.
6. Estimate the radiative forcing contribution of gas X in the perturbed scenario.
7. Compute the incremental radiative forcing as the difference between the results of steps 3 and 6.
8. Add the additional radiative forcing from step 7 to the exogenous radiative forcing path used in the IAM in step 1.
9. Re-run the IAM to compute the damages along the perturbed emissions path.
10. Compute the social cost of gas X for emission year t as the present value of the difference in damages estimated in steps 1 and 9.

Two practical issues associated with implementation are worth noting. First, while the SC-X estimates are associated with a one tonne perturbation, to avoid computational rounding error a 1 Mt perturbation is used and then the resulting change in damages is scaled to get the average effect per tonne. Experiments conducted by Griffiths et al. (2012) to assess the applicability of the SC-CO_2 to non-marginal emission changes show that the average per tonne SC-CO_2 estimate is relatively constant over large differences in perturbation size. Additional experiments in the context of this article found that alternative perturbation sizes do not significantly change the average one tonne social cost estimate. Second, the additional radiative forcing due to the emissions perturbation is computed based on an annual time step, but because DICE and PAGE use longer time steps the average radiative forcing over the time step is added to the model's exogenous radiative forcing vectors.

The remainder of this section describes the procedure for modelling the incremental radiative forcing of a perturbation for CH_4 and N_2O, and explores the sensitivity of these projections to

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two issues. First, it evaluates whether the simple one-box gas cycle model with a constant decay rate produces a close approximation to the forecasts of future atmospheric CH_4 and N_2O concentrations based on a more sophisticated climate model. Second, it explores the sensitivity of the results to the method used for extrapolating non-CO_2 emissions from 2100 to 2300. This is important, because the USG did not specify a particular set of emissions pathways for each constituent gas, instead assuming only that non-CO_2 radiative forcing remains constant past 2100. Such a situation could arise from a myriad of possible individual gas projections and the USG did not specify which it was assuming.

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3.3. Methane

A simple one-box atmospheric gas cycle model for methane specifies the concentration in year t, $C_t^{CH_4}$ [ppb], such that

$$C_t^{CH_4} = C_{t-1}^{CH_4} + d_{CH_4}(C_{pre}^{CH_4} - C_{t-1}^{CH_4}) + g_{CH_4}E_{t-1}^{CH_4}, \tag{1}$$

where d_{CH_4} defines the rate of decay, $C_{pre}^{CH_4}$ [ppb] is the pre-industrial atmospheric concentration, and g_{CH_4} [ppb/Mt] converts emissions, $E_{t-1}^{CH_4}$ [Mt], from mass to atmospheric volume. The mass to volume conversion factor is g_{CH_4} ¼ 0.3597 ppb/Mt and $C_{pre}^{CH_4}$ ¼ 700 ppb, following the IPCC TAR. The rate of decay is set to d_{CH_4} ¼ 1/12 following the IPCC AR4 stated CH_4 lifetime of 12 years. The iteration begins in the year 2006 using the emissions from the EMF-22 scenario (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used so that $C_{2005}^{CH_4}$ ¼ 1774 ppb.

The contribution of atmospheric methane to global radiative forcing, denoted $Q_t^{CH_4}$, is defined using the relationship in Table 6.2 of the IPCC TAR:

$$Q_t^{CH_4} = f\ 0.036\ \ C_t^{CH_4} - \ C_{pre}^{CH_4}\ - [f(C_t^{CH_4}, C_{pre}^{N_2O}) - (C_{pre}^{CH_4}, C_{pre}^{N_2O})]\ , \tag{2}$$

where $C_{pre}^{N_2O}$ [ppb] is the pre-industrial atmospheric concentration of nitrous oxide and

$$f(C^{CH_4}, C^{N_2O}) = 0.47 \ln 1 + 2.01 \times 10^{-5}(C^{CH_4}C^{N_2O})]^{0.75} + 5.31 \times 10^{-15}C^{CH_4}(C^{CH_4}C^{N_2O})^{1.52}\ . \tag{3}$$

The function in expression (3) accounts for the overlapping absorption bands of CH_4 and N_2O, thereby reducing their effective absorption. Parameter f is used to proxy for indirect effects of CH_4 that include the enhancement of stratospheric water vapour and tropospheric ozone changes. Following the IPCC AR4, an enhancement effect of 40% (25% from tropospheric ozone change and 15% for stratospheric water vapour enhancement) is used, such that f ¼ 1.4. The pre-industrial concentration of N_2O is set consistent with the IPCC TAR, such that $C_{pre}^{N_2O}$ ¼ 270 ppb.

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A key simplification in this approach is the constant decay rate used in the atmospheric gas cycle model. As discussed by IPCC Working Group I in Chapter 4 of the TAR, the lifetime of methane emissions in the atmosphere depends on temperature and the concentrations of CO, NOx, and other VOCs in the atmosphere (Ehhalt et al., 2001). Sensitivity analysis is used to understand the potential implications of ignoring these interactions by comparing the incremental atmospheric concentration projected by the simple model described above to the analogous projection from the climate model MAGICC,[3] which, while still relatively simple, incorporates these interactions between the lifetime of CH_4 in the atmosphere and the other gases and climate variables. This exercise uses CH_4 emissions from the EMF-22 MiniCAM reference scenario and considers a one tonne perturbation of CH_4 in 2015. It is noted that these results are robust across alternative emissions levels.[4]

Figure 2(a) presents the projected average decadal increment to atmospheric concentrations using both the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. At the time of the perturbation (2015), the inter-annual time step of MAGICC allows for an uptake of the additional emissions into the atmosphere, whereas the strict annual time step of the simple model causes a year to pass before the change is registered. After the initial year, the models originally differ by around 15%. This difference falls to under 10% within the first decade, with the faster effective growth in the simple model causing its additional concentration to eventually fall below that of MAGICC.

The difference in the incremental radiative forcing from the perturbation between the simple model and MAGICC is also of importance. Although MAGICC relies on similar equations to derive the radiative forcing of atmospheric CH_4 concentrations, it differs in the way it handles indirect effects of CH_4 on tropospheric ozone and stratospheric water vapour, in addition to including other temperature-related feedbacks. Figure 2(b) presents the average additional radiative forcing per decade attributed to the 2015 CH_4 perturbation in both models. The average increase in radiative forcing over the decade is considered because this is the input required by DICE due to its ten-year time step and therefore a more relevant comparison (PAGE requires a similar multi-year average). When considering the average additional radiative forcing over the decade, the initial difference in concentration between MAGICC and the simple model has a minimal effect and the difference in radiative forcing between the two models is less than 2% over the first two decades. However, this difference grows to –18% over the subsequent two decades. This escalation in the difference is in part due to the use of a constant decay rate in the simple model, whereas MAGICC takes into account the growing atmospheric concentrations of other gases and increasing atmospheric temperature, which increase the lifetime of atmospheric CH_4.

To understand the effect that this difference would have on an estimate of the SC-CH_4, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of CH_4, as computed using both the simple model and MAGICC, is added to the exogenous forcing projection. As above, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 2 presents the results of this experiment. In line with the results comparing the radiative forcing perturbations above, the two approaches produce similar social cost estimates for emissions in 2015, where additional analysis has shown these results to hold with PAGE as well. The impact of assuming a constant decay rate is greater further out into the future, due to the projected increase in the atmospheric concentration of other relevant gases and atmospheric temperature that are accounted for in MAGICC, and the social cost

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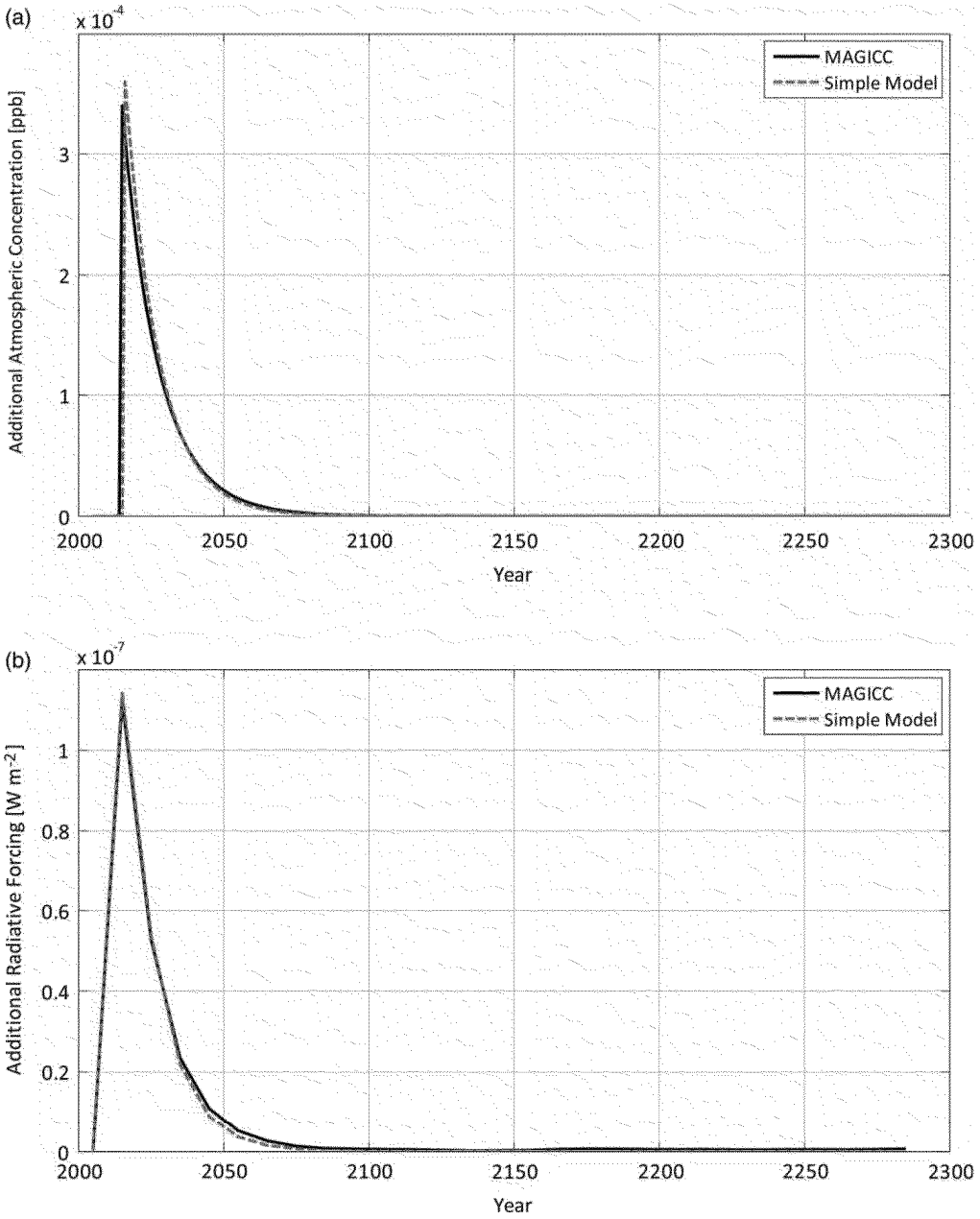

Figure 2 Effects of perturbation in 2015 CH_4 emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

estimates begin to diverge for later emissions years. For the same reason, the two approaches will show greater differences for lower discount rates that give increased weight to future time periods. While over-simplification of the climate system can, in some circumstances, have significant effects on

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TABLE 2 Effect of CH_4 gas cycle model on SC-CH_4 (2007$ per tonne CH_4): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	1135	1183	2 4%
	3.0%	822	851	2 3%
	5.0%	349	354	2 2%
2045	2.5%	2490	2707	2 8%
	3.0%	1933	2084	2 7%
	5.0%	956	1006	2 5%

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social cost estimates (e.g. Marten 2011), the near-term differences based on this simplification seem relatively small considering the precision of such social cost estimates.

3.4. Nitrous oxide

The simple one-box atmospheric gas cycle model for N_2O takes a similar form to the model used for CH_4, such that the concentration of nitrous oxide in year t, $C_t^{N_2O}$ [ppb], is specified as

$$C_t^{N_2O} = C_{t-1}^{N_2O} + d_{N_2O}(C_{pre}^{N_2O} - C_{t-1}^{N_2O}) + g_{N_2O}E_{t-1}^{N_2O}, \tag{4}$$

where d_{N_2O} is the rate of decay, and g_{N_2O} [ppb N_2O/Mt N] converts emissions, $E_{t-1}^{N_2O}$ [Mt N], from mass to atmospheric volume. Following the IPCC AR4, the mass to volume conversion factor is g_{N_2O} ¼ 0.2079 ppb N_2O/Mt N and the rate of decay is d_{N_2O} ¼ 1/114 based on a 114-year lifetime. As with CH_4, the iteration begins in the year 2006 using the emissions from the EMF-22 scenarios (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used, such that $C_{2005}^{N_2O}$ ¼ 319 ppb.

The contribution of atmospheric N_2O to global radiative forcing, denoted $Q_t^{N_2O}$, is defined using the relationship in Table 6.2 of the IPCC TAR, such that

$$Q_t^{CH_4} = 0.12 \left[C_t^{N_2O} - C_{pre}^{N_2O} - [f(C_{pre}^{CH_4}, C_t^{N_2O}) - f(C_{pre}^{CH_4}, C_{pre}^{N_2O})], \right. \tag{5}$$

where $f(C^{CH_4}, C^{N_2O})$ is defined in expression (3).

As with CH_4, a key simplifying assumption is the constant decay rate used in the simple gas cycle model (and potentially the time it takes the gas to become well mixed within the atmosphere). As discussed in the IPCC TAR, the decay rate of N_2O will depend on the atmospheric concentration of N_2O and so will not be constant in reality. To examine the extent to which this impacts the results of the simple model, an analogous set of experiments as conducted for CH_4 were performed. Given future

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N_2O emissions based on the EMF-22 MiniCAM reference scenario, a one tonne N_2O perturbation in 2015 is considered. Figure 3(a) shows the projected atmospheric concentration increase from the perturbation using the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. This comparison illustrates that the simple model tracks the output of MAGICC well for the entire 300-year time horizon. Outside the initial perturbation year, the two projections do not differ by more than 2% within the first century, with the largest difference occurring in the perturbation year, for the same reasons as with CH_4.

Figure 3(b) presents the estimates of average additional radiative forcing per decade as a result of the N_2O perturbation using both models. The additional radiative forcing from the N_2O perturbation in the one-box model is forecast to be slightly lower (7%) in the first decade compared to MAGICC. Subsequently, the difference is within 2% through to 2300.

As with CH_4, to assess the effect that this difference would have on the SC-N_2O, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of N_2O computed using both the simple model and MAGICC is added to the exogenous forcing projection. As before, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 3 presents the results of this experiment. As the comparisons of the projected radiative forcing perturbations would suggest, the difference between the social cost estimates for the two approaches is relatively small. In contrast to the case of CH_4, here an increase in the discount rate increases rather than decreases the divergence between the estimates due to the greater weight being placed on the earlier years when the radiative forcing perturbations have a slightly higher degree of divergence.

3.5. Effect of post-2100 non-CO_2 radiative forcing assumptions

The EMF-22 socio-economic-emissions scenarios used by the USG include years only up to 2100, while the USG ran the IAMs out to 2300. Therefore, additional assumptions were required to extrapolate the scenarios beyond 2100. For the purposes of this study, the most important of these assumptions is that non-CO_2 radiative forcing will remain constant at its 2100 level until 2300. Such a broad assumption was sufficient for the purposes of the USG in estimating the SC-CO_2. However, estimating the social cost of non-CO_2 GHGs requires explicit projections of baseline emissions of non-CO_2 gases in order to correctly determine the effect of the perturbation. The USG's broad assumption regarding the extrapolation of non-CO_2 gases is therefore problematic as constant non-CO_2 radiative forcing post 2100 may occur in an infinite number of ways. For instance, one way to achieve this outcome is to assume that emissions of each non-CO_2 gas falls to a level equal to its respective rate of decay in 2100. This assumption would keep atmospheric concentrations, and in turn radiative forcing, constant. Based on the simple gas cycle models laid out in the earlier sections this implies that, for gas X,

$$E_t^X = \frac{-d_X(C_{pre}^X - C_{2100}^X)}{g_X} \forall t \ . \ 2100. \tag{6}$$

To put this assumption into context, the solid lines in Figure 4(a) and (b) present the emissions paths for CH_4 and N_2O, respectively, under the MiniCAM EMF-22 reference scenario extrapolated using

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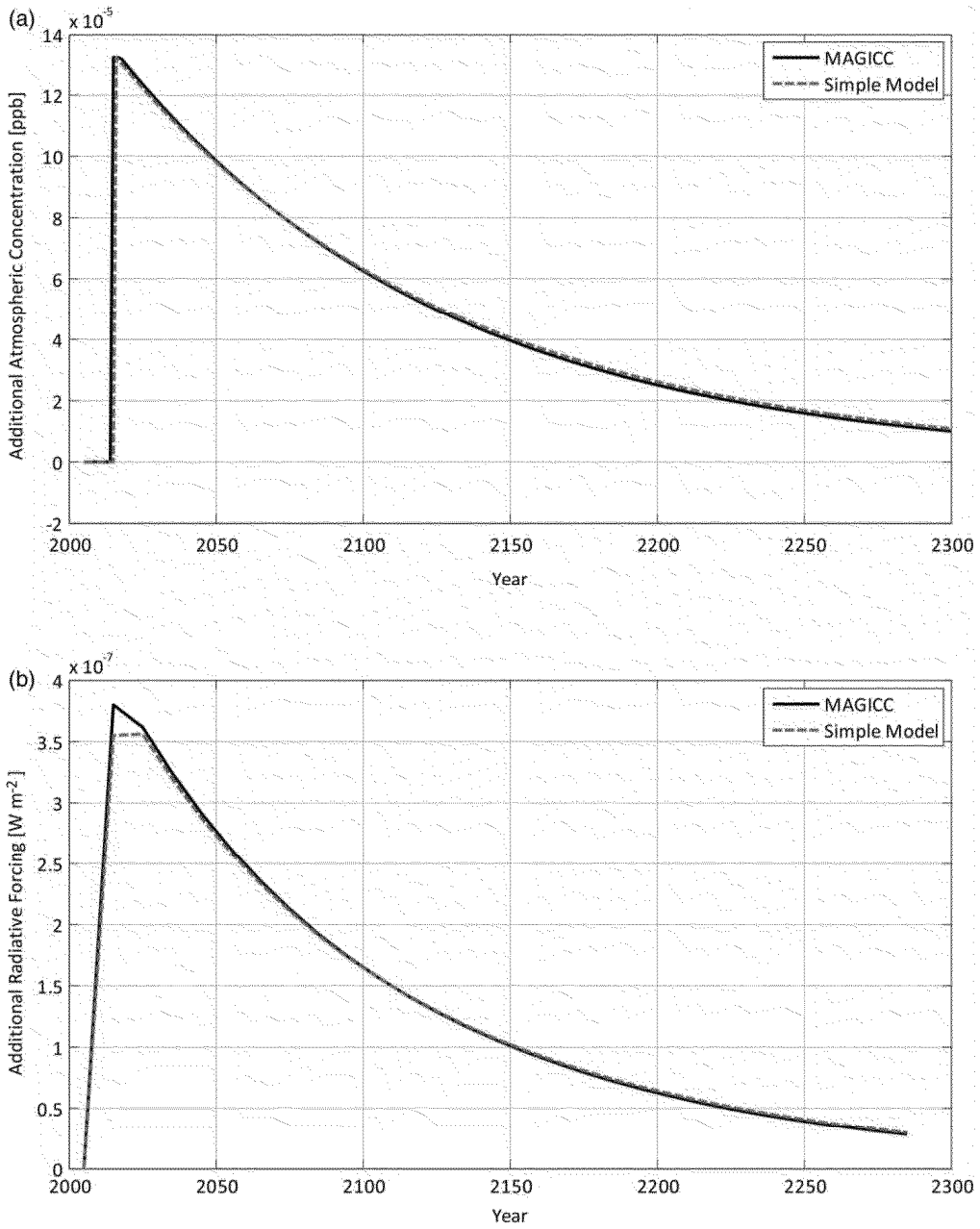

Figure 3 Effects of perturbation in 2015 N_2O emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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TABLE 3 Effect of climate model on SC-N_2O (2007$ per tonne N_2O): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	19,689	19,819	2 1%
	3.0%	12,390	12,525	2 1%
	5.0%	3,346	3,419	2 2%
2045	2.5%	36,968	37,358	2 1%
	3.0%	25,030	25,427	2 2%
	5.0%	8,280	8,528	2 3%

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expression (6), while the dashed lines show two alternative extrapolation approaches, one where emissions are held constant at their 2100 level and one that assumes emissions intensity (emissions/economic output) continues to decline at the same rate forecast by the EMF-22 scenario in 2090–2100 (dotted line). This latter alternative is analogous to the USG assumption regarding industrial CO_2 emissions. The two alternatives will not result in the radiative forcing contribution of gas X remaining constant post-2100, but do not in themselves violate the assumption that overall non-CO_2 radiative forcing remains constant. Noteworthy is the fact that the assumption in (6) is almost analogous to keeping CH_4 emissions constant at their 2100 levels, whereas for N_2O the assumption requires a sudden decrease in emissions of over 35%.

While Figure 4 illustrates that these three extrapolation approaches can lead to vastly different projections for emissions after 2100, the relevant comparison is how these assumptions affect the additional radiative forcing from a perturbation of the gas and in turn the SC-X estimates. Figure 5(a–d) present the additional radiative forcing resulting from a one tonne perturbation based on the simple model presented in Sections 3.1 and 3.2. Figure 5(a) and (b) demonstrates the difference for a perturbation in 2015, whereas Figure 5(c) and (d) represents perturbations in 2045. For CH_4, the cumulative radiative forcing from the projection over the time horizon differs by less than 0.001%, even for a

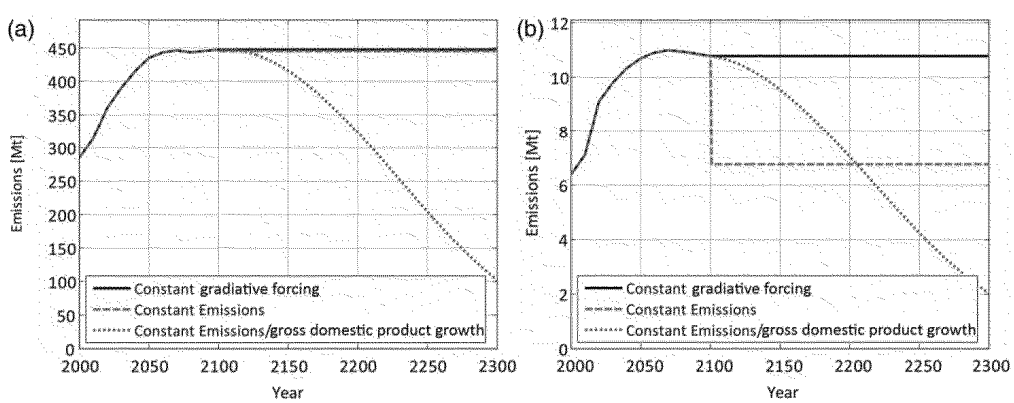

Figure 4 EMF-22 MiniCAM extended emissions scenario: (a) CH_4 emissions; (b) N_2O emissions

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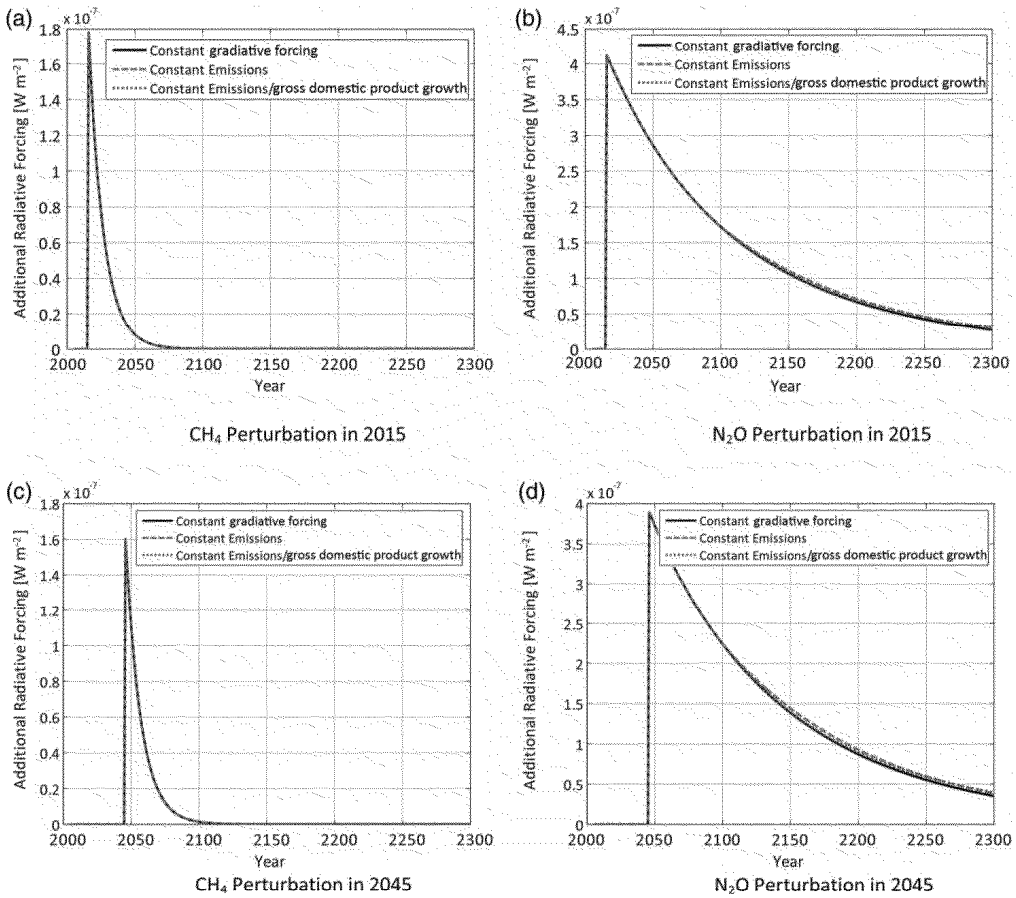

Figure 5 Effect of extrapolation approach on radiative forcing perturbation from simple model: (a) CH_4 perturbation in 2015; (b) N_2O perturbation in 2015; (c) CH_4 perturbation in 2045; (d) N_2O perturbation in 2045

perturbation in 2045. Accordingly, the relevant annual difference is smaller even than one-thousandth of a percent. This result occurs because of the short atmospheric lifetime of the gas, which renders assumptions regarding CH_4 emissions after 2100 unimportant for near-term perturbations. Post-2100 emissions will have a larger effect in the case of N_2O, which has a much longer atmospheric residence time. However, even for a perturbation in 2045, the difference in cumulative additional radiative forcing is less than 2.5% across the extrapolation assumptions.

To examine the impact of these assumptions on SC-CH_4 and SC-N_2O, an experiment was conducted using the DICE model based on the EMF-22 MiniCAM socio-economic-emissions scenario. The results of this experiment are presented in Table 4 for the perturbation year 2045 (noting that the extrapolation method will have greater impact on future emissions years). As may be seen, the relatively short atmospheric lifetime of CH_4 leads to a situation in which post-2100 assumptions do not affect SC-CH_4 estimates, even in 2045. For the longer-lived gas N_2O, in emission year 2045, where the effect of the post-2100 extrapolation approach would be largest, the difference across the three

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TABLE 4 Effect of post-2100 extrapolation on the 2045 SC-X (2007$ per tonne): DICE2010, MiniCAM

Gas	Discount rate	Constant RF	Constant emissions	Constant emissions intensity growth
CH_4	2.5%	2,490	2,490	2,490
	3.0%	1,933	1,933	1,933
	5.0%	956	956	956
N_2O	2.5%	36,968	36,588	36,662
	3.0%	25,030	24,837	24,868
	5.0%	8,280	8,261	8,263

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assumptions is less than 1% and the projections are equivalent to two significant digits. Therefore, in the remainder of this article, non-CO_2 emissions are extrapolated past 2100 using expression (6) to ensure that the gas-specific contribution to overall radiative forcing remains constant in the simple model. While additional study may lead to improvements of long-term forecasts of CH_4 and N_2O emissions and possible correlations, compared to the paths in Figure 5(a), the very minimal effect of such assumptions on the social cost estimates suggests the impact of such efforts would be minimal in this context.

4. Results

For FUND, the social cost of non-CO_2 GHGs is estimated by perturbing the paths of emissions directly, while for DICE and PAGE the approach presented in Section 3 is used. In both cases, all additional assumptions made by the USG are applied, including the five EMF-22 socio-economic-emissions scenarios, the Roe and Baker (2007) distribution for the equilibrium climate sensitivity, and constant discount rates of 2.5%, 3.0%, and 5.0%. Following the USG, the estimates for the expected social cost are averaged across scenarios and models, with each model and scenario given equal weight. Estimates are not combined across discount rates, and a fourth estimate is included representing the 95th percentile when using the 3.0% discount rate. By using the same assumptions and procedures as the USG, estimates of the SC-CO_2 derived in this article are identical to the values used in US Federal rule making. Specifically, these estimates are equivalent to the recent 2013 update of the USG SC-CO_2, which revised the original 2010 USG upwards based on new versions of the IAMs used. The non-CO_2 results, as well as the USG SC-CO_2 estimates, are presented in Table 5 for emissions years 2020 and 2050.[5] Results for additional years, and the results of sensitivity analyses using Ramsey discounting, may be found in Appendix B and C, respectively.

As expected, considering their higher radiative efficacy, the social costs associated with a tonne of CH_4 and N_2O emissions are substantially higher than for CO_2. The values are higher at lower discount rates, although the impact of the discount rate is lower for CH_4 given its relatively short lifetime. Similar to CO_2, the social cost estimates for CH_4 and N_2O increase over time as the climate and economic systems become more stressed, although the growth rate of the social cost estimate may differ between the gases, as discussed in the following.

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TABLE 5 SC-X (2007$ per tonne)

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CO_2	12	43	64	128
	CH_4	550	1,200	1,600	3,200
	N_2O	4,800	15,000	22,000	41,000
2050	CO_2	26	71	97	220
	CH_4	1,400	2,500	3,100	6,900
	N_2O	11,000	27,000	38,000	74,000

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To better understand how the social costs of CH_4 and N_2O compare to CO_2, Table 6 presents the global damage potentials corresponding to the social cost estimates from Table 5. (The disaggregated results, by model and scenario, for 2020 are provided in Appendix B.) As explained in Section 2, the global damage potential for gas X is the ratio of SC-X to SC-CO_2, and therefore by construction captures all the important linkages between emissions and monetized climate change damages (to the degree they are captured by the IAMs) directly within the gas comparison metric. As noted by Frankhauser (1994), this is preferred to the commonly used GWP gas comparison metric, which only measures the additional radiative forcing from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years) and ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages.

The global damage potential of CH_4 decreases with the discount rate due to the relatively shorter atmospheric lifetime. This difference in atmospheric lifetime leads to a situation where lowering the discount rate has a greater impact on the SC-CO_2 than the SC-CH_4. This finding is robust across the models. The estimates in Table 6 also present the same result for N_2O in the aggregate case, although this characteristic is not consistent across the models or the previous literature. Based on the disaggregated results (presented in Appendix B), the results from the DICE model suggests the global damage potential for N_2O increases with lower discount rates due to a lower effective decay rate over the relevant time horizon for N_2O than CO_2. This result is consistent with previous findings by Marten and Newbold (2012). However, for FUND the opposite is seen to hold. Waldhoff et al. (2011) show that this result is primarily due to the inclusion of increased production in the agriculture and forestry sectors from CO_2 fertilization effects. At lower discount rates these benefits place a greater downward

TABLE 6 Global damage potential

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CH_4	46	29	25	25
	N_2O	397	359	353	317
2050	CH_4	52	36	32	31
	N_2O	414	388	387	338

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impact on the SC-CO_2, thereby lowering the global damage potential. If one were to remove those impacts from the FUND model the global damage potential for N_2O becomes relatively insensitive to the discount rate. One would expect the role of the discount rate in determining the global damage potential in PAGE to be the same as in DICE, but the results suggest that this is not the case. It seems most likely that this is because the PAGE model has only ten time steps to cover the entire time horizon, which results in very large, up to 100-year, time steps further out in time. As noted in Section 3, the additional radiative forcing from the N_2O perturbation is implemented as the average across the model's time steps. It seems that PAGE does not average radiative forcing over the time step for CO_2, which causes the global damage potential for N_2O to decrease with the discount rate. It is not clear if this result would hold if the size of the time steps in the model were reduced.

A comparison across models further highlights the importance of CO_2 fertilization impacts on the global damage potential. CO_2 emissions, and the resulting increase in atmospheric concentration, have the potential to increase yields in the agriculture and forestry sector. This characteristic is not shared by other GHG emissions. Accordingly, the FUND model, which explicitly captures this effect, exerts downward pressure on the SC-CO_2 that is not present for the SC-CH_4 and SC-N_2O, allowing for the possibility of substantially higher global damage potential estimates. The results based on the FUND model presented in this article exhibit this effect; however, the CO_2 fertilization effect is not explicitly modelled in DICE and PAGE and therefore they are found to produce lower estimates of the global damage potential. For example, using the 3% discount rate, the global damage potential for CH_4 as estimated by FUND ranges between 58 and 88 depending on the scenario, whereas it ranges from 19 to 28 for DICE and PAGE. As the DICE and PAGE models only consider two natural system impacts, temperature and sea level, if they do implicitly include potential CO_2 fertilization benefits, they are included by using the temperature anomaly as a proxy for the increasing atmospheric CO_2 concentration. Fertilization benefits would therefore be allowed to falsely accrue to perturbations of other GHG emissions besides CO_2. It is not clear the degree to which these models try to incorporate CO_2 fertilization effects and therefore the degree to which this issue is of concern.

Finally, the results in this article show that the 100-year GWP (25 for CH_4 and 298 for N_2O; Forster et al., 2007) probably provides an underestimate of the global damage potential of each gas, a finding consistent with previous studies by Marten and Newbold (2012) and Waldhoff et al. (2011). Unlike the GWP as calculated by the IPCC, the global damage potential will be dependent upon the year of the emissions perturbations, so the degree of underestimation varies by year. For CH_4, the global damage potential in Table 6 is 0–84% higher than the GWP in 2020, increasing to 24–108% in 2050. For N_2O, the global damage potential is 6–33% higher than the GWP in 2020, increasing to 13–39% in 2050. While inaccurate, using the GWP to convert emissions reductions into CO_2 equivalents that can be valued with the SC-CO_2 would probably provide a conservative estimate for the abatement benefits.

For the comparison above, the GWP estimates presented in the AR4 by the IPCC (Forster et al., 2007) were used to maintain consistency with the assumptions regarding the direct and indirect effect of CH_4 and N_2O concentrations within the modelling. The recent AR5 by the IPCC (Myhre et al., 2013) has increased the estimate of the indirect effects of CH_4, which gives a higher 100-year GWP for CH_4 of 28. A reduction in their estimate of the radiative efficacy of N_2O has decreased its 100-year GWP to 265. It is likely that updated modelling of the social cost estimates based on similar assumptions would maintain the finding that the GWP is an underestimate of the global damage potential.

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4.1. Comparison with previous estimates

For comparison, Table 7 presents the social cost estimates, when available, and the global damage potential estimates for CH_4 and N_2O from three recent studies in the literature whose features are more up to date and therefore more directly comparable with this study: Hope (2006a), Waldhoff et al. (2011), and Marten and Newbold (2012). A direct comparison to the longer list of studies presented in Table 1 is more difficult as they are based on models and socio-economic and emissions scenarios that were developed up to 20 years ago in a rapidly evolving field.

The social cost estimates presented in Table 5 are higher than the estimates in Hope (2006a) and Waldhoff et al. (2011) for CH_4, and in the range of Waldhoff et al. (2011) for N_2O. This result holds whether the comparison is made with the aggregate results in Table 5 or the disaggregated model-specific results. One reason for the significant difference in the SC-CH_4 estimates is that the earlier studies rely on older model versions (PAGE2002 and FUND3.5), neither of which include the indirect effects of CH_4 emissions on radiative forcing, but are included within this analysis. As noted in Section 3.3 the indirect effects of CH_4 are modelled as a 40% increase in its effective radiative forcing. The result of this change alone would likely be a greater than 40% increase in the SC-CH_4 due to the nonlinear damage functions. Furthermore, the assumptions regarding preference parameters in the main cases of Hope (2006a) and Waldhoff et al. (2011) lead to effective discount rates that are significantly higher than 3%. Other differences in input assumptions (e.g. equilibrium climate sensitivity, socio-economic emissions scenario) will also lead to differences, although these are likely to be of second-order importance given the relative similarity in the assumptions.

However, the results in Table 5 averaged across the combinations of the three models and five scenarios are relatively similar to those of Marten and Newbold (2012), which focused on a single scenario

TABLE 7 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Discount Rate	Emissions Year	Social cost (2007$/tonne X)[a]		Global damage potential (SC-X/SC-CO_2)	
			SC-CH_4	SC-N_2O	CH_4	N_2O
Hope (2006a)	Ramsey	2001	125	–	20	–
Waldhoff et al. (2011)[b]	Ramsey	2010–2019	265	7,616	26	738
			–	–	8–221	383–3,503
Marten and Newbold (2012)	2.5%	2020	1,500	26,000	23	403
		2050	3,500	50,000	32	444
	3%	2020	1,100	17,000	27	400
		2050	2,900	34,000	36	439
	5%	2020	550	4,900	42	380
		2050	1,500	12,000	53	415

[a]All values are discounted to the year of the emissions perturbation.
[b]The first row presents the base case and the second row presents the range found from sensitivity analysis (over socio-economic scenario, climate sensitivity, pure rate of time preference, climate sensitivity and CO_2 fertilization).

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and model. This result is in part based on the fact that both sets of results include the indirect effects of CH_4, use the same discount rates and equilibrium climate sensitivity distribution, and relatively similar scenarios. The estimates in this study are slightly higher for the SC-CH_4 and slightly lower for the SC-N_2O compared to Marten and Newbold (2012). Of particular interest is the specific comparison of this article's estimates based on DICE 2010 and the MiniCAM scenario to those of Marten and Newbold (2012) using the same scenario, discount rates, and equilibrium climate sensitivity but an the older 2007 version of the DICE model and a more complete climate sub-model. In this case, estimates for both the SC-CH_4 and SC-N_2O (presented in Appendix B) are notably lower. The myriad of differences between the model vintages and climate sub-models make it difficult to assess which differences are most important for explaining this relationship.

As previously noted, the global damage potential may provide a better value with which to compare across studies that estimate the social cost of non-CO_2 GHG emissions, as it helps to control for some of the underlying differences in assumptions across studies. For example, the global damage potential is far less sensitive to the discount rate used than the SC-X values themselves. However, the global damage potential does not address the lack of indirect CH_4 effects, as may be seen in the lower estimates of Hope (2006a) and Waldhoff et al. (2011). In these cases the exclusion of the 40% additional increase in radiative forcing from the indirect effects of the CH_4 perturbation explains the majority of the difference. In comparison to Marten and Newbold (2012), the results presented in Table 6 are relatively similar for CH_4 in both the aggregate and disaggregated results. For N_2O, similar results are found in the DICE estimates, but notable differences are found in how the aggregate results respond to the discount rate, due to the differences in this relationship between the models as noted above.

5. Concluding remarks

This article presents a simple and transparent approach to estimating the social cost of CH_4 (SC-CH_4) and N_2O (SC-N_2O) in a manner that is consistent with estimates of the social cost of CO_2 (SC-CO_2) already in use in benefit–cost analysis (BCA) for US Federal regulations. This approach is used to estimate the SC-CH_4 and SC-N_2O for the period 2010–2050. These directly modelled estimates are found to be larger than approximations of the social costs of these gases based on the application of common physical gas comparison metrics, such as global warming potentials (GWPs), to the SC-CO_2. This result generalizes the empirical findings of Marten and Newbold (2012) that using a GWP-based approximation approach will likely offer a conservative estimate of the social cost of non-CO_2 GHGs.

The social costs associated with emissions of non-CO_2 GHGs are substantial and should be included within the BCAs used to assess the overall welfare implications of policy alternatives. For example, by not including monetized values of the benefits from reducing CH_4 and N_2O emissions, the BCA for recent standards regulating the fuel efficiency and GHG emissions of light duty vehicles implicitly assigned them a value of zero (US EPA, 2010). However, the results of this article suggest that those reductions have benefits of US$85–493 million (2007$) for CH_4 and $1.5–12 million (2007$) for N_2O in the year 2020 alone. Failing to account for such impacts could limit the ability of the analysis to serve as a transparent and informative input into the decision-making process about the relative benefits and costs of regulatory alternatives. That said, by restricting the article to a derivation of social cost estimates consistent with the USG SC-CO_2 estimates, the myriad issues related to

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whether those estimates can themselves be improved are set aside.[6] Any limitations that apply to the USG SC-CO_2 estimates therefore also apply to the SC-CH_4 and SC-N_2O estimates derived here.

Supplemental data

Supplemental data for this article can be accessed 10.1080/14693062.2014.912981.

Notes

1. Examples include Minnesota's draft methodology for setting the value of a tariff to compensate solar panel owners for the surplus power they deliver to utilities (http://www.eenews.net/stories/1059992297, http://mn.gov/commerce/energy/images/DRAFT-MN-VOS-Methodology-111913.pdf), the Northwest Power and Conservation Council's symposium supporting the development of the 7th Power Plan (http://www.nwcouncil.org/energy/powerplan/7/symposiums/greenhouse/agenda), BCA of Canada's Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations (http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html), analysis of climate change projects at the Inter-American Development Bank (correspondence with Patrick Doyle, Senior Climate and Energy Officer, Structured and Corporate Finance Department), the International Monetary Fund's recent Energy Subsidy Reform report (http://www.imf.org/external/np/pp/eng/2013/012813.pdf), and Parry and Strand (2012).
2. An alternative approach for estimating the social cost of GHG emissions could be based on stated preference (SP) surveys designed to elicit respondents' maximum willingness-to-pay for various levels of GHG emission reductions (e.g. Longo, Markandya, & Petrucci, 2008; Soliño, 2010). This approach would not suffer from the difficulties associated with creating and parameterizing a numerical integrated assessment model. However, it would suffer from its own set of difficulties, including well-known general limitations that affect all SP studies including the potential for 'hypothetical bias' (e.g. Carson, 2012; Hausman, 2012; Kling, Phaneuf, & Zhao, 2012), plus difficulties that may be specific to this application stemming from the generally limited knowledge base regarding the potential climatic, biophysical, and especially economic impacts of GHG emissions on current and far future generations that most respondents will bring to the survey.
3. The fork of MAGICC version 5.3 included in Pacific Northwest National Laboratory's open source model GCAM version 2 (Calvin et al., 2009) is used without carbon cycle feedbacks and, unless otherwise specified, an equilibrium climate sensitivity of 3 8C. We note that sensitivity analysis found the general results of this side analysis to be robust to other values of the equilibrium climate sensitivity.
4. The EMF-22 scenario is extended past 2100 assuming that emissions stay constant at the 2100 level. This assumption is revisited later in this article.
5. The PAGE 2009 model restricts the user to representing the entire time horizon, in this case out to 2300, with only ten time steps. This leads to the unrealistic situation in a small number of simulations where the marginal unit of emissions can cause 'catastrophic' climate impacts to occur one period earlier, which could be 100 years earlier in some cases. We consider these occurrences to be a limitation of the model and drop them from the overall distribution of estimates. Appendix A contains further details about this issue.
6. In addition to the critiques previously cited, we point the interested reader to the work of Marten et al. (2013) and Oppenheimer (2013) for a review of literature that considers potential improvements in the assessment and valuation of climate change impacts.

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National Freedom of Information Officer
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Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1) All records discussing, describing, referring to or interpreting the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*").

2) To the extent not provided in response to request #1, all records of information relied upon by the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*") in the development of the *2010 TSD on SCC* and the *2013 TSD on SCC*, including but not limited to:

   a) Any presentations, reports, studies, computer or other analytical models, and data (including modeling data) created by or on behalf of the *IWG on SCC*, or provided to or obtained by the *IWG on SCC*.

   b) Any records that discuss, describe, interpret or otherwise relate to the Integrated Assessment Models ("IAMs") referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to:

      i) any inputs and assumptions (including but not limited to assumptions on discounting, equilibrium climate sensitivity, and socioeconomic variables);

      ii) the results of any modeling runs or scenarios generated by the IAMs (in both paper copies and in original electronic form); and

      iii) the source codes for the DICE, PAGE and FUND models referred to in the *2010 TSD on SCC* or *2013 TSD on SCC* (in the original electronic form, such as native modeling formats).

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c) Any records that identify, discuss, interpret or relate to any uncertainties or error rates of the *2010 TSD on SCC* or the *2013 TSD on SCC* or any of the IAMs referenced in or relied upon by the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to any limitations in using the DICE, PAGE or FUND models to make predictions beyond the year 2100.

d) Any records that discuss, interpret or explain why the social cost of carbon estimated by the *2013 TSD on SCC* is approximately 60% higher than that estimated by the *2010 TSD on SCC*.

e) Any records that discuss, interpret, relate to, explain or make recommendations or decisions regarding global versus domestic measures of the social cost of carbon with respect to the work of the *IWG on SCC* and the *2010 TSD on SCC* or *2013 TSD on SCC*, including but not limited to the calculation or use of a domestic SCC for the United States.

3) Any records discussing, interpreting, transmitting or relating to any critiques, analyses or studies of the *2010 TSD on SCC* or *2013 TSD on SCC*, or any data, information or models relied on or referred to in the *2010 TSD on SCC* or *2013 TSD on SCC*, including but not limited to the work or statements of Robert Pindyck.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and all other types of records in the possession, control or custody of EPA or contractors working for EPA.

For all records responsive to these requests that are not produced based on an asserted exemption from disclosure, please prepare a privilege and/or exemption log describing, at a minimum: (i) the type of record withheld; (ii) the date(s) of the creation of the record; (iii) the subject of the record; (iv) the identity of the author and all recipients of the records; and (v) a detailed description of the basis upon which EPA is withholding the record (e.g., the claim of privilege, FOIA exemption, etc.). To the extent any responsive documents are withheld based upon a claim of privilege or other exemption from disclosure, please produce redacted copies of all non-privileged or non-exempt factual material contained within such documents.

As required by law, please provide the above records within twenty (20) business days of receipt of this FOIA Request. 5 U.S.C. § 552(a)(6)(A)(i). If it appears that it may not be possible to provide all of the records by the statutorily-mandated deadline, please provide the responsive records that are available as of the deadline (i.e., do not withhold responsive records past the

deadline while searching for additional records), and please contact me promptly regarding any scheduling issues.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $500, I ask that you contact me prior to proceeding.

Thank you for your prompt attention to this request. Please direct any inquiries, notices, or determinations to me at (713) 495-4508 or cbell@sidley.com.

Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009618 (2)

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Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1. All records identifying the dates and attendees of meetings, or dates of and participants in teleconferences or webinars involving, the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*"), or any committee, working group, sub-committee, task force or project group thereof.
2. Any government contracts used to hire anyone to assist in the preparation of the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*"), including but not limited to, any government contracts used to hire anyone to perform the Integrated Assessment Modeling referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*.
3. Any records that describe, identify, contain, interpret or provide the dates or substance of briefings of political appointees in the Executive Branch on the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to, PowerPoint presentations. In the response, please produce the requested briefing records in their native original electronic form (PowerPoint, Word, etc.).
4. All electronic mail, WebEx documents, Google Docs, text messages, instant messages, voice mails, facsimiles or any other records relating to the *2010 TSD on SCC* or *2013 TSD on SCC* that were sent to any person outside the *IWG on SCC*, including but not limited to documents sent to or received from: any of the authors of the publications listed in the References section of the *2010 TSD on SCC* or *2013 TSD on SCC*; any other academics; government contractors; consultants; Sierra Club, Natural Resources Defense Council or other

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nongovernmental groups; and any other third-party whatsoever that was not part of the *IWG on SCC*.

5. All records discussing, describing, interpreting or relating to the applicability of or compliance with the Information Quality Act (P.L. 106-554, Section 515, 144 Stat. 2763 (2001)), or any Information Quality Act Guidelines published by the Office of Management and Budget, with respect to the work of the *IWG on SCC* or development, publication, use or dissemination of the *2010 TSD on SCC* or the *2013 TSD on SCC*.

6. All records discussing, interpreting or relating to the applicability of the Administrative Procedure Act (5 U.S.C. § 500 et seq.) to the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to whether those documents should have been published for public review and comment.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and all other types of records in the possession, control or custody of EPA or contractors working for EPA.

For all records responsive to these requests that are not produced based on an asserted exemption from disclosure, please prepare a privilege and/or exemption log describing, at a minimum: (i) the type of record withheld; (ii) the date(s) of the creation of the record; (iii) the subject of the record; (iv) the identity of the author and all recipients of the records; and (v) a detailed description of the basis upon which EPA is withholding the record (e.g., the claim of privilege, FOIA exemption, etc.). To the extent any responsive documents are withheld based upon a claim of privilege or other exemption from disclosure, please produce redacted copies of all non-privileged or non-exempt factual material contained within such documents.

As required by law, please provide the above records within twenty (20) business days of receipt of this FOIA Request. 5 U.S.C. § 552(a)(6)(A)(i). If it appears that it may not be possible to provide all of the records by the statutorily-mandated deadline, please provide the responsive records that are available as of the deadline (i.e., do not withhold responsive records past the deadline while searching for additional records), and please contact me promptly regarding any scheduling issues.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $500, I ask that you contact me prior to proceeding.

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Thank you for your prompt attention to this request. Please direct any inquiries, notices, or determinations to me at (713) 495-4508 or cbell@sidley.com.

Sincerely,

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Christopher L. Bell

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Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1. All records discussing, describing, referring or providing direction to, communicating to or about, or interpreting the formation, organization, structure, authority, activities, meetings, recommendations or decisions of the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*").
2. All records describing or discussing any past, on-going (as of the date of this submission) or planned work of the *IWG on SCC*.
3. All records describing, discussing or interpreting how the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*") have been or are to be used by Federal agencies, including but not limited to the use of these documents in the development and promulgation of regulations and in making policy decisions.
4. All records discussing or interpreting how the *2010 TSD on SCC* or the *2013 TSD on SCC* have been used or relied on, or are planned to be used, by EPA in any regulation proposed or promulgated by EPA, or in any policy decisions made by or guidance documents created by EPA.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and

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Pursuant to the Freedom of Information Act ("FOIA") 5 U.S.C. § 552, and the implementing regulations of the U.S. Environmental Protection Agency ("EPA"), 40 C.F.R. Part 2, I am requesting a copy of the following EPA records:

1. All petitions for rulemaking of any kind submitted to the EPA Administrator related to any statute or regulation under which the EPA Administrator has the authority to promulgate regulations from January 1, 2013, to the present. These include, but are not limited to, petitions under the Clean Air Act, the Clean Water Act, the Resource Conservation and Recovery Act, the Comprehensive Environmental Response, Compensation, and Liability Act, the Toxic Substances Control Act, and the Federal Insecticide, Fungicide, and Rodenticide Act.

2. All notices of intent to sue EPA or its Administrator, dated from January 1, 2013, to the present, under any of the statutes listed above or under the Administrative Procedure Act for:

a. Failure to timely act on any petition for rulemaking;

b. Failure to meet any statutory, regulatory, or other deadline; or

c. Failure to meet any nondiscretionary obligation..

This request is only seeking for the specific items referred to above, all of which would have been submitted to EPA by third parties. Therefore, this request does not seek any records that are exempt from disclosure.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $250, I ask that you contact me prior to proceeding.

Please direct any inquiries, notices, or determinations to me at (202) 736-8281. Thank you for your anticipated assistance.

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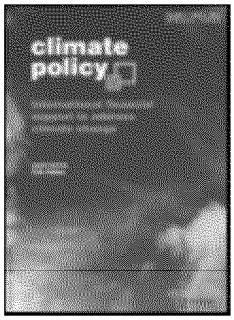

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

Alex L. Marten[a], Elizabeth A. Kopits[a], Charles W. Griffiths[a], Stephen C. Newbold[a] & Ann Wolverton[a]

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Published online: 20 May 2014.

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climate policy

B research article

Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Benefit–cost analysis can serve as an informative input into the policy-making process, but only to the degree it characterizes the major impacts of the regulation under consideration. Recently, the US, amongst other nations, has begun to use estimates of the social cost of CO_2 (SC-CO_2) to develop analyses that more fully capture the climate change impacts of GHG abatement. The SC-CO_2 represents the aggregate willingness to pay to avoid the damages associated with an additional tonne of CO_2 emissions. In comparison, the social costs of non-CO_2 GHGs have received little attention from researchers and policy analysts, despite their non-negligible climate impact. This article addresses this issue by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. By extending existing integrated assessment models, it is possible to develop a set of social cost estimates for these gases that are consistent with the SC-CO_2 estimates currently in use by the US federal government.

Policy relevance

Within the benefit–cost analyses that inform the design of major regulations, all Federal agencies within the US Government (USG) use a set of agreed upon SC-CO_2 estimates to value the impact of CO_2 emissions changes. However, the value of changes in non-CO_2 GHG emissions has not been included in USG policy analysis to date. This article addresses that omission by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. These new estimates are designed to be compatible with the USG SC-CO_2 estimates currently in use and may therefore be directly applied to value emissions changes for these non-CO_2 gases within the benefit–cost analyses used to evaluate future policies.

Keywords: integrated assessment; non-CO_2 GHGs; social cost of carbon

1. Introduction

The social cost of CO_2 (SC-CO_2) is a measure of the monetary value of the damages occurring both within and outside economic markets as the result of an additional unit of CO_2 emissions. Specifically, it represents society's aggregate willingness to pay to prevent future impacts that occur when one additional unit of CO_2 is emitted into the atmosphere in a particular year. Estimates of SC-CO_2

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therefore provide a way to value changes in CO_2 emissions in benefit–cost analyses (BCAs) of policy alternatives. Without an estimate of the SC-CO_2, the benefits of mitigating the climate change impacts from CO_2 emissions would implicitly be valued at zero in BCAs, thereby significantly weakening the information provided by such analyses. Since 2009, the US Federal Government (USG) has used a set of agreed-upon SC-CO_2 estimates in the BCAs used to evaluate major regulations that impact CO_2 emissions (USG, 2010), including over 30 regulatory actions to date. The USG SC-CO_2 estimates are also increasingly being used in analysis and discussions outside the USG (e.g. by states, regional organizations, other nations, international organizations, NGOs, and academic researchers)[1] and have even figured in several recent public hearings and court cases (e.g. Keohane, 2010a, 2010b).

Although CO_2 is the primary anthropogenic GHG, other GHGs such as methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are also important contributors to climate change. The combined effect of all GHGs accumulated in the atmosphere is to increase the Earth's radiative forcing, which is the amount of energy from the Sun that is trapped in the Earth's atmosphere and therefore acts to warm the planet and change the climate. In 2011, the atmospheric CO_2 concentration contributed 64% of overall radiative forcing, while CH_4 and N_2O accounted for approximately 23% (Myhre et al., 2013). Non-CO_2 GHGs, notably CH_4 and N_2O, therefore contribute significantly to the negative impacts on human well-being from climate change. Furthermore, several recent studies have shown that consideration of non-CO_2 GHGs, particularly CH_4 and N_2O, is important for the design of cost-effective climate policy (Reilly et al., 1999; Tol, Heintz, & Lammers, 2003; Weyant, De La Chesnaye, & Blenford, 2006).

The monetary value of changes in emissions of non-CO_2 GHGs has not been included in USG policy analysis to date. This shortcoming prevents the development of accurate and comprehensive assessments of potential regulatory alternatives by the USG and others that rely on the USG SC-CO_2 estimates (Kopp & Mignone 2012; Marten & Newbold, 2012). For example, fossil fuels (e.g. coal and natural gas) have different compositions of GHG emissions across gases when considering the entire process of extraction, production, transmission, and combustion. Thus, if a regulation is anticipated to cause an industry to substitute between fuels, analysts may be providing inadequate information to decision makers and the public about its benefits if only the welfare implications of direct CO_2 emissions are considered while ignoring changes in CH_4 and other GHG emissions (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2011).

A key reason for the value of non-CO_2 GHG emissions impacts not being included in USG analyses so far is that existing estimates of the social cost of non-CO_2 GHGs presented in the literature are inconsistent with USG SC-CO_2 modelling assumptions. For example, the recent US Environmental Protection Agency BCA of new pollution standards for the oil and natural gas industry concluded that, because they are not consistent with the USG SC-CO_2, 'the methane climate benefit estimates available in the current literature are not acceptable to use to value the methane reductions finalized in this rulemaking' (USEPA, 2012). This article seeks to address that gap by developing a new set of social cost estimates for CH_4 and N_2O (SC-CH_4 and SC-N_2O, respectively) that are fully consistent with the modelling assumptions underlying the current USG SC-CO_2 estimates. This article also develops an approach to extending the models used by the USG to generate estimates of the social cost of additional GHGs that are consistent with the latest USG estimates of the SC-CO_2.

It is important to note at the outset that by restricting attention to the derivation of social cost estimates consistent with the USG SC-CO_2 estimates, any limitations that apply to inputs and modelling

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assumptions underlying the USG SC-CO_2 estimates (e.g. Arrow et al., 2013; Kopp & Mignone 2012; Marten, 2011; O'Neil, 2010; Warren, Mastrandrea, Hope, & Hof, 2010) also apply to the SC-CH_4 and SC-N_2O estimates derived here. Thus, while it is anticipated that the USG will continue to improve the models and data it uses to estimate the SC-CO_2, this article focuses on the more immediate task of developing a set of consistent estimates for the social cost of other GHG emissions so that they need not be implicitly assigned a value of zero in USG policy analyses.

The remainder of the article is organized as follows. Section 2 presents an overview of the USG SC-CO_2 estimation approach and how it compares to the existing literature on the social cost of non-CO_2 GHGs, including a discussion of some of the critiques of the approach. Section 3 presents the approach for estimating the SC-CH_4 and SC-N_2O in a manner consistent with the USG SC-CO_2 estimates. Section 4 presents the results and a comparison of the relative social costs to the previous literature and the global warming potential (GWP)-based metric that is often used as an approximation in the absence of direct estimates, and Section 5 provides concluding remarks.

2. Background

In 2009–2010 the USG formed an interagency working group to develop a set of SC-CO_2 estimates for use by all Executive Branch agencies to value marginal changes in CO_2 emissions in regulatory impact analyses (USG, 2010). The goal of this exercise was to improve the accuracy and consistency with which agencies value marginal changes in CO_2 emissions. Before the release of these estimates, CO_2 emissions changes were valued in some but not all regulatory analyses, and the SC-CO_2 estimates used by different agencies varied substantially. The USG recently updated their estimates for the SC-CO_2 by employing new versions of the three underlying integrated assessment models (IAMs), but leaving the original estimation approach and underlying assumptions unchanged (USG, 2013). This section provides a brief overview of the estimation approach and assumptions used by the USG for estimating SC-CO_2, describes some critiques of the approach by other researchers, and discusses the existing literature on the social cost of non-CO_2 GHGs.

2.1. USG SC-CO_2 estimation approach

To estimate the SC-CO_2 the USG used three IAMs that couple simplified models of atmospheric gas cycles and climate systems with highly aggregate models of the global economy and human behaviour to capture the effects that GHG emissions, through their effect on the climate, have on human welfare. Within IAMs, the modelling that guides the transition from emissions into climate impacts is based on scientific assessments, while the mapping of climate impacts into changes in human welfare is based on economic research that has studied the effect of climate on various market and non-market sectors. Nordhaus and Boyer (2000) provide a very informative and detailed description of how such models are developed.[2]

The three models used by the USG are those that feature most prominently in the published social cost of carbon literature: the Dynamic Integrated Climate and Economy (DICE) (Nordhaus, 2008; Nordhaus & Boyer, 2000), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2006b, 2008), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff, Hepburn, & Tol, 2009; Tol, 2002a, 2002b, 2009) models. The USG chose to use the IAMs'

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climate system submodels and the functions that map climate change into economic damages as implemented by the model developers, but adopted a common set of input assumptions for equilibrium climate sensitivity, discount rates, global population, economic output, and GHG emissions projections. The remainder of this section provides a brief description of these common assumptions and the steps used to calculate the SC-CO_2 estimates. Interested readers can find more details in the USG's 2010 technical support document (USG, 2010).

2.1.1. Reference socio-economic-emissions scenarios

The USG selected five scenarios of economic output, population, and GHG emissions projections using results from the 2009 Stanford Energy Modeling Forum exercise number 22 (EMF-22). Four of the scenarios are based on baseline runs from global economic models (MERGE, MESSAGE, MiniCAM, and IMAGE) and span a range of emissions projections and plausible outcomes for future population and economic output absent significant global action to address climate change. These scenarios allowed for internally consistent forecasts of economic output, population, and emissions for the years 2000–2100. The fifth scenario used by the USG is based on the average of the 550 ppm CO_2e stabilization runs for each of the four models from which baseline scenarios were selected to represent potential action by the rest of the world absent US action. Across the five scenarios, atmospheric CO_2 concentrations in 2100 ranged from approximately 450 to 890 ppm (550–1130 ppm in CO_2e). Over the time horizon, the forecasts of the average growth rate for global per capita economic output ranged from 1.5% to 2.0% per year, and the average global population growth rate ranged from 0.4% to 0.5% per year. To run the IAMs through the year 2300, the USG extrapolated the selected EMF scenarios using the following assumptions: starting in 2100 the population growth rate declines linearly to zero in 2200; starting in 2100 the growth rate of economic output per capita declines linearly to zero in 2300; for all years after 2100 the growth rate of the carbon intensity of the global economy (CO_2 emissions/economic output) remains constant at its 2090–2100 average; starting in 2100 net land-use CO_2 emissions decline linearly to zero in 2200; and for all years beyond 2100 non-CO_2 radiative forcing anomalies remain constant at their 2100 levels.

Several limitations of the simplifying assumptions underlying the USG approach to scenario development have been discussed by other researchers. O'Neil (2010) pointed out that the selected EMF scenarios do not reflect the full range of outcomes that appear in other studies in the literature, and Kopp and Mignone (2012) suggested that the selected scenarios may effectively over-sample the peaks of the distributions. As for the extrapolations, while running the models out for multi-century time horizons is not necessary for relatively short-lived GHGs like CH_4, it is important for understanding the impacts of long lived GHGs such as CO_2 and N_2O that will affect human welfare well beyond 2100. As emphasized by O'Neil (2010) and Kopp and Mignone (2012), the state of the world beyond 2100 is highly uncertain and the scenario extrapolation approach taken by the USG represents only one of many possibilities. Furthermore, the extrapolations for each component of the scenarios (economic output, population, emissions) are separate and nothing ensures internal consistency within the scenarios past 2100. As shown by Marten and Newbold (2012), the temporal decomposition of damages for a perturbation of CO_2 and N_2O are relatively similar in shape and therefore the general findings of studies that explore the sensitivity of the SC-CO_2 to these assumptions should also be applicable to the SC-N_2O.

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2.1.2. Equilibrium climate sensitivity

In reduced-form IAMs, the speed and magnitude of temperature change for a given emissions projection are influenced largely by the 'equilibrium climate sensitivity' (ECS) parameter. The ECS represents the long-term global average temperature response to a level of radiative forcing associated with a sustained doubling of atmospheric CO_2 concentration (around 550 ppm). To represent the uncertainty in the responsiveness of the climate system to changing atmospheric conditions, the USG used a probability distribution for the ECS parameter of the form suggested by Roe and Baker (2007). The USG calibrated the parameters of the probability distribution to have a median equal to 3 8C, two-thirds probability that the ECS lies between 2 and 4.5 8C, which was intended to be consistent with the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) consensus statement about the ECS (Meehl et al., 2007). The distribution was truncated from above at 10 8C. This specification of the ECS distribution is retained to maintain consistency with the USG estimates of the SC-CO_2, but it is noted that the recently released AR5 by the IPCC has revisited the equilibrium climate sensitivity and revised the range downwards to 1.5–4.5 8C and no longer provides a most likely value (Collins et al., 2013). The ultimate effect of updating the ECS distribution to be consistent with the IPCC AR5 findings will depend heavily on the central tendency selected for the distribution.

2.1.3. Discount rates

Because the damages from an additional tonne of CO_2 emissions occur over many decades, the discount rate, which reflects the tradeoff between present and future consumption, plays a critical role in estimating the SC-CO_2. In light of disagreement in the literature regarding the appropriate discount rate to use in this context and uncertainty about future conditions that impact the discount rate, the USG used three constant discount rates intended to span a plausible range: 2.5%, 3%, and 5% per year. It is worth noting that the debate regarding not only the appropriate discount rate but also its time path is ongoing (Arrow et al., 2013; Dasgupta, 2008). While the appropriate value for the discount rate will presumably remain an area of active debate for some time to come, there appears to be agreement that the use of a constant discount rate over long time horizons with uncertain changes in the consumption per capita growth is not theoretically consistent. This article uses the same three constant discount rates as the USG estimation process, but in Appendix C results are reported from a series of sensitivity analyses using a Ramsey discounting approach. Similar to Marten and Newbold (2012), it is found that applying Ramsey discounting using plausible values for the components of the consumption discount rate gives a range of social cost estimates that is broadly consistent with the range of results obtained using the constant discount rates.

2.1.4. Calculating the SC-CO_2

The process to estimate the SC-CO_2 for emissions in year t has four steps. First, each model is used to forecast monetized impacts associated with the baseline path of emissions, economic output, and population. Second, each model is re-run with an additional unit of CO_2 emissions in year t to forecast monetized impacts for all years beyond t along this perturbed path of emissions. Third, the marginal damages in each year are calculated as the difference between the monetized impacts forecast in steps 1 and 2. Finally, the resulting path of marginal damages is discounted and summed to calculate

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the present value of the marginal damages in the year when the additional unit of emissions used to perturb the model is emitted.

The USG repeated this process with each model, discount rate, and socio-economic-emissions scenario for each decade between 2010 and 2050. Because the ECS parameter is modelled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run represents a distribution over the SC-CO_2 in each year. These distributions were estimated using 10,000 simulations in each model run. Therefore, the exercise produced 45 separate distributions of the SC-CO_2 for a given emissions year, based on the three models, three discount rates, and five socio-economic-emissions scenarios considered. To provide a range of estimates that reflects this uncertainty but still emphasizes the central tendency, the distributions from each of the models and scenarios were equally weighted and combined to produce three separate probability distributions for the SC-CO_2 in a given year, one for each assumed discount rate. Four SC-CO_2 estimates were selected from these three probability distributions to reflect the global damages caused by one tonne of CO_2 emissions. Three estimates are based on the average SC-CO_2 across the three models and five socio-economic-emissions scenarios for the 5%, 3%, and 2.5% discount rates, respectively. The fourth value is the 95th percentile of the SC-CO_2 distribution at the 3% discount rate, and was chosen to represent potential higher-than-expected impacts from anthropogenic GHG emissions.

2.2. Existing estimates of the social cost of non-CO_2 GHG emissions

A significant limitation of the aforementioned USG interagency process is that the social costs of non-CO_2 GHG emissions were not estimated. Therefore, as an alternative to applying direct estimates for the social costs of non-CO_2 GHG emissions in the primary BCA, several recent USG regulatory analyses have approximated the benefits of non-CO_2 GHG emissions reductions in sensitivity analyses by transforming the non-CO_2 GHG emissions to 'CO_2-equivalents' using estimates of the GWP for the GHG in question and then using the USG SC-CO_2 for valuation (e.g. US EPA, 2012, 2013).

Gas comparison metrics, such as the GWP, have been designed to measure the impact of different GHGs relative to CO_2, where the point of comparison along the pathway from emissions to monetized damages (depicted in Figure 1) may differ across measures. The GWP, in particular, is designed to measure the additional radiative forcing (i.e. the amount of energy absorbed by atmospheric concentrations of GHGs) from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years). The GWP and other gas-comparison metrics are problematic as an SC-CO_2 scalar in BCA, as the remaining linkages in the pathway depicted in Figure 1 are complex and non-linear. Marten and Newbold (2012) demonstrate that using the GWP to adjust SC-CO_2 estimates to capture the impact of non-CO_2 gases provides a significant improvement over the implicit assumption that they are zero when such benefits are left unquantified, but may still underestimate mitigation benefits. Alternative gas comparison metrics that compare GHGs at different points in the chain of

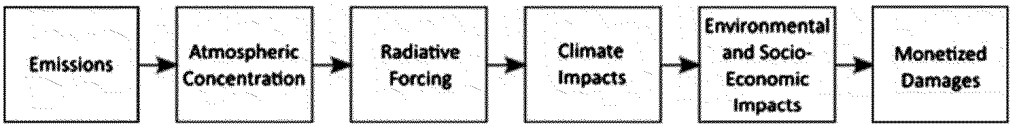

Figure 1 Path from GHG emissions to monetized damages

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causation (e.g. global temperature change potential (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005), peak commitment temperature (Smith et al., 2012), temperature proxy index (Tanaka, O'Neill, Rokityanskiy, Obersteiner, & Tol, 2009)) have also been shown to be imperfect substitutes for direct estimates.

Several researchers have directly estimated the social cost of non-CO_2 GHG emissions using IAMs, although the number of such estimates is small compared to the large number of SC-CO_2 estimates available in the literature. Among these previous direct estimates there is considerable variation in the model versions and input assumptions used. See Table 1 for a summary of the 11 non-CO_2 studies published to date.

As shown in Table 1, the estimates cover emissions years from 1990 to 2050, although the specific perturbation year is not stated in all studies. The studies also cover a wide range of constant and variable discount rate specifications and consider a range of baseline socio-economic and emissions scenarios that have been developed over the last 20 years. Finally, some studies in the literature have chosen not to report the social cost estimates directly. Instead, they opt to report only the 'global damage potential', which is a ratio of the social cost of gas X to the SC-CO_2. Normalizing the SC-CH_4 or

TABLE 1 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Model	Time horizon	Discount rate	Emissions year	Scenario[a]	Climate sensitivity
Reilly and Richards (1993)	N/A	140 years	2, 5, 8%	1990	N/A	N/A
Fankhauser (1994)	N/A	230 years	Ramsey	1991–2030	IS92[b]	N/A
Kandlikar (1995)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Kandlikar (1996)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Hammitt et al. (1996)	N/A	2200	1, 3, 5%	1995–2015	IS92a,c,e	1.5, 2,5, 4.5 8C
Tol (1999)	FUND 1.6	2100	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Tol et al. (2003)	FUND 1.7	2200	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Hope (2005)	PAGE95	2200	Ramsey	2000	SRES A2	Probabilistic, mode of 3 8C
Hope (2006a)	PAGE2002	2200	Ramsey	2001	SRES A2	Probabilistic, mean of 3 8C
Waldhoff et al. (2011)	FUND 3.5	3000	Ramsey	2010–2019	FUND, SRES A1B, A2, B1, B2	2, 3, 4.5 8C
Marten and Newbold (2012)	DICE2007 w/ MAGICC	2300	Ramsey, 2.5, 3, 5%	2010–2050	EMF-22 MiniCAM Base	Probabilistic,median of 3 8C

[a]IS90 scenarios are based on the IPCC First Assessment Report (IPCC, 1990); IS92 scenarios are based on the IPCC Supplementary Report (IPCC, 1992); SRES scenarios are based on the IPCC Special Report on Emissions (IPCC, 2000); the FUND scenario is the default scenario in the FUND model; EMF-22 scenarios are based on results from Stanford's Energy Modeling Forum's 22nd exercise (Clarke et al., 2009).[b]The particular IS92 scenario used was not specified.

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SC-N_2O estimate using the SC-CO_2, in part, controls for differences in the modelling to allow for a better comparison with other estimates in the literature.

Fankhauser (1994) was one of the first to develop estimates of the average SC-CH_4 and SC-N_2O for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt, Jain, Adams, and Wuebbles (1996) also developed estimates of SC-CH_4 and SC-N_2O for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006a) developed estimates for the SC-CH_4 in 2000 using the FUND and PAGE models, respectively. Waldhoff, Anthoff, Rose, and Tol (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal CO_2, CH_4, N_2O, and SF_6 emissions for the average year in the 2010 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios from the IPCC special report on emissions (IPCC, 2000) in addition to the default FUND scenario. In Section 4, the specific results of these previous studies are discussed with a comparison to the estimates obtained in the present study.

The above-mentioned previous studies provide a basic understanding of the relative social costs of different GHGs but do not provide sufficient information about how this relationship changes over time. Marten and Newbold (2012) used an IAM that couples the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) with economic components of the 2007 version of William Nordhaus' DICE model to directly estimate the social cost of marginal CO_2, CH_4, and N_2O emissions. They estimated the annual social costs for the years 2010–2050 along a single socio-economic-emissions pathway given uncertainty about the equilibrium climate sensitivity parameter. An advantage of their approach is that through the use of a more detailed, yet still relatively simple, climate model their results are not affected by over-simplification of temperature response or atmospheric chemistry, which have been shown to have non-negligible effects on the estimates of social costs (Marten, 2011; Warren et al., 2010).

The work of Marten and Newbold (2012) uses many of the assumptions used by the USG in its estimation of SC-CO_2, including discount rates, the equilibrium climate sensitivity distribution, and post-2100 socio-economic and emissions extrapolations. However, they focus on only one of the three models and one of the five socio-economic-emissions scenarios used by the USG. Furthermore, they use a different climate sub-model, which leads their estimate of the SC-CO_2 to be different from the USG estimate, even for the same IAM and scenario combination. Therefore, although these studies, including Marten and Newbold (2012), have increased our understanding about the relative social costs of GHG emissions, they have not provided a set of estimates that are entirely consistent with the USG SC-CO_2 estimates. In Section 4, the estimates derived in this article are compared with those of Marten and Newbold (2012) to more clearly demonstrate the similarities and differences in the two sets of estimates for SC-CH_4 and SC-N_2O.

3. Estimating the social cost of non-CO_2 GHGs consistent with USG SC-CO_2

The primary obstacle in estimating the social cost of non-CO_2 GHG emissions in a manner consistent with the USG SC-CO_2 estimates is that not all of the IAMs used include explicit representations of the non-CO_2 gases of interest. This section describes the degree to which non-CO_2 GHGs are currently

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represented in the default versions of DICE, PAGE, and FUND, and then discusses how they are amended to estimate the social cost of these gases.

3.1. Representation of non-CO_2 GHGs in DICE, PAGE, and FUND

The FUND model explicitly considers CH_4, N_2O, and SF_6 in addition to CO_2. The model uses one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels. For CH_4 and N_2O, FUND estimates the additional radiative forcing imposed by the atmospheric buildup of these gases using the simplified expressions presented in Chapter 6 of the IPCC's Third Assessment Report (TAR) (Ramaswamy et al., 2001). FUND also augments the TAR expression for the additional radiative forcing from CH_4 to account for the influences of stratospheric water vapour and tropospheric ozone changes. Because FUND uses CH_4 and N_2O emissions as inputs and internally computes their impact on the climate system, it is possible to directly estimate the social cost of those gases without modifying the model.

In the DICE model, the only GHG that is explicitly represented is CO_2; an exogenous radiative forcing projection is used to account for the impact of all other gases on the climate. To develop an exogenous radiative forcing pathway consistent with the emissions scenarios used to estimate the SC-CO_2, the USG decomposed the default DICE exogenous radiative forcing vector into CH_4, N_2O, F-gases, aerosols, and other residual forcing components. The USG then replaced the radiative forcing attributed to CH_4, N_2O, and F-gases with estimates associated with the EMF-22 scenarios. As non-CO_2 emissions are not a direct input into DICE, it is not possible to simply perturb the emissions projection and re-run the model to obtain a forecast of additional damages.

The 2002 version of the PAGE model, which was used by the USG in developing its first set of estimates (USG, 2010), includes an atmospheric model for CH_4 and SF_6, but represents the effects of other non-CO_2 GHGs in an exogenous radiative forcing projection. Presumably to simplify the process and maintain consistency with DICE, the USG did not use PAGE's internal CH_4 component. Instead, the same exogenous radiative forcing projection was used for the effect of CH_4, N_2O, and F-gas emissions as was used for DICE. Since then, a N_2O component has been added to the PAGE model, although in the recent 2013 SC-CO_2 update the USG maintained the approach of using the same single exogenous forcing projection as was applied to DICE (USG, 2013). Therefore PAGE, as implemented by the USG, faces the same limitations as DICE with respect to estimating the social costs of marginal non-CO_2 emissions that are consistent with the USG SC-CO_2 estimates. For these reasons, computing estimates for the social cost of non-CO_2 gases in DICE and PAGE requires either replacing the climate component of these models with a more complete representation, as was done with DICE by Marten and Newbold (2012), or deriving an estimate of the path of additional radiative forcing that would result from a perturbation of the gas in question. This article uses the latter approach for DICE and PAGE, as the former would represent a substantial change to the underlying IAMs and would have implications for the SC-CO_2 estimates, making this work inconsistent with the USG SC-CO_2 estimates currently used in regulatory analysis.

3.2. Estimating the social cost of non-CO_2 GHGs in DICE and PAGE

The process used in this article to estimate the social cost of non-CO_2 GHGs in DICE and PAGE as implemented by the USG requires first generating a forecast of the additional radiative forcing

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associated with a perturbation of a non-CO_2 gas's emissions in a single year, and then adding this radiative forcing perturbation to each model's exogenous radiative forcing projection. To determine the additional radiative forcing associated with the emission perturbation, there is a need to model the change in atmospheric concentration and the radiative forcing associated with the additional concentration. For both CH_4 and N_2O, a simple one-box atmospheric gas cycle model with a constant decay rate is used to estimate the atmospheric concentration of each gas based on its assumed emissions. The use of a one-box gas cycle for CH_4 and N_2O with constant decay follows the approach used by the IPCC to compute GWPs (Forster et al., 2007) and the FUND model (Anthoff & Tol, 2013). In both the baseline and the perturbed case, the contribution of the gas to the global radiative forcing anomaly is determined by the forcing relationships presented in the IPCC TAR (Ramaswamy et al., 2001), which were not updated by the IPCC in AR4. The incremental radiative forcing is defined by the difference between the baseline forcing path and the emissions path that includes a one tonne perturbation in a given year. Next, the path of additional radiative forcing is added to the stream of exogenous radiative forcing in each IAM to estimate the climate damages in the perturbed scenario. These damages are then compared to the baseline damages to determine the social cost of gas X (SC-X). Specifically, the process is as follows:

1. Run the IAM as described in the SC-CO_2 technical support document (USG, 2010) to estimate baseline damages.
2. Estimate the baseline atmospheric concentration for gas X.
3. Estimate the baseline radiative forcing contribution of gas X.
4. Perturb the stream of gas X emissions by one tonne in year t.
5. Estimate atmospheric concentration for gas X in the perturbed scenario.
6. Estimate the radiative forcing contribution of gas X in the perturbed scenario.
7. Compute the incremental radiative forcing as the difference between the results of steps 3 and 6.
8. Add the additional radiative forcing from step 7 to the exogenous radiative forcing path used in the IAM in step 1.
9. Re-run the IAM to compute the damages along the perturbed emissions path.
10. Compute the social cost of gas X for emission year t as the present value of the difference in damages estimated in steps 1 and 9.

Two practical issues associated with implementation are worth noting. First, while the SC-X estimates are associated with a one tonne perturbation, to avoid computational rounding error a 1 Mt perturbation is used and then the resulting change in damages is scaled to get the average effect per tonne. Experiments conducted by Griffiths et al. (2012) to assess the applicability of the SC-CO_2 to non-marginal emission changes show that the average per tonne SC-CO_2 estimate is relatively constant over large differences in perturbation size. Additional experiments in the context of this article found that alternative perturbation sizes do not significantly change the average one tonne social cost estimate. Second, the additional radiative forcing due to the emissions perturbation is computed based on an annual time step, but because DICE and PAGE use longer time steps the average radiative forcing over the time step is added to the model's exogenous radiative forcing vectors.

The remainder of this section describes the procedure for modelling the incremental radiative forcing of a perturbation for CH_4 and N_2O, and explores the sensitivity of these projections to

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two issues. First, it evaluates whether the simple one-box gas cycle model with a constant decay rate produces a close approximation to the forecasts of future atmospheric CH_4 and N_2O concentrations based on a more sophisticated climate model. Second, it explores the sensitivity of the results to the method used for extrapolating non-CO_2 emissions from 2100 to 2300. This is important, because the USG did not specify a particular set of emissions pathways for each constituent gas, instead assuming only that non-CO_2 radiative forcing remains constant past 2100. Such a situation could arise from a myriad of possible individual gas projections and the USG did not specify which it was assuming.

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3.3. Methane

A simple one-box atmospheric gas cycle model for methane specifies the concentration in year t, $C_t^{CH_4}$ [ppb], such that

$$C_t^{CH_4} = C_{t-1}^{CH_4} + d_{CH_4}(C_{pre}^{CH_4} - C_{t-1}^{CH_4}) + g_{CH_4}E_{t-1}^{CH_4}, \tag{1}$$

where d_{CH_4} defines the rate of decay, $C_{pre}^{CH_4}$ [ppb] is the pre-industrial atmospheric concentration, and g_{CH_4} [ppb/Mt] converts emissions, $E_{t-1}^{CH_4}$ [Mt], from mass to atmospheric volume. The mass to volume conversion factor is g_{CH_4} ¼ 0.3597 ppb/Mt and $C_{pre}^{CH_4}$ ¼ 700 ppb, following the IPCC TAR. The rate of decay is set to d_{CH_4} ¼ 1/12 following the IPCC AR4 stated CH_4 lifetime of 12 years. The iteration begins in the year 2006 using the emissions from the EMF-22 scenario (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used so that $C_{2005}^{CH_4}$ ¼ 1774 ppb.

The contribution of atmospheric methane to global radiative forcing, denoted $Q_t^{CH_4}$, is defined using the relationship in Table 6.2 of the IPCC TAR:

$$Q_t^{CH_4} = f \quad 0.036 \quad C_t^{CH_4} - \quad C_{pre}^{CH_4} \quad - [f(C_t^{CH_4}, C_{pre}^{N_2O}) - (C_{pre}^{CH_4}, C_{pre}^{N_2O})] \quad , \tag{2}$$

where $C_{pre}^{N_2O}$ [ppb] is the pre-industrial atmospheric concentration of nitrous oxide and

$$f(C^{CH_4}, C^{N_2O}) = 0.47 \ln 1 + 2.01 \times 10^{-5}(C^{CH_4}C^{N_2O})]^{0.75} + 5.31 \times 10^{-15}C^{CH_4}(C^{CH_4}C^{N_2O})^{1.52} \quad . \tag{3}$$

The function in expression (3) accounts for the overlapping absorption bands of CH_4 and N_2O, thereby reducing their effective absorption. Parameter f is used to proxy for indirect effects of CH_4 that include the enhancement of stratospheric water vapour and tropospheric ozone changes. Following the IPCC AR4, an enhancement effect of 40% (25% from tropospheric ozone change and 15% for stratospheric water vapour enhancement) is used, such that f ¼ 1.4. The pre-industrial concentration of N_2O is set consistent with the IPCC TAR, such that $C_{pre}^{N_2O}$ ¼ 270 ppb.

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A key simplification in this approach is the constant decay rate used in the atmospheric gas cycle model. As discussed by IPCC Working Group I in Chapter 4 of the TAR, the lifetime of methane emissions in the atmosphere depends on temperature and the concentrations of CO, NOx, and other VOCs in the atmosphere (Ehhalt et al., 2001). Sensitivity analysis is used to understand the potential implications of ignoring these interactions by comparing the incremental atmospheric concentration projected by the simple model described above to the analogous projection from the climate model MAGICC,[3] which, while still relatively simple, incorporates these interactions between the lifetime of CH_4 in the atmosphere and the other gases and climate variables. This exercise uses CH_4 emissions from the EMF-22 MiniCAM reference scenario and considers a one tonne perturbation of CH_4 in 2015. It is noted that these results are robust across alternative emissions levels.[4]

Figure 2(a) presents the projected average decadal increment to atmospheric concentrations using both the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. At the time of the perturbation (2015), the inter-annual time step of MAGICC allows for an uptake of the additional emissions into the atmosphere, whereas the strict annual time step of the simple model causes a year to pass before the change is registered. After the initial year, the models originally differ by around 15%. This difference falls to under 10% within the first decade, with the faster effective growth in the simple model causing its additional concentration to eventually fall below that of MAGICC.

The difference in the incremental radiative forcing from the perturbation between the simple model and MAGICC is also of importance. Although MAGICC relies on similar equations to derive the radiative forcing of atmospheric CH_4 concentrations, it differs in the way it handles indirect effects of CH_4 on tropospheric ozone and stratospheric water vapour, in addition to including other temperature-related feedbacks. Figure 2(b) presents the average additional radiative forcing per decade attributed to the 2015 CH_4 perturbation in both models. The average increase in radiative forcing over the decade is considered because this is the input required by DICE due to its ten-year time step and therefore a more relevant comparison (PAGE requires a similar multi-year average). When considering the average additional radiative forcing over the decade, the initial difference in concentration between MAGICC and the simple model has a minimal effect and the difference in radiative forcing between the two models is less than 2% over the first two decades. However, this difference grows to –18% over the subsequent two decades. This escalation in the difference is in part due to the use of a constant decay rate in the simple model, whereas MAGICC takes into account the growing atmospheric concentrations of other gases and increasing atmospheric temperature, which increase the lifetime of atmospheric CH_4.

To understand the effect that this difference would have on an estimate of the SC-CH_4, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of CH_4, as computed using both the simple model and MAGICC, is added to the exogenous forcing projection. As above, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 2 presents the results of this experiment. In line with the results comparing the radiative forcing perturbations above, the two approaches produce similar social cost estimates for emissions in 2015, where additional analysis has shown these results to hold with PAGE as well. The impact of assuming a constant decay rate is greater further out into the future, due to the projected increase in the atmospheric concentration of other relevant gases and atmospheric temperature that are accounted for in MAGICC, and the social cost

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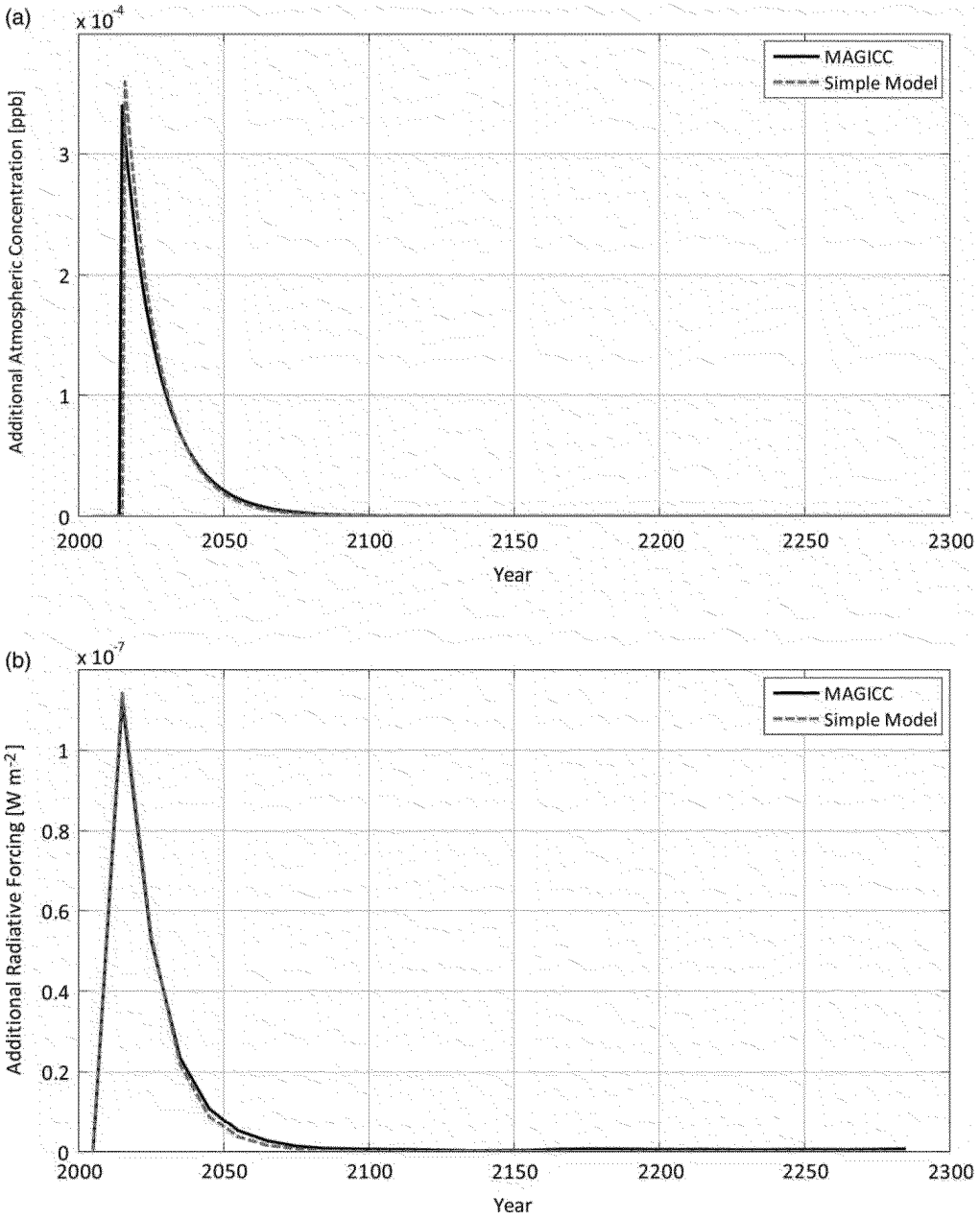

Figure 2 Effects of perturbation in 2015 CH_4 emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

estimates begin to diverge for later emissions years. For the same reason, the two approaches will show greater differences for lower discount rates that give increased weight to future time periods. While over-simplification of the climate system can, in some circumstances, have significant effects on

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TABLE 2 Effect of CH_4 gas cycle model on SC-CH_4 (2007$ per tonne CH_4): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	1135	1183	2 4%
	3.0%	822	851	2 3%
	5.0%	349	354	2 2%
2045	2.5%	2490	2707	2 8%
	3.0%	1933	2084	2 7%
	5.0%	956	1006	2 5%

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social cost estimates (e.g. Marten 2011), the near-term differences based on this simplification seem relatively small considering the precision of such social cost estimates.

3.4. Nitrous oxide

The simple one-box atmospheric gas cycle model for N_2O takes a similar form to the model used for CH_4, such that the concentration of nitrous oxide in year t, $C_t^{N_2O}$ [ppb], is specified as

$$C_t^{N_2O} = C_{t-1}^{N_2O} + d_{N_2O}(C_{pre}^{N_2O} - C_{t-1}^{N_2O}) + g_{N_2O}E_{t-1}^{N_2O}, \tag{4}$$

where d_{N_2O} is the rate of decay, and g_{N_2O} [ppb N_2O/Mt N] converts emissions, $E_{t-1}^{N_2O}$ [Mt N], from mass to atmospheric volume. Following the IPCC AR4, the mass to volume conversion factor is g_{N_2O} ¼ 0.2079 ppb N_2O/Mt N and the rate of decay is d_{N_2O} ¼ 1/114 based on a 114-year lifetime. As with CH_4, the iteration begins in the year 2006 using the emissions from the EMF-22 scenarios (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used, such that $C_{2005}^{N_2O}$ ¼ 319 ppb.

The contribution of atmospheric N_2O to global radiative forcing, denoted $Q_t^{N_2O}$, is defined using the relationship in Table 6.2 of the IPCC TAR, such that

$$Q_t^{CH_4} = 0.12 \left[C_t^{N_2O} - C_{pre}^{N_2O} - [f(C_{pre}^{CH_4}, C_t^{N_2O}) - f(C_{pre}^{CH_4}, C_{pre}^{N_2O})], \right. \tag{5}$$

where $f(C^{CH_4}, C^{N_2O})$ is defined in expression (3).

As with CH_4, a key simplifying assumption is the constant decay rate used in the simple gas cycle model (and potentially the time it takes the gas to become well mixed within the atmosphere). As discussed in the IPCC TAR, the decay rate of N_2O will depend on the atmospheric concentration of N_2O and so will not be constant in reality. To examine the extent to which this impacts the results of the simple model, an analogous set of experiments as conducted for CH_4 were performed. Given future

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N_2O emissions based on the EMF-22 MiniCAM reference scenario, a one tonne N_2O perturbation in 2015 is considered. Figure 3(a) shows the projected atmospheric concentration increase from the perturbation using the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. This comparison illustrates that the simple model tracks the output of MAGICC well for the entire 300-year time horizon. Outside the initial perturbation year, the two projections do not differ by more than 2% within the first century, with the largest difference occurring in the perturbation year, for the same reasons as with CH_4.

Figure 3(b) presents the estimates of average additional radiative forcing per decade as a result of the N_2O perturbation using both models. The additional radiative forcing from the N_2O perturbation in the one-box model is forecast to be slightly lower (7%) in the first decade compared to MAGICC. Subsequently, the difference is within 2% through to 2300.

As with CH_4, to assess the effect that this difference would have on the SC-N_2O, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of N_2O computed using both the simple model and MAGICC is added to the exogenous forcing projection. As before, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 3 presents the results of this experiment. As the comparisons of the projected radiative forcing perturbations would suggest, the difference between the social cost estimates for the two approaches is relatively small. In contrast to the case of CH_4, here an increase in the discount rate increases rather than decreases the divergence between the estimates due to the greater weight being placed on the earlier years when the radiative forcing perturbations have a slightly higher degree of divergence.

3.5. Effect of post-2100 non-CO_2 radiative forcing assumptions

The EMF-22 socio-economic-emissions scenarios used by the USG include years only up to 2100, while the USG ran the IAMs out to 2300. Therefore, additional assumptions were required to extrapolate the scenarios beyond 2100. For the purposes of this study, the most important of these assumptions is that non-CO_2 radiative forcing will remain constant at its 2100 level until 2300. Such a broad assumption was sufficient for the purposes of the USG in estimating the SC-CO_2. However, estimating the social cost of non-CO_2 GHGs requires explicit projections of baseline emissions of non-CO_2 gases in order to correctly determine the effect of the perturbation. The USG's broad assumption regarding the extrapolation of non-CO_2 gases is therefore problematic as constant non-CO_2 radiative forcing post 2100 may occur in an infinite number of ways. For instance, one way to achieve this outcome is to assume that emissions of each non-CO_2 gas falls to a level equal to its respective rate of decay in 2100. This assumption would keep atmospheric concentrations, and in turn radiative forcing, constant. Based on the simple gas cycle models laid out in the earlier sections this implies that, for gas X,

$$E_t^X = \frac{-d_X(C_{pre}^X - C_{2100}^X)}{g_X} \forall t \ . \ 2100. \tag{6}$$

To put this assumption into context, the solid lines in Figure 4(a) and (b) present the emissions paths for CH_4 and N_2O, respectively, under the MiniCAM EMF-22 reference scenario extrapolated using

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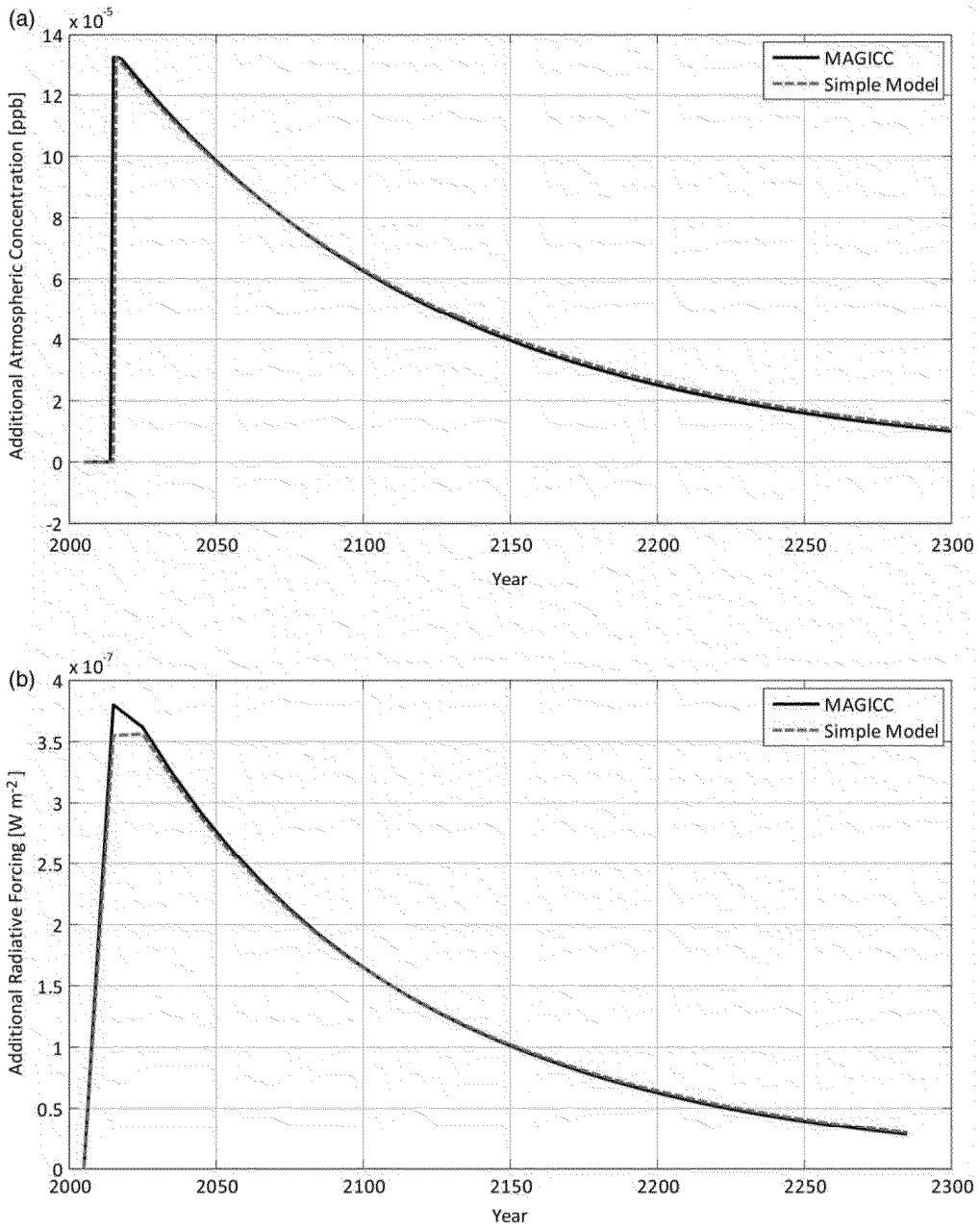

Figure 3 Effects of perturbation in 2015 N_2O emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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TABLE 3 Effect of climate model on SC-N_2O (2007$ per tonne N_2O): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	19,689	19,819	2 1%
	3.0%	12,390	12,525	2 1%
	5.0%	3,346	3,419	2 2%
2045	2.5%	36,968	37,358	2 1%
	3.0%	25,030	25,427	2 2%
	5.0%	8,280	8,528	2 3%

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expression (6), while the dashed lines show two alternative extrapolation approaches, one where emissions are held constant at their 2100 level and one that assumes emissions intensity (emissions/economic output) continues to decline at the same rate forecast by the EMF-22 scenario in 2090–2100 (dotted line). This latter alternative is analogous to the USG assumption regarding industrial CO_2 emissions. The two alternatives will not result in the radiative forcing contribution of gas X remaining constant post-2100, but do not in themselves violate the assumption that overall non-CO_2 radiative forcing remains constant. Noteworthy is the fact that the assumption in (6) is almost analogous to keeping CH_4 emissions constant at their 2100 levels, whereas for N_2O the assumption requires a sudden decrease in emissions of over 35%.

While Figure 4 illustrates that these three extrapolation approaches can lead to vastly different projections for emissions after 2100, the relevant comparison is how these assumptions affect the additional radiative forcing from a perturbation of the gas and in turn the SC-X estimates. Figure 5(a–d) present the additional radiative forcing resulting from a one tonne perturbation based on the simple model presented in Sections 3.1 and 3.2. Figure 5(a) and (b) demonstrates the difference for a perturbation in 2015, whereas Figure 5(c) and (d) represents perturbations in 2045. For CH_4, the cumulative radiative forcing from the projection over the time horizon differs by less than 0.001%, even for a

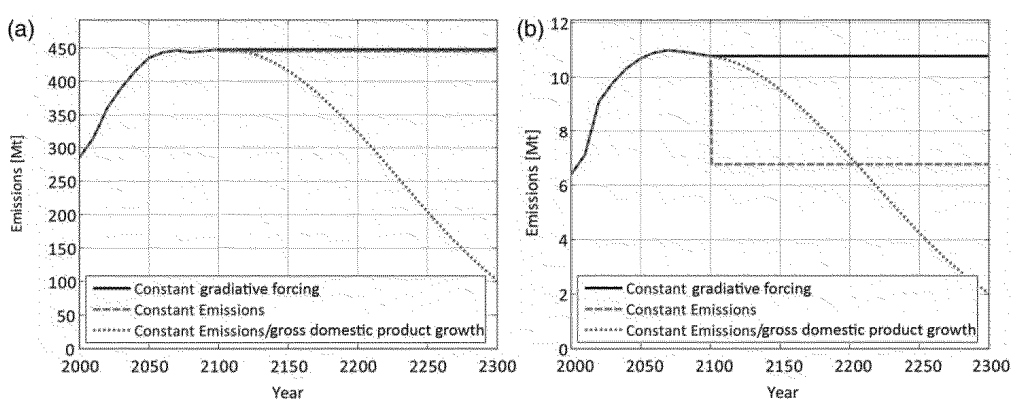

Figure 4 EMF-22 MiniCAM extended emissions scenario: (a) CH_4 emissions; (b) N_2O emissions

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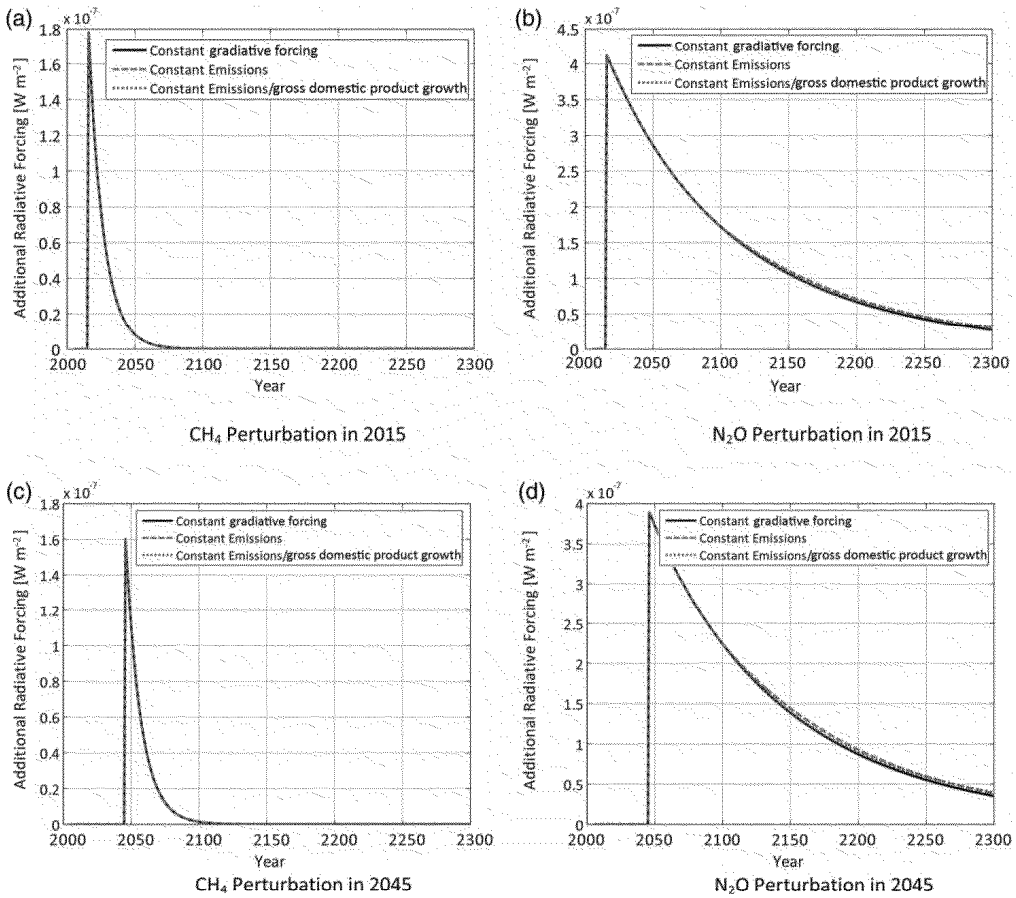

Figure 5 Effect of extrapolation approach on radiative forcing perturbation from simple model: (a) CH_4 perturbation in 2015; (b) N_2O perturbation in 2015; (c) CH_4 perturbation in 2045; (d) N_2O perturbation in 2045

perturbation in 2045. Accordingly, the relevant annual difference is smaller even than one-thousandth of a percent. This result occurs because of the short atmospheric lifetime of the gas, which renders assumptions regarding CH_4 emissions after 2100 unimportant for near-term perturbations. Post-2100 emissions will have a larger effect in the case of N_2O, which has a much longer atmospheric residence time. However, even for a perturbation in 2045, the difference in cumulative additional radiative forcing is less than 2.5% across the extrapolation assumptions.

To examine the impact of these assumptions on SC-CH_4 and SC-N_2O, an experiment was conducted using the DICE model based on the EMF-22 MiniCAM socio-economic-emissions scenario. The results of this experiment are presented in Table 4 for the perturbation year 2045 (noting that the extrapolation method will have greater impact on future emissions years). As may be seen, the relatively short atmospheric lifetime of CH_4 leads to a situation in which post-2100 assumptions do not affect SC-CH_4 estimates, even in 2045. For the longer-lived gas N_2O, in emission year 2045, where the effect of the post-2100 extrapolation approach would be largest, the difference across the three

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TABLE 4 Effect of post-2100 extrapolation on the 2045 SC-X (2007$ per tonne): DICE2010, MiniCAM

Gas	Discount rate	Constant RF	Constant emissions	Constant emissions intensity growth
CH_4	2.5%	2,490	2,490	2,490
	3.0%	1,933	1,933	1,933
	5.0%	956	956	956
N_2O	2.5%	36,968	36,588	36,662
	3.0%	25,030	24,837	24,868
	5.0%	8,280	8,261	8,263

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assumptions is less than 1% and the projections are equivalent to two significant digits. Therefore, in the remainder of this article, non-CO_2 emissions are extrapolated past 2100 using expression (6) to ensure that the gas-specific contribution to overall radiative forcing remains constant in the simple model. While additional study may lead to improvements of long-term forecasts of CH_4 and N_2O emissions and possible correlations, compared to the paths in Figure 5(a), the very minimal effect of such assumptions on the social cost estimates suggests the impact of such efforts would be minimal in this context.

4. Results

For FUND, the social cost of non-CO_2 GHGs is estimated by perturbing the paths of emissions directly, while for DICE and PAGE the approach presented in Section 3 is used. In both cases, all additional assumptions made by the USG are applied, including the five EMF-22 socio-economic-emissions scenarios, the Roe and Baker (2007) distribution for the equilibrium climate sensitivity, and constant discount rates of 2.5%, 3.0%, and 5.0%. Following the USG, the estimates for the expected social cost are averaged across scenarios and models, with each model and scenario given equal weight. Estimates are not combined across discount rates, and a fourth estimate is included representing the 95th percentile when using the 3.0% discount rate. By using the same assumptions and procedures as the USG, estimates of the SC-CO_2 derived in this article are identical to the values used in US Federal rule making. Specifically, these estimates are equivalent to the recent 2013 update of the USG SC-CO_2, which revised the original 2010 USG upwards based on new versions of the IAMs used. The non-CO_2 results, as well as the USG SC-CO_2 estimates, are presented in Table 5 for emissions years 2020 and 2050.[5] Results for additional years, and the results of sensitivity analyses using Ramsey discounting, may be found in Appendix B and C, respectively.

As expected, considering their higher radiative efficacy, the social costs associated with a tonne of CH_4 and N_2O emissions are substantially higher than for CO_2. The values are higher at lower discount rates, although the impact of the discount rate is lower for CH_4 given its relatively short lifetime. Similar to CO_2, the social cost estimates for CH_4 and N_2O increase over time as the climate and economic systems become more stressed, although the growth rate of the social cost estimate may differ between the gases, as discussed in the following.

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TABLE 5 SC-X (2007$ per tonne)

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CO_2	12	43	64	128
	CH_4	550	1,200	1,600	3,200
	N_2O	4,800	15,000	22,000	41,000
2050	CO_2	26	71	97	220
	CH_4	1,400	2,500	3,100	6,900
	N_2O	11,000	27,000	38,000	74,000

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To better understand how the social costs of CH_4 and N_2O compare to CO_2, Table 6 presents the global damage potentials corresponding to the social cost estimates from Table 5. (The disaggregated results, by model and scenario, for 2020 are provided in Appendix B.) As explained in Section 2, the global damage potential for gas X is the ratio of SC-X to SC-CO_2, and therefore by construction captures all the important linkages between emissions and monetized climate change damages (to the degree they are captured by the IAMs) directly within the gas comparison metric. As noted by Frankhauser (1994), this is preferred to the commonly used GWP gas comparison metric, which only measures the additional radiative forcing from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years) and ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages.

The global damage potential of CH_4 decreases with the discount rate due to the relatively shorter atmospheric lifetime. This difference in atmospheric lifetime leads to a situation where lowering the discount rate has a greater impact on the SC-CO_2 than the SC-CH_4. This finding is robust across the models. The estimates in Table 6 also present the same result for N_2O in the aggregate case, although this characteristic is not consistent across the models or the previous literature. Based on the disaggregated results (presented in Appendix B), the results from the DICE model suggests the global damage potential for N_2O increases with lower discount rates due to a lower effective decay rate over the relevant time horizon for N_2O than CO_2. This result is consistent with previous findings by Marten and Newbold (2012). However, for FUND the opposite is seen to hold. Waldhoff et al. (2011) show that this result is primarily due to the inclusion of increased production in the agriculture and forestry sectors from CO_2 fertilization effects. At lower discount rates these benefits place a greater downward

TABLE 6 Global damage potential

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CH_4	46	29	25	25
	N_2O	397	359	353	317
2050	CH_4	52	36	32	31
	N_2O	414	388	387	338

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impact on the SC-CO_2, thereby lowering the global damage potential. If one were to remove those impacts from the FUND model the global damage potential for N_2O becomes relatively insensitive to the discount rate. One would expect the role of the discount rate in determining the global damage potential in PAGE to be the same as in DICE, but the results suggest that this is not the case. It seems most likely that this is because the PAGE model has only ten time steps to cover the entire time horizon, which results in very large, up to 100-year, time steps further out in time. As noted in Section 3, the additional radiative forcing from the N_2O perturbation is implemented as the average across the model's time steps. It seems that PAGE does not average radiative forcing over the time step for CO_2, which causes the global damage potential for N_2O to decrease with the discount rate. It is not clear if this result would hold if the size of the time steps in the model were reduced.

A comparison across models further highlights the importance of CO_2 fertilization impacts on the global damage potential. CO_2 emissions, and the resulting increase in atmospheric concentration, have the potential to increase yields in the agriculture and forestry sector. This characteristic is not shared by other GHG emissions. Accordingly, the FUND model, which explicitly captures this effect, exerts downward pressure on the SC-CO_2 that is not present for the SC-CH_4 and SC-N_2O, allowing for the possibility of substantially higher global damage potential estimates. The results based on the FUND model presented in this article exhibit this effect; however, the CO_2 fertilization effect is not explicitly modelled in DICE and PAGE and therefore they are found to produce lower estimates of the global damage potential. For example, using the 3% discount rate, the global damage potential for CH_4 as estimated by FUND ranges between 58 and 88 depending on the scenario, whereas it ranges from 19 to 28 for DICE and PAGE. As the DICE and PAGE models only consider two natural system impacts, temperature and sea level, if they do implicitly include potential CO_2 fertilization benefits, they are included by using the temperature anomaly as a proxy for the increasing atmospheric CO_2 concentration. Fertilization benefits would therefore be allowed to falsely accrue to perturbations of other GHG emissions besides CO_2. It is not clear the degree to which these models try to incorporate CO_2 fertilization effects and therefore the degree to which this issue is of concern.

Finally, the results in this article show that the 100-year GWP (25 for CH_4 and 298 for N_2O; Forster et al., 2007) probably provides an underestimate of the global damage potential of each gas, a finding consistent with previous studies by Marten and Newbold (2012) and Waldhoff et al. (2011). Unlike the GWP as calculated by the IPCC, the global damage potential will be dependent upon the year of the emissions perturbations, so the degree of underestimation varies by year. For CH_4, the global damage potential in Table 6 is 0–84% higher than the GWP in 2020, increasing to 24–108% in 2050. For N_2O, the global damage potential is 6–33% higher than the GWP in 2020, increasing to 13–39% in 2050. While inaccurate, using the GWP to convert emissions reductions into CO_2 equivalents that can be valued with the SC-CO_2 would probably provide a conservative estimate for the abatement benefits.

For the comparison above, the GWP estimates presented in the AR4 by the IPCC (Forster et al., 2007) were used to maintain consistency with the assumptions regarding the direct and indirect effect of CH_4 and N_2O concentrations within the modelling. The recent AR5 by the IPCC (Myhre et al., 2013) has increased the estimate of the indirect effects of CH_4, which gives a higher 100-year GWP for CH_4 of 28. A reduction in their estimate of the radiative efficacy of N_2O has decreased its 100-year GWP to 265. It is likely that updated modelling of the social cost estimates based on similar assumptions would maintain the finding that the GWP is an underestimate of the global damage potential.

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4.1. Comparison with previous estimates

For comparison, Table 7 presents the social cost estimates, when available, and the global damage potential estimates for CH_4 and N_2O from three recent studies in the literature whose features are more up to date and therefore more directly comparable with this study: Hope (2006a), Waldhoff et al. (2011), and Marten and Newbold (2012). A direct comparison to the longer list of studies presented in Table 1 is more difficult as they are based on models and socio-economic and emissions scenarios that were developed up to 20 years ago in a rapidly evolving field.

The social cost estimates presented in Table 5 are higher than the estimates in Hope (2006a) and Waldhoff et al. (2011) for CH_4, and in the range of Waldhoff et al. (2011) for N_2O. This result holds whether the comparison is made with the aggregate results in Table 5 or the disaggregated model-specific results. One reason for the significant difference in the SC-CH_4 estimates is that the earlier studies rely on older model versions (PAGE2002 and FUND3.5), neither of which include the indirect effects of CH_4 emissions on radiative forcing, but are included within this analysis. As noted in Section 3.3 the indirect effects of CH_4 are modelled as a 40% increase in its effective radiative forcing. The result of this change alone would likely be a greater than 40% increase in the SC-CH_4 due to the nonlinear damage functions. Furthermore, the assumptions regarding preference parameters in the main cases of Hope (2006a) and Waldhoff et al. (2011) lead to effective discount rates that are significantly higher than 3%. Other differences in input assumptions (e.g. equilibrium climate sensitivity, socio-economic emissions scenario) will also lead to differences, although these are likely to be of second-order importance given the relative similarity in the assumptions.

However, the results in Table 5 averaged across the combinations of the three models and five scenarios are relatively similar to those of Marten and Newbold (2012), which focused on a single scenario

TABLE 7 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Discount Rate	Emissions Year	Social cost (2007$/tonne X)[a]		Global damage potential (SC-X/SC-CO_2)	
			SC-CH_4	SC-N_2O	CH_4	N_2O
Hope (2006a)	Ramsey	2001	125	–	20	–
Waldhoff et al. (2011)[b]	Ramsey	2010–2019	265	7,616	26	738
			–	–	8–221	383–3,503
Marten and Newbold (2012)	2.5%	2020	1,500	26,000	23	403
		2050	3,500	50,000	32	444
	3%	2020	1,100	17,000	27	400
		2050	2,900	34,000	36	439
	5%	2020	550	4,900	42	380
		2050	1,500	12,000	53	415

[a]All values are discounted to the year of the emissions perturbation.
[b]The first row presents the base case and the second row presents the range found from sensitivity analysis (over socio-economic scenario, climate sensitivity, pure rate of time preference, climate sensitivity and CO_2 fertilization).

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and model. This result is in part based on the fact that both sets of results include the indirect effects of CH_4, use the same discount rates and equilibrium climate sensitivity distribution, and relatively similar scenarios. The estimates in this study are slightly higher for the SC-CH_4 and slightly lower for the SC-N_2O compared to Marten and Newbold (2012). Of particular interest is the specific comparison of this article's estimates based on DICE 2010 and the MiniCAM scenario to those of Marten and Newbold (2012) using the same scenario, discount rates, and equilibrium climate sensitivity but an the older 2007 version of the DICE model and a more complete climate sub-model. In this case, estimates for both the SC-CH_4 and SC-N_2O (presented in Appendix B) are notably lower. The myriad of differences between the model vintages and climate sub-models make it difficult to assess which differences are most important for explaining this relationship.

As previously noted, the global damage potential may provide a better value with which to compare across studies that estimate the social cost of non-CO_2 GHG emissions, as it helps to control for some of the underlying differences in assumptions across studies. For example, the global damage potential is far less sensitive to the discount rate used than the SC-X values themselves. However, the global damage potential does not address the lack of indirect CH_4 effects, as may be seen in the lower estimates of Hope (2006a) and Waldhoff et al. (2011). In these cases the exclusion of the 40% additional increase in radiative forcing from the indirect effects of the CH_4 perturbation explains the majority of the difference. In comparison to Marten and Newbold (2012), the results presented in Table 6 are relatively similar for CH_4 in both the aggregate and disaggregated results. For N_2O, similar results are found in the DICE estimates, but notable differences are found in how the aggregate results respond to the discount rate, due to the differences in this relationship between the models as noted above.

5. Concluding remarks

This article presents a simple and transparent approach to estimating the social cost of CH_4 (SC-CH_4) and N_2O (SC-N_2O) in a manner that is consistent with estimates of the social cost of CO_2 (SC-CO_2) already in use in benefit–cost analysis (BCA) for US Federal regulations. This approach is used to estimate the SC-CH_4 and SC-N_2O for the period 2010–2050. These directly modelled estimates are found to be larger than approximations of the social costs of these gases based on the application of common physical gas comparison metrics, such as global warming potentials (GWPs), to the SC-CO_2. This result generalizes the empirical findings of Marten and Newbold (2012) that using a GWP-based approximation approach will likely offer a conservative estimate of the social cost of non-CO_2 GHGs.

The social costs associated with emissions of non-CO_2 GHGs are substantial and should be included within the BCAs used to assess the overall welfare implications of policy alternatives. For example, by not including monetized values of the benefits from reducing CH_4 and N_2O emissions, the BCA for recent standards regulating the fuel efficiency and GHG emissions of light duty vehicles implicitly assigned them a value of zero (US EPA, 2010). However, the results of this article suggest that those reductions have benefits of US$85–493 million (2007$) for CH_4 and $1.5–12 million (2007$) for N_2O in the year 2020 alone. Failing to account for such impacts could limit the ability of the analysis to serve as a transparent and informative input into the decision-making process about the relative benefits and costs of regulatory alternatives. That said, by restricting the article to a derivation of social cost estimates consistent with the USG SC-CO_2 estimates, the myriad issues related to

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whether those estimates can themselves be improved are set aside.[6] Any limitations that apply to the USG SC-CO_2 estimates therefore also apply to the SC-CH_4 and SC-N_2O estimates derived here.

Supplemental data

Supplemental data for this article can be accessed 10.1080/14693062.2014.912981.

Notes

1. Examples include Minnesota's draft methodology for setting the value of a tariff to compensate solar panel owners for the surplus power they deliver to utilities (http://www.eenews.net/stories/1059992297, http://mn.gov/commerce/energy/images/DRAFT-MN-VOS-Methodology-111913.pdf), the Northwest Power and Conservation Council's symposium supporting the development of the 7th Power Plan (http://www.nwcouncil.org/energy/powerplan/7/symposiums/greenhouse/agenda), BCA of Canada's Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations (http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html), analysis of climate change projects at the Inter-American Development Bank (correspondence with Patrick Doyle, Senior Climate and Energy Officer, Structured and Corporate Finance Department), the International Monetary Fund's recent Energy Subsidy Reform report (http://www.imf.org/external/np/pp/eng/2013/012813.pdf), and Parry and Strand (2012).
2. An alternative approach for estimating the social cost of GHG emissions could be based on stated preference (SP) surveys designed to elicit respondents' maximum willingness-to-pay for various levels of GHG emission reductions (e.g. Longo, Markandya, & Petrucci, 2008; Soliño, 2010). This approach would not suffer from the difficulties associated with creating and parameterizing a numerical integrated assessment model. However, it would suffer from its own set of difficulties, including well-known general limitations that affect all SP studies including the potential for 'hypothetical bias' (e.g. Carson, 2012; Hausman, 2012; Kling, Phaneuf, & Zhao, 2012), plus difficulties that may be specific to this application stemming from the generally limited knowledge base regarding the potential climatic, biophysical, and especially economic impacts of GHG emissions on current and far future generations that most respondents will bring to the survey.
3. The fork of MAGICC version 5.3 included in Pacific Northwest National Laboratory's open source model GCAM version 2 (Calvin et al., 2009) is used without carbon cycle feedbacks and, unless otherwise specified, an equilibrium climate sensitivity of 3 8C. We note that sensitivity analysis found the general results of this side analysis to be robust to other values of the equilibrium climate sensitivity.
4. The EMF-22 scenario is extended past 2100 assuming that emissions stay constant at the 2100 level. This assumption is revisited later in this article.
5. The PAGE 2009 model restricts the user to representing the entire time horizon, in this case out to 2300, with only ten time steps. This leads to the unrealistic situation in a small number of simulations where the marginal unit of emissions can cause 'catastrophic' climate impacts to occur one period earlier, which could be 100 years earlier in some cases. We consider these occurrences to be a limitation of the model and drop them from the overall distribution of estimates. Appendix A contains further details about this issue.
6. In addition to the critiques previously cited, we point the interested reader to the work of Marten et al. (2013) and Oppenheimer (2013) for a review of literature that considers potential improvements in the assessment and valuation of climate change impacts.

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BEFORE THE ENVIRONMENTAL PROTECTION AGENCY

PETITION FOR RULEMAKING PURSUANT TO SECTION 21 OF THE TOXIC SUBSTANCES CONTROL ACT, 15 U.S.C. § 2620, CONCERNING THE REGULATION OF CARBON DIOXIDE

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CENTER FOR BIOLOGICAL DIVERSITY

DONN J. VIVIANI, PhD

PETITIONERS

June 30, 2015

NOTICE OF PETITION

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The Center for Biological Diversity ("Center") is a non-profit, public interest environmental organization dedicated to the protection of native species and their habitats through science, policy and environmental law. The Center has over 800,000 members and online activists throughout the United States and around the world. The Center's Oceans Program and its supporters are specifically concerned with the conservation of marine species, the preservation of ocean ecosystems and the effective implementation of U.S. environmental laws, including the Toxic Substances Control Act. The Center submits this petition on its own behalf and on behalf of its members and staff with an interest in protecting the marine environment.

Donn J. Viviani, PhD, is a retired U.S. Environmental Protection Agency scientist. He was the Director of the Climate Policy Assessment Division in the Office of Policy, Economics and Innovation. He also served as Chairman of the Great Lakes Water Board's Toxic Substances Committee and as a member of the Science Coordinating Committee for the International Joint Commission for the Great Lakes. Dr. Viviani enjoys the ocean and submits this petition, in part, so his grandchildren will be able to enjoy it as well. Dr. Viviani also submits a supplement to the petition, under his signature only, and respectively requests that it be considered.

ACTION REQUESTED

Pursuant to section 21 of the Toxic Substances Control Act ("TSCA" or the "Act"), 15 U.S.C. § 2620, and section 553(e) of the Administrative Procedure Act ("APA"), 5 U.S.C. § 553(e), the Center for Biological Diversity and Donn J. Viviani (collectively, "Petitioners") hereby petition the Administrator of the U.S. Environmental Protection Agency ("EPA") to promulgate regulations protecting public health and the environment from the serious harms associated with anthropogenic emissions of carbon dioxide, including ocean acidification. Specifically, Petitioners request that EPA adopt a rule under section 6 of the Act, 15 U.S.C. § 2605, requiring manufacturers and processors to mitigate these emissions.

This petition sets in motion a specific process, placing definite response requirements on EPA. Specifically, TSCA stipulates that the agency "*shall* either grant or deny the petition" within 90 days following its receipt, "promptly commenc[ing] an appropriate [rulemaking]

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proceeding" if such action is warranted. 15 U.S.C. § 2620(b)(3) (emphasis added). Conversely, should EPA deny this petition, the agency must publish the reasons for denial in the Federal Register. 15 U.S.C. § 2620(b)(3); *see also* 5 U.S.C. § 555(e) ("Prompt notice shall be given of the denial in whole or in part of a written application, petition, or other request of an interested person made in connection with any agency proceeding."). Pursuant to 15 U.S.C. § 2620(b)(4), petitioners may file suit in federal district court to challenge an adverse or untimely determination. *See also* 5 U.S.C. §§ 702, 706.

As described in this petition, anthropogenic emissions of carbon dioxide satisfy the standard for regulation set forth at 15 U.S.C. § 2605. For example, EPA has acknowledged that these emissions have the potential to alter ocean chemistry, thus imperiling important marine ecosystems and presenting an unreasonable risk of injury to the environment. Accordingly, the agency must promptly commence the proposed rulemaking to reduce and mitigate these harms. In the event that EPA concludes that there are insufficient data and experience upon which to determine or predict the effects of carbon dioxide emissions, we alternatively request that the agency adopt a rule under section 4 of the Act, 15 U.S.C. § 2603, requiring manufacturers and processors responsible for the generation of carbon dioxide to undertake testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Dated this 30th day of June 2015.

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INTRODUCTION

Ocean acidification — caused by carbon dioxide ("CO_2") emissions — is a severe threat to the marine environment and the health of people who depend on oceans and coasts. Because of the unreasonable risk that CO_2 poses to the environment and human health, this petition seeks rulemaking under the Toxic Substances Control Act ("TSCA") to regulate CO_2 from cradle to grave.

About 28% of CO_2 emissions from power generation, cement production, industry, and other sources are absorbed by the ocean. These CO_2 emissions cause seawater to become more acidic and corrosive to sea life. Anthropogenic CO_2 emissions have increased the acidity of the oceans on average by 30%, and by the end of the century scientists predict that the oceans will become 150-170% more acidic.

While the most dangerous consequences of CO_2 on our oceans are still to come, harmful impacts on the environment are already well-documented.

- Billions of oyster larvae have perished in the Pacific Northwest due to ocean acidification;
- 53% of pteropods, plankton that form the base of the marine food web, along the West Coast have severely dissolved shells because of the corrosive nearshore conditions; and
- Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%.

These are just some of the harmful environmental impacts of ocean acidification caused by CO_2 emissions. Anthropogenic CO_2 emissions are contributing to increasingly corrosive conditions for marine animals, and will continue to grow more severe absent actions to promptly reduce CO_2 pollution in the atmosphere.

TSCA was enacted in part to address the threat of ozone depletion caused by chlorofuorocarbon (CFC) emissions. And here again TSCA regulation is needed where airborne emissions are causing damage to our environment — this time threatening ocean ecosystems, fish and shellfish industries, and communities that depend on oceans and coral reefs.

Petitioners specifically request that EPA take the following actions:

1. **Make a determination under TSCA § 6 that CO_2 presents an unreasonable risk of injury to health or the environment; and**
2. **Initiate rulemaking to control CO_2; or**
3. **If EPA finds data inadequate to make a §6 determination then EPA must initiate rulemaking for testing under TSCA § 4.**

This petition presents scientific evidence that establishes that CO_2 presents an unreasonable risk of injury to the environment, and therefore EPA must take action under TSCA section 6.

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I. The Toxic Substances Control Act

Congress enacted TSCA, 15 U.S.C. §§ 2601 *et seq.*, "to assure that … innovation and commerce in … chemical substances and mixtures do not present an unreasonable risk of injury to health or the environment."[1] Accordingly, lawmakers required those responsible for the manufacture and processing of these compounds to develop "adequate data" describing their effects, and authorized EPA to devise and implement reasonable controls to prevent the risk of injury to health or the environment.[2]

Section 6 of TSCA mandates that EPA "shall" regulate a chemical substance for which

> there is a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance or mixture, or that any combination of such activities, presents or will present an unreasonable risk of injury to health or the environment.[3]

Permissible regulations include requirements prohibiting or "limiting the amount of such substance … which may be manufactured, processed, or distributed in commerce."[4] EPA can also require processors "to give public notice of such risk [of injury], and . . . to replace or repurchase such substance . . . to adequately protect health or the environment."[5] In assessing risk, EPA must consider:

> (A) the effects of such substance or mixture on health and the magnitude of the exposure of human beings to such substance or mixture,
> (B) the effects of such substance or mixture on the environment and the magnitude of the exposure of the environment to such substance or mixture,
> (C) the benefits of such substance or mixture for various uses and the availability of substitutes for such uses, and
> (D) the reasonably ascertainable economic consequences of the rule, after consideration of the effect on the national economy, small business, technological innovation, the environment, and public health.[6]

Thus, if there is a reasonable basis to conclude that a proposed rule is necessary to protect the environment, then EPA must grant a petition for rulemaking and initiate rulemaking procedures. Factual certainty is not required; instead, the agency may "base its action on scientific theories, consideration of projections from available data, modeling using reasonable assumptions, and extrapolations from limited data."[7] Even if EPA determines that another federal law "could

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[1] 15 U.S.C. § 2601(b)(3) (2012). Within the meaning of TSCA, the term "chemical substance" includes "any organic or inorganic substance of a particular molecular identity." *Id.* § 2602(2).
[2] *Id.* § 2601(b)(1) & (2).
[3] *Id.* § 2605(a) (emphasis added).
[4] *Id.* § 2605(a)(1)(B).
[5] *Id.* § 2605(b)(2)(B).
[6] *Id.* § 2605(c)(1). E.
[7] Lead Fishing Sinkers; Response to Citizens' Petition and Proposed Ban, 59 Fed. Reg. 11,122, 11,138 (Mar. 9, 1994) (*citing* H.R. Rep. No. 1341, 9th Cong., 2d Sess. 32 (1976)).

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[sufficiently] eliminate[] or reduce[]" the risk associated with a particular chemical substance, the agency may elect to regulate the substance under TSCA, provided that a "comparison of the estimated costs" and "relative efficiency" reveals that such action promotes the public interest.[8]

In the event that EPA lacks adequate data and experience upon which to determine the health and environmental risks associated with a particular chemical substance, the agency "*shall* by rule require that testing be conducted on such substance."[9] Specifically, Section 4 of the Act authorizes EPA to compel manufacturers and processors to evaluate the safety of substances that "may present an unreasonable risk of injury to health or the environment" or that "[are] or will be produced in substantial quantities" and, thus, "may reasonably be anticipated to enter the environment in substantial quantities" or result in "significant or substantial human exposure."[10] TSCA provides for testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Over forty years ago, the Council on Environmental Quality warned of the "high priority need" for a new legal authority capable of ensuring the safe use of toxic chemicals.[11] Despite TSCA's powerful potential, however, EPA has accomplished very little under the Act. This petition presents substantial scientific evidence demonstrating that anthropogenic emissions of CO_2 pose an unreasonable risk to human and environmental health. Indeed, studies show that significant and potentially irreversible harm has already occurred. As the Council recognized decades ago, "[w]e should no longer be limited to repairing [this] damage after it has been done; nor should we continue to allow the entire population or the entire environment to be used as a laboratory." Instead, EPA must take prompt action to reduce and mitigate the anthropogenic production of CO_2.

II. EPA Must Issue a Rule to Regulate or Require Tests for CO_2 Causing Ocean Acidification

CO_2 presents an unreasonable risk of injury to the environment because its exposure to the ocean changes seawater chemistry with harmful impacts on marine life and ecosystems. Substantial evidence supports this conclusion and is discussed in this petition. Accordingly, this petition seeks a rulemaking to regulate CO_2 under TSCA.

This petition requires EPA to make a determination under TSCA section 6 if the injury to the environment and health from CO_2 is unreasonable. Alternately, if the Agency demonstrates that the existing science is insufficient to make a determination under TSCA section 6, EPA must initiate test rules under TSCA section 4 to develop the missing information needed to determine if the TSCA section 6 trigger is met and how best to mitigate the harm.

A. TSCA Authorizes EPA to Act on CO_2

To enable the achievement of TSCA's ambitious objectives, Congress broadly defined EPA's jurisdiction under the Act. As described above, TSCA explicitly directs EPA to initiate

[8] *Id.*
[9] *Id.* § 2603 (emphasis added).
[10] *Id.*
[11] Council on Envtl. Quality, Toxic Substances at v (April 1971).

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rulemaking upon finding that "the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance" threatens public health or the environment.[12] TSCA then authorizes the regulation of "chemical substances" that are "in commerce," a test met by CO_2. Indeed, CO_2 is already on the TSCA inventory as a "chemical in commerce."[13] CO_2 necessarily qualifies as a "chemical substance," a category that includes "any organic or inorganic substance of a particular molecular identity."[14] Moreover, the anthropogenic emissions at issue are in commerce; federal courts have previously concluded that air emissions[15] and "incidental byproducts of industrial chemical processes" are within the scope of EPA's authority under the Act.[16] Existing scientific evidence demonstrates that the anthropogenic production of CO_2 has already damaged marine ecosystems and endangered vulnerable portions of the human population. For the reasons described below, EPA must promptly reduce and mitigate these harms.

1. CO_2 Is a Chemical Substance

First, carbon dioxide is a "chemical substance" falling within the scope of the Act. The Act defines "chemical substance" as "any organic or inorganic substance of a particular molecular identity, including any combination of such substances occurring in whole or in part as a result of a chemical reaction or occurring in nature and (ii) any element or uncombined radical."[17]. CO_2 meets this definition. CO_2 is a chemical substance that occurs both in nature and as a result of a chemical reaction. It consists of a carbon atom bonded to two oxygen atoms:

$$O=C=O$$

It is identified by molecular formula CO_2 and by CAS number 124-38-9.

2. CO_2 Is in Commerce

Second, CO_2 is in commerce, and it is already on the TSCA inventory (CAS 124-38-9) with "chemical in commerce" as the stated reason for regulation.[18] Under TSCA's statutory text, "commerce" is defined as "trade, traffic, transportation, or other commerce . . . between a place in a State and any place outside of such state, or . . . which affects trade, traffic, transportation, or commerce."[19] CO_2 is primarily produced as a byproduct from the combustion of fossil fuels; according to the EPA, CO_2 emissions account for 77% of greenhouse gas emissions worldwide.[20]

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[12] *Id.* §§ 2605(a), 2603(a)(1)(A)(i), 2506(a). Although TSCA does not define "disposal," other federal environmental laws explain that this term encompasses "the discharge, deposit, injection, dumping, spilling, leaking, or placing of any solid waste or hazardous waste into or on any land or water so that such solid waste or hazardous waste or any constituent thereof may enter the environment or be emitted into the air or discharged into any waters, including ground waters." 42 U.S.C. §§ 6903(3), 9601(29).
[13] EPA, Substance Registry at http://1.usa.gov/1IBS1w6 (last accessed June 28, 2015).
[14] 15 U.S.C. § 2602(2). This definition excludes specific compounds already subject to federal control, such as pesticides, tobacco products, nuclear materials and food, drugs and cosmetics. *Id.* § 2602(2)(B).
[15] *Citizens for a Better Env't v. Thomas*, 704 F. Supp. 149, 152 (E.D. Ill. 1989).
[16] *Envtl. Def. Fund v. Envtl. Prot. Agency*, 636 F.2d 1267, 1271 (D.C. Cir. 1980).
[17] 15 U.S.C. § 2602(2)(A).
[18] EPA, Substance Registry at http://1.usa.gov/1IBS1w6.
[19] 15 U.S.C. § 2602(3).
[20] EPA, Global Greenhouse Gas Emissions Data, http://www.epa.gov/climatechange/ghgemissions/global.html (last updated June 21, 2013; last accessed June 28, 2015).

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The most voluminous sources of greenhouse gas emissions are energy suppliers,[21] industry,[22] land use and forestry,[23] agriculture,[24] transportation,[25] commercial and residential buildings,[26] and waste and wastewater.[27] All of these emitters produce CO_2 as a byproduct of their ordinary processes.

TSCA's statutory and regulatory text support the proposition that CO_2 emitted as a byproduct of industrial processes can be regulated under TSCA because CO_2 in this context is manufactured, meaning "produce[d] . . . with the purpose of obtaining an immediate or eventual commercial advantage."[28] All of the industries listed above which emit CO_2 are performed to obtain an immediate or eventual commercial advantage, as all of these industries are commercial and part of a competitive market. Therefore, incidental production of CO_2 is manufactured or produced "for a commercial purpose," and is found "in commerce" pursuant to TSCA regulations.

Accordingly, CO_2 emissions fit the regulatory definition of a chemical substance produced for a commercial purpose. This is bolstered by the broad definition of "commerce" in the TSCA statute; at the very least, CO_2 emissions "affect" trade, traffic, transportation, and commerce.

TSCA's purpose and regulatory text support the regulation of chemical substances that are an incidental byproduct, and indeed EPA has regulated chemical byproducts under TSCA before. For example, PCBs are regulated under TSCA even when they are only incidentally produced as a byproduct of industrial processes.[29] EPA regulates PCB "byproducts" for which there are no separate commercial intents, and TSCA regulates inadvertently vented PCB emissions.[30] Moreover, EPA's authority under TSCA broadly defines what it regulates under "disposal" of PCBs to include intentional and accidental disposal.[31] EPA has also previously prohibited wastes from chemical manufacturing under TSCA.[32]

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[21] Which emit greenhouse gases through "[t]he burning of coal, natural gas, and oil for electricity and heat." *Id.*

[22] Which emit greenhouse gases through "fossil fuels burned on-site at facilities for energy" and "chemical, metallurgical, and mineral transformation processes not associated with energy consumption." *Id.*

[23] Which emit "carbon dioxide . . . from deforestation, land clearing for agriculture, and fires or decay of peat soils." *Id.*

[24] "Greenhouse emissions from agriculture mostly come from the management of agricultural soils, livestock, rice production, and biomass burning." *Id.*

[25] Which emit greenhouse gases through "fossil fuels burned for road, rail, air, and marine transportation." *Id.*

[26] Which emit greenhouse gases from "on-site energy generation and burning fuels or heat in buildings or cooking in homes." *Id.*

[27] Which emit carbon dioxide through the "incineration of some waste products that were made with fossil fuels, such as plastics and synthetic textiles." *Id.*

[28] 40 C.F.R. § 710.3; 40 C.F.R. § 704.3 ("Manufacture for commercial purposes also applies to substances that are produced coincidentally during the manufacture, processing, use, or disposal of another substance or mixture, including both byproducts that are separated from that other substance or mixture and impurities that remain in that substance or mixture. Such byproducts and impurities may, or may not, in themselves have commercial value. They are nonetheless produced for the purpose of obtaining a commercial advantage since they are part of the manufacture of a chemical product for a commercial purpose.").

[29] 44 Fed. Reg. 31525 (May 31, 1979); 40 C.F.R. § 761.

[30] *See, e.g.,* 40 C.F.R. Part 761.

[31] 40 C.F.R. § 761.3.

[32] 45 Fed. Reg. 592 (March 11, 1980);40 C.F.R. § 775 (1980) (prohibiting disposal of 2,3,7,8-tetracholorodibenzo-p-dioxin (TCDD) a manufacturing waste).

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Further, CO_2 emissions are in commerce as they are traded, bought, and sold as carbon offsets. CO_2 is also produced for commerical purposes including for uses in fertilizer, beverage carbonation, dry ice, refrigeration, pressurization, fire extinguishment, and packaging.

B. EPA Should Initiate Rulemaking to Control CO_2 under TSCA

Petitioners request that EPA make finding that CO_2 presents or will present an unreasonable risk of injury to the environment or health. TSCA requires that EPA "shall" initiate rulemaking upon finding "a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use or disposal of a chemical substance of mixture … presents or will present an unreasonable risk of injury to health or the environment."[33]

The information and supporting documents provided in this petition indicate that CO_2 is already causing injury to the environment due to ocean acidification. The scientific evidence further supports that the injury to the environment and health will grow more severe as CO_2 pollution continues. EPA cannot deny that CO_2 is harming the environment. Indeed, EPA acknowledges that ocean acidification poses risk:

> Ocean acidification, like Climate change is primarily caused by increasing carbon dioxide (CO_2) concentrations in the atmosphere. As a result of absorbing large quantities of human made CO_2 emissions the ocean chemistry is changing, which is likely to negatively affect important marine ecosystems and species including coral reefs, shellfish, and fisheries.

(Environmental Protection Agency 2010).

EPA must find that such injury is an unreasonable risk.[34] While Congress did not define the phrase "unreasonable risk," EPA has interpreted relevant legislative history to require that the agency:

> balance the benefits derived from risk reduction against the social and economic costs incurred, taking into account such factors as the extent and magnitude of risk posed; the societal consequences of removing or restricting use of products; availability and potential hazards of substitutes; and impacts on industry, employment, and international trade.[35]

No specific factual determination is necessary to establish "unreasonable risk." For example, even under the stricter standard of 15 U.S.C. § 2606, EPA need not present evidence of actual injury before obtaining emergency injunctive relief to control "immanently hazardous chemical substance[s] or mixture[s]."[36] For the reasons discussed below, application of the agency's balancing test supports the additional regulation of CO_2.

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[33] 15 U.S.C. § 2605(a).
[34] *Id.*
[35] EPA, Guidance for Petitioning the Environmental Protection Agency Under Section 21 of the Toxic Substances Control Act, 50 Fed. Reg. 46,825 (Nov. 13, 1985).
[36] *See* H.R. Conf. Rep. No. 94-1679 78 (1976).

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According to scientific experts: "Reducing CO_2 emissions is the only way to minimise [sic] long-term, large-scale risks" (IBGP et al. 2013).

1. CO_2 Pollution Presents an Unreasonable Risk of Injury to the Environment

There is clear consensus among leading national and international scientific bodies that anthropogenic CO_2 causes changes in ocean chemistry that harm the marine environment. The Intergovernmental Panel on Climate Change ("IPCC") determined that human sources of CO_2 have caused a significant decline in surface ocean pH (Rhein et al. 2013), and over 90 national academies of sciences, including the United States', have signed a statement that ocean acidification will "cause grave harm to important marine ecosystems as CO_2 concentrations reach 450 ppm and above" (Interacademy Panel 2009). The Interacademy Panel concluded that CO_2 has increased ocean acidity with "potentially profound consequences for marine plants and animals" including severe threats to coral reefs, polar ecosystems, and a likely reduction in marine food supplies (*Id.*). The National Research Council also acknowledges that "existing data support a growing consensus in the research community that most documented responses to acidification reflect impairment of physiological capacity or performance" for marine life with likely substantial socioeconomic impacts (National Research Council 2013). The U.S. National Climate Assessment concluded that ocean acidification will alter marine ecosystems in dramatic ways including threatening coral reef habitats and causing reduced growth and survival of shellfish in all regions (Doney et al. 2014).

EPA acknowledges that "ocean acidification presents a suite of environmental changes that would likely negatively affect ocean ecosystems, fisheries, and other marine resources." 75 Fed. Reg. 13538 (Mar. 22, 2010). EPA previously concluded that greenhouse gases, including CO_2, endanger public health and the environment in part because of ocean acidification.[37]

There is no doubt that CO_2 pollution is changing ocean chemistry and harming the marine environment. Unabated, there will be severe and detrimental impacts on marine ecosystems, the economy, and public health. Accordingly, EPA must find that CO_2 poses an unreasonable risk to the environment and health.

a. CO_2 Causes Irreversible Ocean Acidification

Ocean acidification is a major threat to the marine environment. The oceans have absorbed CO_2 emitted into the atmosphere from power plants, manufacturing, cement production, and land use changes. Between 1750 and 2011, human activities have released 375 gigatons of carbon into the atmosphere, and approximately half of that has been absorbed by the oceans (Rhein et al. 2013). Each day about 22 million metric tons of CO_2 is taken up by the oceans (Feely et al. 2008). This uptake of CO_2 is changing ocean chemistry, causing the oceans to become more acidic. Since the industrial revolution surface ocean pH has declined by 0.11 units on average, corresponding with

[37] EPA, Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act 80 (Dec. 7, 2009).

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a 30% increase in acidity (Orr et al. 2005; Caldeira & Wickett 2005).[38] If emissions continue unabated, ocean acidity will increase up to 170% by the end of the century (IBGP et al. 2013).

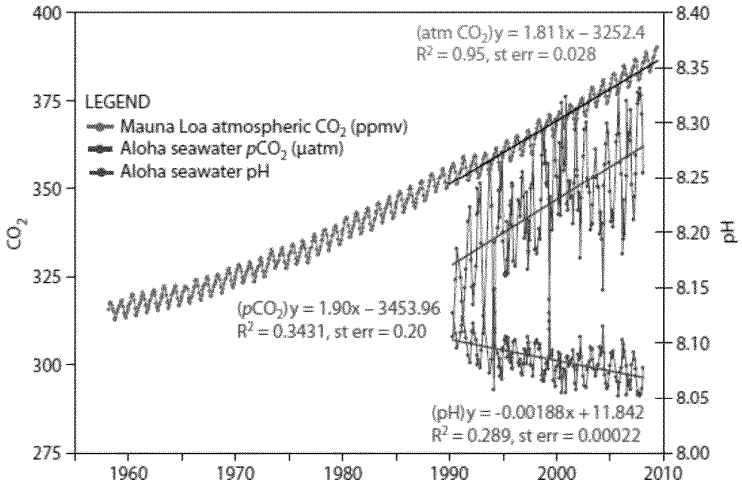

Figure 1. Time series of atmospheric CO 2 at Mauna Loa (ppmv) and surface ocean pH and pCO2 (µatm) at Ocean Station Aloha in the subtropical North Pacific Ocean (see inset map). Note that the increase in oceanic CO 2 over the period of observations is consistent with the atmospheric increase within the statistical limits of the measurements. (Feely et al. 2009).

Anthropogenic ocean acidification exceeds the trend in natural variability significantly, up to 30 times in some regions (Friedrich et al. 2012). The rate of change in ocean acidity is unprecedented in the past 300 million years, a period that includes four mass extinctions (Honisch et al. 2012; Zeebe 2012). The seawater chemistry change is an order of magnitude faster than what occurred 55 million years ago during Paleocene-Eocene Thermal Maximum, which is considered to be the closest analogue to the present, and during that period 96% of marine species went extinct (*Id.*). The current changes in seawater chemistry are irreversible on human timescales (Royal Society 2005).

CO_2's impact on ocean chemistry is fundamentally altering the marine environment with negative impacts on marine species, habitats and ecosystems.

i. What Is Ocean Acidification

When the ocean absorbs CO_2 from the atmosphere it changes ocean chemistry. CO_2 that is absorbed by seawater reacts to form carbonic acid, which dissociates to form bicarbonate and releases hydrogen ions. This reaction reduces the amount of carbonate ions and decreases pH. The oceans store a significant amount of the CO_2 pollution from human activities (Royal Society 2005). While this has provided society with an important service of buffering against climate change impacts, it comes at a cost to the marine environment.

[38] Because the pH scale is logarithmic a small decrease is a significant change in acidity; for example, a decrease of 0.1 pH is an approximate 30 percent increase in acidity.

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Globally, surface water pH has declined 0.11 units on average between 1750 and 1994 (Sabine et al. 2004). Long-term monitoring has documented the impact of increasing atmospheric CO_2 on declining seawater pH in the Pacific and Atlantic Oceans (*see* Figure 2). Results from time-series stations in the North Atlantic and North Pacific show a decrease of about 0.002 pH per year (Rhein et al. 2013).

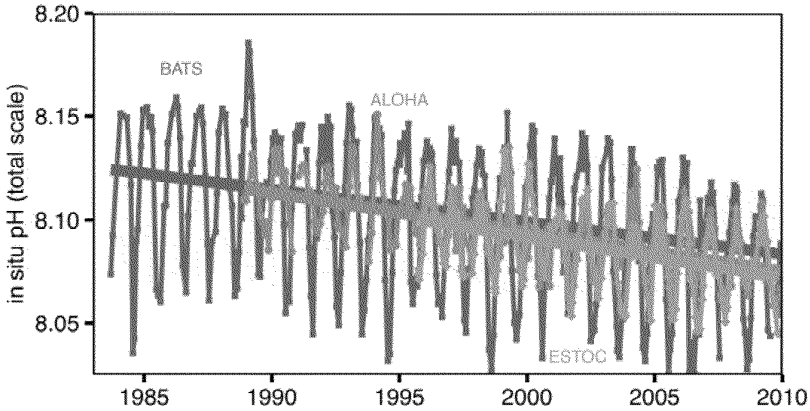

Figure 2. Long-term trends of surface seawater pH at three subtropical ocean time series in the North Atlantic and North Pacific Oceans, including (a) Bermuda Atlantic Time-series Study (BATS, 31°40'N, 64°10'W; green) and Hydrostation S (32°10', 64°30'W) from 1983 to present (updated from Bates, 2007); (b) Hawaii Ocean Time-series (HOT) at Station ALOHA (A Long-term Oligotrophic Habitat Assessment; 22°45'N, 158°00'W; orange) from 1988 to present (updated from Dore et al., 2009) and (c) European Station for Time series in the Ocean (ESTOC, 29°10'N, 15°30'W; blue) from 1994 to present (updated from González-Dávila et al., 2010). Atmospheric pCO2 (black) from the Mauna Loa Observatory Hawaii is shown in the top panel. Lines show linear fits to the data, whereas Table 3.2 give results for harmonic fits to the data (updated from Orr, 2011).(Rhein et al. 2013)

Ocean acidification not only makes the oceans more acidic, but it also reduces the amount of carbonate ions available for animals to build the shells and skeletons they need to survive. Carbonate is an important constituent of seawater because many organisms form their shells and skeletons by complexing calcium and carbonate. Waters that are supersaturated with aragonite are generally good for shell-building, while undersaturated waters (<1.0 Ω_{ar}) are corrosive to some marine animals. Corals require supersaturated waters above 3.3 Ω_{ar} (Meissner et al. 2012). Globally, there has been a decrease of about -0.4 Ω_{ar} (Gruber et al. 2012). The aragonite saturation state has declined 16% since the Industrial Revolution due, in large part, to anthropogenic CO_2 (Feely et al. 2012a; Ishii et al. 2011). Modeling of the oceans' aragonite saturation predicts that by the end of the century up to 75% of ocean volume could be undersaturated with respect to aragonite (Joos et al. 2011).

ii. Observed and Predicted Acidification

CO_2 has already had measurable impacts on seawater chemistry. Some regions, such as those with upwelling systems or high latitudes, are especially vulnerable to ocean acidification.

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1. Pacific Coast

The West Coast is already experiencing adverse impacts of ocean acidification. As early as 2008, a survey off the coasts of Washington, Oregon, and California revealed that this region is already experiencing corrosive waters not expected until mid-century (See figure 3) (Feely 2008). Researchers found seawater undersaturated with respect to aragonite upwelling onto large portions of the continental shelf, reaching shallow depths of 40 to 120 meters (*Id.*). According to the study, the waters were last at the surface approximately 50 years ago when atmospheric CO_2 concentrations were much lower (Feely et al. 2008). Feely et al. report that in the Pacific Ocean there has been a decrease of the saturation state of surface seawater with respect to aragonite and calcite as well as an upward shoaling of the saturation horizon by about 1-2 meters per year on average, due in large part to anthropogenic CO_2 (R. A. Feely, Sabine, et al. 2012). As a result, marine organisms in surface waters, in the water column, and on the sea floor along the West Coast of the United States are already being exposed to corrosive water during the upwelling season.

Modeling of the California Current System demonstrates that the area is rapidly approaching year-round undersaturation with respect to aragonite and it is departing significantly from natural variability (Hauri et al. 2013). Time series monitoring shows that the aragonite saturation state along the California coast is much lower than would be expected in the North Pacific (Harris, DeGrandpre et al. 2013). Surface Ω_{ar} values ranged between 0.66 and 3.9 compared to an estimated pre-industrial range of 1.0 to 4.7. While some areas, like Puget Sound, already exhibit undersaturated conditions every year (Feely, Klinger, et al. 2012; Reum et al. 2014), scientists predict that most shallow shelf areas along the West Coast will become undersaturated with respect to aragonite within the next 20-30 years (Capone & Hutchins 2013; Gruber et al. 2012).

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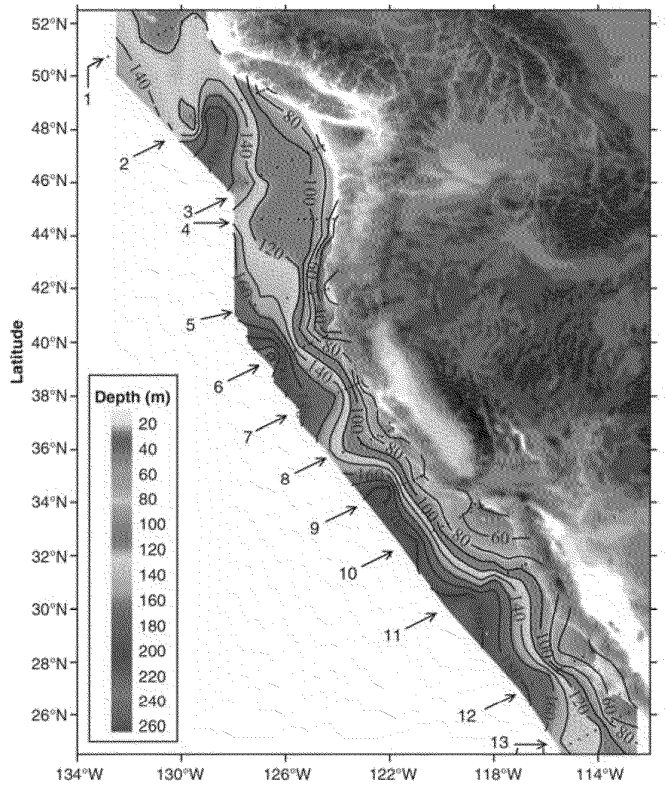

Figure 3. Distribution of the depths of the undersaturated water (aragonite saturation < 1.0; pH < 7.75) on the continental shelf of western North America from Queen Charlotte Sound, Canada, to San Gregorio Baja California Sur,Mexico. On transect line 5, the corrosive water reaches all the way to the surface in the inshore waters near the coast. The black dots represent station locations (Feely et al. 2008).

2. *Alaskan Waters*

High latitude waters are the "bellwether" of ocean acidification because these will be the first ocean regions to become persistently undersaturated with respect to aragonite as a result of greenhouse gas pollution (Fabry et al. 2009; Steinacher et al. 2009). High-latitude waters have naturally lower carbonate ion concentrations and saturation states due to a combination of cold temperatures which increase the solubility of CO_2 and ocean mixing patterns (Fabry et al. 2009; Mathis et al. 2011a). As early as 2016, 10% of Arctic surface waters are expected to be undersaturated with respect to aragonite for at least one month per year (Steinacher et al. 2009).

Recent observations of calcium carbonate saturation states in the North Pacific and Bering Sea have found that full water column undersaturation of calcium carbonate due to ocean acidification is already prevalent. Mathis et al. (2011a) reported that extensive areas of bottom waters over the Bering Sea shelf are becoming undersaturated with respect to aragonite for at least several months (July to September), and some areas of bottom water were already observed to be undersaturated with respect to calcite (Fabry et al. 2009, Mathis et al. 2011a).

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Scientists predict that polar waters will be corrosive to shellbuilding animals within decades (IBGP et al. 2013). A 2015 study of observations in the Chukchi and Beaufort Seas in the Arctic indicates that within 15 years waters will become so corrosive that it will be difficult for marine animals to build and maintain their shells (Mathis et al. 2015). The highly productive fisheries of Alaska are in some of the most rapidly changing seawater conditions (Mathis et al. 2014).

3. Sub-tropical Waters

Subtropical waters have experienced declining saturation states due to ocean acidification. Within decades, scientists believe that ocean acidification will impair coral growth (IBGP et al. 2013). Models show that by the end of the century, most coral reef areas will no longer have aragonite saturation states that are optimal for coral growth. A 10-year study of the Caribbean region found a strong regional decrease in aragonite saturation state between 1996-2006, from 4.05 to 3.9, resulting from CO_2 (Gledhill et al. 2008). Modeling predicts that under various emissions scenarios the coral reefs in the Caribbean will be thermally and chemically stressed between now and 2030 (Meissner et al. 2012). Even under the most optimistic scenario, 98% of reefs will be stressed by 2050 (*Id.*). In the Pacific subtropical ocean near Hawaii, there are nearly 20 years of time-series measurements of significant decreasing seawater pH that match the ocean's uptake of atmospheric CO_2 (Dore et al. 2009)

4. Atlantic Coast

Even ocean waters not at high latitude, in upwelling systems, or containing coral reefs ecosystems are, or will soon be, exhibiting signs of ocean acidification. Observations of East Coast waters during all seasons show that while they remain supersaturated with respect to aragonite, by the end of this century, saturation states of aragonite and calcite will decrease by 20–40%, with the lowest Ωar dropping to 1.3 in some seasons (Jiang et al. 2010). A survey of the Atlantic Coast showed that waters in the Northeast and particularly the Gulf of Maine are the most susceptible to ocean acidification (Wang 2013).

iii. CO_2 Kills and Injures Marine Life

High-CO_2 waters seriously harm marine wildlife and the entire ocean ecosystem. When CO_2 concentrations in seawater increase, the availability of carbonate ions decreases, making it more difficult for marine organisms to form, build, and maintain the calcium carbonate shells and skeletons required for their survival. As seawater becomes more corrosive, it can kill fish eggs and inhibit the development of, and essentially dissolve, the shells of small crustaceans, baby shellfish, and other tiny creatures at the base of the food web (Fabry 2008). Ocean acidification also harms and stresses fish, squid, and other animals that do not build shells (*Id.*). Not only does ocean acidification directly threaten various types of marine animals, it also has implications for the broader marine environment and food web.

The harmful effects of ocean acidification have already begun to occur. For example, ocean acidification has caused:

- A massive die-off of oysters in the Pacific Northwest (Barton et al. 2012; R. a. Feely, Sabine, et al. 2012; Washington State Blue Ribbon Panel 2012);

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- Declines in abundance and size of the California mussel, blue mussel and goose barnacle in tidepools correlated with a severely declining pH (Wootton et al. 2008);
- Sluggish growth of corals in the Caribbean and Great Barrier Reef (De'ath et al. 2009; De'ath et al. 2012; Gledhill et al. 2008); and
- Shells of plankton to dissolve off the California Coast and thinner and weaker shells of plankton in the Southern Ocean (Bednarsek 2014; Moy et al. 2009).

In a meta-analysis of over 400 experiments examining the impacts of ocean acidification on marine organisms, Kroeker et al. (2013) found the biological effects to be generally large and negative. This analysis was restricted to experiments with pH manipulations of less than 0.5 units, in order to reflect the predicted level of ocean acidification by the end of the century (IPCC 2007). By limiting the analysis to small variations in pH, this study shows that within the foreseeable future ocean acidification will have "profound repercussions for marine organisms" (Kroeker et al. 2010). While the negative effect of ocean acidification was most pronounced for calcification and survival (27% reductions in both responses), the study also revealed significant negative effects on growth and reproduction (11 to 19%, respectively). In addition, abundance was reduced by 15%. The strength of this analysis suggests that the patterns highlighted in this study are a robust representation of the current literature on ocean acidification.

While most of the worst consequences of ocean acidification are predicted for the future, scientists have already observed damage from CO_2 in the oceans. Additionally, the impacts of ocean acidification can affect the entire marine food web by altering habitat, prey availability, and species interactions.

b. High-CO_2 Waters Injure the Growth, Survival, Fitness, and Reproduction of Marine Animals

The primary known harm of CO_2 in the oceans is that it impairs the growth and survival of animals that build shells. Because ocean acidification reduces the availability of carbonate ions that marine animals use to calcify their shells and skeletons, CO_2 reduces the ability of these animals to build their protective structures (Doney et al. 2009). Acidified waters can also damage and dissolve shells.

These negative effects have been observed in the ocean as well as documented in laboratory studies. Corals, coralline algae, plankton, mollusks, and other shellfish exposed to future levels of ocean acidification have all experienced problems (Kleypas & Yates 2009; Kuffner et al. 2007; Barton et al. 2012; Talmage & Gobler 2011; Talmage & Gobler 2009; Orr et al. 2005; Riebesell et al. 2000).

i. Molluscs, Echinoderms, and Crustaceans

High CO_2 waters are lethal to shellfish. Since 2005, waters off the coast of Washington and Oregon have been killing oysters and other molluscs. Shellfish hatcheries in Washington and Oregon reported massive mortalities of oyster larvae (Washington State Blue Ribbon Panel 2012).Wild oysters also failed to reproduce in Willapa Bay, Washington (*Id.*). Scientists have definitively linked oyster production failures to high-CO_2 ocean waters that were used to raise larvae (Barton et al. 2012).

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In response to reported shellfish hatchery problems in Oregon, Barton et al. reported the results of their observations from the Whiskey Creek Hatchery on Netarts Bay in the summer of 2009 (Barton et al. 2012). Unlike previous laboratory experiments, this study analyzed calcifying organism responses in the ambient-water CO_2 chemistry of Oregon's coastal waters. Larval production and mid-stage growth (~120 um to ~150 um) of the oyster, *Crassostrea gigas*, were both significantly negatively correlated with the chemistry of waters in which larval oysters were spawned and reared for the first 48 hours of life. Although the impact of the exposure was not immediate, the delayed reaction caused a significant decline in growth for mid-sized oyster larvae and reduced overall production. The findings corroborate other laboratory studies that show that many marine species, especially at the larval stage, are adversely affected by ocean acidification.

Scientific studies have demonstrated that even modest pH declines affect the sensitive and vulnerable early developmental stages of organisms because these life histories have specific environmental needs (Kurihara 2008) (*see* Figure 10, below, showing negative effects from low pH treatments). A number of studies have found a delay in development or less development, degraded shells, decreased rate of metamorphosis, shell thickness, and loss of hinge integrity (Ross et al. 2011a). The resulting reduced larval size can reduce the feeding efficiency of larvae, and smaller larvae are more susceptible to starvation because they encounter comparatively less food (Kurihara & Shirayama 2004). Sub-lethal effects of elevated acidity can severely alter the composition and fitness of larvae, and given the high mortality rates of larvae in the water column and during the transition to benthic settler, small perturbations to larvae potentially may have large alterations to settlement dynamics, post-settlement mortality, recruitment, and ultimately adult populations (Ross et al. 2011).

Watson et al. (2009) exposed one day-old oyster larvae to a range of pH conditions, from 7.6 to 8.1, for 10 days and showed significant decline in the survival and growth of young larvae at lower pH. Waldbusser et al. (2010), in a study on the Chesapeake Bay, showed that even modest changes in pH present conditions that are corrosive to shells and have physiological impacts on adult and larval oysters. Biocalcification declined significantly with a reduction of 0.2 pH units, making juvenile bivalves more susceptible to predation and other mortality factors (*Id.*).

Negative effects have been seen on the metamorphosis, size, and survival of larval hard clams (*Mercenaria mercenaria*), bay scallops (*Argopecten irradians*), and Eastern oysters (*Crassostrea virginica*) at levels of CO_2 predicted to occur in the 21st century (Talmage & Gobler 2011). At 650 ppm, or an approximate drop of 0.3-0.4 from pre-industrial values, both *M. mercenaria* and *A. irrandians* larvae exhibited dramatic declines (over 50%) in survivorship as well as significantly delayed matamorphosis and significantly smaller size. *C. virginica* also experienced lowered growth and delayed metamorphosis at this level, an indicator that current and future increases in CO_2 populations may deplete or alter the composition of shellfish populations in coastal ecosystems (*Id.*).

The Olympia oyster, *Ostrea lurida*, a foundation species in estuaries along the Pacific coast, exhibits clear decline in larval growth and settlement as levels of CO_2 affect seawater pH. (Hettinger et al. 2012). Oysters in this experiment were raised at three levels of seawater pH,

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including a control (8.0) and two additional levels (7.9 and 7.8). Larvae reared under pH 7.8 exhibited a 15% decrease in larval shell growth rate, and a 7% decrease in shell area at settlement, compared to larvae reared under control conditions. Impacts were even more pronounced a week after settlement, with juveniles that had been reared as larvae under reduced pH exhibiting a 41% decrease in shell growth rate.

Oysters on the Atlantic coast also experience the ill effects of ocean acidification. Dickinson et al. (2012) found negative effects on juvenile eastern oysters after exposure to water with a 0.2 pH change. Exposure of the oysters to elevated acidity led to a significant increase in mortality, reduction of tissue energy stores and negative soft tissue growth, indicating energy deficiency. Under ocean acidification conditions, thermal tolerance is impaired in oyster larvae, leading to reduced development, size and increased abnormality (Ross et al. 2011; Parker et al. 2010). Similar results have been found in red abalone, with thermal tolerance impaired at pH 7.87 compared to control (pH 8.05) (Zippay and Hoffman 2010).

In studies with edible mussel (*Mytilus edulis*) and Pacific oyster (*Crassostrea gigas*) researchers found a strong decline of calcification under ocean acidification conditions (Gazeau et al. 2007). Based upon these results, researchers concluded that mussel and oyster calcification may decrease by 25% and 10%, respectively, by the end of the century." (*Id.*). Oysters and mussels also exhibit development abnormalities when exposed to acidification (Kurihara 2008). When oyster eggs were reared under pH 7.8, they showed malformations of their shell, and when reared under pH 7.4, more than 70% of the larvae were either completely non-shelled, or only partially shelled, and only 4% of CO_2 treated embryos developed into normal larvae by 48 hours after fertilization, in contrast to about 70% successful development in control embryos.

The shrimp *Palaemon pacificus* displayed variable responses at different developmental stages, pH and length of exposure (Kurihara 2008). Following long term (30 weeks) exposure of adults to pH 7.89 and 7.64, survival and egg production in early developmental stages decreased in both treatments. Findlay et al. (2010) found a slower rate of development of embryos in the common intertidal northern hemisphere barnacle *Semibalanus balanoides* with an estimated 19 days delay in reaching 50% hatching stage at pH 7.7. Other amphipods have exhibited metabolic changes in response to acidification levels greater than what is allowed under the federal criterion (Hauton et al. 2009).

Echinoderms exhibit delayed and asymmetrical development when exposed to acidified conditions. In the absence of adequate adaptation or acclimation, lowered pH levels will have a range of sub-lethal effects on sea urchins, brittlestar and seastar larvae from a range of geographical regions (Ross et al. 2011). Larvae of the ecological keystone brittlestar, *Ophiothrix fragilis*, either were abnormal, had altered skeletal proportions, or asymmetry during skeletogenesis, and there was a delay in development at pH levels of 7.9, or approximately 0.3 units below current surface levels (Gutowska et al. 2009). Other experiments on brittlestar in low pH waters resulted in dramatic results; acidification of 0.2 units induced 100% larval mortality within an eight day period. Control larvae showed 70% survival over the same period. Because the calcite skeleton of the larval brittlestar aids key functions such as feeding and vertical migration, and defense against predators, abnormal development of the skeleton will have drastic consequences for fitness. The developmental abnormalities may be exacerbated by temperature

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increases predicted for the end of the century; some scientists suggest that this may result in the disappearance of echinoderms from the surface oceans within the next 50-100 years (Ross et al. 2011a).

Reproductive success is compromised by ocean acidification. The fertilization rate of sea urchins decreases with increasing CO_2 concentrations (8.1 to 6.8 pH) (Kurihara 2008). In another sea urchin experiment utilizing six CO_2 concentrations, with a pH between 8.01 (control) and 6.83, cleavage rate, developmental speed, and larval morphology all declined with increased CO_2 concentration (Kurihara & Shirayama 2004). At a 0.2 change from control, effects could be seen on the morphology and development of the larvae, and these effects became more pronounced with greater pH changes (*Id.*) (*see* Figure 4, below). The authors concluded that "all the effects of raised CO_2 concentration observed in this study would have a negative impact on the survival of sea urchin embryos in their early life history." A recent study showed that sea urchin sperm flagellar motility was significantly reduced when seawater pH decreased by .3 units, from 8.0 to 7.7 (Suwa et al. 2010). As discussed above, decreased flagellar motility has severe consequences for fertilization and subsequent population dynamics; if sperm lose their ability to find eggs, the population size will necessarily diminish.

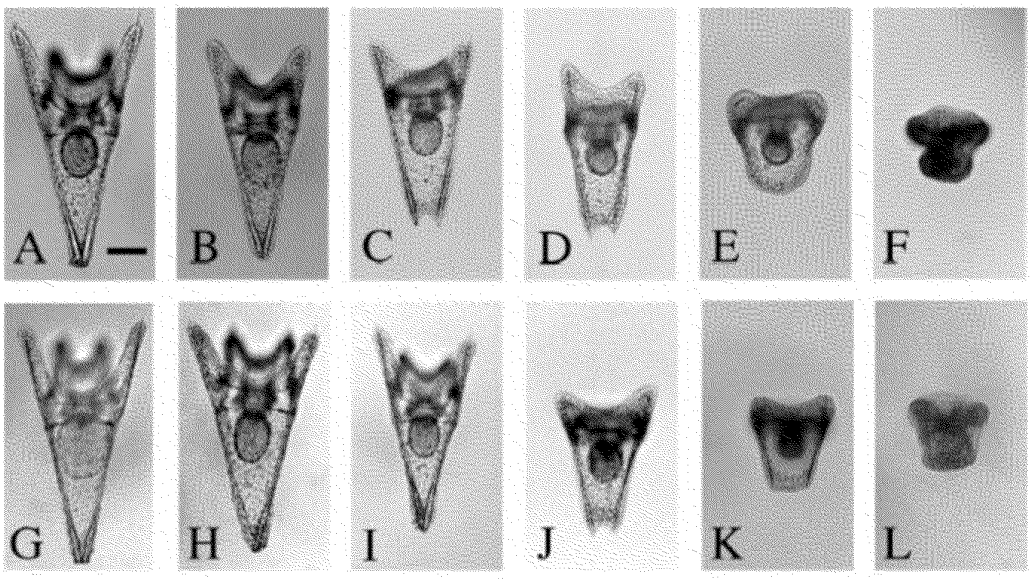

Fig. 6. *Hemicentrotus pulcherrimus*. Morphology of 4-armed pluteus larvae cultured for 3 d in (A–F) CO_2-seawater and (G–L) HCl-seawater. (A & G) control (pH 8.0); (B & H) +500 ppm (pH 7.8); (C & I) +1000 ppm (pH 7.6); (D & J) +2000 ppm (pH 7.4); (E & K) +5000 ppm (pH 7.0); (F & L) +10 000 ppm (pH 6.8). Scale bar = 50 µm

Figure 4. Declining development of sea urchin larvae exposed to acidified waters (Kurihara & Shirayama 2004).

Even moderate increases in atmospheric CO_2 and ensuing acidification adversely affect the growth of both gastropods and sea urchins (Shirayama & Thornton 2005). Before the end of this century, atmospheric CO_2 is likely to increase by more than 200 ppm, decreasing the pH of the ocean by approximately 0.3 units from pre-industrial levels. Two species of sea urchin as well as the gastropod *Strombus luhanus* were exposed for six months to waters with this level of elevated CO_2, and all three species exhibited similar consequences. Increased CO_2 negatively affected growth rate, calcification, shell height and body mass, and metabolic activity

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(Shirayama & Thornton 2005). The developing embryos of the gastropod and intertidal snail *Littorina obtusata* also demonstrate slower overall development time, altered embryonic movement, and modification of shell shape in hatchlings while exposed to acidified waters (pH 7.6) (Ellis et al. 2009).

Arnold et al. (2009) investigated the effect of ocean acidification on lobsters and found that indirect disruption of calcification and carapace mass may adversely affect the competitive fitness and recruitment success of larval lobsters with serious consequences for population dynamics and marine ecosystem function

Reduced metabolism is expected to impair predator-prey interactions, as well as have consequences for growth, reproduction, and survival. Metabolic suppression has previously been reported to occur in a variety of adult marine invertebrates, including crabs, squid, worms, bivalves, pteropods and amphipods (Albright 2011). Slowed metabolism is generally achieved by halting energy-expensive processes, such as protein synthesis, and therefore may lead to reductions in growth and reproductive potential (*Id.*). The blue mussel *Mytilus edulis* has strong physiological mechanisms by which it is able to protect body tissues against short-term exposure to acidified seawater, but these come at an energetic cost, and will result in reduced growth during long term exposures (Bibby et al. 2008). Consequently, the predicted long-term changes to sea water are likely to have a significant effect on the health and survival of blue mussel populations (*Id.*). Mussel beds are a dominant coastal habitat and provide food and structure for a diverse array of species in an otherwise physically stressful environment; any decline in their population structure will lead to a reduction in appropriate habitat for a myriad of other species.

In summary, acidified waters impact the development, growth, and reproductive success of a suite of echinoderms, crustaceans, and molluscs. A growing body of information is becoming available on the effecting of declining pH on these organisms and their ecosystems. The results of these studies are clear; as pH falls even 0.2 units from pre-industrial values, these organisms will struggle to survive in their increasingly acidic environment.

ii. Corals

Coral reef ecosystems, which are estimated to harbor one-third of marine species and which support the livelihoods of a half billion people, are particularly threatened by ocean acidification. Some corals are already experiencing reduced calcification (De'ath et al. 2009; Cooper et al. 2008; Bates et al. 2010; Gledhill et al. 2008). Due to the ocean acidification and warming, reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations of 450 ppm (Veron et al. 2009; Bijma et al. 2013). Prominent coral scientists have called for reducing atmospheric CO_2 to less than 350 ppm to protect coral reefs from collapse (Veron et al. 2009, Frieler et al. 2012). Coral reefs cannot exist below 7.8 pH units (Fabricius et al. 2011), and the threshold for coral growth is 3.3 Ω_{ar} (Meissner et al. 2012).

Ricke et al. (2013) analyzed aragonite saturation state (Ω_{ar}) surrounding reefs in CMIP5 simulations under several representative concentration pathway (RCP) scenarios (Ricke et al. 2013). The study found that in preindustrial times, 99.9% of reefs adjacent to open ocean in the CMIP5 ensemble were located in regions with $\Omega a > 3.5$. Accordingly, the study used $\Omega a = 3.5$ as

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an upper bound viability threshold for corals, while also examining thresholds of $\Omega a = 3.25$ and 3. Under a business-as-usual scenario (RCP 8.5), every coral reef considered was projected to be surrounded by water with $\Omega_{ar} < 3$ by the end of the 21st century and the reefs' long-term fate was independent of their specific saturation threshold. Under scenarios with significant CO_2 emissions abatement, the Ω_{ar} threshold for reefs was critical to projecting their fate. The study concluded that the "results indicate that to maintain a majority of reefs surrounded by waters with $\Omega_{ar} > 3{:}5$ to the end of the century, very aggressive reductions in emissions are required."

Corals are among the ecosystems most threatened by ocean acidification. To date, most scientific investigations into the effects of ocean acidification on coral reefs have been related to the reefs' unique ability to produce voluminous amounts of calcium carbonate (Kleypas & Yates 2009). The persistence of carbonate structures on coral reefs is essential in providing habitats for a large number of species and maintaining the extraordinary biodiversity associated with these ecosystems. As a consequence of ocean acidification, the ability of marine calcifiers to produce calcium carbonate will decrease, resulting in a transition from a condition of net accretion to one of net erosion, with drastic consequences for the role and function of these ecosystems (Kleypas & Yates 2009).

Coral reefs are predicted to drastically lower their calcification rates in the near future, and historical records show that calcification rates have already fallen relative to pre-industrial values. According to scientists, the main reef building organisms will calcify up to 50% less relative to pre-industrial rates by the middle of this century (*Id.*). A drop of approximately 60% coral reef calcification is projected for the end of the century, when pH is predicted to fall 0.5 units below pre-industrial values (Caldeira & Archer 2007). Many studies suggest calcification rates could be reduced between 20-60% at 560ppm, or 7.9 pH, and that a reduction of this magnitude would fundamentally alter reef structure and function (Convention on Biological Diversity 2009). According to the model of Silverman et al. (2009), developed from field observations from more than 9,000 reef locations, all coral reefs are expected to reduce calcification by more than 80% relative to their pre-industrial rate at 560 ppm (0.3 pH change), and at this point "all coral reefs will cease to grow and start to dissolve." The Interacademy Panel on International Issues concurs; "at current emission rates models suggest that all coral reefs and polar ecosystems will be severely affected by 2050 or potentially even earlier."

In a meta-analysis on coral calcification responses to ocean acidification, the coral calcification declined by a mean of 15% per unit decrease in aragonite saturation state ($2 < \Omega < 4$) (Chan and Connolly 2013). On current emission trends, calcification will decline 22% on average for corals by the end of the century (*Id.*). This falls to the lower range of responses that have been predicted by ocean acidification researchers and described above, which the authors believe reflects variation in the calcification responses of different corals.

Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%, (Caldeira & Archer 2007), and data from the Great Barrier Reef indicates a 14% decline in calcification rates between 1990 and 2005 (De'ath et al. 2009). Other studies in the Great Barrier reef indicate a decline of approximately 21%, and analysis of coral growth records confirm that this decline is unprecedented in recent centuries (Cooper et al. 2008). A model based on field samples shows that calcification of coral reefs in French

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Polynesia declined 15% between the pre-industrial period and 1992, and that rates will decline 40% by 2050, when CO_2 levels reach 560 ppm (pH 7.9) (Anthony et al. 2011). Near Bermuda, historical records show that coral skeletal density has decreased 33%, and coral calcification rates have declined by 52% as a result of changes in seawater carbonate chemistry (Bates et al. 2010). These observed changes have occurred even before a 0.2 unit decline in ocean pH; as atmospheric CO_2 continues to rise and lower pH values, calcification rates will maintain their precipitous decline.

Ocean acidification acts in concert with ocean warming and coral bleaching in furthering coral reef decline (Anlauf et al. 2011) (observing a 3% reduction in acidification with a 0.2 decline in pH, and a 30% decline when acidification is coupled with 1° C warming). While natural variability in the annual cycle and interannual variability may account for some of the observed change in coral growth rates, scientists are "virtually certain" that anthropogenic trends already exceed natural variability (Friedrich et al. 2012). Studies projecting the combined impacts of ocean acidification and ocean warming on corals predict that coral erosion will exceed calcification rates at atmospheric CO_2 concentrations of 450 to 500 ppm, (Hoegh-Guldberg et al. 2007), and all coral reefs will begin dissolve at CO_2 concentrations of 560 ppm (Silverman et al. 2009). These figures correspond to a 0.2 and 0.3 unit drop in pH, respectively, as compared to pre-industrial values. Van Hooidonk et al. (2014) presented updated global projections for threats to coral reefs from ocean warming and ocean acidification based on ensembles of IPCC AR5 climate models using the Representative Concentration Pathways (RCPs). For all tropical reef locations, the study projected absolute and percentage changes in aragonite saturation state (Ω_{ar}) for the period between 2006 and the onset of annual severe bleaching.

In the Caribbean, a recent study concluded that "coral reef communities are likely to be essentially gone from substantial parts of the Southeast Caribbean by the year 2035" (Buddemeier et al. 2011). The Great Barrier Reef has lost 50% of its coral cover since 1985 as a result of the combined effects of ocean acidification, global warming, coral bleaching, coral predation by starfish, and cyclone damage (De'ath et al. 2012). In short, due to the synergistic impacts of ocean acidification, mass bleaching, and local impacts, coral reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations 450 ppm, or pH 8.0, a level that is expected before mid-century (Veron et al. 2009).

Many experimental studies show declining calcification rates and other ill effects when corals are exposed to acidified waters. Decreases in calcification rates across a suite of benthic species and calcifying systems range from 3 to 60% for a doubling in pCO_2, which corresponds to a 0.3 reduction in pH (Abbasi & Abbasi 2011). The average response of corals is a 30% decline in calcification in response to a doubling in pCO_2 (*Id.*). In a study of an assemblage of corals exposed to conditions designed to mimic the change that may be experienced in the next 50-100 years (pH decline of 0.22 to 0.28 units), calcification rates declined between 44% and 80%.

The coral *Acropora palmata* (listed as threatened under the Endangered Species Act), once the dominant reef building coral in the Caribbean, experiences impaired fertilization, settlement, and growth with increasing pCO_2 (Albright et al. 2010). The cumulative impact of ocean acidification on fertilization and settlement success is an estimated 52% and 73% reduction in the number of larval settlers on the reef under pCO_2 conditions projected for the middle and end

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of this century, respectively (0.2 and 0.5 decline in pH) (*Id.*). After only 8 days of high CO_2 conditions (pH 7.75), *Acropora* experiences a statistically significant (18%) reduction in calcification rate (Murubini et al. 2003). Furthermore, there 22 coral species listed as threatened under the Endangered Species Act primarily because of threats from ocean warming, acidification and disease. The rule proposing listing for the corals found that ocean acidification was one of the highest priority threats for corals:

> Ocean acidification has the potential to cause substantial reduction in coral calcification and reef cementation. Further, ocean acidification adversely affects adult growth rates and fecundity, fertilization, pelagic planula settlement, polyp development, and juvenile growth.

77 Fed. Reg. at 73230 (Dec. 7, 2012). In other words, ocean acidification is driving the extinction of corals and the destruction of coral reef ecosystems.

Experimental studies evaluating the effects of ocean acidification on early life history stages of corals generally conclude that primary polyp growth is hindered by increasing acidity (Albright et al. 2010, Cohen & Holcomb 2009). Renegar and Riegl (2005) showed a significant decrease in the growth rate of *Acropora cervicornis* larvae at pH levels 0.3-0.5 units below control. Larvae of the common Atlantic golf ball coral, *Favia fragum*, shows significant delays in both the initiation of calcification and subsequent growth of the primary corallite in acidic waters (8.17 – 7.54 pH) (Cohen & Holcomb 2009). Visible changes in the skeletal development were observed in all non-control treatments, and in the most acidic waters skeletal development was 75% less than the control.

Acidification also affects cold water corals. Cold water corals have a worldwide but patchy distribution, and are often found in areas with highly productive fisheries (De Mol et al. 2002; Kenyon et al. 2003). Overall, more than two-thirds of all known coral species are cold water corals (Roberts & Hirshfield 2012; Cairns 2007). Recent exploration and research that has begun to search for, map, and observe cold water corals has found that these organisms are fragile, long-lived, slow-growing, very sensitive to physical or environmental disturbance and adapted for a specific environmental niche (McDonough & Puglise 2003). Alaskan waters are already showing widespread evidence of ocean acidification as a result of greenhouse gas emissions (Mathis et al. 2011a). By 2100, 70% of cold-water corals will be exposed to corrosive waters (Convention on Biological Diversity 2009). Conditions in waters typically inhabited by cold-water corals are even less favorable for calcification than those experienced by warm water corals; this may cause cold-water corals to be affected earlier and more strongly by CO_2-related ocean acidification than their warm water counterparts (Abbasi & Abbasi 2011).

The vulnerable early developmental and reproductive stages of cold water corals may be especially strongly impacted (Kurihara 2008; Dupont & Thorndyke 2009; Kroeker et al. 2010). In an experiment on the cold-water coral *Lophelia pertusa*, lowering the pH by 0.3 units relative to the ambient level resulted in calcification being reduced by 56% (Maier et al. 2009). Lower pH reduced calcification more in fast growing, young polyps (59% reduction) than in older polyps (40% reduction). Thus, corals' larvae and young corals are significantly more susceptible to ocean acidification than adults, and will likely show a higher degree of reduced calcification

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and growth with reduced pH, making young and larval corals less likely to survive to maturity as the ocean continues to absorb anthropogenic CO_2 and as climate change progresses.

In addition to reduced calcification rates, the strength of cementation may also be reduced in waters with a lower pH, promoting higher rates of physical and bio-erosion (Manzello et al. 2008). Once coral reefs experience lowered calcification and poor cementation, erosion and reef flattening can result, which severely reduced the structural heterogeneity of reefs and lowers its potential to support biodiversity. An important new study of reef bioerosion determined that the combined effects of lower calcification with increased bioerosion can significantly degrade coral reefs (Wissshak et al. 2012). In the study, a common bioeroding sponge in the Great Barrier Reef was observed on massive Porites. The sponge was more effective at bioerosion of the corals at high CO_2, ranging from 17% increase from present day levels to 61% increase at the highest CO_2 treatment. The researchers describe the important role of balancing the antagonistic processes of calcification and bioerosion in a reef for a healthy coral ecosystem, and predict detrimental consequences under ocean acidification as calcification declines and bioerosion increases.

Bioerosion may result in a loss of change in fish assemblages, lower densities of commercially important species, and lower rates of larval fish recruitment (Feary et al. 2007). Weaker reef calcification and cementation also increases the potential for reef damage as storm frequency and intensity increases with continued global warning, leading to further reef degradation (*Id.*). In a study looking at the impacts of storm damage and ocean acidification, researchers concluded that table coral populations are vulnerable to collapse (Madin et al. 2012). In the Indo-Pacific, table corals provide an important role in the reef ecosystem by creating reef structure and sheltering other reef species. They are also particularly vulnerable to ocean acidification, thermal stress, bleaching, disease and stress from storm waves. The table corals will become more vulnerable to storm waves as ocean acidification reduces calcification and increases bioerosion, therefore weakening their cementation and structure. Madin et al. (2012) found that a coral colony was four times more likely to be dislodged by a storm wave by the end of the century ocean acidification levels. Because of this vulnerability, the results showed that table corals are prone to large and rapid declines in coral cover.

Numerous biological responses independent of calcification are also negatively impacted by ocean acidification. Corals in acidifying waters are likely to be in a nutritionally or energetically stressed state and thus less likely to initiate reproduction, or successfully reproduce, due to negative impacts of ocean acidification on all stages of the reproductive cycle (Maier et al. 2009; McCulloch et al. 2012). Sperm flagellar motility also declines in response to decreasing pH. If sperm lose their ability to find eggs in the vast extent of the sea, the life of marine organisms is potentially limited. Sperm flagellar motility, which is indispensable for fertilization, is regulated by an elevation of intracellular sperm pH (Morita et al. 2010). While 69% of *Acropora* sperm were motile at pH 8.0, 46% were motile at pH 7.8, and fewer than 20% at pH 7.7 (*Id.*). Additionally, the physiological costs associated with reproduction are more likely to result in the demise of the organism due to the compounding stressors from ocean acidification and climate change (Wood et al. 2008, Cohen & Holcomb 2009). Significant reductions in metabolism have been observed for coral larvae following exposure to waters with a 0.2 decline in pH, levels projected to occur by the middle of this century (Albright & Langdon 2011).

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Albright et al. (2010) concluded that with increased CO_2 concentrations to those projected to occur in this century (560 atm to 800 atm, or a 0.3 to 0.5 decline in pH from pre-industrial values), the fertilization success of the tropical reef-building coral *Acropora palmata* decreased by 12-13%, settlement success reduced 45-69%, and linear extension was significantly reduced. The compounding effect of these impacts translated to 52-73% reduction in the number of larval settlers on the reef. Albright et al. (2010) predicted that the net impact on recruitment would actually be greater than that given that the depressed post-settlement growth is likely to result in elevated rates of post-settlement mortality. This corroborates other studies showing negative impacts on early-stage tropical corals.

Albright and Langdon (2011) tested the effects of ocean acidification on sexual recruitment of tropical corals. Larval metabolism was depressed by 27% at acidification levels expected by mid-century (0.3 pH reduction) and 63% at end-of-century acidification levels (0.4-0.5 pH reduction). Settlement was also reduced 42-45% and 55-60% at the mid and end-of-century levels respectively, relative to controls (Albright & Langdon 2011). Another study of larvae of tropical corals showed that short-term or long term exposure of larvae to ocean acidification decreased their metamorphosis (Suwa et al. 2010). This means that even when larval survivorship is unchanged, the success of recruiting new corals could be inhibited by ocean acidification (*Id.*).

Additionally, under conditions of acidification planktonic larvae lose their preference for settlement on the optimal crustose coralline algae communities (Doropoulos et al. 2012). Crustose coralline algae in turn, will experience a lower recruitment rate as marine waters become more acidic. Crustose coralline algae, a red calcifying algae, is of key importance in coral reef ecosystems, stabilizing reef structures and providing an important food source for benthic organisms (Convention on Biological Diversity 2009). Crustose coralline algae form a major calcifying component of the marine benthos from polar to tropical regions and are considered to influence the settlement of coral recruits. With a mean pH change of 0.26 between control and treatment, Kuffner et al. (2007) found that crustose coralline algae growth rates declined by 40%, and recruitment rate and percentage cover decreased by 78% and 92%, respectively.

In sum, reproduction is critical to maintaining a healthy coral reef population, and the long-term impacts of ocean acidification on reproduction, especially on larval settlement and growth, may significantly reduce the corals' ability to recover or maintain a population in the face of human caused disturbances and anthropogenic CO_2 emissions. This would result in a lack of reproductive capacity, genetic bottlenecks, and population collapse (Dupont et al. 2010; Ross et al. 2011).

As the world's oceans become more acidic and less saturated with carbonate minerals, corals are expected to build weaker skeletons and experience slower growth rates, which will make it more difficult for corals to retain competitive advantage over other marine organisms (Guinotte et al. 2006). As coral skeletons weaken, they will become increasingly at risk of storm damage and bioerosion, which will reduce the structural complexity of the reef system, reducing habitat quality and diversity alongside the loss of coastal protection functions (Hoegh-Guldberg et al. 2007). At greater than 550 ppm, coral reef ecosystems will be reduced to "crumbling

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frameworks." (*Id.*). Extensive studies have demonstrated that small changes in ocean chemistry will cause a suite of negative impacts, from reduced calcification rates to lowered reproductive success.

iii. Plankton

Plankton, which comprise the basis of the marine food web, are among the calcifying organisms adversely affected by ocean acidification. Changes to calcifying zooplankton, such as pteropods and foraminfera, have the potential to affect the ecological and tropic dynamics which govern the exchange of energy and cycling of nutrients throughout the marine food web (Gattuso & Hansson 2011). For example, the shelled pteropod, *Limacina helicina*, an Arctic pelagic mollusc, is a food source for higher predators such as fishes, whales and birds that are particularly important in high latitude areas. *L. helicina* makes up about 60 percent of the pink salmon diet (Comeau et al. 2012). A decline of pteropod population would likely cause dramatic changes to various pelagic ecosystems, and impact the commercially important salmon fishery; a 10% decrease in pteropods can lead to a 20% reduction in pink salmon body weight (Aydin 2005).

Pteropods form integral components of food webs, and are considered an overall indicator of ecosystem health (Orr et al. 2005). Studies have shown that pteropods exposed to a pH value predicted for the end of this century exhibited a 28% decrease in calcification (Comeau et al. 2009). Experiments on *L. helicina* showed that changes from 8.05 pH to 7.89 pH (Δ -0.16 units) cased shell dissolution and cracks appeared at 7.76pH, and linear extension of the shell decreased as a function of declining pH (Comeau et al. 2012). Samples show dissolution already happening in areas that have low aragonite saturation states. A sampling study off the coasts of California, Oregon, and Washington showed average to severe dissolution of *L. helicina* for 53% of onshore individuals and 24% of offshore individuals (Bednarsek 2014). A sampling study in 2008 of the Southern Ocean found severe dissolution of *L. helicina* in Ω_{ara} 1.0 (Bednarsek 2012). Another study found shell weights of one form of Antarctic species declined 35% from 1997-2006 (Roberts unpublished).

Ample studies corroborate that high CO_2 waters dissolve the shells of *L. helicina* and reduce calcification rates. Comeau et al. (2010) noted decreased calcification for *L. helicina* with decrease in aragonite saturation. Lishka (2012) looked at overwintering *L. helicina* and L. retroversa in the Arctic and noted that they do not calcify in the winter, and they are subject to dissolution under high CO_2 conditions. Bednarsek (2012) looked at *L. helicina* and *Clio pyramidata* from the Southern Ocean under different aragonite saturation states and recorded dissolution stages.

Modeling by Comeau et al. (2012) shows that by the end of the century *Limacina helicina* will not be able to calcify over much of the Arctic because of aragonite undersaturation—prediction may be conservative because it did not account for shell dissolution. Commentary suggests that as waters warm these pteropods will be trapped in acidified conditions and will "disappear entirely by the end of the century." Modeling suggests that waters in the California Current will be undersaturated year-round by 2050 (Gruber 2012). Modeling of the Arctic suggests that by mid-century the Bering Sea will be persistently undersaturated with respect to aragonite (Mathis 2011). An analysis of survey measurements in 2005-2006 and 1991-1992 demonstrated a

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shoaling of the aragonite saturation state in waters off Alaska (Feely et al. 2012). In the North Pacific the aragonite saturation state shoaled to depths less than 200 m between 40˚N and 50˚N (*Id.*). On average, the calcite saturation horizon in the Pacific shoaled about 1 m/yr from 1991 to 2006 (*Id.*).

Other species of plankton are also harmed by CO_2. Another pteropod, *Clio pyramidata,* kept in aragonite undersaturated waters began to dissolve within two days (Orr et al. 2005). Some coccolithophorids are also susceptible to ocean acidification. Studies showed that CO_2 related changes to seawater caused reduced calcification, resulting in malformed and incomplete shells. Calcification of cocolithophorids declined 15-44%, and their shells were malformed as pH changed up to about 0.3 units (Riebesell et al. 2000). Coccolithophorids are globally distributed and bloom in massive areas affecting the optical properties of the ocean, reflecting light from the earth, and play a major role in the ocean carbon cycle. Elevated CO_2 concentrations also reduce the shell mass of foraminifera (Kleypas et al. 2006). Modern shell weights of foraminifera in the Southern Ocean are 30–35% lower than those from preindustrial sediments, which is consistent with reduced calcification induced by ocean acidification (Moy et al. 2009).

iv. Cephlopods and Fish

The negative physiological effects of ocean acidification are not confined to invertebrates. For example, the gametes, embryos, and larvae of vertebrates such as fish are vulnerable to changes in ocean chemistry and have shown impairments in their homing and predator/prey detection capabilities.

Changes in the ocean's CO_2 concentration result in accumulation of CO_2 in the tissues and fluids of fish and other marine animals, called hypercapnia, and increased acidity in the body fluids, called acidosis. These impacts can cause a variety of problems for marine animals, including difficulties with acid-base regulation, calcification, growth, respiration, energy turnover, predation response, and mode of metabolism (Pörtner et al. 2005; Pörtner et al. 2004). Studies have shown adverse impacts in squid and fish, among other animals (Rosa & Seibel 2008; Ishimatsu et al. 2004; Pörtner et al. 2004). For example, when exposed to acidification, orange clownfish suffer a type of brain malfunction that interferes with their homing abilities and makes them 5-9 times more likely to swim toward a predator (Munday et al. 2009; Simpson et al. 2011; Ferrari et al. 2011).

Laboratory experiments have shown that ocean acidification at levels expected to occur within this century impairs larval orange clownfish and damselfish sensory abilities and behavior, making it more difficult for them to locate suitable settlement sites on reef habitat and avoid predators. Specifically, ocean acidification disrupts smell, hearing, and behavior of larval orange clownfish, (Munday et al. 2009; Nilsson et al. 2012), making larval clownfish attracted to odors from predators and unfavorable habitat (Munday et al. 2010; Dickson et al. 2010). Olfactory cues that prompted avoidance or neutral behavior in controls (pH 8.15) stimulated strong preference behavior in larvae raised at pH 7.8, in addition to significant reduction in response to usually positive preferences. Ocean acidification also impairs the hearing capacity of larval clownfish, which is predicted to have negative effects on settlement success and survival (Simpson et al. 2011).

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Similarly, research on six damselfish species found that ocean acidification impairs larval damselfish smell, vision, learning, behavior, and brain function, leading to higher risk of mortality. For example, in acidified waters, larval damselfish (1) become attracted to predator odors and display much riskier behaviors, making them more prone to predation; two species suffered a five-fold to nine-fold increase in predation rate at CO_2 levels of 700 to 850 ppm, or 0.3 pH units below control (Munday et al. 2009; Ferrari et al. 2011); (2) cannot discriminate between habitat olfactory cues, making it more difficult to locate appropriate settlement habitat (Devine et al. 2011); (3) settle on the reef during dangerous times—the full moon rather than new moon—when they are more vulnerable to predation (Devine et al. 2011); (4) fail to visually recognize or evade important predator species; (5) cannot learn to respond appropriately to a common predator by watching other fish react or by smelling injured fish, unlike fish under normal conditions (*Id.*); and (6) suffer disruption of an important neurotransmitter which is thought to result in the sensory and behavioral impairment observed in acidified conditions (Nilsson et al. 2012).

An animal's ability to transport oxygen is reduced by pH changes (Pörtner 2005). Water breathing animals have a limited capacity to compensate for changes in the acidity (Haugan 2006). For example, fish that take up oxygen and respire CO_2 through their gills are vulnerable because decreased pH can affect the respiratory gas exchange (Royal Society 2005). Changes in metabolic rate are caused by the changes in pH, carbonates, and CO_2 in marine animals (Haugan 2006).

Squid, for example, show a very high sensitivity to pH because of their energy intensive manner of swimming (Royal Society 2005). Because of their energy demand, even under a moderate 0.15 pH change squid have reduced capacity to carry oxygen and higher CO_2 pressures are likely to be lethal (Pörtner 2004). Even species more tolerant to pH changes experience decreased metabolism from increased CO_2 in the water (Pörtner 2004). For example, as much as 50% mortality was observed in copepods after only six days of exposure to waters with a pH level 0.2 units below the control (Pörtner 2005). Reducing pH by 0.3 pH cased a 31% decline in metabolic rate and a 45% decrease in activity level for the jumbo squid, an important predator in the Easter Pacific (Rosa & Seibel 2008).

In fish, pH also affects circulation. Fishexposed to high concentrations of CO_2 in seawater experience cardiac failure and increased mortality (Ishimatsu 2004). At lower concentrations sublethal effects can be expected that can seriously compromise the fitness of fish. Juvenile and larval stages of fish were found to be even more vulnerable (Ishimatsu 2004).

In sum, ocean acidification can have many adverse effects on marine animals that can reduce their fitness and survival (Royal Society 2005). Many marine animals have low thresholds for long-term CO_2 exposure (Pörtner 2005).

c. Other Environmental Impacts of Ocean Acidification

i. Increased Toxicity of Harmful Algal Blooms and Sediments

Ocean acidification may already be increasing the toxicity of harmful algal blooms known as "red tides." These toxic red tides poison shellfish, marine mammals, fish, and even cause

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paralytic shellfish poisoning in people. High CO_2 levels in seawater magnify the toxins of harmful algae. (Fu et al. 2012; Avery O Tatters et al. 2013; Tatters et al. 2012; Avery O. Tatters et al. 2013). Studies of the genus *Pseudo-nitzscia* show that the toxicity of diatoms which produce a neurotoxin increases significantly under ocean acidification conditions. A -0.5pH change caused toxin production in the diatoms to increase 4.2-fold and a -0.3pH unit change increased the toxicity 2.5-fold (Tatters et al. 2012). Many studies on the effects of ocean acidification and algal blooms have been conducted at CO_2 levels that are already occurring in California, and the increase in the toxicity of harmful algal blooms in Southern California (and resulting mass mortalities of fish and marine mammals) may be due, in part, to acidified waters (*Id.*) However, these studies suggest that the damage will become much worse.

Additionally, research shows that under conditions of ocean acidification sediments become more toxic (Roberts, Birchenough et al. 2013). Ocean acidification makes sediment-bound metals more available and thus more toxic for aquatic life (*Id.*) For example, ocean acidification increases the toxicity of copper (Campbell & Mangan 2014).

ii. Noise Pollution Increases in Low pH Waters

Ocean acidification can also decrease the sound absorption of seawater, causing sounds to travel further with potential impacts on marine mammals and other marine life sensitive to the sounds of vessel traffic, seismic surveys, and other noise pollution (Hester et al. 2008). Sound travels 10-15 percent further with a change of 0.1 pH, and it is predicted to increase about 40 percent by mid-century (Hester et al. 2008). Additionally, a decline of 0.3 pH units causes a 40 percent decrease in the sound absorption of surface seawater and sound may travel 70 percent farther, further affecting sensitive marine mammals (Brewer et al. 2009).

d. Ocean Acidification's Ecosystem Impacts

While the full implications of elevated CO_2 on marine ecosystems are not well-documented, there is high confidence that there will be negative ecosystem consequences from ocean acidification. The exact changes are difficult to predict, but some of the anticipated impacts include loss of diversity, loss of abundance of calcifying species, shifting prey and predator interactions, and loss of suitable habitat.

New mesocosm studies have sought to understand some of the potential ecosystem impacts of CO_2. Studies of biodiversity near underwater volcanic vents demonstrate reduced richness in high-CO_2 waters. For example, coral species diversity declined by about 39% between low and high-CO_2 sites, with the reefs shifting from complex communities to a coral reef dominated by massive Porites. Most importantly, the researchers found that coral reef development ceases at 7.7 pH, and they concluded that a pH decline below 7.8 would be "catastrophic for coral reefs" (Fabricius et al. 2011). Scientists also observed that in high-CO_2 waters the loss of complex coral reef habitat resulted in a loss of diversity of reef-associated species such as crustaceans and crinoids (Fabricius et al. 2014). Looking at the macroinvertebrates, the density declined 48% between control and high-CO_2 areas and taxa diversity declined by 77% (*Id.*).

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Loss of species diversity associated with ocean acidification can also result from changes in competitive interactions. A study of a rocky reef near volcanic vents documented that macro algae outcompeted calcareous species in low-pH waters (Kroeker et al. 2012). The researchers explained that under the high-CO_2 conditions the calcifying species grew more slowly while the seaweed took hold and that grazing of seaweed was depressed (*Id.*). In another study, while the areas near volcanic vents lacked scleractinian corals and had low abundance of sea urchins and coralline algae, invasive algal species benefited from the acidified conditions (Hall-Spencer et al. 2008).

Research on the diversity the intertidal community in the Pacific Northwest documented a shift from a ecosystem dominated by calcifying animals to one with non-calcifying organisms as pH declined. Researchers documented declines in abundance and size of the California mussel, blue mussel, and goose barnacle in tidepools on the Olympic Coast in Washington (Wootton et al. 2008). They found that in years with low pH waters the calcifying animals were replaced by non-calcifying organisms (*Id.*).

The synergistic impacts of ocean acidification and warming are also potentially severe. Ocean acidification may induce a negative climate feedback that may increase temperature rise. Mesocosm studies found that ocean acidification may amplify global warming through decreasing biogenic production of the marine sulfur component dimethylsulphide which can impact cloud albedo (Six 2013). Ocean acidification therefore may also contribute to climate change impacts on the environment.

2. Risk Reduction Costs and Benefits

EPA must make a determination whether the risk of ocean acidification is unreasonable and this constitutes a balancing of costs and benefits. While it is EPA's burden to conduct this analysis, petitioners present some limited data on (1) the socio-economic costs of CO_2 pollution in light of ocean acidification, (2) the feasibility of controls on CO_2 pollution, and (3) the social cost of carbon including the costs of delaying action to reduce and mitigate CO_2 pollution.

a. Socioeconomic Costs of Ocean Acidification

The release of CO_2 into the environment is already having social and economic impact, and these impacts are predicted to become even more concerning. Primary economic concerns are from the loss of fisheries and coral reefs. Ocean acidification also poses food security and nutrition risks.

U.N. Convention on Biological Diversity estimated costs on the predicted damage of ocean acidification and predicts that the oceans will lose more than $1 trillion in value annually from ocean acidification (Convention on Biological Diversity 2014). CO_2 related ocean warming and acidification will threaten marine food resources by disrupting marine communities, promoting harmful algal blooms and the spread of some diseases, and increasing contaminants in fish and shellfish (Tirado et al. 2010).

The United Nations Environment Programme reported that ocean acidification's impact on marine organisms is a threat to food security (UNEP 2010). The report documents that ocean

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acidification is measurable and increasing, which poses a threat to fisheries resources and the billions of people that have a marine-based diet (United Nations Environment Programme 2010). Seafood has been shown to prevent hundreds of thousands of premature deaths, as well as significantly reduce infant morbidity; a decline of seafood availability will decrease these benefits. Some populations, including subsistence fishing populations and poor communities, depend on seafood and mortality and morbidity can result from the loss of these food sources (Mozaffarian 2006). For example, 95% of Alaskan households do some sort of subsistence fishing, and 17% of the state's population, 120,000 people, depend on subsistence fishing (Mathis et al. 2014). Many subsistence fishers also have cultural ties threatened by ocean acidification. Accordingly, CO_2 can result in social and environmental justice concerns that must also be assessed and weighed (Convention on Biological Diversity 2014).

Not only will ocean acidification affect global food webs and ecosystems, it will have a direct effect on the global economy. The U.S. economy is very dependent on the health of the ocean. In 2009, the ocean economy contributed over $223 billion annually to the U.S. gross domestic product and provided more than 2.6 million jobs (NOAA, http://oceanservice.noaa.gov/facts/oceaneconomy.html). Cooley and Doney (2009) estimate that if just a 10-25% decrease in United States mollusk harvests from 2007 were to occur today, $75-187 million in direct revenue would be lost each year henceforth, with a net loss of $1.7-10 billion through mid-century, when pH levels are approximately 0.3 units below pre-industrial values. In Washington State alone, the seafood industry generates $1.7 billion for gross state product and employs 42,000 people (Washington State Blue Ribbon Panel 2012). Already, shellfish hatchery failures in Washington have caused an economic stir and caused some hatcheries to relocate. Alaska's commercial fishing industry is valued at over $4 billion a year, and supports 90,000 jobs—recreational fishing and fishing tourism add even more value. Meanwhile, Alaska is ranked among the most vulnerable areas to acidification.

Tropical coral reefs provide ecosystem services, such as habitat and nursery functions for commercial and recreational fisheries and coastal protection. As reefs decline in acidified waters, there will be an ecological shift to a new ecosystem state dominated by less commercially valuable species. In 2009, Brander et al. estimated the annual economic damage of ocean acidification-induced coral reef loss to escalate rapidly over time, reaching $870 billion by 2100 (Brander et al. 2009a). In 2014, Brander et al. increased the anticipated loss of ecosystem services from corals to be $1000 billion (UNEP 2014). Shoreline protection offered by coral reefs and the services it provides by preventing loss of life, property damage and erosion are also reduced by CO_2 emissions.

Lane et al. (2014) modeled three major U.S. locations for shallow water reefs -- South Florida, Puerto Rico, and Hawaii – to project future reef cover and the economic values generated by coral reefs for a greenhouse gas emissions mitigation scenario that represents international implementation of policies to reduce global emissions (resulting in a CO_2 concentration of 427 ppm in 2100), compared to a business as usual greenhouse gas emissions scenario resulting in a CO_2 concentration of 785 ppm in 2100. The study estimated that reducing emissions would result in an "avoided loss" in Hawaii of approximately $10.6 billion in recreational use values compared to business as usual. Reducing emissions was projected to provide fewer economic benefits in Puerto Rico and South Florida, where sea-surface temperatures are already close to

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bleaching thresholds and coral cover is projected to drop well below 5% cover under both scenarios by 2050, and below 1% cover under both scenarios by 2100 (Lane et al. 2014).

As discussed previously, the toxicity of harmful algal blooms increases under conditions of ocean acidification. These toxins not only poison marine mammals, but also cause paralytic shellfish poisoning in people. Scientists hypothesize that some of the increases red tides off the coast of Southern California may be related to ocean acidification, though this has yet to be confirmed. In turn, harmful algal blooms cost the United States approximately $82 million each year from impacts to fisheries, public health, management, and lost recreational opportunities (Hoagland and Scatasta 2006).

A recent study estimated that the damage our oceans will face from emissions-related problems will amount to $428 billion a year by 2050 and nearly $2 trillion per year by the century's end (Noone et al. 2012).

> Acidification impacts processes so fundamental to the overall structure and function of marine ecosystems that any significant changes could have far-reaching consequences for the oceans of the future and the millions of people that depend on its food and other resources for their livelihoods.

(Doney et al. 2009). There is also a significant cost to delaying action. According to a recent report by the Council of Economic Advisers, delaying the implementation of policies to mitigate climate change could significantly increase economic damages, in addition to worsening environmental harm.[39]

While there are still large unknowns on the biological consequences of ocean acidification, the science we have is clear: from shellfish to corals, and from pteropods to fish, our marine resources are threatened by the acidification of our ocean waters.

b. Risk Reduction Methods

There are several ways to reduce risk from CO_2. EPA should use a suite of tools to reduce emissions, sequester CO_2, mitigate harms, and promote alternatives. Under TSCA EPA has authority to:[40]

- prohibit or limit the amount of production or distribution of a substance in commerce;
- prohibit or limit the production or distribution of a substance for a particular use;
- limit the volume or concentration of the chemical produced;
- prohibit or regulate the manner or method of commercial use;
- require warning labels and/or instructions on containers or products;
- require notification of the risk of injury to distributors and, to the extent possible, consumers;

[39] Executive Office of the President of the United States, The Cost of Delaying Action to Stem Climate Change at 1 (July 2014).
[40] 15 U.S.C. § 260.

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- require record-keeping by producers;
- specify disposal methods; and
- require replacement or repurchase of products already distributed.

EPA also may impose any of these requirements in combination or for a specific geographical region. [41] Specifically, the agency must impose controls sufficient "to protect adequately against such risk using the least burdensome requirement."[42]

There is evidence that many industries could employ existing technology to achieve meaningful emissions reductions affordably. EPA's own data demonstrate that lower pollution rates are readily achievable for many industrial sources of CO_2. For example, the agency has identified dozens of "control measures and energy efficiency options that are currently available for pulp and paper mill processes," ranging from technological upgrades to improved equipment maintenance.[43] Similarly, EPA has compiled more than a decade of reports on "cost-effective" control strategies and other approaches available to reduce cement plant CO_2 emissions, "includ[ing], for example, energy efficiency measures, reductions in cement clinker content, and raw materials substitution."[44]

Although cost-effective strategies to reduce CO_2 emissions are available, existing controls have not reduced CO_2 emissions sufficiently to protect against environmental harm. For example, most natural gas power plants have *never* exceeded the agency's recently proposed emissions limit, thus indicating that existing and newly constructed facilities could easily satisfy a more stringent standard.[45] Because energy-related CO_2 pollution accounts for more than eighty percent of U.S. greenhouse gas production, readily achievable reductions in this sector would significantly benefit the environment.[46] Similarly, the pulp and paper industry ranks among the largest consumers of energy,[47] and emitted nearly 58 million metric tons of CO_2 equivalent gases in 2004.[48] Moreover, market incentives and regulatory controls are effective in increasing the rate of innovation for technologies that can reduce CO_2 emissions.

If a chemical presenting an unreasonable risk to health and the environment has already been distributed, EPA may prescribe procedures by which relevant manufacturers and purchasers must replace or repurchase that chemical.[49] In the present situation, we urge the agency to exercise its

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[41] *Id.*
[42] 15 U.S.C. § 2605(a).
[43] *See* EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 11 (2010).
[44] EPA, National Emission Standards for Hazardous Air Pollutants From the Portland Cement Manufacturing Industry and Standards of Performance for Portland Cement Plants, 75 Fed. Reg. 54,970, 54,997 (Sep. 9, 2010).
[45] Ctr. for Biological Diversity, Comments on Standards of Performance for Greenhouse Gas Emissions from New Stationary Sources: Electric Utility Generating Units (Proposed Rule) Docket No. EPA-HQ-OAR-2013-0495 at 13-14 (May 9, 2014).
[46] U.S. Dept. of State, U.S. Climate Action Report at 16 (2010).
[47] *See* U.S. Energy Information Administration, First Use of Energy for All Purposes (Fuel and Nonfuel), 2010 (Mar. 2013), http://www.eia.gov/consumption/manufacturing/data/2010/#r1.
[48] EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 7 (2010).
[49] 15 U.S.C. § 2605(a)(7)(C).

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authority to remediate existing harm by requiring that responsible parties mitigate past CO_2 emissions.

There are numerous approaches to mitigating and sequestering CO_2 emissions that EPA must evaluate. Effective land use and agricultural practices can significantly reduce carbon emissions and sequester CO_2. Federal programs aimed at consumers can reduce CO_2 emissions. For example, EPA's Energy Star program has prevented 1.8 billion tons of greenhouse gas emissions by providing information that helps customers select energy efficient devices. Sequestration of CO_2 in products, infrastructure, and waste management are among numerous methods that could be cost-effective to mitigate CO_2 pollution.

c. Social Costs of Carbon

In any analysis of the cost and benefits of reducing CO_2 pollution, the costs of failing to address the problem of global warming should be included. Most efforts to quantify the social costs of carbon underestimate the real-world costs of CO_2 pollution. Nevertheless, EPA may not ignore these costs.

Global emissions must be less than 1000 Gt of CO_2 between 2000 and 2050 to avoid dangerous climate change, which scientists have recommended that this means maintaining temperature change below 2° C.[50] This means keeping atmospheric CO_2 to 450 ppm, a threshold below which experts also use for ocean acidification (Veron et al. 2009; Silverman et al. 2009; Interacademy Panel 2009; McNeil & Matear 2008; Sea et al. 2007). For example, coral scientists predict that at 450 ppm, reef-building will be severely diminished or will cease altogether (Veron et al. 2009). But the global community has already used a substantial portion of this CO_2 budget, emitting 305 Gt of CO_2 between 2000 and 2008 alone.[51] As a result, the years between now and 2020 have been dubbed the "critical decade."[52] Because carbon emissions must peak soon and decline thereafter, the sooner emissions peak, the less severe the subsequent annual reductions will need to be;[53] correspondingly, if emissions are not sufficiently curbed in this decade, avoiding catastrophic damages will require much more drastic, disruptive and costly measures and may no longer be possible at all. Nonetheless, if action is taken immediately, it is both technologically and economically feasible to reduce emissions by 2020 and lay the groundwork for future emissions reductions.[54]

Every year that the world delays its efforts to reach sustainable levels of greenhouse gas emissions represents a lost opportunity of tremendous economic significance. McKinsey & Company estimated in 2009 that for every year of delay, 1.8 Gt of potential CO_2 abatement is foregone.[55] This delay, and the accompanying Gts of lost CO_2 abatement, has a price tag, as the

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[50] Australia Department of Climate Change and Energy Efficiency, The Critical Decade: Climate Science, Risks and Responses at 53 (May 2011), *available at* http://www.scribd.com/doc/56043375/The-Critical-Decade-Climate-Change-Commision-Report.
[51] *Id.*
[52] *Id.*
[53] UNEP, The Emissions Gap Report at 14 (Nov. 2010), *available at* http://www.unep.org/publications/ebooks/emissionsgapreport/; for a discussion of economic implications of these facts, *see infra.*
[54] *Id.* at 23.
[55] McKinsey & Company, Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve at 16 (2009), *available at* www.worldwildlife.org/climate/WWWFBinaryitem11334.pdf.

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damage caused by CO_2 emissions accelerate while the cumulative amount of greenhouse gases in the atmosphere rises, both because of the increasingly dire damages wrought by rising temperatures and other greenhouse gas effects, *and* because of the delay factor itself. If governments delay mitigation in the present, the emissions reduction curve in future years necessarily becomes much steeper, requiring much more drastic and costly emission reduction mechanisms with tremendous economy-wide disruptions, just to "catch up" with the lost opportunities from prior years to reach a sustainable emissions trajectory—or risk undergoing unsustainable climatic extremes.

Economists have sought to quantify the costs of waiting to embark upon an emissions reduction path. In 2007, researchers used the DICE model[56] to estimate the cost of delaying mitigation for a given period of time and then switching to an optimal abatement trajectory. According to their findings, the global cost of ten years of delay, relative to starting on an optimal trajectory in the present, ranges from hundreds of billions to several trillion dollars.[57] For instance, this study estimates that it would cost somewhere between $200 and $400 billion dollars to delay action for ten years and then embark upon a mitigation strategy that would result in stabilization at 3 °C (a level now universally understood to far exceed the dangerous). The cost of delaying mitigation soars into the trillions of dollars as the delay continues, until it ultimately becomes impossible to achieve a certain level of temperature stabilization. According to this study, more than thirty years' delay of changing the current course would make it impossible – no matter what the expense – to stabilize temperature rises at 2° C above pre-industrial levels.

EPA and other federal agencies have been using the social cost of carbon to estimate the climate benefits of rulemakings since it was first developed by a dozen agencies (including USDA, CEQ and EPA) and published by the Interagency Working Group in 2010.[58] The social cost of carbon, usually expressed as a dollar-per-ton figure, provides an estimate of the economic damages associated with an increase in CO_2 emissions, conventionally one metric ton, in a given year. The dollar figure can also represent the value of damages avoided for emission reductions achieved by federal rulemakings. The social cost of carbon is designed to provide a comprehensive estimate of climate change damages, including, but not limited to, changes in net agricultural productivity, human health, and property damages from increased flood risk. However, given current modeling and data limitations, even EPA has conceded that that the social cost of carbon protocol is likely a conservative estimate because it does not yet account for all important damages.[59] Nevertheless, the protocol is designed for use in regulatory processes like this one. In 2013 the Federal Interagency Working Group increased its estimates of the social cost of carbon, using the same 3% annual discount rate, by 50%.[60] The 2013 estimates are 50% higher for emissions in 2010, with greater percentage increases in subsequent years. Yet, even these social

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[56] DICE stands for the Dynamic Integrated Climate and Economy model developed by William Nordhaus in 1990.
[57] Keller, K. et al., The Regrets of Procrastination in Climate Policy, Environmental Research Letters (2007), *available at* iopscience.iop.org/1748-9326/2/2/024004/.
[58] EPA, The Social Cost of Carbon, http://www.epa.gov/climatechange/EPAactivities/economics/scc.html (last accessed June 28, 2015).
[59] *Id.*
[60] Interagency Working Group on Social Cost of Carbon, United States Government, Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 (Nov. 2013) at 3, available at http://www.whitehouse.gov/sites/default/files/omb/assets/inforeg/technical-updatesocial-cost-of-carbon-for-regulator-impact-analysis.pdf.

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cost of carbon figures significantly underestimate the true social cost of carbon, possibly by several orders of magnitude.

Economists have noted that the social cost of carbon is far greater than the $21 per ton of CO_2 assumed by interagency protocol in 2010 and greater than the 2013 revision.[61] There are several inadequacies that make the values too conservative. Foremost, the models fail to evaluate ocean acidification—to the contrary the models consider the ocean a sink for CO_2. The FUND model used in the Working Group's analysis wholly excludes consideration of climate-induced catastrophic events. But the Working Group weighs the values generated by each of the three models equally, even though the FUND model's values is significantly lower[62] than the others, and consequently pulls down the final value of the social cost of carbon. The potential for catastrophic climate events, and the increasing likelihood that tipping points will be reached even sooner than anticipated, are increasingly serious risks, however, and, despite the associated uncertainties, must be fully represented in any evaluation of the social cost of carbon. Instead, the Working Group employed a risk-neutral approach, clearly inappropriate in light of the vast majority of scientific studies. Also, the models used fail to account fully or even partially for certain highly complex aspects of climate change, including the possibility of interrelations between different sectors and accelerating damage feedback loops, non-CO_2 emissions,[63] and social and political instability. Moreover, the valuation techniques and discount rates used to reach these values are inherently problematic and fail to represent the full value of all losses from climate change, in significant part because some cannot be reduced to monetary terms.

Other evaluations of the social cost of carbon attempt to account for these omitted factors. The Stern Review, in particular, reaches a SCC of $85/ton of CO_2 (in 2000 dollars).[64] For comparison purposes with a Working Group value of $21 in 2005 dollars, this amount is equivalent to

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[61] F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon (2010) (the social cost of carbon could be over $800 per ton of CO2 equivalent; F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon, in Economics, vol. 6 (Apr. 4, 2012) (reaching similar conclusions), available online at http://www.economics-ejournal.org/economics/journalarticles/2012-10 (last visited June 27, 2014); P. Epstein et al., Full cost accounting for the life cycle of coal, Ann. N.Y. Acad. Sci. (2011) (estimating the social cost of coal at between $10 and $100 per ton of CO2 equivalent); L. Johnson & C. Hope, The social cost of carbon in U.S. regulatory impact analyses: an introduction and critique, J. Envtl. Stud. & Sci. (Sept. 9, 2012) (finding a social cost of a ton of CO2 emissions to be 2.6 to over 12 times larger than the Interagency Working Group's central estimate of $21 per ton of CO2) available online athttp://link.springer.com/article/10.1007%2Fs13412-012-0087-7 (last visited June 27, 2014) E. Stanton et al., Comments on the 2013 Technical Update of the Social Cost of Carbon, January 27, 2014.

[62] Interagency Working Group on the Social Cost of Carbon, Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, at 16-A-11, Fig. 16-A-4.2, *available at* http://www.rff.org/Publications/WPC/Pages/Estimating-the-Social-Cost-of-Carbon-for-Regulatory-Impact-Analysis.aspx.

[63] For instance, the estimated social cost of methane and SF_6, are, respectively, $105/tonne and $200,000/tonne. *See* Intergovernmental Panel on Climate Change, Climate Change 2007 Synthesis Report 822, *available at* http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html. For a critical analysis of the Working Group's assumptions, *see also* Ackerman, F. and Stanton, E. A., The Social Cost of Carbon A Report for the Economics for Equity and the Environment Network (April 1, 2010), *available at* http://www.e3network.org/papers/SocialCostOfCarbon_SEI_20100401.pdf.

[64] Nicholas Stern, Stern Review on the Economics of Climate Change Part III: The Economics of Stabilisation at 287 (2006), *available at* http://webarchive.nationalarchives.gov.uk/+/http:/www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm.

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$96.25/ton in 2005. The Stern Review uses the PAGE model, which explicitly models for the risk of catastrophic climate change.[65] In contrast with the Working Group, the Stern Review uses a mean temperature increase of 3.9 °C for its baseline scenario (consistent with the Third IPCC Report) and a 4.3 °C increase for its higher climate scenario. The resulting higher value of the social cost of carbon is thus very likely to be a closer approximation of the real cost of CO_2.

Meanwhile, the costs of reducing CO_2 emissions are well worth taking prompt action. The "central estimates of the annual costs of achieving stabilisation between 500 and 550ppm CO_2 are around 1% of global GDP, if we start to take strong action now. [...] It would already be very difficult and costly to aim to stabilise at 450ppm CO_2e. If we delay, the opportunity to stabilise at 500-550ppm CO_2e may slip away.'"(Stern 2006). Likewise, the benefits of addressing CO_2 for ocean acidification also have the ancillary effect of slowing global warming and preventing costs associated with climate change.

The recently proposed rule to reducing power plant CO_2 emissions calculates both costs and benefits—notably the benefits far exceed the costs. The recently proposed rules for reducing power plant carbon emissions, calculates both costs and benefits for a more modest reduction. EPA projects that the annual compliance cost will be $4.3 to $5.5 billion (in 2011 dollars, depending on discount rate) in 2020 and $5.5 billion (for a 5% discount rate) in 2030.[66] The total combined climate benefits and health co-benefits are estimated to be $15.6 to $88 billion in 2020 and $32.3 to $151 billion in 2030 (depending on discount rate and the options chosen).[67] The insurance industry also is well aware of the potential costs of failing to address CO2 emissions and its associated effects, including: "[h]urricanes and other flooding events … [h]ealth issues associated with heat waves… more airborne allergens, rising temperatures, greater humidity, more wildfires, and more dust and particulate pollution may considerably exacerbate upper respiratory disease (rhinitis, conjunctivitis, sinusitis, asthma) and cardiovascular disease."[68] A European insurance company estimates losses from extreme climate change events of 37% within a decade, over $1 trillion under bad circumstances.[69] The increasing frequency and severity of storms in the U.S. has caused damages to increase 60-fold from 1950s to the 1990s.[70]

Petitioners ask that action to mitigate ocean acidification under TSCA be initiated, either through TSCA section 6 (e.g., requiring "repurchasing" relief using sequestration, emission reductions, etc.), or through section 4 in order to determine the need for action under section 6 and the most effective mitigation strategies. In any case, petitioners suggest that costs be apportioned among

[65] According to the Working Group itself, DICE "offers the best insight into the SCC if the world were to experience catastrophic climate change." *See* Working Group, *supra* note 62, at 16-A-35.
[66] EPA, Regulatory Impact Analysis Technical Document EPA-452/R-14-002 (June 2014).
[67] *Id.*
[68] National Association of Insurance Commissioners, The Potential Impact of Climate Change on Insurance Regulation at 10 (2008).
[69] See e.g. Allianz, Climate Change and the Financial Sector: An Action Plan; Evan Mills, Responding to Climate Change: The Insurance Industry Perspective.
[70] Mills, E. Insurance in a Climate of Change, Science 308: 1040 (2005).

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CO_2 emission contributors according to the cumulative CO_2 emission inventory information EPA has collected.[71]

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In summary, the weight of the scientific information on ocean acidification is sufficient to make a determination that CO_2 poses an unreasonable risk, to the extent that EPA declines to find the data adequate, then EPA must develop a test rule under TSCA section 4 as described below.

C. Alternatively, EPA Must Require Testing to Develop Adequate Data

EPA must make a determination as to whether adequate data exist to evaluate the environmental and health effects of CO_2. There is well-established scientific information on the risk of CO_2 on the environment, but if EPA determines that the data are insufficient then it must develop a testing rule.

In enacting TSCA, Congress declared that "adequate data should be developed with respect to the effect of chemical substances and mixtures on health and the environment and that the development of such data should be the responsibility of those who manufacture and those who process such chemical substances and mixtures."[72] Accordingly, section 4 directs EPA to require additional testing upon determining that "the manufacture, distribution in commerce, processing, use, or disposal of chemical substance or mixture … may present an unreasonable risk of injury to health or the environment," or if the chemical is produced in substantial quantities and there is a potential for a substantial quality to be released into the environment.[73]

1. CO_2 May Present an Unreasonable Risk

As described in depth in this petition, CO_2 may present an unreasonable risk to the environment. EPA interprets this to mean that there is a "substantial (i.e., more than theoretical) probability" of unreasonable risk to the environment or health.[74] The information in this petition meets the threshold for a testing rule and establishes a substantial probability that CO_2 poses an unreasonable risk to the environment, but EPA need not even make such a determination because CO_2 is produced in such large volumes that it clearly meets the criterion of exposure of substantial quantities being released into the environment.

2. Substantial Quantities of CO_2 Are Released into the Environment

It is undeniable that substantial qualities of CO_2 are released into the environment. EPA established a threshold value of one million pounds for a release of a chemical to be substantial. *TSCA Section 4(a)(1)(B) Final Statement of Policy; Criteria for Evaluating Substantial*

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[71] This could be structured similar to the sponsorship format used in TSCA's High Production Volume (HPV) Program.
[72] 15 U.S.C. § 2601(b)(1).
[73] 15 U.S.C. § 2603 (a)(1)(A), (B)(i).
[74] *Chemical Mfrs. Ass'n v. EPA*, 859 F.2d 977, 988 (D.C. Cir. 1988).

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Production, Substantial Release, and Substantial or Significant Human Exposure, 58 Fed. Reg. 28736, 28746 (May 14, 1993). According to the IPCC:

> From 1750 to 2011, CO_2 emissions from fossil fuel combustion and cement production have released 375 [345 to 405] GtC to the atmosphere, while deforestation and other land use change are estimated to have released 180 [100 to 260] GtC. This results in cumulative anthropogenic emissions of 555 [470 to 640] GtC.

(IPCC 2013, Summary for Policymakers).

In 2012, a total of 9.7 gigatonnes of CO_2 were released into the atmosphere from fossil fuel combustion and cement production (Global Carbon Project 2013). These emissions are expected to increase to 9.9 gigatonnes in 2013 (*Id.*). The United States contributed 14% of CO_2 emissions to the atmosphere (*Id.*). Models estimate that between 2003 and 2012, the oceans absorbed 27% of CO_2 from the atmosphere (*Id.*). Over the next millennium, the oceans will absorb 90% of anthropogenic CO_2 (Kleypas et al. 2006).

Therefore, the threshold of substantial release is exceeded by more than a million times over.

3. Recommendations for Testing

EPA should consider a test rule to fill the information gaps needed to make a determination of whether CO_2 presents an unreasonable risk of injury to the environment. Some recommendations for consideration include:

- Testing CO_2 reduction strategies. For example, research and development for emissions reduction strategies that include alternative practices, conservation, alternative fuels. Testing CO_2 sequestration and capture approaches, and assessing attainable CO_2 emissions reductions for industries with significant CO_2 emissions.
- Conducting a vulnerability assessment for marine and coastal species and ecosystems. Determining atmospheric CO_2 levels necessary to conserve marine ecosystems from dangerous ocean acidification. Emissions scenarios are important for informing policy approaches to acidification.
- Forecasting species' responses to ocean acidification using modeling tools to predict range shifts, demographic and population trends, and physiological responses across taxonomic groups using a range of climate models, emissions scenarios, and management timelines (25, 50, 100 years). Identify wildlife species and ecosystems imperiled by ocean acidification by evaluating range shift models and population viability models run under future ocean acidification levels. Recommend conservation actions, including protected status, for species that are most at risk. Protect species across their range since populations are likely to have different adaptations to local oceanic conditions.
- Determining the economic values of ecosystems that are at risk from ocean acidification and the costs of reducing CO_2 emissions to preserve those ecosystems.

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Additionally, EPA can use guidance on research needs based on existing research plans. There are a number of sources recommending research and data needs (National Research Council 2013; Washington State Blue Ribbon Panel 2012; National Research Council 2010).

According to TSCA, developing the data is "the responsibility of those who manufacture and those who process such chemical substances and mixtures."[75] For example, responsibility could be apportioned based on the historical carbon emissions from the EPA Greenhouse Gas Emission Inventory together with current emissions. Typically for test rules with multiple responsible parties consortiums are set up to comply.[76] Here, for example, utilities, cement and lime manufacturers, waste incinerators, and other large producers of CO_2 should be responsible for developing unbiased, independent data.

While this may seem like a complicated undertaking, EPA has successfully completed more complex test rules. For example, from 1998 through the present, the agency used three sets of regulatory test rules under TSCA to collect chemical data for almost 3,000 high production volume (HPV) chemicals, including over 10,000 individual studies with data from domestic and foreign producers.[77]

EPA must develop test rules under TSCA section 4 for research and data development focused on information essential for making a definitive TSCA section 6 finding. These would include risk, benefit and cost information.

D. Inadequacy of Existing CO_2 Reduction Strategies

Petitioners are aware that the Agency has recently planned and initiated several emission reduction actions aimed at slowing the rate at which carbon emissions are increasing. However, these actions by themselves, while laudable, will not stabilize atmospheric CO_2 at a level which will prevent widespread harm from ocean acidification.

1. Global Greenhouse Gas Emissions Are Increasing Substantially

The atmospheric concentration of CO_2 reached 400 parts per million (ppm) for the first time in human history in May, 2013, compared to the pre-industrial concentration of ~280 ppm (Scripps Institution of Oceanography 2013). The current CO_2 concentration has not been exceeded during the past 800,000 years and likely not during the past 15 to 20 million years (Denman et al. 2007; Tripati et al. 2009). Atmospheric CO_2 emissions have risen particularly rapidly since the 2000s (Raupach et al. 2007; Friedlingstein et al. 2010). The global fossil fuel CO_2 emissions growth rate was 1.0% per year in the 1990s compared with 3.1% per year since 2000, and this growth rate has largely tracked or exceeded the most fossil-fuel-intensive emissions scenarios projected by the IPCC (A1FI and RCP 8.5) since 2000 (Raupach et al. 2007, Peters et al. 2012). The CO_2 emissions growth rate fell slightly in 2009 due largely to the global financial and economic

[75] 15 U.S.C. § 2601
[76] 15 U.S.C. § 2602 (b)(3)(A)
[77] EPA, High Production Volume (HPV) Challenge; http://www.epa.gov/chemrtk/index.htm (last accessed June 28, 2015).

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crisis; however, the decrease was less than half of what was expected and was short-lived (Fiedlingstein et al. 2010). In 2014 and 2015, global CO_2 concentrations exceeded 400ppm.[78]

2. U.S. Measures to Reduce Greenhouse Gas Emissions Are Insufficient

EPA has taken some initial steps toward curbing greenhouse pollution under the Act. In 2009, the agency issued a formal finding that greenhouse pollution endangers public health and welfare and moved to limit emissions from passenger cars and trucks. The EPA also acknowledged that major new or modified "stationary" sources of greenhouse pollution, like power plants and factories, must obtain permits and control their emissions before beginning construction. However, it narrowed the scope of this requirement considerably under its so-called "tailoring rule," which initially limits the permitting program to only a few hundred very large sources of greenhouse gases, letting a huge number of smaller — but still significant — sources off the hook.

While existing domestic laws including the Clean Air Act, Energy Policy and Conservation Act, Clean Water Act, Endangered Species Act and others provide authority to executive branch agencies to require greenhouse gas emissions reductions from virtually all major sources in the United States, these agencies are either failing to implement or only partially implementing these laws for greenhouse gases. The landmark 2014 pact with China to reduce greenhouse gas emissions is significant, but there is little to ensure it is enforced and implemented. According to the plan, United States will reduce CO_2 emissions 26 to 28% below 2005 levels by 2025.

Proposed power plant rules also fail to do enough to cut CO_2 pollution. Using the Clean Air Act, the president aims to reduce existing power plant emissions 30 percent below 2005 levels (or about 7.7 percent below 1990 levels, the base year for the international climate treaty) by 2030. But international scientists warned years ago that developed countries like the United States must reduce their emissions 25 percent to 40 percent below 1990 levels by 2020 to avoid tipping the scales further toward a climate catastrophe. Likewise, the recently announced plans to limit power plant emissions (Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units) focuses on emission reduction. Power plants are responsible for about a third of our carbon emissions, and the rule is designed to reduce those emissions by almost a third by 2030. This would result in a 10% decrease in 15 years. Stabilizing atmospheric concentration to prevent further acidification of the oceans would require about an 80% decrease in all emissions. Clearly this is a good first step, but by itself inadequate to address acidification.

EPA has issued a rulemaking regulating greenhouse gas emissions from automobiles that will reduce greenhouse emissions emitted per vehicle mile traveled by passenger vehicles in the future. But because the improvements are modest and more vehicles are projected to drive more miles in the future, the rule will not reduce emissions from this sector overall but will only slow the rate of increase.[79] Meanwhile, even the government concedes that "these reductions in emissions are not sufficient by themselves to reduce total HD vehicle emissions below their 2005

[78] NOAA, Trends in Atmospheric Carbon Dioxide, http://www.esrl.noaa.gov/gmd/ccgg/trends/
[79] EPA, Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule, 75 Fed. Reg. 25324 (May 7, 2010).

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levels by 2020."[80] This means that the vehicle rule is far from achieving emissions goals agreed to by the U.S. in the Copenhagen Accord, which aim to keep global warming below 2˚C.

The EPA has also to date issued only a single proposed rule under the new source pollution standard program for stationary sources of pollution, for electric generating units (power plants). While there is enormous potential to reduce emissions through this program overall and through the power plants rule in particular, the EPA has instead proposed a weak and flawed rule that it admits will not reduce emissions from these sources between now and 2020 compared to what would be expected without the rule.[81] Indeed, in the rulemaking the EPA conceded that new power plant rule on greenhouse gas emissions "will not have direct impact on U.S. emissions of greenhouse gases under expected economic conditions."[82]

While full implementation of our flagship environmental laws, particularly the Clean Air Act, would provide an effective and comprehensive greenhouse gas reduction strategy, due to their non-implementation, existing domestic regulatory mechanisms must be considered inadequate to protect marine species from climate change and ocean acidification.

3. International Measures to Reduce Greenhouse Gas Emissions Are Inadequate

International initiatives are also currently inadequate to effectively address climate change. The United Nations Framework Convention on Climate Change, negotiated in 1992 at Rio de Janeiro, Brazil, provides the forum for the international negotiations. In the Framework Convention, signed and ratified by the United States, the world agreed to take the actions necessary to avoid dangerous climate change. Parties to the Convention also agreed as a matter of fairness that the world's rich, developed countries, having caused the vast majority of emissions responsible for the problem, would take the lead in solving it. It was not until the 1997 meeting in Kyoto, Japan, that the first concrete, legally binding agreement for reducing emissions was signed: the Kyoto Protocol. The Protocol requires the world's richest countries to reduce emissions an average of 5 percent below 1990 levels by 2012, while developing nations also take steps to reduce emissions without being subject to binding emissions targets as they continue to raise their standard of living. The United States has been a major barrier to progress in the international negotiations. After the Clinton administration extracted many concessions from the rest of the world in exchange for the United States signing on in Kyoto, the Senate rejected the equity principles behind the Convention, saying the United States should not agree to reduce its own emissions unless all other countries — regardless of their responsibility or ability — were similarly bound. Citing the same excuses, President George W. Bush repudiated the Kyoto Protocol entirely. Thus the United States is the only industrialized country in the world that has yet to ratify the Kyoto Protocol. The United States negotiating team under both the George W. Bush and the Obama administrations has pursued two primary objectives in the international talks: to refuse any legally binding emissions reduction commitments until all other

[80] NHTSA, Medium- and Heavy-Duty Fuel Efficiency Improvement Program – Final Environmental Impact Statement (June 2011).
[81] EPA, Standards of Performance for Greenhouse Gas Emissions for New Stationary Sources: Electric Utility Generating Units, 77 Fed. Reg. 22392, 22430-33 (April 13, 2012).
[82] *Id.* at 22401.

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countries— but particularly China and India — do so, and to push back the date for a new agreement. Not surprisingly, the United States had failed to meet its (never ratified) Kyoto pledge to reduce emissions to 7.2% below 1990 levels by 2012; to the contrary, U.S. emissions have increased by 10.5% since 1990 (EPA 2012).

Moreover, the Kyoto Protocol's first commitment period only sets targets for action through 2012, and there is still no binding international agreement governing greenhouse gas emissions in the years beyond 2012. While the 2009 U.N. Climate Change Conference in Copenhagen called on countries to hold the increase in global temperature below 2□C (an inadequate target for avoiding dangerous climate change), the non-binding "Copenhagen Accord" that emerged from the conference, and the subsequent "Cancún Accords" of 2010 and "Durban Platform" of 2011 failed to enact binding regulations that limit emissions to reach this goal.[83] Even if countries were to meet their Copenhagen and Cancún pledges, analyses have found that collective national pledges to cut greenhouse gas emissions are inadequate to achieve the 2°C target, and instead suggest emission scenarios leading to 2.5□C to 5□C warming (Rogelj et al. 2010; UNEP 2011; UNEP 2010). As of July 2013, many governments were not implementing the policies needed to meet their inadequate 2020 emission reduction pledges, making it more difficult to keep global temperature rise to 2□C and likely leading to a temperature rise of at least 3.5□C (USGCRP 2013). As noted in the NMFS Management Report, the U.S. has yet to issue regulations to limit greenhouse gas emissions in accordance with its pledge under the Copenhagen Accord (NMFS 2012).

CONCLUSION

In conclusion, this petition requires EPA to make a determination whether CO_2 poses an unreasonable risk to the environment therefore requiring regulation under section 6 of TSCA. In an extensive review of the literature on the impact of ocean acidification on marine fauna and ecosystem processes, the authors found that while additional research is called for, sufficient information exists to state with certainty that deleterious impacts on some marine species are unavoidable, and that substantial alteration of marine ecosystems is likely over the next century. (Fabry et al. 2008). If, nonetheless, EPA determines that the information is insufficient to make such a finding it must develop testing rules pursuant to TSCA section 4.

[83] The non-legally binding Copenhagen Accord of 2009 and Cancún Accords of 2010 recognize the objective of limiting warming to 2°C above pre-industrial temperatures, but do not enact binding regulations to achieve this goal (http://cancun.unfccc.int/cancun-agreements/main-objectives-of-the-agreements/#c33; unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf). According to the Durban Platform, developed and developing nations agreed to a process to develop a "new protocol, another legal instrument, or agreed outcome with legal force that will be applicable to all Parties to the UN climate convention"; this legal instrument must be developed as of 2015 and will not take effect until 2020 (unfccc.int/resource/docs/2011/cop17/eng/l10.pdf).

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First Meeting
Committee on Assessing Approaches to Updating the Social Cost of Carbon

September 2, 2015

Room 208
Keck Center
500 5th St., NW
Washington, DC 20001

AGENDA

Wednesday, September 2, 2015

OPEN SESSION (open to the public)

9:30 Introductions
Maureen Cropper and Richard Newell, Panel Co-Chairs
MaryEllen O'Connell, Interim Director, Board on Environmental Change and Society
Marisa Gerstein Pineau, Program Officer

9:45 Presentation: Sponsor's Interests and Goals for the Study
Ken Gillingham, Council of Economic Advisers
Q&A: **Richard Newell and Maureen Cropper**, Moderators

10:45 *Break*

11:00 Presentation: Methodology for the Social Cost of Carbon Estimates
Elizabeth Kopits or Alex Marten, U.S. Environmental Protection Agency
Q&A: **Richard Newell and Maureen Cropper**, Moderators

12:45 Closing Remarks
Maureen Cropper and Richard Newell, Co-Chairs

1:00 Adjourn Open Session

Suggested Background Sources 08/07/2015

(a) Construction of the SCC

In addition to the 2010 and 2013 (July 2015 revision) TSDs we would recommend Greenstone et al. (2013) as a good overview of the estimates and the process.

Michael Greenstone, Elizabeth Kopits, and Ann Wolverton. Developing a social cost of carbon for US regulatory analysis: A methodology and interpretation. *Review of Environmental Economics and Policy*, 7(1):23-46, 2013.

(b) Background on the structure of each of the IAMs

Weyant (2014) provides a good overview of integrated assessment models (IAMs) and the state of the science, for those that might be new to the modeling. Nordhaus (2014) provides a good overview of modeling the SCC using IAMs and the DICE model in particular, while Anthoff and Tol (2013) provides a good overview of the FUND model and the uncertainty surrounding the estimates. Reilly et al. (2013) provide a nice overview of modeling climate impacts in IAMs with more detailed representations of the global economy.

John Weyant. Integrated assessment of climate change: state of the literature. *Journal of Benet-Cost Analysis*, 5(3):377-409, 2014.

William Nordhaus. Estimates of the social cost of carbon: Concepts and results from the DICE-2013r model and alternative approaches. *Journal of the Association of Environmental and Resource Economists*, 1(1/2):273-312, 2014.

David Anthoff and Richard Tol. The uncertainty about the social cost of carbon: A decomposition analysis using FUND. *Climatic Change*, 117(3):515-530, 2013.

John Reilly, Sergey Paltsev, Ken Strzepek, Noelle E Selin, Yongxia Cai, Kyung-Min Nam, Erwan Monier, Stephanie Dutkiewicz, Jeery Scott, Mort Webster, et al. Valuing climate impacts in integrated assessment models: the MIT IGSM. *Climatic Change*, 117(3):561-573, 2013.

(c) Climate science components of the IAMs

This paper by Warren et al. (2010), while a little out dated, provides a high level overview of the climate models used in the IAMs.

Rachel Warren, Michael D Mastrandrea, Chris Hope, and Andries F Hof. Variation in the climatic response to SRES emissions scenarios in integrated assessment models. *Climatic Change*, 102(3-4):671-685, 2010.

(d) Views on ECS and how they have changed since AR4

Roe (2009) is an excellent background piece on climate sensitivity and what drives the uncertainty

around estimates of the parameter. Rogelj et al. (2014) provides a good overview of changing knowledge about climate sensitivity (including from AR4 to AR5) and puts those changes in context.

Gerard Roe. Feedbacks, timescales, and seeing red. *Annual Review of Earth and Planetary Sciences*, 37:93-115, 2009.

Joeri Rogelj, Malte Meinshausen, Jan Sedlacek, and Reto Knutti. Implications of potentially lower climate sensitivity on climate projections and policy. *Environmental Research Letters*, 9(3):031003, 2014.

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1:00 Adjourn Open Session

To: Stallworth, Holly[Stallworth.Holly@epa.gov]
Cc: Zarba, Christopher[Zarba.Christopher@epa.gov]; McGartland, Al[McGartland.Al@epa.gov]; DeMocker, Jim[DeMocker.Jim@epa.gov]; Rennert, Kevin[Rennert.Kevin@epa.gov]; Marten, Alex[Marten.Alex@epa.gov]
From: Wolverton, Ann
Sent: Tue 9/22/2015 2:59:45 PM
Subject: white papers and memos for economy-wide SAB panel
CGE social cost white paper final.pdf
NonCGE to estimate social cost memo final.pdf
CGE benefits white paper final.pdf
crosswalk for first two sections of SAB charge.pdf
Glossary of terms for first SAB meeting.pdf

Hi Holly,

Attached are two white papers and a memo to inform the SAB Panel's discussion of the first two sections of the charge on social cost and benefits. In addition, as requested by the Panel, we have constructed a crosswalk between the charge and relevant sections of the white papers and memo as well as a glossary.

Finally, I will forward a few supplementary materials in a separate email that are referenced regularly in some of the white papers in case the SAB Panel wants them – these supplementary materials are not required reading.

We'd also like to set up a time next week to chat with you and Chris. Specifically, we'd like to discuss the plan for the October meeting and a few issues that came up during the July call.

Let me know if you have any questions.

Regards,

Ann

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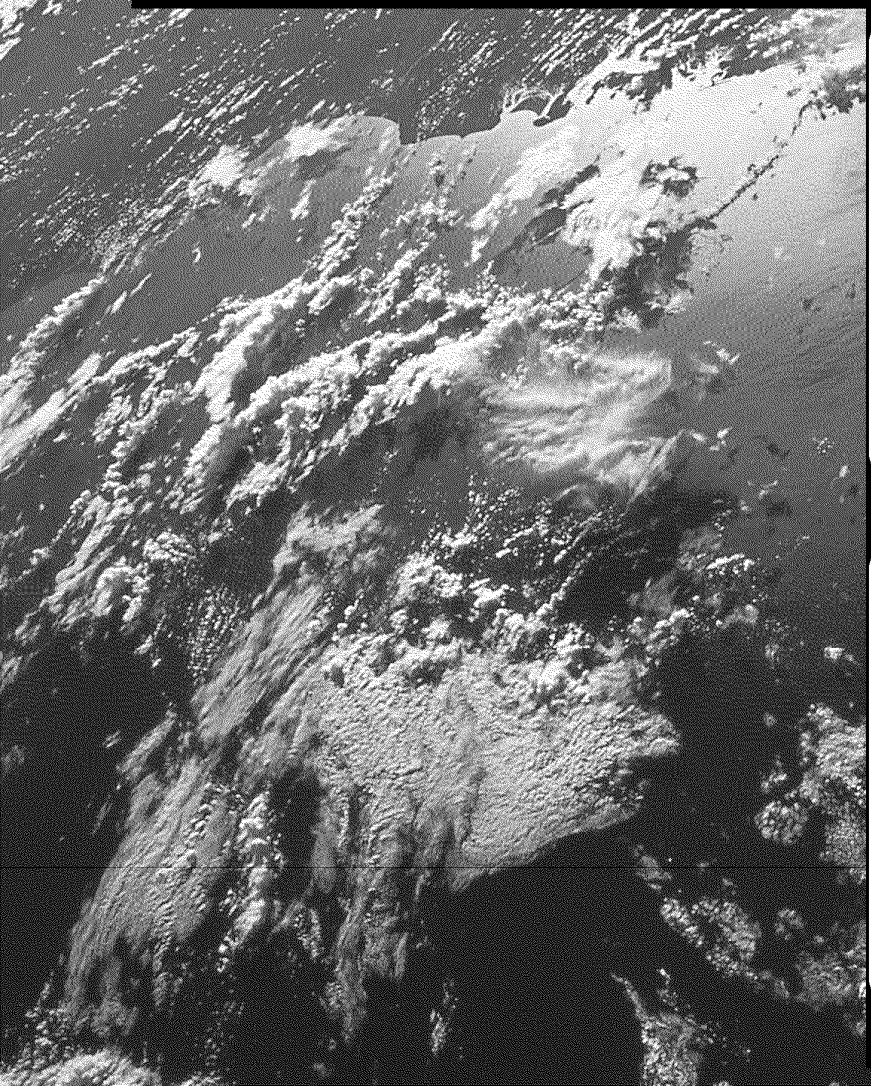
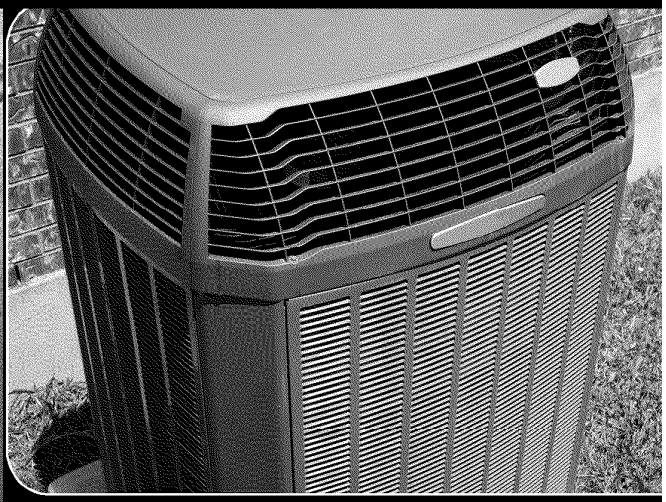
Understanding the Social Cost of Carbon

A Technical Assessment





Understanding the Social Cost of Carbon

A Technical Assessment

3002004657

Technical Update, October 2014

EPRI Project Manager

S. Rose

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The Electric Power Research Institute (EPRI) prepared this report.

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D. Turner
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T. Wilson

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We would like to start by thanking the analysts at the U.S. Environmental Protection Agency and the social cost of carbon (SCC) model developers for assistance with acquiring the model code and input files and for thoughtfully responding to our detailed questions regarding the models and development of the U.S. Government SCC estimates. Specifically, we thank Elizabeth Kopits, Alex Marten, Steve Newbold, Ann Wolverton, Charles Griffiths, David Anthoff, and Chris Hope. This study also benefitted from guidance and encouragement from Richard Richels, as well as a variety of individual technical conversations with Chris Forest, Klaus Keller, Robert Kopp, and Robert Mendelsohn. We also thank panelists and participants at EPRI's 19th Annual Energy and Climate Change Research Seminar for constructive feedback, in particular Jeff Hopkins, Brent Dorsey, and Adele Morris.

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ABSTRACT

The social cost of carbon (SCC) is a monetary estimate of the climate change damages to society from an additional unit of carbon dioxide (CO_2) emitted to the earth's atmosphere. In 2010, the United States Government (USG) developed SCC estimates to value the benefits of CO_2 emissions reductions in federal rulemakings. In 2013, the USG revised their estimates following the same procedure, but with newer versions of the underlying models, and the SCCs notably increased. SCC estimates of one kind or another have been applied in almost fifty federal regulations since 2008, including rules associated with appliances, transportation, industry, and power generation. However, not until earlier this year have the USG estimates been subject to explicit public comment.

Despite their use, the USG SCC estimates are difficult to interpret and evaluate. What does the central value of $37 per metric ton of CO_2 mean? What sorts of damages to society does it represent? What are the key drivers of estimated damages? How good is the current estimation approach, and can it be improved?

The USG SCC estimates are the result of significant aggregation across many dimensions: time, socioeconomic scenarios, uncertain parameters, world regions, damage categories, and models. This aggregation obscures the underlying details and drivers of results, as well as the variation across models. Making sense of the estimates requires delving into these details. Overall, there is a need for greater technical clarity on what underlies the estimates.

This study presents an in-depth examination of the three models underlying the current USG SCC estimates (DICE, FUND, and PAGE) as well as the overall USG approach. Specifically, we assess the major SCC modeling components—projected socioeconomics and emissions, climate modeling, and climate damages modeling— in isolation. For each component, we review the modeling, program the component from all three models, develop and run diagnostic scenarios, and make comparisons to learn about and assess the raw modeling and results (undiscounted and disaggregated to underlying elements). With the component assessments in hand as a technical basis, we then evaluate the USG approach of combining 150,000 model results to determine a USG SCC. In the climate and damage component assessments we explore a variety of perspectives, including deterministic and probabilistic model responses, and total and incremental model responses. The latter is particularly relevant because the SCC is an estimate of damages from an incremental increase in CO_2 emissions.

Our assessment reveals significant variation across models in their structure, behavior, and results and identifies fundamental issues and opportunities for improvements. The objective of this work is to improve understanding of SCC modeling and estimates in order to inform and facilitate public discussion, future SCC modeling and use, and future climate research broadly.

Keywords
Climate change
Impacts
Damages
Social cost of carbon

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Executive Summary

Understanding the Social Cost of Carbon: A Technical Assessment

The social cost of carbon (SCC) is a monetary estimate of the climate change damages to society from an additional unit of carbon dioxide (CO_2) emitted to the earth's atmosphere. SCC estimates are derived from models that simulate long-run global economic, energy, and climate systems, and the potential consequences of climate change. In 2010, the United States Government (USG) developed SCC estimates to value the benefits of CO_2 emissions reductions in federal rulemakings. In 2013, the USG revised their estimates following the same procedure but with newer versions of the underlying models, and the SCCs notably increased. SCC estimates of one kind or another have been applied in almost fifty U.S. federal regulations across agencies since 2008, including rules applying to appliances, transportation, industry, and power generation. The USG SCC estimates are also being utilized at state and local levels and in both regulatory and non-regulatory contexts. However, not until earlier this year have the USG estimates been subject to explicit public comment.

Current USG SCC estimates are difficult to interpret and evaluate. What does the USG central value of $37 per metric ton of CO_2 mean? What sorts of damages to society does it represent? What are the key drivers of estimated damages? How do the individual models that underlie the estimate differ, and why? How good is the current approach, and can it be improved?

The objective of this study is to improve understanding of USG SCC modeling and estimates in order to inform public discussion, future SCC modeling and application, and future research. To better understand the estimates and what they represent, we examine in-depth the models underlying the current SCC estimates and the USG approach for applying the models. In a

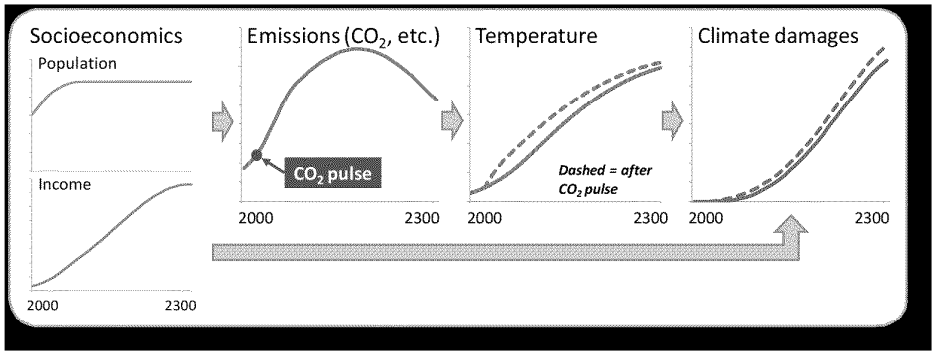

Figure ES-1
Modeling causal chain for computing the social cost of carbon. Solid lines represent reference projections. Dashed lines represent projections after a CO_2 emissions pulse in a particular year (e.g., 2020). Emissions include CO_2 and non-CO_2 greenhouse gases and aerosols. The illustrative figure is for CO_2. Other climate variables are not explicitly modeled (e.g., precipitation, extreme weather events). Sea-level rise (not shown), also a part of the causal modeling chain, is driven by temperature change and drives sea level rise related climate damages. Socioeconomics (population and economic growth) drives emissions (and hence, temperature change and sea level rise), as well as climate damages directly by defining the society vulnerable to potential climate change and its adaptation capacity.

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companion report, expected in 2015, we examine applications of the SCC and provide technical insight for appropriate application.

Background – How the SCC has been Estimated by the USG

Three publicly-available, highly aggregated, integrated assessment models—DICE, FUND and PAGE—were used to compute the USG SCC estimates. These models have long histories and have produced most of the SCC estimates in the recent scientific literature. Also, they can be run with alternative input assumptions to explore uncertainties. Each model computes the SCC by simulating the 'causal chain' from greenhouse gas emissions to climate change to climate damages, for both a reference path and a pulsed emissions path, to estimate the additional future damages from an additional metric ton pulse of CO_2 (Figure ES-1). The SCC therefore is an estimate of the additional climate damages from an extra unit of emissions, and can be used to estimate the potential benefits of a unit of emissions avoided, which is its primary use in U.S. rulemakings.

The USG ran each of the models tens of thousands of times with alternative socioeconomic and emissions futures, climate system uncertainty, and uncertainties in some model-specific parameters. Each run produced a projection of estimated annual additional damages to society for the next three hundred years from a CO_2 pulse. The thousands of results were then discounted and averaged to create a single USG SCC for each of the discount rates considered (2.5%, 3%, and 5%). For example, $37 per metric ton CO_2 is the average of 150,000 projections of incremental damages from a 1 metric ton change in CO_2 in 2015 discounted at 3% (Figure ES-2). The procedure was repeated with CO_2 pulses in future years through to 2050 to provide estimates for the value of CO_2 changes in different years. The final SCC results over time are shown in Figure ES-2. Proposed and final regulations use the four time streams of estimates, and occasionally only one time stream depending on the rule.

Our Study Approach

The USG SCC estimates are an aggregation of results across models, over time, across world regions, across impact categories, and across many scenarios. This aggregation however obscures the underlying details and differences. Making sense of the estimates requires delving into these details. Our study examines the inner workings of the models to elucidate the key drivers and assess main components of the SCC. We then are able to reflect on the overall USG approach of combining model results to produce the official USG SCCs.

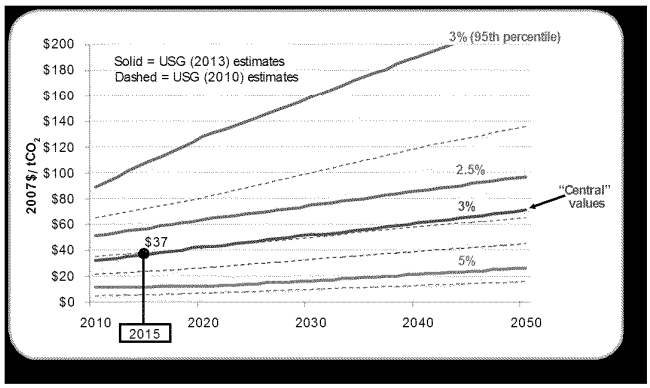

Figure ES-2
U.S. Government Social Cost of Carbon Estimates. Each point on the bottom three lines is the average SCC value for a specific year and given discount rate, averaging results across the three models used, alternative socioeconomic scenarios, a distribution of potential climate sensitivities (i.e., the amount of warming for a doubling of greenhouse gas concentrations in the atmosphere), and random model specific parameters. "3% (95th percentile)" is the 95th percentile from the distribution of the 150,000 SCC estimates discounted at 3%. USG SCC estimates were revised in 2013 following the same procedure but with newer versions of the models, and estimates notably increased. Source: Developed from USG (2010) and USG (2013).

Specifically, we carry out four separate technical assessments. First, we assess each of the major components independently—socioeconomics and emissions, climate, and climate damages. For each component, we review the modeling, program the component from all three models, develop and run diagnostic scenarios, and make comparisons to learn about and assess the raw modeling and results (undiscounted and disaggregated to underlying elements). With the component assessments in hand as a technical basis, we then assess the overall USG experimental design.

For example, we isolated the algorithms from each model that calculate temperature change from emissions so that we could compare the climate results of the three models with common emissions inputs, and so that we could contrast this part of the models to more sophisticated approaches. Similarly, we isolated the algorithms that calculate climate damages from temperature change to compare damage estimates in response to varying levels of climate change and socioeconomic vulnerability and identify the main elements of damages within each model. In our assessments we provide many perspectives on how the model components behave—total and incremental responses, results through the year 2100 and 2300, aggregated and disaggregated, deterministic and probabilistic, and reference responses and sensitivities. We evaluate both the total and incremental responses of the models—the latter because the SCC is an estimate of damages from an incremental increase in CO_2 emissions, and

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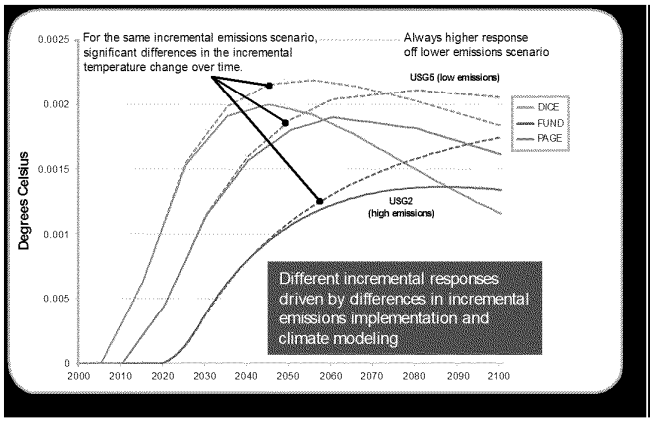

Figure ES-3
Annual incremental global mean temperature increase to 2100 with common high (solid, USG2) and low (dashed, USG5) emissions scenarios from a 1 billion tonne of carbon (1 GtC) increase in emissions in 2020. Because the SCC is an estimate of damages from an incremental increase in CO_2 emissions, we evaluate the incremental temperature responses of the models. For incremental emissions off of the same reference scenario (e.g., USG5), we observe significant differences in the projected incremental temperature change over time driven by differences in incremental emissions implementation and climate modeling. In all models we find a higher incremental temperature response off of lower emissions scenarios. [Section 5]

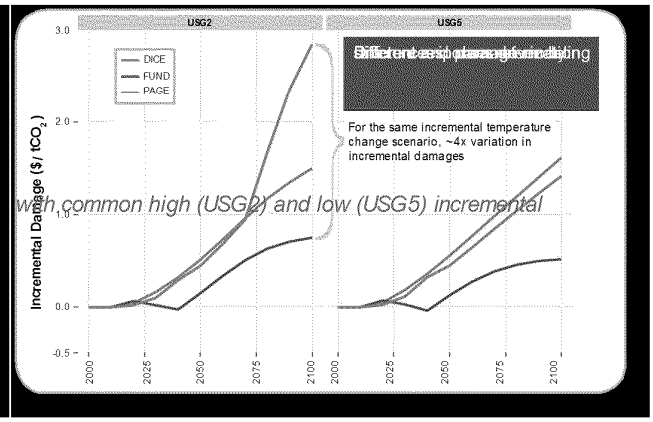

Figure ES-4
Annual incremental global climate damages to 2100

the former because total results are the reference conditions for the incremental results, as context for thinking about damages and for direct comparison to other analyses.

Comparison of the USG SCC Integrated Assessment Modeling

From our assessments, we find significant differences in the models in all three components—socioeconomics/emissions, climate change, and climate damages. For instance, in the socioeconomics and emissions component, the models vary in how they implement the standardized socioeconomic and emissions assumptions, which results in the models actually "seeing" different (i.e., non-standardized) socioeconomic and emissions inputs (Section 4). This discrepancy propagates all the way through the causal chain, affecting the temperature levels and climate damages comprising the USG SCC estimates.

In the climate modeling component, we find significant differences in the translation of emissions into estimated temperature change (Section 5). For example, in Figure ES-3 the temperature response by 2040 to an incremental increase in 2020 emissions is almost twice as high in DICE as it is in FUND. And, in the climate damage component, the models differ greatly in their calculation of potential damages for the same temperature change (Section 6). For example, Figure ES-4 illustrates that the models produce markedly different incremental annual damages for the same incremental temperature increase, differing by as much as a factor of four over the next century.

Differences in the calculations of projected total temperature change, sea level rise, and climate damages underlie the differences in the incremental responses. For instance, in one case, the models project 1˚C of variation in global warming by 2100 with the same emissions inputs (Figure ES-5); and, for the same projected temperature change and societal conditions, a factor of three difference in total damages by 2100, with estimates ranging from net benefits to net damages for much of the next century (Figure ES-6). The differences in the temperature responses result from differences in the modeling of key climate system elements—the carbon cycle, non-CO_2 radiative forcing, forcing to temperature translation, and climate sensitivity responsiveness, while the differences in damage responses result from differences in damage modeling structure and parameterization—e.g., regional temperature estimation, responsiveness of individual

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damages to temperature and income, regional damage modeling, and adaptation responses.

Functional relationships are implied within the damage components of the models and our analysis teases them out, finding DICE and PAGE total damages more responsive to projected temperature and income levels than FUND (Figure ES-7), and sectoral and regional damages within and across models responding differently to temperature change (Figures ES-8 and ES-9).

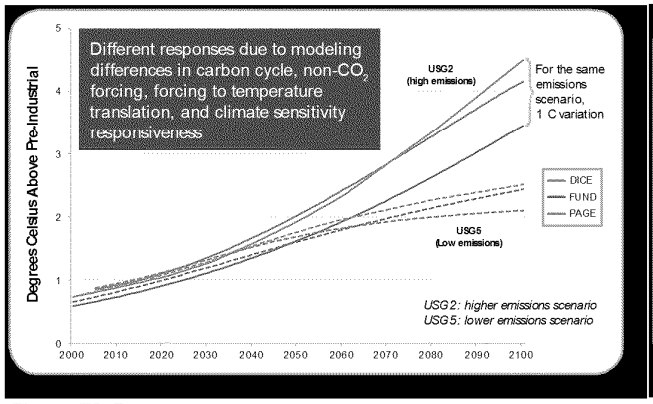

Figure ES-5
Annual global mean temperature increase to 2100 with common high (solid, USG2) and low (dashed, USG5) emissions scenarios. For the same emissions scenario (USG2), we observe 1˚C of variation in projected temperature in 2100. The differences in temperature response are due to modeling differences in carbon cycle, non-CO_2 radiative forcing, forcing to temperature translation, and climate sensitivity responsiveness. After 2100, variation across models can grow and the ordinal ranking can change depending on the scenario (i.e., lowest to highest projected temperature). [Section 5]

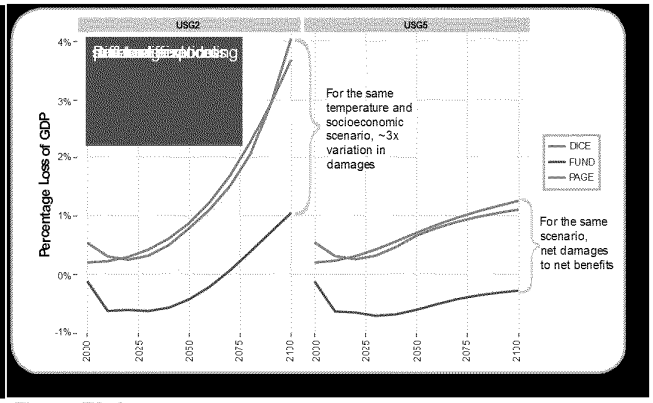

Figure ES-6
Annual global climate damages to 2100 as a percent of global GDP with common high (USG2) and low (USG5) temperature projections. For the same temperature and socioeconomic scenario (USG2), projected global damages vary by a factor of three across models, with estimates ranging from net benefits to net damages for much of the century. The observed differences in projected damages are due to differences in damage modeling structure and parameterization. Projected damages are greater with the higher temperature scenario (USG2). Projected annual global damages grow substantially beyond 2100, and more quickly with DICE and PAGE than FUND (not shown). [Section 6]

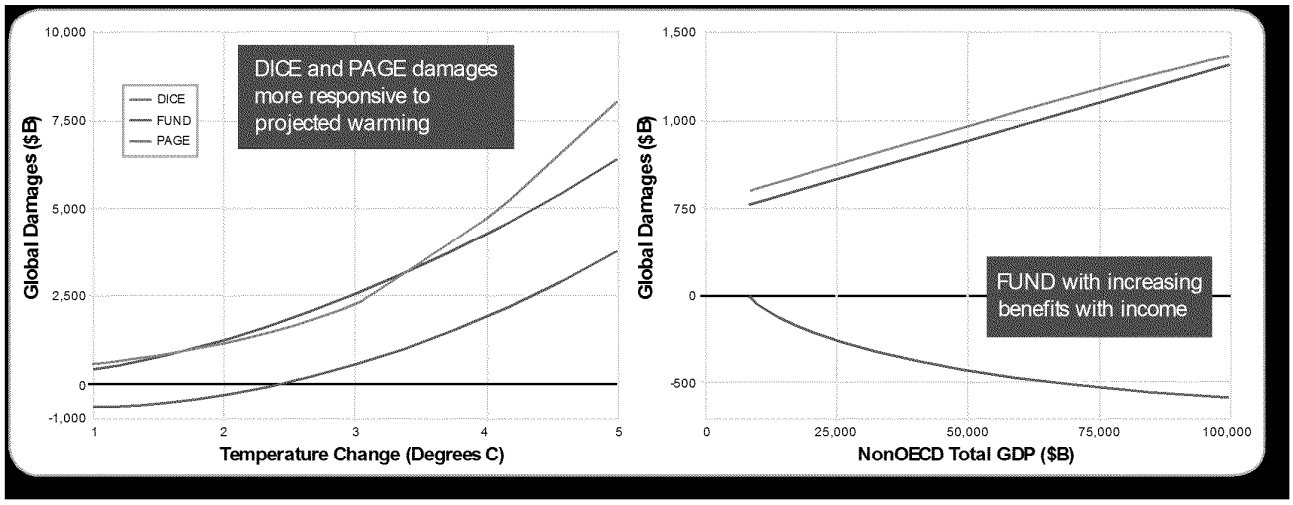

Figure ES-7
Total climate damages in 2050 as a function of temperature (left) and non-OECD income (right). Y-axis' scales vary. The figures are for a reference condition for the left and right figures respectively of 2050 USG2 socioeconomics and 1.8˚C of global mean temperature increase. We observe that damage estimates from DICE and PAGE are more responsive to projected warming, and FUND net benefits increase with the size of the economy for lower levels of warming. At higher levels of warming, by 2100, DICE and PAGE are more responsive to income than FUND, and FUND produces net damages that increase with income. All three models are more responsive to temperature than to income. Beyond 2050, the differences in responsiveness are even greater. The ~~differences in responses across models are driven by differences in the damage specifications and adaptation modeling. [Section 6]~~

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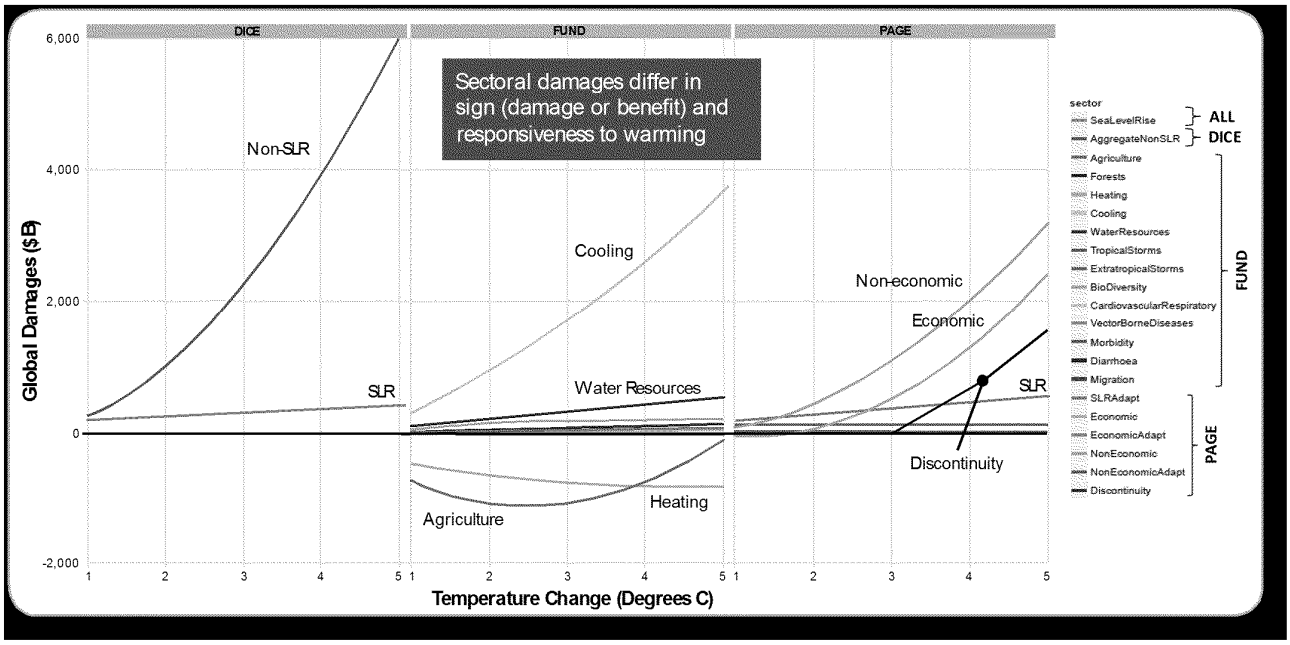

Figure ES-8
Sectoral climate damages by model as a function of temperature for 2050 and USG2. The figures are for the year 2050 with a reference condition of USG2 socioeconomics. Projected sectoral damages differ in sign (damage or benefit) and responsiveness to warming (steepness), and particular sectors are driving results. Beyond 2050 (not shown), the dominance of certain sectors increases—non-SLR damages in DICE, cooling demand and agriculture in FUND, and non-economic and economic damages in PAGE. PAGE includes separate adaptation cost categories. [Section 6]

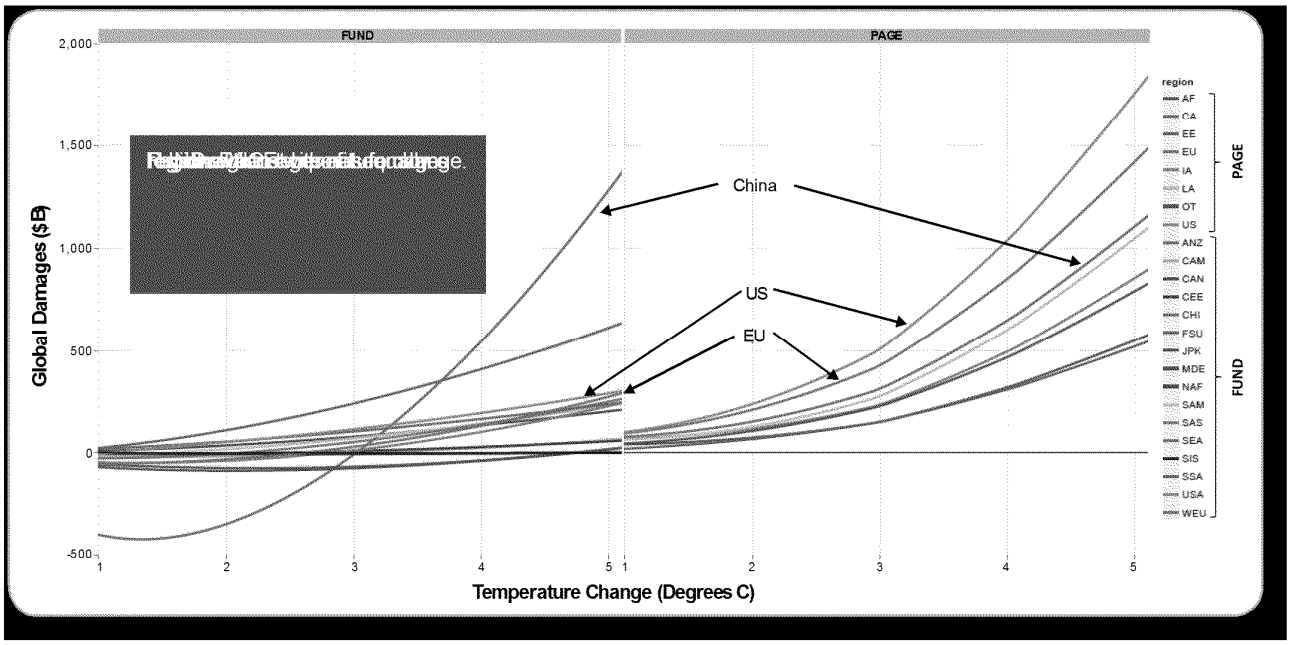

Figure ES-9
Regional climate damages by model as a function of temperature. The figures are for 2050 with a reference condition of USG2 socioeconomics. Projected regional damages are not equally responsive to temperature change. Differences are due to estimated regional temperatures, damage modeling structure, and parameterization. See Appendix A for region definitions. [Section 6]

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Table ES-1
Most and least sensitivity models for key variables and inputs. Characterizations of sensitivity based on our assessment of level results (˚C or $B) through 2100. Some models are consistently more or less sensitive than the other models across the various sequential elements in the causal modeling chain. The table provides ordinal rankings of responsiveness. The differences in the magnitudes of responsiveness are also important (as results in the main report suggest). [Sections 5 and 6]

Sensitivity of	Most sensitive model(s)	Least sensitive model(s)
Projected temperature change (˚C) to alternative emissions assumptions	DICE	FUND
Projected temperature change (˚C) to alternative climate sensitivity assumptions	PAGE	FUND
Projected total climate damages ($B) to alternative temperature change projections	PAGE	FUND
Projected total climate damages ($B) to alternative income level assumptions	At low levels of warming – FUND (with increasing net benefits) At high levels of warming – PAGE (with increasing net damages)	At low levels of warming – DICE & PAGE (with increasing net damages) At high levels of warming – FUND (with increasing net damages)

While differences in sectoral and regional structure make direct comparison challenging, we can still identify prominent damage sectors and regions in each model (Figures ES-8 and ES-9). In DICE, non-sea level rise (non-SLR) damages are the most responsive to temperature. In FUND, it is cooling energy demand, heating energy demand, agricultural productivity, and water resources. And, in PAGE, it is SLR and non-economic damages at low levels of warming, and non-economic, economic and discontinuity damages that accumulate quickly with greater warming. Interestingly, SLR damages grow most quickly with temperature in DICE and PAGE, despite FUND projecting the largest increase in sea levels (Section 6).

Regionally, fundamental structural differences exist. PAGE scales regional damages off of estimated damages for the European Union, while FUND models individual regions, and DICE models only global damages. Within the models, we find PAGE projecting net damages for all regions and levels of warming, and FUND projecting net benefits for a number of regions, even up to 4.5˚C of global temperature rise. Furthermore, at lower levels of warming, developing regions dominate FUND's damages (China and the Former Soviet Union, FSU), while developed regions dominate PAGE's damages (EU, US, and Other OECD (OT)). At higher levels of warming, developing region damages continue to dominate in FUND while becoming more prominent in PAGE, but developed region damages are still prominent in PAGE and much larger than those from FUND.

The differences in the responsiveness of sectoral and regional damages result in dramatic variation across models in the scale, composition, and location of the damage responses to an incremental increase in CO_2. For instance, Figure ES-10 shows a custom decomposition of incremental damages for USG2 (a high emissions scenario) that illustrates the dominance of non-SLR damages in DICE in the first century, damages in agriculture and cooling demand in FUND, especially in China, and non-economic and economic damages in PAGE with an increase in expected discontinuity damages towards the end of the first century.

Overall, across our component analyses, we find some models consistently more sensitive to alternative standardized assumptions and some consistently less sensitive (Table ES-1). The distribution of SCC results from each model will reflect a combination of these responses across the causal modeling chain within each model.

The discussion to this point was based on our deterministic analyses of model behavior. Our assessment also explores the model specific parametric uncertainties included in the USG approach. In the USG modeling, within the climate and damage components, FUND and PAGE are run with their own parametric uncertainty. DICE, on the other hand, is run without model specific parametric uncertainty. We ran probabilistic scenarios with the FUND and PAGE components to learn about the character of those uncertainties and found the models capturing substantially different component uncertainty. Specifically, in the climate system, PAGE models significantly more uncertainty than FUND, and produces a broader distribution for potential temperature change. And, in the damage component, FUND models significantly more uncertainty than PAGE, yet PAGE produces higher average damages (Figures ES-11 and ES-12).

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Note that, in addition to the observations above, we summarize and discuss more detailed component specific observations in each of our modeling component assessments within the main report (Sections 4, 5, and 6).

Assessment of the USG Approach

The USG developed a novel analytical framework for generating their SCC estimates—one that attempts to account for a variety of uncertainties by using multiple models running both standardized and model specific uncertainties. This approach is novel because, to date, SCC estimates in the literature have been generated by individual models with non-standardized uncertainties. The approach is also novel because U.S. regulatory analyses typically use individual models (e.g., the Integrated Planning Model used at the U.S. EPA, and the CAFE Compliance and Effects Model used at the U.S. National Highway Traffic Safety Administration). However, our technical analyses reveal a number of issues with the approach that should be considered going forward:

- **Significant structural differences across models:** Substantial structural differences in the models contribute

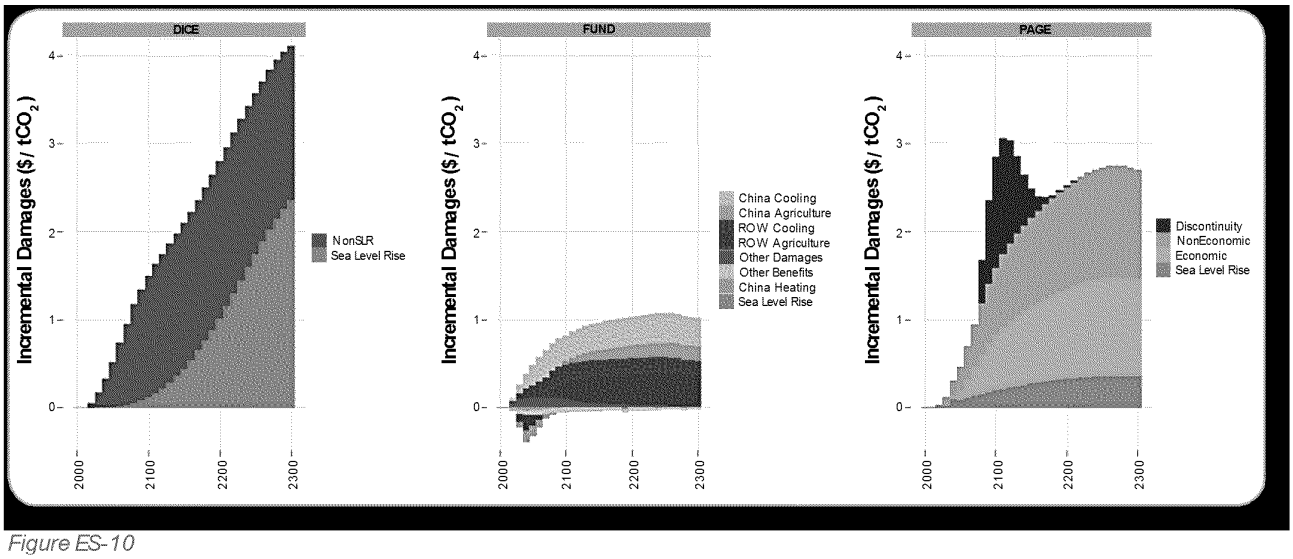

Figure ES-10
Key drivers of annual incremental global climate damages to 2300 from a 1 GtC increase in 2020 with common reference USG2 temperature and socioeconomic projections. Annual total incremental damages increase over time in all models, with the drivers of incremental damages varying by model and with time. In DICE, non-SLR damages dominate through 2100 and are more evenly distributed with SLR damages after 2100. In FUND, cooling and agricultural damages and benefits dominate results, with China accounting for approximately half of cumulative incremental damage changes, primarily from increased cooling demand. In PAGE, non-economic and economic damages dominate, with an incremental increase in the expected value of discontinuity damages towards the end of the first century. In PAGE through 2050, 45% of damages are in the EU and US (not shown). Beyond 2050, damages in non-OECD regions grow slightly faster than damages in OECD regions. Incremental SLR damages grow most quickly in DICE beyond 2050. [Section 6]

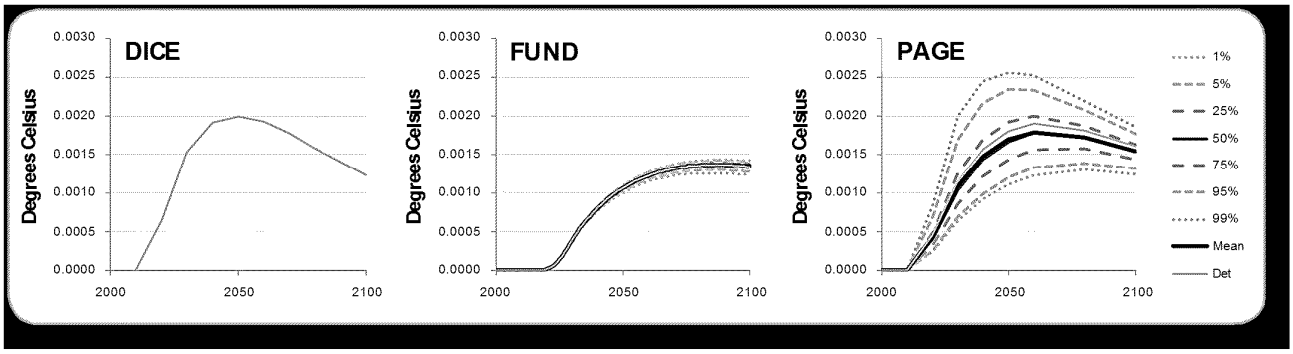

Figure ES-11
Incremental global mean temperature uncertainty to 2100 with model specific parametric uncertainty and a common high (USG2) emissions scenario. [Section 5]

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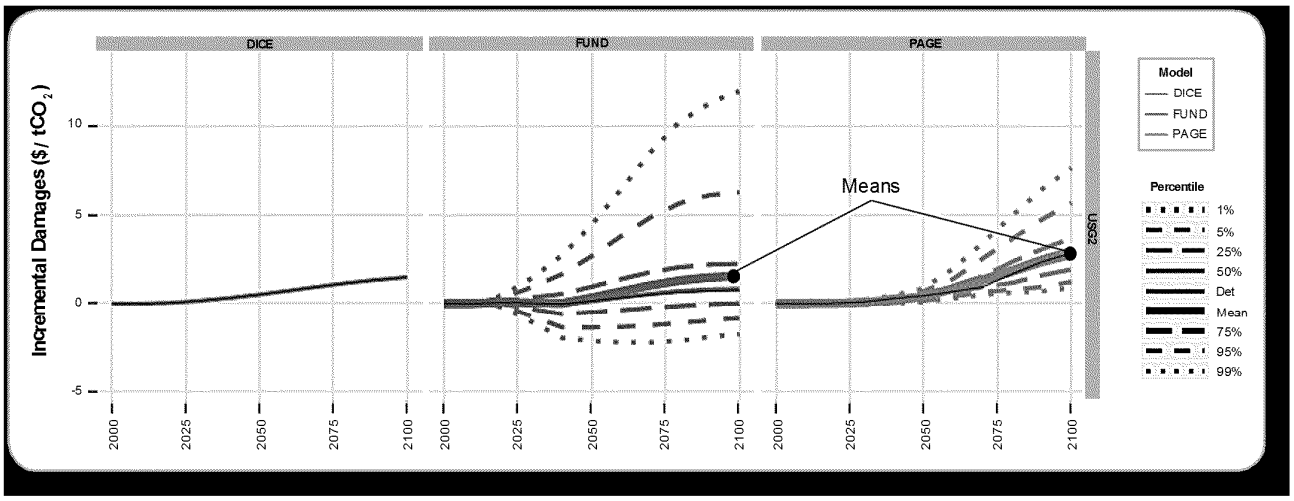

Figure ES-12
Incremental global climate damage uncertainty to 2100 with model specific parametric uncertainty and a common high (USG2) temperature scenario. [Section 6]

to the differences in model results that we observe (like those above). Do these structural differences reflect differences in expert scientific opinion? Or, are they differences to resolve, or uncertainties to be explicitly evaluated in the overall approach? For instance, the models consider different sets of emissions and radiative forcing categories—the drivers for projected temperature. The models also have stark differences in key pieces of the climate modeling (e.g., the carbon cycle, climate sensitivity, climate feedbacks, and projected climate change uncertainty), with some elements excluded entirely from some models. Furthermore, unique model specific factors dominate results in the damage components and therefore raise questions about their representation within each model and across models—e.g., agricultural CO_2 fertilization, cooling energy demand, global damages dominated by China, regional scaling of damages, rapidly growing global non-economic damages, potential discontinuity damages, and damages that increase quadratically with temperature (Figures ES-8, ES-9, and ES-10). Finally, we find dramatic differences in estimated damages across models for comparable regions and sectors that are not explored or explained (Section 6).

- **Consideration of uncertainty:** Uncertainty is included in the USG SCC modeling in three ways—(i) by running standardized alternative inputs through the models (socioeconomics and emissions, climate sensitivity), (ii) by using three models to address model specification uncertainty, and (iii) by examining model-specific parametric uncertainty. Our assessments suggest that each should be revisited. For the standardized uncertainties, we identify implementation issues that introduce artificial variation, as well as reasonable alternative specifications and potential constraints to consider. For model structural uncertainty, as noted above, further evaluation is needed to assess whether the differences across the three models provide insights. For model specific parametric uncertainties, we find substantial inconsistencies in the climate change and damage uncertainties considered across models (e.g., Figures ES-11 and ES-12). In addition, we also find other categories of uncertainty that appear important but are not currently included in the modeling—e.g., socioeconomic structure, alternative climate modeling, alternative specifications for the USG 2013 revisions, and alternative extrapolations of input assumptions to the year 2300. For instance, uncertainty in socioeconomic structure was not considered, yet it is what defines the relationship between society and emissions and drives both projected climate and damages. We also identify alternative, and more sophisticated climate modeling that produces total, incremental, and probabilistic climate responses that differ from those resulting from the USG models (Section 5).

- **Comparability and independence of model results:** The inconsistencies across the three models (e.g., implementation, structural, uncertainties considered) raise questions about the statistical comparability of the results, which, along with independence, is statistically required for averaging results as is currently done in the USG approach. Our observations suggest that the modeling may not meet

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these requirements. In addition to the comparability issue, the models are likely not independent given that some damage formulations are based on previous results from the other models. (Section 6).

- **Robustness of overall results:** The current USG SCC results may not be robust, i.e., insensitive to reasonable alternative assumptions and modeling. The potential issue follows from our observations regarding the sensitivity of the modeling to alternative assumptions, and the issues we identified in the current consideration of uncertainties, including the existence of reasonable alternative assumptions and modeling.

- **Experimental design challenges:** There are issues to consider with the overall experimental design of the USG approach. Key among them is the multi-model approach and the consistency and comparability issues noted above. Other experimental design issues we identify include a variety of inconsistencies, some across models, some in other dimensions (e.g., 2300 extensions, discounting) and a lack of transparency.

Recommendations

Based on our extensive analyses and observations, there are a number of opportunities for improving the USG SCC approach that will increase public and scientific confidence in the resulting SCC estimates and applications using those estimates. We offer the following recommendations:

1. **Internal review of the modeling:** A detailed review by agency analysts of modeling differences, alternatives, and uncertainties represented would be beneficial to better understand differences, resolve or justify those differences, improve comparability, improve uncertainty representation, and enhance robustness.

2. **Revisit experimental design:** Given the challenges we have identified associated with a multi-model approach, including ensuring consistency, comparability, and independence, a new framework would be a practical consideration. For example, for this particular purpose, one could separately develop the best approach for each causal component, instead of choosing an existing model in its entirety. This could provide improved capability, greater experimental control of uncertainties, statistical comparability of scenario results, and transparency.

3. **Evaluate robustness:** Robustness was not evaluated in the USG SCC exercise, but would be useful to provide greater confidence in final SCC estimates. In particular, a fuller characterization and discussion of uncertainty and a subsequent analysis of robustness would be valuable. Such an evaluation would test the sensitivity of results to alternatives and develop an experimental design that produces results that are robust to alternatives excluded. Robust estimates will be more stable, which is important for regulatory contexts that drive investment decisions.

4. **Peer review the approach and models:** As noted, the USG SCC framework is a novel approach. Peer review of the approach, or an alternative future approach, would be pragmatic and valuable. External peer review of the modeling framework (e.g., models, runs, aggregation), uncertainties (standardized, model specific, and specifications), and other elements would lead to improved methods and provide the public with greater confidence in the resulting estimates. Explicit peer review of the individual models, as is commonly done for models used for regulatory processes, would also be valuable.

5. **Provide additional documentation and justification:** Additional modeling details and underlying results of estimates (like those contained in this study), including intermediate results (like incremental temperature and SLR changes), as well as justification for modeling choices, will facilitate public and scientific communications and interpretation, and increase public confidence.

6. **Provide application guidance:** This report focuses on SCC estimation. However, SCC application is also an issue. Guidance on the proper use of the USG SCC estimates is needed to avoid misapplication and increase consistency across regulatory applications.

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1
INTRODUCTION

The social cost of carbon (SCC) is a monetary estimate of the global climate change damages to society from an additional metric ton of carbon dioxide (CO_2) emitted to the earth's atmosphere. The SCC estimates the value of future incremental climate change impacts on health, agriculture, coastal areas, energy demand, threshold risks, and other societal concerns. The SCC is computed from a causal chain of projections over hundreds of years—from projected population and economic growth, to greenhouse gas emissions, to temperature change and sea level rise, and finally to monetary consequences for society. Given its scope of modeling global economic and biophysical process for centuries, a great deal of uncertainty surrounds the SCC.

SCC estimates date back to the early 1990s, but have received increasing attention as governments have adopted estimates as a means for valuing the rulemaking benefits of reducing CO_2 emissions. In 2013, the United States Government (USG) released revised SCC estimates with a central value of $37 per metric ton of CO_2 for today's emissions (2015), with more damages estimated from future emissions. The revised estimates are notably (50-100%) higher than the initial 2010 USG estimates, and have led to a great deal of public discussion. SCC estimates of one kind or another have been applied in almost fifty U.S. federal regulations across agencies since 2008, including rules applying to appliances, transportation, industry, and power generation. The USG SCC estimates are also being utilized at state and local levels and in both regulatory and non-regulatory contexts. However, not until earlier this year have the USG estimates been subject to explicit public comment.

The SCC is complex to compute and the USG SCC estimates are the result of significant aggregation. As such, the USG SCC estimates are difficult to interpret and evaluate. What does the USG central value of $37 per metric ton of CO_2 mean? What sorts of damages to society does it represent? What are the key drivers of damages? How do the individual models differ, and why? How good is the current approach, and can it be improved?

There is a need for greater technical clarity on what underlies and drives the SCC estimates. The USG SCC estimates are the culmination of socioeconomic, climate, and damage modeling and aggregation of results across models, over time, across world regions, across impact categories, and across many scenarios. This aggregation however obscures the underlying details and differences. Making sense of the estimates requires delving into these details.

EPRI has undertaken an initiative aimed at better understanding, and advancing SCC methods. This study in particular elucidates and assesses the modeling and raw detailed results underlying USG SCC approach. Our study examines the inner workings of the models to elucidate the key drivers and assess main components of the SCC. We then are able to reflect on the overall USG approach of combining model results to produce the official USG SCCs.

Specifically, we model and assess the individual components of the modeling with diagnostic analyses and consideration of alternatives. We also evaluate the overall experimental design. Through our assessment, we observe significant variation across models in underlying behavior and results and identify fundamental issues and opportunities for improvements.

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With this study we hope to improve understanding of SCC modeling and estimates to inform public discussion and facilitate improved SCC analyses, and climate change research broadly (climate change impacts analyses in general, climate science, climate economics, and integrated assessment). In a companion report, expected in 2015, we examine applications of the SCC and provide technical insight for appropriate application.

Before beginning our assessment, we provide an overview of the social cost of carbon—the concept and computational methods—and describe the USG approach for estimating the SCC. We then begin our assessment, evaluating the major components one at a time—socioeconomics and emissions, climate modeling, and climate damages modeling. Each is an independent assessment that isolates and evaluates model behavior within the component. In our assessments, we evaluate both the total and incremental responses of the models—the latter because the SCC is an estimate of damages from an incremental increase in CO_2 emissions. We then reflect on the overall USG approach of combining model results to produce the official USG SCCs. Finally, we conclude and offer thoughts about future research needs.

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2
SCC OVERVIEW & USG SCC APPROACH

SCC overview

The social cost of carbon (SCC) is the net present value of global climate change impacts from one additional net global metric ton (tonne) of carbon dioxide emitted to the atmosphere at a particular point in time. The SCC is calculated by simulating the 'causal chain' from greenhouse gas emissions to climate change to climate damages, for both a reference path and a pulsed emissions path, to estimate the additional future damages from an additional metric ton pulse of CO_2.

Figure 2-1 provides a cartoon of the SCC modeling causal chain and the incremental effects of a CO_2 emissions pulse in about 2020. The pulse produces both projected incremental climate change (as represented by temperature change) and incremental climate damages. The incremental damages are the area between the solid and dashed damage projections, and the SCC is the discounted value of the incremental damages. As an estimate of the additional climate damages from a unit of emissions, the SCC can also be used to estimate the benefits of a unit of CO_2 avoided, which is its primary use to date in U.S. rulemakings.

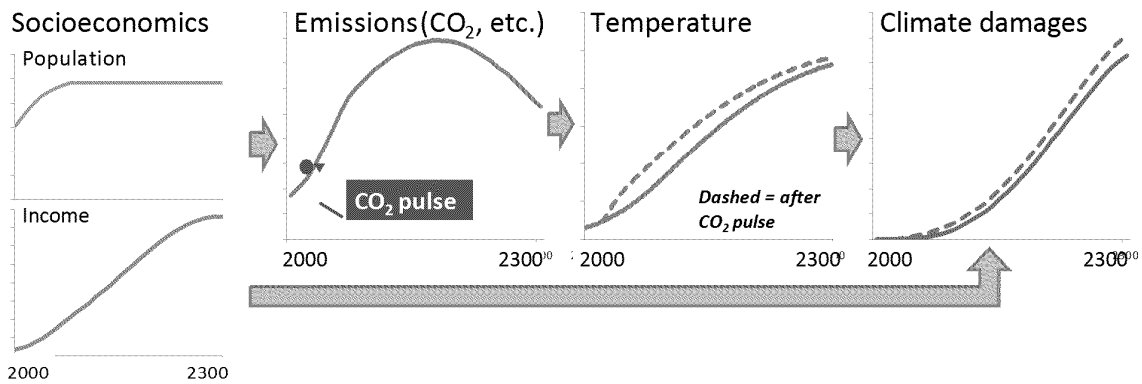

Figure 2-1
Modeling causal chain for computing the social cost of carbon

Figure note: Solid lines represent reference projections. Dashed lines represent projections after a CO_2 emissions pulse in a particular year (e.g., 2020). Emissions include CO_2 and non-CO_2 greenhouse gases and aerosols. The illustrative figure is for CO_2. Other climate variables are not explicitly modeled (e.g., precipitation, extreme weather events). Sea level rise (not shown), also a part of the causal modeling chain, is driven by temperature change and drives sea level rise related climate damages. Socioeconomics (population and economic growth) drives emissions (and hence, temperature change and sea level rise), as well as climate damages directly by defining the society vulnerable to potential climate change and its adaptation capacity.

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Only a few of models have generated SCC estimates to date, with three models responsible for most of the latest estimates directly or indirectly via model variants—DICE, FUND, and PAGE. Estimates from SCC models represent a variety of potential climate damages, including damages to health (mortality and morbidity), agriculture, forestry, coastal areas from sea level rise, water resources, energy consumption (space cooling and heating), human migration, extreme weather (e.g., hurricanes), ecosystems, and catastrophic threshold risks (e.g., ice-sheet collapse). However, the damage types included and formulations vary by model. SCC estimates are typically estimates of potential global damages, i.e., damages realized throughout the world. Only a fraction of the estimated SCC global damages are U.S. damages (e.g., Anthoff et al., 2011; Rose, 2012; and Section 6 of this study).

Damage functions within models are based on sector specific climate change impacts studies in the literature. As such, the literature constrains SCC modeling in terms of damage representation. Also, SCC modeling can lag behind detailed understanding of potential damages since developing formulations suitable for SCC modeling requires separate dedicated effort.

A vast range of SCC estimates have been produced dating back to the 1990s. Figure 2-2 portrays results from a 2008 meta analysis, where the estimates range from -\$3 to \$655/tCO_2. Additional estimates have been generated since. The range in Figure 2-2 reflects differences in models, assumptions, and the types of damages included. Fundamental differences in modeling, such as these, mean that many estimates in the literature are not comparable, which is an obstacle for decision-makers looking for a robust estimate or ranges of estimates for policy use.

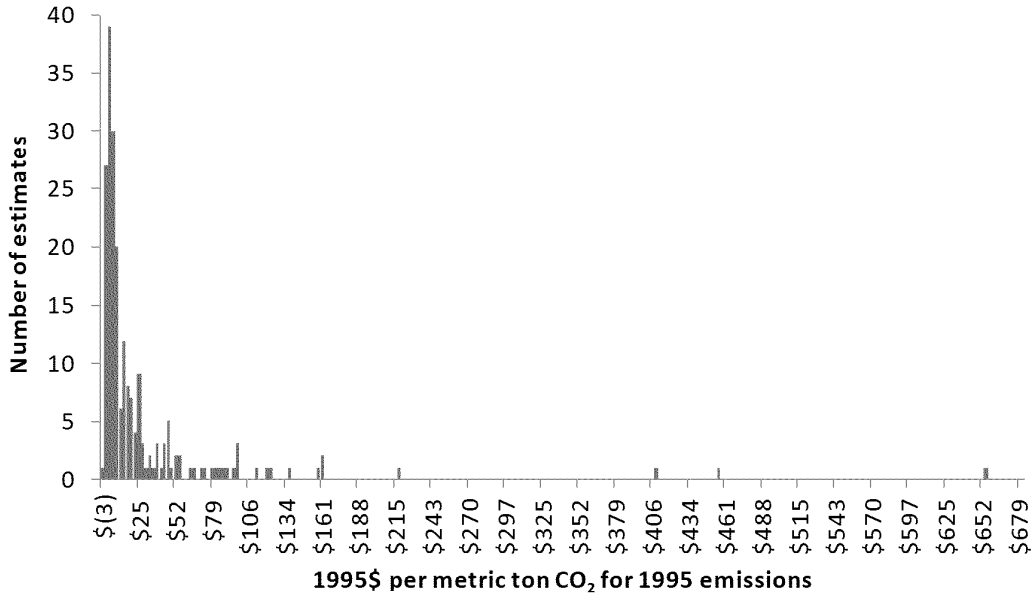

Figure 2-2
Histogram of SCC estimates in the literature

Source: Developed from Tol (2008). This figure should not be regarded as a statistical distribution. Fundamental differences in the modeling mean the estimates are not statistically comparable.

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Computing the SCC requires confronting a number of challenging issues, including global vs. domestic values, time horizon, uncertainty, discounting, and equity weighting. Economics provides some guidance for addressing these issues (Rose, 2012).

SCC estimates have been applied in domestic policy by a handful of countries to date, including the United Kingdom, European Union, and the United States (U.S.). SCC estimates are also being utilized at state and local levels in the U.S. and in both regulatory and non-regulatory contexts.

USG SCC estimates

Estimates of one kind or another have been applied in almost fifty U.S. federal regulations across agencies since 2008, including rules applying to appliances, transportation, industry, and power generation. Table 2-1 provides examples of U.S. rules using SCC values and the particular values used. Some regulations use multiple SCC estimates, some only use one. Prior to 2010, United States Government (USG) agencies used their own SCC estimates. In 2010, the USG developed SCC estimates to consistently value the benefits of CO_2 emissions reductions across all federal rulemakings (USG, 2010). In 2013, the USG revised their estimates following the 2010 methodology but with newer versions of the underlying models (USG, 2013).

Figure 2-3 shows a graphical depiction of the current USG SCC estimates (USG, 2013), as well as the USG (2010) estimates. There are four trajectories of estimates over time. Each point on the bottom three lines in Figure 3 is the average SCC value for a specific year and given discount rate—2.5%, 3%, or 5% (details below). Higher discount rates "discount" projected future damages more, thereby giving greater weight to nearer-term damages in net present value results. The SCC increases over time because future additional emissions occur when the climate system is projected to be more stressed due to higher future atmospheric concentrations and larger societies that imply greater climate damage vulnerability. The "3% (95th percentile)" SCC trajectory is the 95th percentile SCC from the distribution of SCC estimates generated in the USG exercise discounted at 3%. The USG SCCs notably increased from 2010 to 2013, on the order of 50-100% depending on the discount rate and year. A variety of model revisions contributed to the increase (see discussion below).

A wide range of SCC estimates underlie the USG SCCs, with results varying substantially across models (Figure 2-4). For instance, PAGE produces the highest average SCC estimates and more uncertainty than the other models, while FUND produces the lowest average SCC estimates. For all models, averages and uncertainty decline with higher discount rates due to greater discounting of the models' estimates of positive annual damages over the next three centuries. SCC results also vary by socioeconomic and emissions assumptions, with variation differing across models.

These results raise many questions. What do the differences mean? Why do some models produce higher or lower average estimates? Why do some models exhibit more or less uncertainty? What drives models to be more or less sensitive to discounting, or alternative assumptions about socioeconomic and emissions futures? Our study pursues these types of questions. The averaged USG SCC trajectories belie considerable underlying variation between the three models. Such discrepancies are masked by the aggregate results and motivate our disaggregated exploration into the individual models and components.

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Table 2-1
Sample of recent U.S. Government social cost of carbon use and values

Values for 2010 Emissions in 2007$/t$CO_2$, values have been adjusted as necessary. Developed from Rose (2012).

Agency	Year	Rule	Central value(s)	Range		Annual growth
				Low	High	
U.S. EPA	2014	Carbon pollution emission guidelines for existing stationary sources: electric utility generating units, proposed rule	32	11	89	1.6 - 2.3%
U.S. EPA-U.S. NHTSA	2010	Light-duty vehicle greenhouse gas & fuel economy standards, MY 2012-2016, final rule	21	5	65	1.1 - 3.7%
U.S. DOE	2010	Small electric motor energy conservation standards, final rule	21	5	65	1.1 - 3.7%
U.S. EPA-U.S. NHTSA	2009	Light-duty vehicle greenhouse gas & fuel economy standards, MY 2012-2016, proposed rule	22	5	61	3.0%
U.S. DOE	2009	Refrigerated beverage vending machines energy conservation standards, final rule	22	5	61	3.0%
U.S. EPA	2009	Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program	19 - 96	-7	781	3.0%
U.S. NHTSA	2009	Passenger cars and light trucks fuel economy standards, MY 2011, final rule	35	--	86	2.4%
U.S. EPA	2008	Regulating Greenhouse Gas Emissions under the Clean Air Act	19 - 96	-7	781	3.0%
U.S. DOE	2008	Gas ranges and ovens standard, final rule	21	--	--	2.4%
U.S. DOE	2008	Air conditioning equipment standard, final rule	21	--	--	2.4%
U.S. NHTSA	2008	Passenger cars and light trucks fuel economy standards, MY 2011-2015, proposed rule	7	--	14	2.4%

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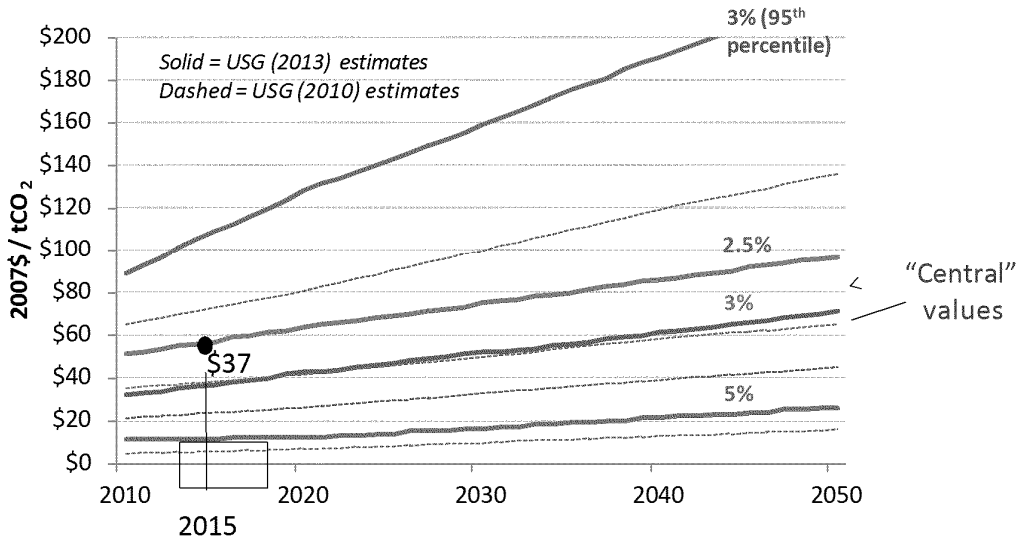

Figure 2-3
U.S. Government social cost of carbon estimates

Figure note: Each point on the bottom three lines is an average SCC value for a specific year and given discount rate, averaging results across models, alternative socioeconomic scenarios, a distribution of potential climate sensitivities, and random model specific parameters. "3% (95th percentile)" is the 95th percentile from the distribution of the 150,000 SCC estimates discounted at 3%. Source: Developed from USG (2010) and USG (2013).

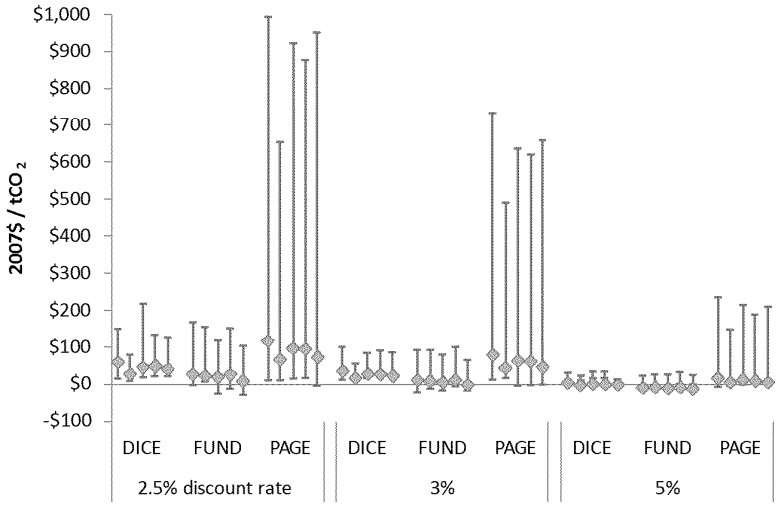

Figure 2-4
USG 2020 SCC average and 1st – 99th percentile values by discount rate, model, and reference socioeconomic/emissions assumption

Figure note: The figure shows SCC results from USG (2013), with averages in blue and 1st to 99th percentiles in red. Each percentile range reflects USG standardized and model specific parametric uncertainties. Source: Developed from USG (2013).

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USG SCC approach

The USG approach was developed in 2010 (USG, 2010) and re-applied with updated models in 2013 (USG, 2013) to generate the current USG SCC estimates. USG estimates were released twice in 2013, in May and November, with the latter correcting for an error in one of the models that resulted in only a minor change to the overall USG SCCs. The November estimates are the values currently applied in rulemaking analyses.

USG experimental design

Six features define the USG modeling experimental design (Table 2-2). Three publicly-available, highly aggregated, integrated assessment models—DICE, FUND and PAGE—were used to compute SCC estimates.[1] These models have long histories and have produced most of the SCC estimates in the recent scientific literature. Also, they can be run with alternative input assumptions to explore uncertainties.

Table 2-2
USG SCC experimental design features

Feature	Detail
Multiple SCC models	3 models—DICE, FUND, PAGE
Standardized uncertainties	- 5 reference socioeconomic and emissions scenarios (each extended from 2100 to 2300) - 1 distribution for the climate sensitivity parameter
Model specific parametric uncertainties	In FUND and PAGE climate and damage components
Standardized discounting	3 constant discount rates – 2.5%, 3%, and 5%
Thousands of SCC results	150,000 SCC estimates for a given discount rate and year (3 models x 5 socioeconomic scenarios x 10,000 runs each)
Aggregation of results	- Average of 150,000 results for each discount rate and year - "3% (95th percentile)" value is 95th percentile from distribution of 150,000 results with 3% discounting

The USG ran each of the models 10,000 times for each of five standardized alternative socioeconomic and emissions futures, with random draws for the climate sensitivity parameter and model specific parameters each time. Each run produced a projection of estimated annual additional damages to society for the next three hundred years from a CO_2 pulse in a particular year. The thousands of results were then discounted and averaged to create a single USG SCC

[1] There are a variety of IAMs in the literature that vary in complexity based on their research interests. Most IAMs have focused on energy, land use and socioeconomic transformations and therefore have more modeling sophistication in those areas (e.g., Kriegler et al., 2014; Clarke et al., 2009). DICE, FUND, and PAGE, on the other hand, have limited detail in these aspects, and have instead chosen to focus on overall global climate damages.

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for each of the discount rates considered (2.5%, 3%, and 5%). Thus, the USG SCCs are averages across models, socioeconomic futures, and parametric uncertainties. For example, $37 per metric ton CO_2 is the average of 150,000 projections of incremental damages from a 1 metric ton change in CO_2 in 2015 discounted at 3% (Figure 2-3). The procedure was repeated with CO_2 pulses in future years through to 2050 to provide estimates for the value of CO_2 changes in different years. Intermediate 5-year USG SCC values (e.g., 2025) are simple interpolations between surrounding decadal values. The final SCC results over time are what are shown in Figure 2-3.

Details regarding the standardized USG uncertainties (socioeconomics and emissions, climate sensitivity) and the model specific parametric climate and damage modeling uncertainties are discussed in our respective component assessments.

Table 2-3
Background on USG SCC models

	DICE	FUND	PAGE
Full name	Dynamic Integrated model of Climate & the Economy	Climate Framework for Uncertainty, Negotiation and Distribution	Policy Analysis of the Greenhouse Effect
Main model developer(s)	William Nordhaus	Richard Tol, David Anthoff	Chris Hope
Version used in USG (2013)	DICE 2010	FUND 3.8	PAGE 2009
USG (2013) model references	Nordhaus (2010) and website (below)	Anthoff and Tol (2013a)	Hope (2013), Hope (2011a, 2011b, 2011c)
Version used in USG (2010)	DICE 2007	FUND 3.5	PAGE 2002
Website	http://www.econ.yale.edu/~nordhaus/homepage/RICEmodels.htm	http://www.fund-model.org/	http://climatecolab.org/resources/-/wiki/Main/PAGE

2013 modeling revisions

The 2013 USG SCC revisions reflect updates to the individual models by the developers of the models rather than changes in the USG approach. Table 2-3 provides background information on the model versions used for the 2013 USG SCCs, and Table 2-4 summarizes the 2013 modifications to each model and, as possible, indicates the modification's directional implication for SCC estimates from that model. We have also characterized the type of modification in each case—revision, change, fix, or new. A variety of modification types occurred within and across the models, with updates, formulation changes, corrections, and completely new features. Note that the models developed in different areas—with modifications occurring to climate modeling, sea level rise modeling, and/or damage modeling—and, modifications to similar areas occurred with different implementations. Thus, the modifications were not standardized across models. Overall, there was not a concerted effort to evaluate and improve all the models in the same areas. It is not clear which modifications have been published, and in what form. Some of the references provided are working papers, and there is also a fundamental difference between research application publication and model peer review. The USG documentation and references

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provide some description of the modifications, but revision details are not always clear. In general, there is little discussion of potential alternative specifications or uncertainties regarding the modifications in each model, or justification for the formulations implemented and the potential sensitivity of resulting SCC estimates. This would be a worthwhile area to explore given the substantial impact of the 2013 revisions on the USG SCCs (Figure 2-3).

Table 2-4
Summary of model modifications associated with 2013 USG SCCs

Model	Modification	SCC implication	Type
DICE	Carbon cycle parameters - weaker ocean uptake	+	Revision
	Sea level dynamics and valuation - explicit modeling	-	Change
FUND	Space heating	+	Fix
	Sea level rise and land loss	?	Fix
	Transient temperature response	+	Change
	Methane - account for additional radiative forcing effects	+	New
PAGE	Sea level rise	?	Change
	Revised damage function to account for saturation - modified GDP loss function	?	Fix
	Regional scaling factors	?	Revision
	Probability of discontinuity	+	Revision
	Adaptation	+	Revision
	Change in land/ocean carbon uptake	?	Revision
	Regional temperature change	?	Revision

A plus sign implies an increase in the model's SCCs relative to that model's 2010 values. Revision Types: Revision = updated; Change = formulation change; Fix = issue fixed; New = new feature.

What wasn't revised in 2013

While the USG SCCs were revised to reflect new scientific knowledge as represented in the model modifications discussed above, the overall experimental design was unchanged. Specifically, the following modeling features have been in place for both the 2010 and 2013 estimates:

- The multi-model approach and the three models used
- The five socioeconomic & emissions projections
- The methodology for extending the socioeconomic and emissions assumptions from 2100 to 2300
- The climate sensitivity distribution assumption

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- The discounting implementation
- The results averaging approach
- The types of uncertainties considered and their specifications – standardized and model specific (except for 2013 modifications)

Furthermore, a number of issues were raised in the technical documentation in 2010 (USG, 2010) that have yet to be resolved:

- Whether to consider the value of risk changes in SCC calculations
- Valuing changes in non-CO_2 greenhouse gases (e.g., methane, CH_4; nitrous oxide, N_2O; fluorinated gases)
- Assigning differential weights to regional damages (sometimes referred to as equity weighting)
- Use of domestic SCC values (i.e., U.S. only incremental damage estimates)
- Consideration of omitted impacts

The above lists are decisions that have yet to be revisited, but are candidates for revision in future USG SCC modeling. In addition, climate change synthesis research is available that could lead to modeling updates to, for instance, socioeconomic projections, climate modeling, and climate damage functions (e.g., IPCC, 2013, 2014; Mclillo et al., 2014).

Finally, it is important to note that the overall USG approach has not undergone peer review, and not until earlier this year, have the USG estimates been subject to explicit public comment. Both the 2010 and 2013 USG SCC estimates were introduced to the public within the context of rulemakings, as such, the estimates and the approach have had limited public and scientific review. The public comment period however helped initiate a public and scientific discussion.

Even though the three models have individually produced peer reviewed journal articles, as well as books, for a variety of applications, the USG SCC approach for producing SCC estimates is unique. It is a novel methodology defined by the features in Table 2-2. The methodology employs multiple models in a specified uncertainty analysis with aggregation procedures (over time, scenarios, and models). Each feature in Table 2-2 is a peer reviewable methodological choice, as are the individual models themselves, including modifications.

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3
OUR ASSESSMENT APPROACH

Our study examines the inner workings of the models to elucidate the key drivers and assess main components of the SCC. We then are able to reflect on the overall USG approach of combining model results to produce the official USG SCCs.

Our technical assessment is made up of four separate technical assessments. First, we assess each of the major components of the modeling causal chain independently (Figure 3-1):

- Component 1 – Socioeconomics and emissions (Section 4),
- Component 2 – Climate change modeling (Section 5), and
- Component 3 – Climate damage modeling (Section 6).

The component assessments provide a thorough understanding of the modeling and the basis for our fourth assessment—assessment of the overall USG experimental design.

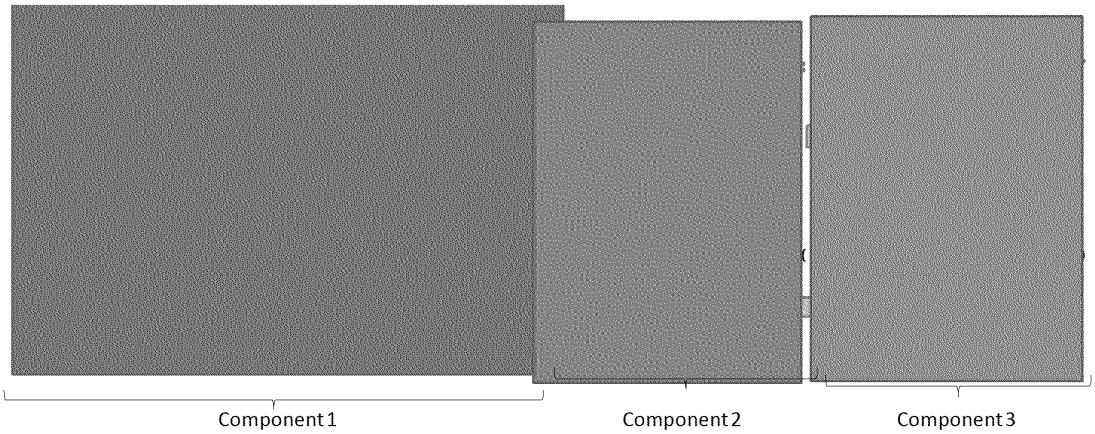

Figure 3-1
The three causal modeling components being assessed

For each component, we carry out a systematic assessment. Specifically, we review the modeling, program the component from all three models, develop and run diagnostic scenarios, and make comparisons to learn about and assess the raw modeling and results (undiscounted and disaggregated to underlying elements).

Our goal is to describe the models—qualitatively and quantitatively. The model comparison diagnostics analysis, in particular, provides a rigorous quantitative characterization of how the component works within each model and how it differs. Here we code the component's equations and run the component to evaluate model responses to a variety of diagnostic scenarios that are designed to elucidate and compare component behavior. This provides a solid understanding of the component and differences across models from which we then explore whether there are valid alternatives in the scientific literature, for instance alternative modeling approaches, sensitivities, and/or specifications.

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As an example, we coded the climate algorithms that calculate temperature change from emissions projections so that we could compare the climate results of the three models with common emissions inputs, and so we could contrast this part of the models to more sophisticated approaches. Similarly, we isolated the algorithms that calculate climate damages from temperature change to compare damage estimates in response to varying levels of climate change and socioeconomic vulnerability and identify the main elements of damages within each model.

In our assessments we provide many perspectives on how the model components behave. We evaluate both the total and incremental responses of the models—the latter because the SCC is an estimate of damages from an incremental increase in CO_2 emissions, and the former because total results are the reference conditions for the incremental results, as context for thinking about damages and for direct comparison to other analyses. We explore aggregated and disaggregated results, and reference responses and sensitivities. We also evaluate nearer-term (to 2100) and longer-term (to 2300) model behavior. Finally, in the climate and damage components, we evaluate the probabilistic responses of the models for model specific parametric uncertainties, as well as standardized uncertainties.

We begin each component assessment section with an overview describing what we can learn from the assessment and our approach for the component, followed by a summary of our key observations. After the introductory material, we characterize the current USG modeling, and then undertake our assessment of the component. Note that the component assessments are compartmentalized. Thus differences across models found in one component are not carried forward to the next component. Instead, for each component, we undertake a controlled analysis with inputs that we standardize, which allows us to isolate component behavior and differences across models.

Finally, note that we do not calculate the SCC or offer alternative SCC estimates. Our goal is to understand and assess the inner workings of the models, thus we focus on undiscounted and disaggregated results over time and space (regions and sectors).

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4
COMPONENT ASSESSMENT 1 – SOCIOECONOMICS & EMISSIONS

What we can learn

Uncertainty regarding socioeconomics and emissions is considered in the USG SCC calculations via the five alternative futures that were selected as inputs to the models. Four of the futures are "baseline" futures with no climate policy and one is a "policy" future consistent with stabilizing atmospheric concentrations by 2100 at 550 ppm CO_2-equivalent. Each future is considered equally likely to occur. The five futures were chosen to span a broad range of possible futures, and the projections associated with each future were extended by the USG from the year 2100 to 2300. The USG exercise extended the socioeconomic and emissions inputs to 2300 to capture potential climate damages beyond 2100 from an incremental increase in CO_2 emissions due to the long atmospheric lifetime of CO_2 and potential long-run carbon cycle effects.

This component assessment explores four questions:

- What sort of socioeconomic & emissions uncertainty is currently captured?
- Is there additional uncertainty to consider?
- Are the results sensitive to alternative assumptions?
- Are there modeling implementation issues to consider?

To explore the first two questions regarding represented uncertainty, we compare the five selected futures to the literature. The third question is discussed in this section, but explored explicitly in the damage component assessment. For the last question, we reflect on the component set-up and implementation.

Key observations

- *Model implementation*: We observe that the USG SCC use of the models deviates from each model's standard formulation to different degrees.
- *Socioeconomic and emissions implementation inconsistencies*: We find inconsistencies in implementation of the standardized socioeconomic & emissions inputs across models that confound SCC results.
- *Uncertainty captured*: The five futures were chosen to span a broad range of possible futures. However, it appears that the focus was on spanning a range of global fossil and industrial CO_2 futures. The role of socioeconomic uncertainty (e.g., population and income) was not explicitly incorporated, and there is broader uncertainty to consider in this space. Socioeconomic uncertainty is important because, as is shown in our damage component assessment, damage estimates are sensitive to socioeconomic assumptions.
- *Additional uncertainty*: Our observations indicate that there is an additional category of uncertainty to consider—uncertainty in socioeconomic structure. Socioeconomic structure defines the relationship between society and emissions and drives both projected climate and

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damages. Uncertainty in socioeconomic structure is not captured by the selected futures in the USG exercise; however, it is relevant to SCC calculations.

- *Likelihood of futures*: Equal weighting of all alternative socioeconomic and emissions futures may not be appropriate as all futures may not be equally likely. While it is difficult to assign probabilities to specific socioeconomic and emissions futures, it is possible to recognize unreasonable futures that are unlikely or less likely.
- *Policy socioeconomic & emissions future inconsistency*: We find the 550 ppm CO_2-equivalent "policy" future to be problematic due to its construction. The policy future lacks internal consistency and consistency with the baseline futures.
- *Issues with extensions to 2300*: The 2300 extrapolation approach raises issues regarding (a) consistency, (b) likelihood, and (c) additional uncertainty.

What is done

Modeling description

In describing the socioeconomic and emissions modeling in the USG exercise, it is useful to distinguish the published standard formulation of the three models from the USG implementation. It is also useful to consider the details of implementing the standardized socioeconomic input projections in the USG exercise. Both have implications for SCC estimation. Our description of the modeling is based on our review of model documentation (Nordhaus, 2010; Anthoff and Tol, 2013a; Hope, 2011a), USG (2010, 2013), USG SCC model code and input files, and the EMF-22 study (Clarke et al., 2009) from which the future scenarios were derived.

Each of the three models has a unique socioeconomic and emissions structure in its standard published formulation. The models are similar in that each has socioeconomic projections of income and population and corresponding emissions and forcing projections. However, the formulations differ. FUND and PAGE assume income and population futures, while DICE derives income from population. PAGE also assumes an emissions future, while DICE and FUND derive emissions from socioeconomic development and energy and emissions intensity assumptions (Table 4-1).

The USG experimental design deviates to different degrees from each model's standard structure (Table 4-1). For instance, for DICE, income, population, CO_2 emissions, and non-CO_2 forcing are all exogenous inputs in the USG exercise. However, only population and non-CO_2 forcing are exogenous in the model's standard construction. For PAGE, non-CO_2 emissions are handled quite differently in the USG exercise. In the standard formulation, PAGE models emissions, concentrations and forcing for CO_2, nitrous oxide (N_2O), methane (CH_4), a "linear gas," and sulfur dioxide (SO_2). However, in the USG exercise, only CO_2 and SO_2 emissions, concentrations and forcing are explicitly modeled, and other forcings are derived outside the model and included exogenously. For FUND, the socioeconomic and emissions structure is preserved. However, issues arise in implementing the USG socioeconomic inputs (discussed below).

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Table 4-1
Standard and USG modified model structure

(Only USG modeling differences from standard structure noted, i.e., "--" indicates no difference.)

	DICE		FUND		PAGE	
Projection	**Standard**	**USG**	**Standard**	**USG**	**Standard**	**USG**
Population	Exogenous	--	Exogenous	--	Exogenous	--
Income	Endogenous	Exogenous	Exogenous	--	Exogenous	--
Fossil & Industrial CO_2	Endogenous	Exogenous	Endogenous	--	Exogenous	--
Land CO_2	Endogenous	Exogenous	Exogenous	--	Exogenous	--
Non-CO_2 Kyoto gases (CH_4, N_2O, Fluorinated-gases)	Included via Other radiative forcing	--	Emissions exogenous (SF_6 is the only F-gas modeled), forcing endogenous	--	Emissions exogenous, forcing endogenous	Included via Other radiative forcing
SO_2	Included via Other radiative forcing	--	Endogenous emissions & forcing	--	Emissions exogenous, forcing endogenous	-- *
Other radiative forcing	Exogenous	--	None	--	Exogenous	--

** PAGE regional SO_2 emissions projections are identical across USG socioeconomic and emissions scenarios.*

USG sensitivities

Uncertainty regarding socioeconomics and emissions is considered in the USG SCC calculations via the five alternative socioeconomic and emissions futures that were selected as inputs to the models. Four of the futures are "baseline" futures with no climate policy and one is a "policy" future consistent with stabilizing atmospheric concentrations by 2100 at 550 parts per million (ppm) CO_2-equivalent. Each future consists of a set of projections for GDP, population, fossil and industrial CO_2 emissions (F&I CO_2), land CO_2 emissions, and non-CO_2 emissions and forcing. The socioeconomic, emissions, and forcing data in the USG exercise are drawn from scenario data from the Energy Modeling Forum's 22nd Study (Clarke et al., 2009), which was a multi-model scenario exercise of ten integrated assessment models exploring the cost and energy transformation implications of climate targets and international cooperation. The baseline futures are reference "no climate policy" scenarios associated with four of the ten models participating in the EMF-22 study.[2] The "policy" future was derived from averaging the 550 scenario results

[2] The USG exercise used the EMF-22 model names as labels for the five socioeconomic and emissions futures. We have chosen to use generic labels, instead of the model names, to avoid confusion about use of the EMF-22 models or additional connotation that might result from using the model names. Specifically, we use USG1, USG2, USG3, USG4, and USG5 instead of IMAGE, MERGE Optimistic, MESSAGE, MINICAM, and 550 ppm average respectively. The EMF-22 models were not deployed for the USG SCC application, only a subset of results from the previous EMF-22 study, with its own objectives, were used to varying degrees to develop inputs for the USG SCC

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from each of the four models associated with the baseline futures. Each of the five futures is implicitly considered equally likely to occur in the USG exercise (because SCC estimates from each are given equal weight in the averaging used to derive the overall USG SCC estimates).

The five standardized inputs used by the USG SCC exercise are shown in Figure 4-1 at the global scale. Baseline scenarios are shown as solid lines, and the policy scenario as dashed. Details regarding the implementation of each input are noted in Table 4-2. Note that FUND and PAGE need regional population and GDP. However, the regions differ from those reported in EMF-22 (Table 4-3). Thus, some translation was required to create the regional inputs required by FUND and PAGE. The five futures were chosen to span a broad range of possible futures. How well they represent possible futures is discussed below in the assessment.

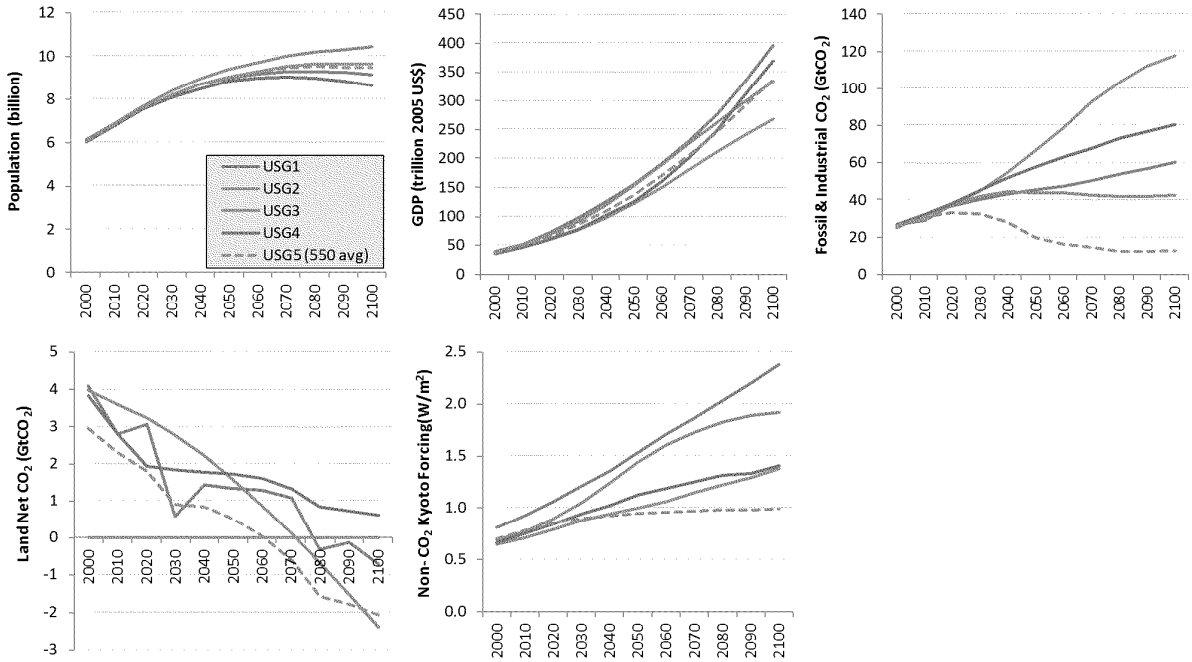

Figure 4-1
USG global socioeconomic, emissions, and forcing inputs to 2100

To estimate potential long-run climate damages, the socioeconomic and emissions inputs were extrapolated from 2100 to 2300. The following assumptions were used in the USG exercise to extend the socioeconomic and emissions inputs from 2100 to 2300:

- Assume a linear decline in population growth rate from 2100 that reaches zero in the year 2200.
- Assume a linear decline in per capita GDP growth rate from 2100 that reaches zero in the year 2300.

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models. For instance, the climate outcomes from the EMF-22 models are not used in the USG exercise, and the EMF-22 models were not, and are not, generating SCC estimates.

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- Assume a fixed fossil and industrial carbon intensity (F&I CO_2/GDP) growth rate from 2100 to 2300 equal to the declining 2090-2100 growth rate.
- Assume a linear decline in net land use CO_2 emissions from 2100 that reaches zero in the year 2200.
- Assume non-CO_2 radiative forcing is constant from 2100 to 2300 at 2100 levels.

Table 4-2
USG SCC socioeconomic and emissions input implementation

	EMF-22 based inputs					Other input
	GDP	Population	F&I CO_2	Land CO_2	Kyoto Non-CO_2	Other Non-CO_2**
DICE	Global levels	Global levels	Global emissions	Global emissions	CH_4, N_2O, & fluorinated gas forcing*	Aerosols and residual forcing
FUND	Regional per capita income growth	Regional population growth	Derived regional emissions based on regional per capita income and population growth and FUND emissions coefficients	Derived regional emissions based on regional per capita income and population growth and FUND emissions coefficients	CH_4, N_2O, & SF_6 emissions	Global SO_2 emissions
PAGE	Regional growth rates	Regional growth rates	Regional emissions	Regional emissions	CH_4, N_2O, & fluorinated gas forcing*	Regional SO_2 emissions & other forcing

** Derived from EMF-22 reported total Kyoto radiative forcing and computed CO_2 radiative forcing.*

*** Model specific inclusion and implementation of non-Kyoto emissions and forcing. Non-Kyoto emissions and forcing not reported in EMF-22.*

Table 4-3
Model regions

EMF-22	DICE	FUND	PAGE
3 global regions & 4 individual countries	**1 region**	**16 regions**	**8 regions**
Group 1 (Annex 1 minus Russia), Group 2 (Brazil, Russia, India, China), Group 3 (ROW), US, EU, China, India	World	USA, WEU, CAN, JPK, ANZ, CEE, FSU, MDE, CAM, SAM, SAS, SEA, CHI, NAF, SSA, SIS	USA, EU, Other OECD, FSU & ROE, China & CP Asia, India & SE Asia, Africa & ME, Latin America

See Appendix A for SCC model region definitions.

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The resulting input projections to 2300 at the global level are shown in Figure 4-2.

The USG socioeconomic and emissions modeling approach described above was developed for the 2010 SCC estimates and retained for the 2013 estimates.

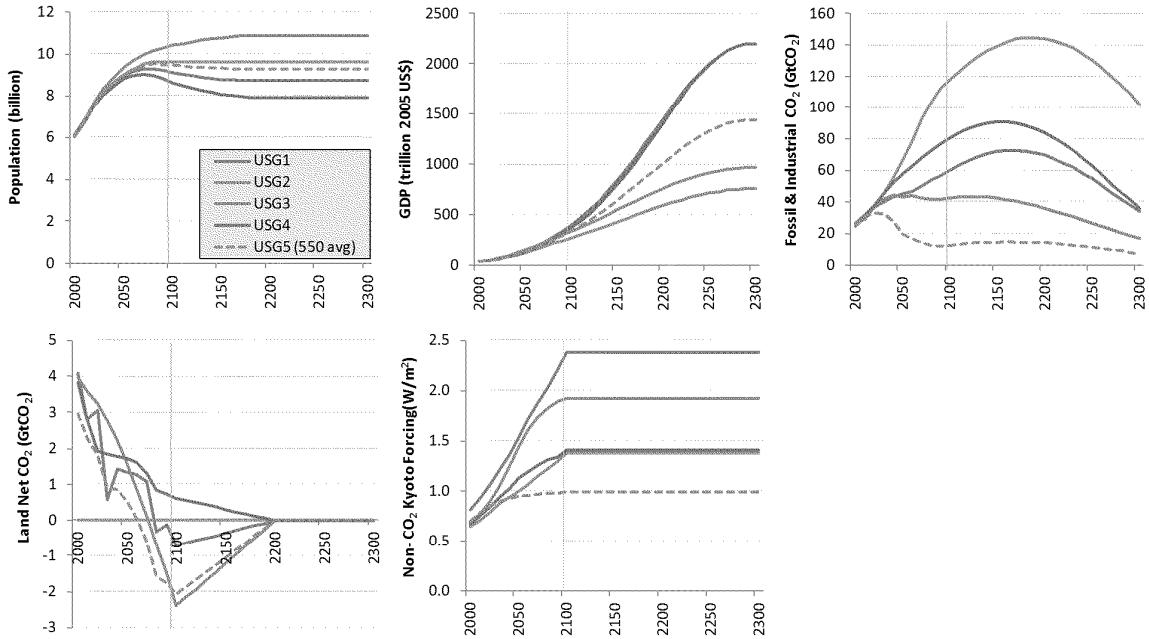

Figure 4-2
USG global socioeconomic, emissions, and forcing inputs to 2300

Assessment

Socioeconomic and emissions inputs

We begin our assessment with an exploration of the represented socioeconomic and emissions uncertainty by comparing the five selected futures to the literature. Our assessment looks at the individual elements associated with each future, relationships between elements, and additional elements. We then discuss whether SCC results might be sensitive to alternative assumptions. Finally, we comment on the component set-up and implementation described above.

Comparing to the EMF-22 scenarios, it appears that the USG exercise focus was on spanning a range of global fossil and industrial CO_2 futures. Consider the USG baseline scenarios juxtaposed with the baseline results from all ten models participating in the EMF-22 study (Figure 4-3). From this cursory perspective, we find that the four USG SCC baseline scenarios approximately span the global fossil and industrial baseline CO_2 projections from EMF-22, only missing the top of the range slightly. A look into the other variable dimensions reveals that the scenarios to a lesser degree span the EMF-22 global income projections while fully spanning the EMF-22 global population projections. However, this high-level perspective can be a bit misleading, and is not particularly intuitive in terms of interpreting and evaluating the alternative futures. Therefore, we next look at relationships between variables and regional perspectives.

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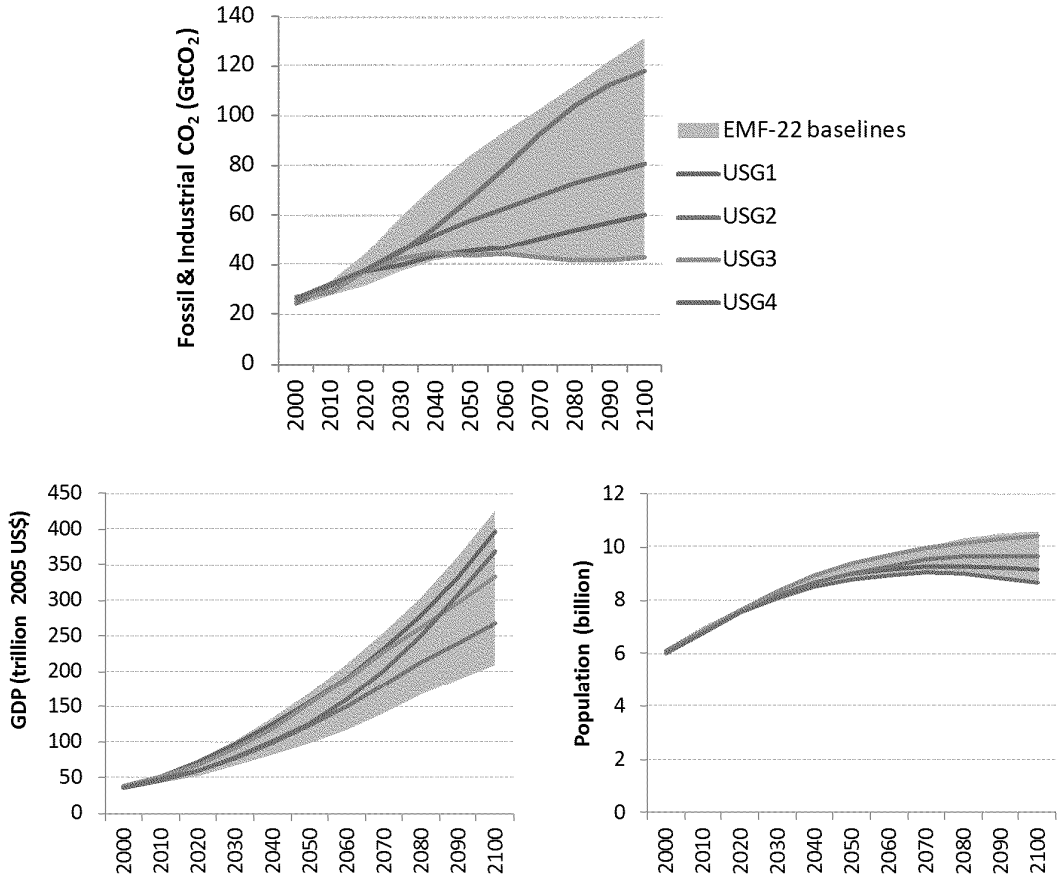

Figure 4-3
Baseline global fossil & industrial CO_2, global GDP, and global population for USG futures and EMF-22 range

Uncertainty about socioeconomic futures derives from uncertainty about the potential development of society, which is reflected in the relationships between socioeconomic variables. For instance, how much richer might individuals become and how might they use energy? And, will that energy be CO_2 intensive? From a second look at Figure 4-3, we find that USG2 has the highest fossil & industrial CO_2 emissions future but the lowest income growth, and mid-level population growth. Conversely, USG1 has substantially lower global fossil and industrial CO_2 emissions (second from bottom baseline future) but the highest income growth, and lower population than USG2. Thus, the results in these two scenarios are derived from very different stories regarding socioeconomic structure. USG2 is a less wealthy society that is more energy intensive and fossil fuel dependent, while USG1 is a wealthier society that is less energy intensive and less fossil fuel dependent. The ordinal ranking of all four scenarios by 2100 levels is summarized in Table 4-4. From this more nuanced perspective, we see that assumptions about socioeconomic structure are a part of socioeconomic uncertainty. Next, we explore whether there is uncertainty in future socioeconomic structure, and whether it matters to SCC calculations.

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Table 4-4
Ordinal ranking of scenarios by global values in 2100

(The table indicates the ordinal ranking of each scenario for each variable, with "1" indicating that the scenario has the highest value in 2100 for that variable and "4" indicating that the scenario has the lowest value in 2100.)

	F&I CO2	GDP	Pop
USG1	3	1	3
USG2	1	4	2
USG3	4	3	1
USG4	2	2	4

Comparing economic growth to fossil and industrial CO_2 emissions growth, we find that all ten of the EMF-22 models project that the baseline economy will grow faster than CO_2 emissions. In Figure 4-4, this is shown by all the points lying below the forty-five degree line.[3] Thus, all the models project increasing CO_2 emissions and income with declining emissions intensity of income (output). Income and emissions growth slows in the second half of the century, but emissions intensity of output continues to decline. What is most interesting in Figure 4-4 is the variation in projected socioeconomic structure. Similar economic growth futures can result in very different CO_2 emissions growth (blue boxes), and similar CO_2 emissions growth futures can result from very different economic growth (red boxes). These differences are due to differences in the projected energy intensity of output and the emissions intensity of energy.

The global picture of socioeconomic structure is informative, but still somewhat intangible. Entertaining alternative socioeconomic futures is more tractable at the regional level. We are able to construct similar regional pictures from the EMF-22 data. For instance, see Figure 4-5 for U.S. and China pictures. Not surprisingly, we observe less variation in socioeconomic structure for the U.S. than China. However, in both regions we find significant variation in economic growth underlying similar CO_2 emissions growth.

One could go even further into socioeconomic structure to more comprehensively and rigorously evaluate and characterize socioeconomic uncertainty, and therefore evaluate and characterize emissions uncertainty. CO_2 emissions can be explained in terms of a number of intensities that describe the evolution of socioeconomic structure—e.g., per capita income, energy intensity of output, and emissions intensity of energy. This structural decomposition of CO_2 emissions is typically referred to as the Kaya identity (Kaya, 1993):

CO_2 emissions

= (population) x (GDP / population) x (energy consumption / GDP) x (CO_2 / energy consumption)

= (population) x (per capita income) x (energy intensity of output) x (CO_2 emissions intensity of energy)

[3] Eleven results are shown in the figure because one model reported results for an additional variant with pessimistic economic growth assumptions. As an equally plausible baseline future, it is relevant to our analysis and included in the figure.

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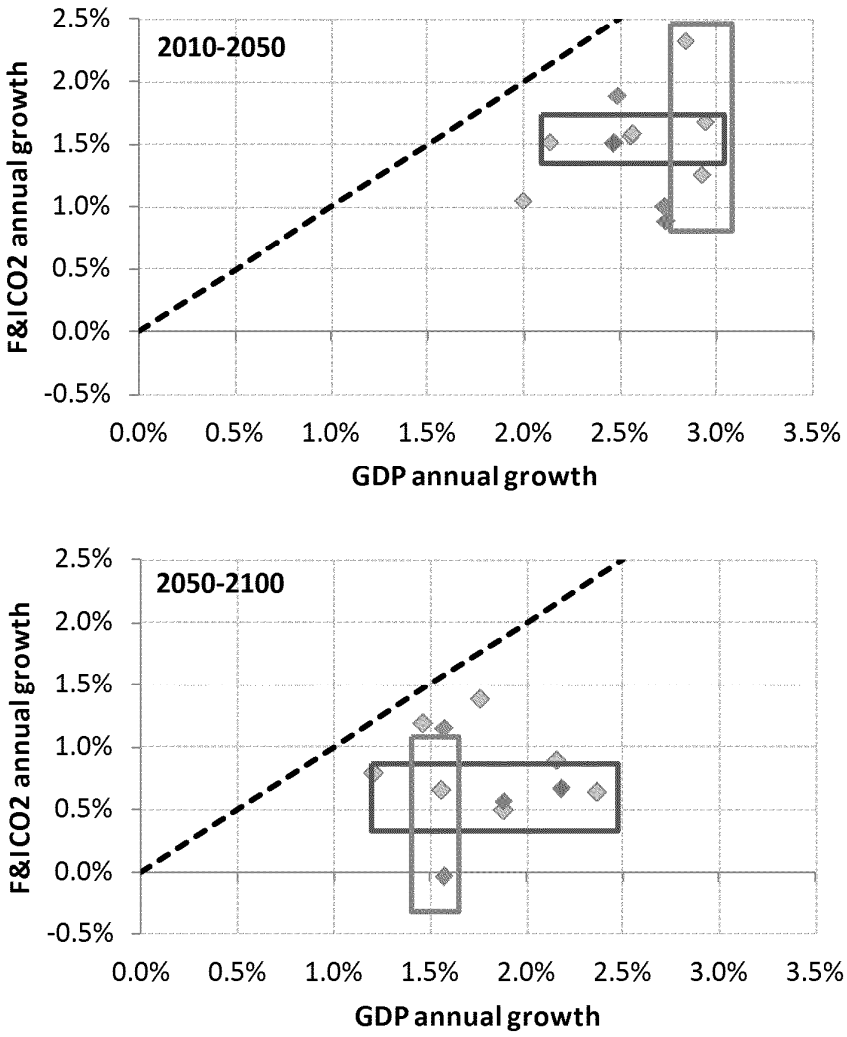

Figure 4-4
EMF-22 baseline global F&I CO_2 & GDP annual average growth 2010-2050 (top) and 2050-2100 (bottom)

Figure notes: Growth rates for the USG scenarios are colored (USG1=purple, USG2=blue, USG3=green, USG4=red)

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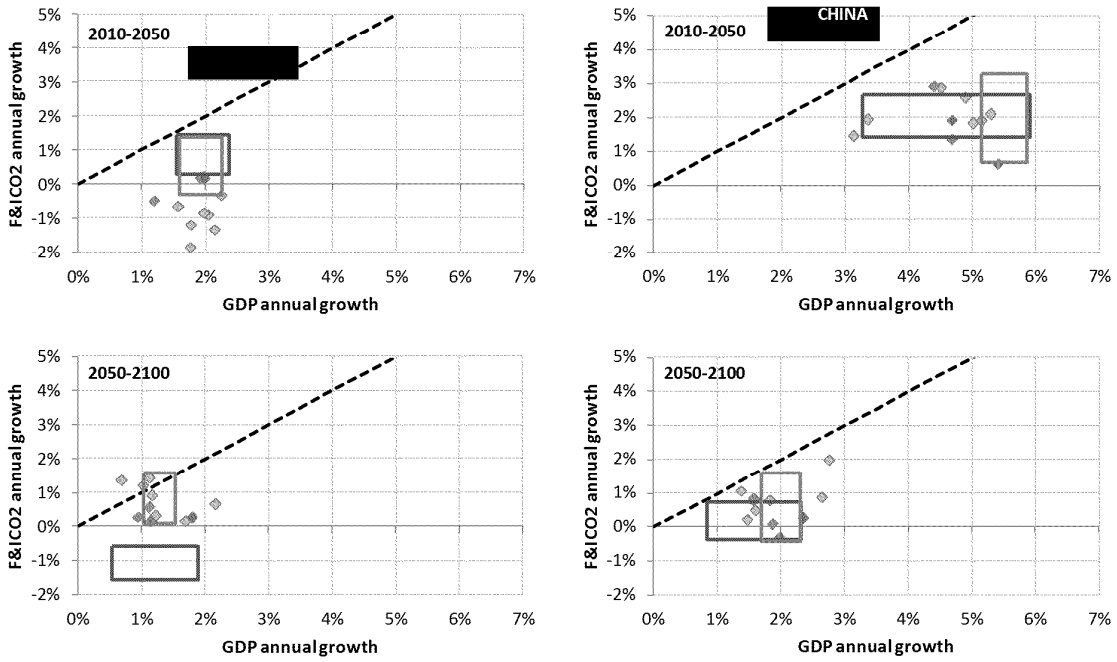

Figure 4-5
EMF-22 baseline US and China F&I CO_2 & GDP annual average growth 2010-2050 (top) and 2050-2100 (bottom)

Figure notes: Growth rates for the USG scenarios are colored (USG1=purple, USG2=blue, USG3=green, USG4=red)

There are other structural dimensions one could also consider, e.g., the evolution of per capita energy use. Uncertainties in intensities are the building blocks of economic and emissions uncertainty. Figure 4-6 provides an example for uncertainty in global energy intensity and the emissions intensity of energy using the EMF-22 data. All the models project baseline improvements in the energy efficiency of output, but across models we find both increases and decreases in the emissions intensity of energy over time, which reflects an increased or decreased dependence of fossil fuels respectively. The figure suggests that there is greater uncertainty in energy intensity growth with models producing similar emissions intensity changes over time from a broad range of energy system futures. This insight is supported by a more detailed deconstruction of Asian emissions projections that found energy intensity and per capita income uncertainty to be the key determinants of variation in CO_2 projections for individual Asian countries (Blanford et al., 2011).

These comparisons illustrate the importance of socioeconomic structure. It defines the relationships between projected income, population, and emissions. We also see that there is clearly uncertainty in socioeconomic structure, and relationships between socioeconomics and emissions are not unique (e.g., higher income does not necessarily imply higher emissions). Finally, we observe that uncertainty about socioeconomic structure is not reflected in the USG socioeconomic and emissions scenarios, and therefore the USG SCC results. However, does it matter?

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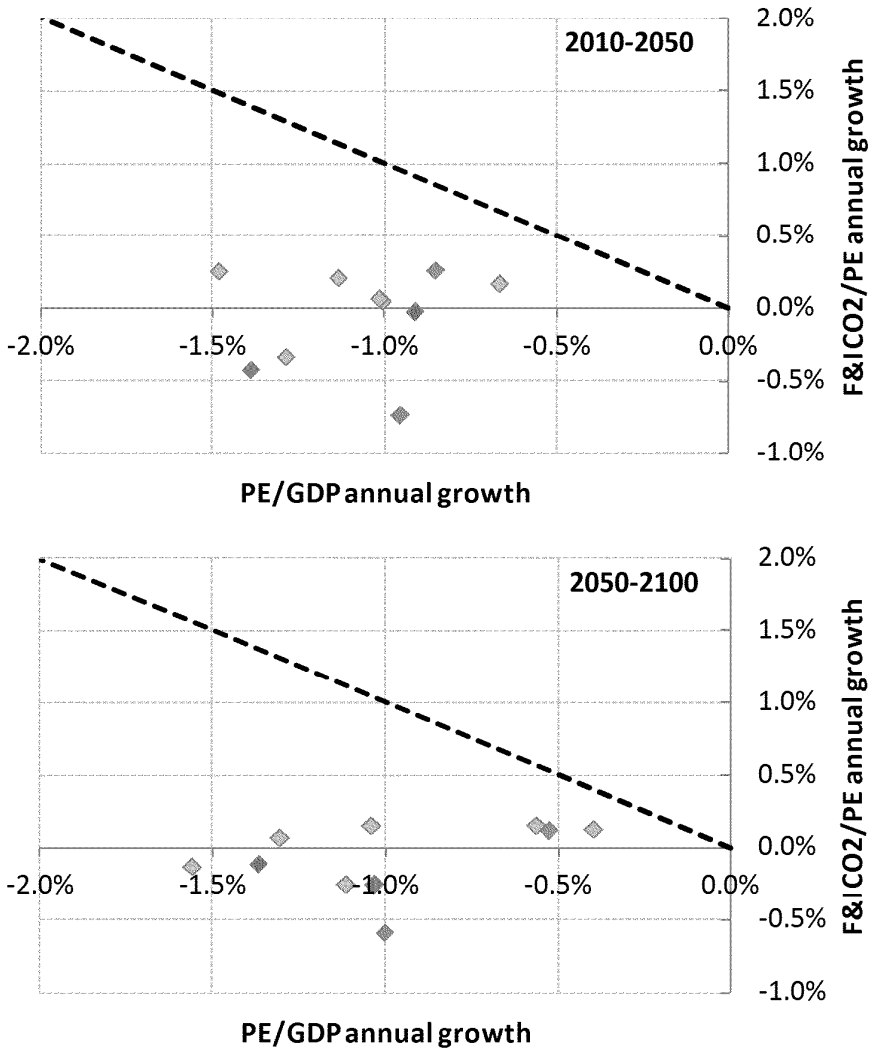

Figure 4-6
EMF-22 baseline global energy intensity (PE/GDP) and emission intensity of energy (F&I CO_2/PE) average annual growth 2010-2050 (top) and 2050-2100 (bottom)

Figure notes: Growth rates for the USG scenarios are colored (USG1=purple, USG2=blue, USG3=green, USG4=red)

Socioeconomic structure is important because it has implications for both climate and climate damage results (recall Figure 2-1). Socioeconomic structure drives emissions, which drives projected climate change, and socioeconomic structure defines societal size and composition, which drives climate vulnerability and adaptation potential. Table 4-5 summarizes how socioeconomics influences damages in the three USG SCC models via these two pathways—projected climate change (from projected emissions) and societal vulnerability. In our climate damages component assessment we explicitly evaluate the sensitivity of damages to socioeconomic assumptions and find them to be an influential driver.

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Table 4-5
Drivers of climate damages

	Temperature	CO_2 Concentration	Total Income	Per Capita Income	Population Size/Composition	Other
DICE	X		X			
FUND	X	X	X	X	X	X
PAGE	X		X	X		

"Other" for FUND includes energy efficiency improvements and other technological progress.

We conclude this section by noting that EMF-22 is but one study with socioeconomic projections, and the study was not focused on exploring socioeconomic and emissions futures uncertainties. Additional literature needs to be considered to more fully characterize the socioeconomic and emissions uncertainty space. For instance, population uncertainty extends beyond that represented in EMF-22. Recall Figure 4-3 that showed only moderate variation in global population projections. There is, however, significant uncertainty in potential population driven by uncertainty in fertility, life expectancy, and other elements such as migration. For example, the United Nations (2014) and Lutz et al. (2007) provide probabilistic population estimates based on such uncertain drivers that produce 95% confidence intervals for global population in 2100 of approximately 9 to 13.5 billion and 5 to 12.5 billion respectively (Figure 4-7). There are also additional socioeconomic and emissions scenarios (e.g., Kriegler et al., 2014, Clarke et al., 2014), as well as explicit estimates of uncertain socioeconomic parameters (e.g., Webster et al., 2008; Abt Associates, 2012). The USG exercise needs to develop coherent alternative socioeconomic futures that consider uncertainty in population, income, and socioeconomic structure that together define emissions uncertainty.

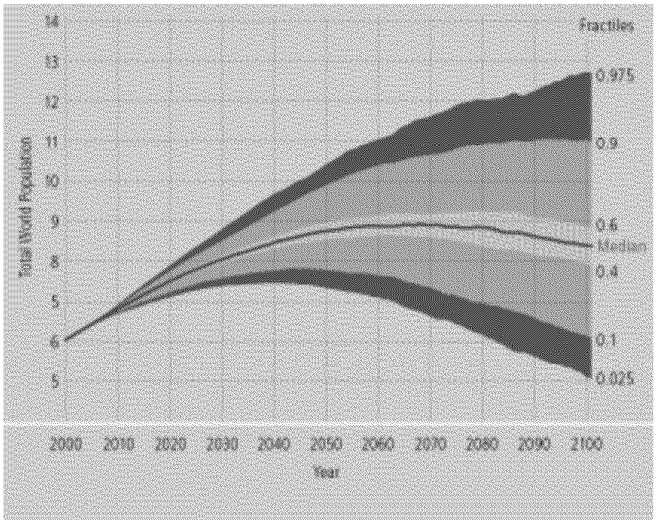

Figure 4-7
Lutz et al. (2007) probabilistic global population projection

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Implementation

Inconsistencies

A number of inconsistencies are evident in the USG modeling implementation. First, as shown in Tables 4-1 and 4-2, the models are structurally inconsistent in the radiative forcing considered. DICE and PAGE include a fuller set of radiative forcing constituents than FUND, where FUND's radiative forcing includes forcing only from Kyoto gases and SO_2 emissions. This issue has climate modeling implications and is discussed in our climate modeling component assessment (Section 5).

Second, the EMF-22 socioeconomic and emissions assumptions are implemented differently across the models. The standardized socioeconomic, emissions, and forcing inputs, as shown in Figures 4-1 and 4-2, are what are run directly through the DICE climate and damage model components in the USG SCC exercise. However, implementation in FUND and PAGE is a bit more complicated. Both models are regionally resolved and require regional inputs re-aggregated from EMF-22 results (Table 4-3). In addition, EMF-22 socioeconomic and emissions levels are not directly implemented (Table 4-2). Instead, growth rates are implemented; and, in FUND, regional fossil and industrial CO_2 emissions are derived within the model using FUND's own energy and emission intensity assumptions (versus those implicitly within the EMF-22 emissions projections). Furthermore, a variety of non-CO_2 emissions and forcing combinations are implemented across the models, with non-CO_2 forcing (Kyoto and Other) completely exogenous in DICE, FUND modeling some Kyoto non-CO_2 forcings endogenously, and PAGE modeling SO_2 forcing endogenously and other non-CO_2 forcing included exogenously.

As a result of these implementation differences, the socioeconomic and emissions inputs run through the models are inconsistent, and a contributing factor to differences in SCC results across models. These inconsistencies should be addressed because they create differences in the results that are not meaningful uncertainty. Additional artificial variation is also introduced by differences in EMF-22 data implementation with respect to model years and time structure in the climate models. This issue is discussed in the climate model component assessment (Section 5).

The likelihood of futures

One USG experimental design question is whether the alternative socioeconomic and emissions scenarios should be considered equally likely and therefore given equal weight in the SCC calculations. The USG fifth scenario, the policy scenario (USG5), runs squarely up against this issue, while the baseline scenarios require more subtle thinking. While it is difficult to assign probabilities to specific socioeconomic and emissions futures, it is possible to recognize unreasonable futures. For instance, the EMF-22 scenario specification for the policy scenario assumes immediate global and full economy-wide participation in pursuing a 550 ppm 2100 concentration climate objective (USG, 2010; Clarke et al., 2009). As shown in Figure 4-1 (dashed line), this implies a sharp deviation from current global CO_2 emissions trends. This is obviously inconsistent with current policies and observed CO_2 emissions trends. As such, it is not likely part of the statistical population of possible futures from which we should be sampling, i.e., it is certainly less likely than the baselines, and arguably has zero probability. Mitigation

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scenarios consistent with current trends would be more reasonable to consider, such as the fragmented participation scenario from the recent EMF-27 study (Kriegler et al., 2014).[4]

Are there reasonableness bounds to baseline futures as well? Consideration of potential constraints is practical, especially with considering scenarios that run through 2300. For instance, fossil resource limits could constrain emissions through resource scarcity, and increasing air pollution concerns with growing global fossil fuel combustion could lead to regional policies that moderate fossil fuel use and emissions. Typically, modeling assumes a tightening of air pollution policies over time as countries grow (see, for instance, Rose et al., 2014). We discuss resource scarcity more below with respect to the extensions to 2300.

Average policy scenario

The USG5 policy socioeconomic and emissions future is a USG exercise construct. It was derived by averaging the 550 policy scenario results from the four EMF-22 models that produced the four baseline socioeconomic and emissions projections used by the USG exercise. Specifically, each of the variables was averaged separately (i.e., average population projection, average income projection, average fossil & industrial CO_2 emissions projection, etc.), and the set of average projections constitute the USG5 future. This approach is problematic for two reasons. First, the outcome lacks internal consistency; and second, the resulting projections are inconsistent with the baseline scenarios. Regarding the former, conceptually a scenario is a complete and cohesive story with internal consistency between emissions drivers and emissions such that there are well defined relationships. A single model is designed specifically to produce a scenario—an internally consistent story. However, consistency between the variables in USG5 is lost in the averaging, as the relationships between variables are no longer valid. The result is not a scenario at all. Regarding the latter inconsistency, averaging also destroys consistency with the baseline scenarios, which is desirable if trying to independently account for climate policy uncertainty in potential socioeconomic and emissions futures.

Extensions to 2300

The 2300 extensions raise a number of issues: inconsistency, likelihood, and uncertainty. We discuss these issues sequentially. First, the USG extension approach results in inconsistency across variables. Specifically, the land-use CO_2 emissions and non-CO_2 radiative forcing extensions have no relationship in the USG design to the population, GDP, and fossil and industrial CO_2 emissions extensions, as well as each other. As a group, the extensions lack a coherent, viable, and intuitive storyline (or set of storylines) that drive all of the extensions from 2100 to 2300.

Second, annual fossil and industrial CO_2 emissions reach over 140 $GtCO_2$/year in the USG2 scenario, with cumulative emissions of over 20,000 $GtCO_2$ by 2200 and over 33,000 $GtCO_2$ by 2300. These numbers are high compared to current estimates of global fossil fuel reserves of 3,674 to 7,113 $GtCO_2$ (IPCC, 2013; Rogner et al., 2012). As a matter of fact, all of the projections except USG5 result in post-2100 cumulative CO_2 emissions in excess of estimated fossil reserves (Table 4-6). Thus, USG1 through USG4 are assumed to be using up current fossil

[4] The EMF-22 Study offers delayed mitigation scenarios, but even those scenarios assume Annex 1 countries are jointly pursuing a 550 ppm climate policy from today.

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reserves and accessing estimated fossil resources.[5] This in itself is not implausible given potential increases in energy prices and technological improvements over time. However, it further illustrates the need to consider socioeconomic structure and its uncertainty in the development of socioeconomic and emissions assumptions.

Table 4-6
Cumulative fossil and industrial CO_2 emissions in the USG assumptions and estimated fossil fuel reserves

Cumulative CO_2 emissions ($GtCO_2$)		
	By 2200	By 2300
USG1	11,207	16,741
USG2	20,024	33,023
USG3	8,113	10,864
USG4	14,092	20,504
USG5	3,691	4,843
Estimated reserves ($GtCO_2$)	3,674 - 7,113	

Finally, when evaluating potential climate consequences over the next three hundred years, socioeconomic and emissions uncertainty is germane. The USG exercise, however, does not consider alternative 2300 extensions. A variety of coherent futures are plausible. For instance, global population growth could instead continue to be positive or negative to 2300 instead of declining to zero by 2200 as is currently assumed (United Nations, 2004). Meanwhile, per capita income growth could continue to be positive with declining carbon intensity slowing or increasing (possibly due to fossil resource constraints). A variety of coherent alternative socioeconomic and emissions futures could be developed off of population uncertainty using plausible alternative intensity assumptions. How much they matter to net present value calculations, like the SCC, is something that needs to be evaluated.

[5] Reserves and resources are defined according to Rogner et al. (2012). 'Reserves' are defined as "quantities that geological and engineering information indicate with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions." 'Resources' are "detected quantities that cannot be profitably recovered with current technology, but might be recoverable in the future, as well as those quantities that are geologically possible, but yet to be found."

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5
COMPONENT ASSESSMENT 2 – CLIMATE CHANGE MODELING

What we can learn

Each of the three models used by the USG to estimate SCC values includes a reduced-form climate model describing (i) the accumulation of CO_2 emissions in the atmosphere; (ii) the translation of atmospheric concentrations of CO_2 to radiative forcing; (iii) the radiative forcing characterization of non-CO_2 emissions; and (iv) temperature response to the resulting radiative forcing trajectory (parameterized by climate sensitivity). Together, these processes define the temperature change response for a given reference emissions futures. They also define the incremental temperature change response for an incremental increase in CO_2, which is a key part of a SCC calculation. However, model results for climate variables, including the incremental climate responses, are not published in the USG's documentation, or more generally, in model specific publications—peer reviewed or otherwise. Thus, we do not know to what extent the climate modeling is similar or dissimilar across the models, and to what extent the climate modeling might be contributing to differences in SCC results.

In this section, we assess the climate modeling component within the three USG models. Specifically, we explore the following questions:

- How do the climate models underlying SCC calculations behave, and are they similar?
- What do the incremental climate responses look like from each model, and are they similar?
- How do the USG SCC model responses compare to more detailed climate models?
- Are there climate modeling implementation issues to consider?

To explore these questions, we code the climate model components of each of the USG SCC models and run controlled diagnostic scenarios designed to illuminate and compare the nature of the carbon cycle, radiative forcing, and temperature responses of each model. For the first two questions, we undertake a cross model comparison using standardized inputs that isolate climate modeling behavior. Initially, we use deterministic scenarios to reveal the fundamental nature of each climate model's total responses, as well as incremental responses to an incremental CO_2 emissions pulse. To elucidate and compare the shape of the response functions, we perform sensitivity analyses. We then evaluate the probabilistic responses for model specific parametric uncertainties. Throughout, we explore results to 2100 and 2300, the latter being the full USG SCC calculation time horizon. We explore the third question through direct comparison of carbon cycle and climate results to results from more detailed models. For this comparison, we use deterministic, sensitivity, and probabilistic scenarios—total and incremental—to reflect upon potential alternative climate outcomes to those from the USG models. Finally, we reflect on the climate modeling component set-up and implementation.

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Key observations

- *Overall*: From our assessment, we find significant variation in climate responses across the USG models, i.e., the translation of emissions into estimated temperature change. Some of the variation is due to implementation inconsistencies. However, some is due to structural and parametric differences across models. Whether these differences across models are useful information, as reflections of model structural uncertainty would be important to establish. In general, it is unclear whether the results across the models are comparable. For the USG SCC application, where results are combined across models, it is necessary to establish that the different formulations are equally valid, independent, and important for capturing unique and valuable information regarding uncertainty. Equally valid and independent formulations would produce results that are statistically comparable and amenable to averaging. Finally, consideration of alternative climate modeling would be practical. Our comparison to more detailed climate modeling finds potentially meaningful differences in climate responses, and uncertainty, from those reflected in the USG models. Below, we summarize key individual climate modeling observations.
- *Modeling structure and implementation*: We find that the climate component structures and specifications of the USG SCC models vary substantially across models. The mode of application in the USG exercise also varies across models, with different implementations and uncertainties contributing to differences in outcomes. For instance, there are inconsistencies in non-CO_2 emissions and radiative forcings included, climate feedbacks included, climate sensitivity modeling, uncertainties considered, and incremental CO_2 pulse implementation. In addition, we find that climate component model revisions associated with the 2013 USG SCC values were not standardized across models, nor uncertainty evaluated, except for some individual model consideration.
- *Differences in key factors*: We find four key factors contributing to the differences we observe in projected temperature increase across the three models (discussed below). The key factors are differences in carbon cycle modeling, modeling of non-CO_2 radiative forcing representation, translation of total radiative forcing to temperature, and climate sensitivity responsiveness. This observation suggests that uncertainties should be considered in each of these dimensions. Some degree of uncertainty is represented by using multiple models, and with the model specific parametric uncertainties, but the validity of differences needs to be evaluated.
- *Climate modeling behavior*: From our deterministic diagnostic analysis of the climate components of each of the USG SCC models, we find the models producing notably different projected CO_2 concentrations, radiative forcing, and temperature change. CO_2 concentrations increase most quickly in DICE and least quickly in PAGE, but DICE and PAGE projected CO_2 forcing is more responsive to concentrations than FUND, with substantial variation in projected non-CO_2 forcing across models. In a deterministic setting, these differences result in a one degree Celsius variation in projected temperature by 2100 in a higher emissions scenario, and just under a half degree Celsius variation in 2100 in a lower emissions scenario.
- *Sensitivity of climate results*: We find the DICE climate projections to 2100 to be most sensitive to alternative emissions projections, and the FUND climate projections to be the least sensitive. However, PAGE temperature projections are significantly more sensitive to assumed climate sensitivity than the other models, and FUND temperature projections are the

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least sensitive. A contributing factor is differences across models in how climate sensitivity affects temperature transition.

- *Incremental climate modeling behavior*: The differences in climate modeling noted, as well as differences in the implementation of an incremental emission pulse, result in significant variation in the magnitude and shape over time of the incremental climate response to a marginal increase in CO_2 emissions across the three models. For example, the deterministic temperature response by 2050 to an incremental increase in 2020 emissions can vary by a factor of two. Behind the temperature outcomes, we find notable differences in the size and timing of the initial atmospheric CO_2 concentration spike and, over time, differences in carbon cycle assumptions playing-out with respect to land and ocean carbon uptake and climate feedbacks from terrestrial carbon sinks, which are only present in FUND and PAGE. Differences in climate feedback modeling contribute to stark differences in CO_2 concentration responses across emissions scenarios, with DICE projecting no difference in incremental concentration responses between emissions scenarios, and FUND and PAGE projecting differences, but in opposite directions. Ultimately, incremental temperature responses peak and decline in all models, but DICE peaks earliest, followed by PAGE, with FUND peaking well after the other models.
- *Incremental climate response off a lower emissions scenario*: In addition to variation in incremental responses across models, we also make another important observation. In all models, we find *higher* incremental temperature increases from scenarios with *lower* emissions. This effect is due to the concave logarithmic function relating CO_2 forcing to CO_2 concentrations.
- *Model specific parametric uncertainty*: In the USG exercise, the models are considering very different parametric uncertainty in their climate modeling. FUND and PAGE each have a number of uncertain independent parameters (11 and 10 respectively), which differ between the two models in type and specification, while DICE does not consider any model specific uncertainty. From our probabilistic runs, we find that there is substantially larger uncertainty being represented in PAGE, compared to FUND (and of course DICE), as reflected in PAGE's broader distribution for potential temperature change. The significant differences in the uncertainty represented across models contributes to questions regarding the comparability of results.
- *Climate results to 2300*: We find substantially higher CO_2 concentrations, radiative forcing, and temperature increases post-2100 than observed pre-2100, especially from the higher emissions scenario. More importantly, we find greater differences in projected climate across the models, including changes in the ordinal ranking (highest to lowest ordering of results). The differences in projected forcing across models increase post-2100, driven primarily by differences in carbon cycle modeling and CO_2 forcing that result in lower radiative forcing futures from PAGE and accelerating total forcing futures from FUND. FUND's climate feedback also results in temperature growth rates post-2100 much higher than DICE and PAGE in both high and low emissions scenarios. In the higher emissions scenario, we observe a one degree Celsius variation in 2300 (similar to 2100), but with FUND now highest (versus lowest), and in the low emissions scenario two degrees of variation in 2300 (versus a half degree in 2100). Post-2100 *incremental* climate responses also exhibit larger variation than observed pre-2100, including a shift in ordinal ranking, with FUND and PAGE incremental results post-2100 much more responsive to the emissions scenarios than they

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were pre-2100. FUND's incremental temperature response peaks post-2100, versus pre-2100 peaks from the other models, with FUND's peak also at a lower level. Finally, PAGE is considering substantially more model specific temperature change uncertainty (total and incremental) to 2300 than the other models.

- *Comparison to more sophisticated climate models*: With alternative standardized emissions assumptions, we run and compare the USG climate modeling to that of more sophisticated models. We find that the alternative modeling notably broadens the range of possible climate outcomes and suggests that alternative climate modeling representations and uncertainties are valid and important for the USG SCC exercise to consider going forward. Specifically, we identify alternative, and more sophisticated climate modeling that produces total, incremental, and probabilistic climate responses that differ from those resulting from the USG models. For instance, incremental CO_2 concentration increases spike and decline like in the USG models but, unlike the USG models, then increase due to carbon cycle feedbacks. Also, we find alternative modeling of the incremental response more sensitive to the emissions scenario than the USG models. Furthermore, we run probabilistic scenarios, which have an alternative characterization of parametric uncertainty, and find substantial differences from the USG models in projected carbon cycle and climate output distributions, such as FUND suggesting significantly less temperature uncertainty and risk, and PAGE suggesting significantly more than our alternative probabilistic climate modeling. This finding suggests that there are additional uncertainties to consider in carbon cycle, forcing, and temperature modeling, and their parametric uncertainty.
- *Component uncertainty consideration:* Our various climate modeling observations identify a variety of additional uncertainty to consider within the climate system, including alternative climate models and parametric uncertainty specifications, alternative climate sensitivity distributions, and uncertainty in 2013 modeling revisions.

What is done

Modeling description

The climate component in each of the three models includes the following:

- a representation of the carbon cycle, i.e. CO_2 concentrations as a function of emissions,
- a radiative forcing function for CO_2 concentrations,
- a set of equations or assumptions about the concentrations and/or radiative forcing from non-CO_2 emissions, and
- a function of global mean temperature over time that responds to radiative forcing and climate sensitivity.

In each of these elements, there are structural and parametric differences across the models (Table 5-1). Below we discuss the various differences after we describe USG modifications to the standard modeling. The USG approach only standardized one climate modeling assumption—the distribution of potential climate sensitivity parameter values.

USG modifications

The USG SCC climate modeling components are modified versions from the standard climate modeling of each model. Specifically, for DICE, time steps are changed from 5-years to 10-

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years, and CO_2 concentrations are averaged across time periods. For PAGE, time steps are shifted to a different variable time step scheme, and non-CO_2 emissions are handled quite differently. As discussed in Section 4, in the standard formulation, PAGE assumes N_2O, CH_4, linear gas, and SO_2 emissions and then models concentrations and forcing. However, in the USG exercise, only SO_2 is explicitly modeled (emissions, concentrations and forcing), and other forcings are derived outside the model and included exogenously.

Table 5-1
USG SCC climate modeling component structural characteristics

Characteristic		DICE	FUND	PAGE
Atmospheric concentrations				
	CO_2	3-box carbon cycle	5-box carbon cycle	1-box carbon cycle
	Non-CO_2 Kyoto	Not modeled	CH_4, N_2O, SF_6	Not modeled
	Non-CO_2 non-Kyoto	Not modeled	SO_2	SO_2
Radiative forcing				
	CO_2	Natural log coefficient: 5.48	Natural log coefficient: 5.35	Natural log coefficient: 5.5
	Non-CO_2 Kyoto	Exogenous	CH_4, N_2O, SF_6	Exogenous
	Non-CO_2 non-Kyoto	Exogenous	SO_2	SO_2, non-SO_2 exogenous[6]
Global mean temperature		Adjustment speed a function of climate sensitivity & surface temperature modulated by ocean heat uptake	Adjustment speed a function of climate sensitivity	Direct function of ocean temperature
Regional temperatures		n/a	Yes (implicit)	Yes (explicit)
Climate feedback		None	Terrestrial carbon stock loss with temperature	Terrestrial carbon stock loss with temperature
Time steps		10-year	1-year	Variable (10-year 2000-2060, 20-year 2060-2100, 100-year 2100-2300)

Time step and accounting

The time structure varies across the models. In DICE, there is a ten-year time step with a decadal sum of emissions driving the change in concentrations in the subsequent decade. In FUND, there is a one-year time step with emissions in a given year driving the change in concentrations in that year. In PAGE, there is a ten-year time step initially, widening to twenty-year steps, and then 100-year steps beyond 2100, with average annual emissions in the previous and current time step driving the change in concentrations in the current time step. As a result of these differences, it is not possible to conduct a purely standardized experiment to compare the responsiveness across models to an emissions pulse in a particular year. This by itself will introduce an artificial range of variation in climate outcomes and resulting SCC estimates (i.e., not based on systematic variation of uncertain parameters).

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[6] PAGE SO2 forcing projections are identical across USG socioeconomic and emissions scenarios because PAGE regional SO2 emissions projections are identical across scenarios.

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Carbon cycle

In each model, carbon accumulates in the atmosphere according to a compact set of linear equations, with only a fraction of emitted carbon accumulating (due to absorption by land and ocean sinks of the remainder) and gradually decaying over many decades. The carbon cycles are structured differently across models in terms of carbon movement from one carbon pool to another over time, and the coefficients for the equations governing this movement. There is also variation in the starting value and, as discussed above, the timing relationship relative to emissions. An additional non-linear feedback is included in FUND and PAGE—a so-called climate feedback. In both models, higher temperatures are assumed to adversely affect terrestrial carbon stocks and result in additional emissions, thereby accelerating growth in atmospheric carbon stocks, and subsequently temperature. In DICE, this feedback is not represented (at least explicitly). In FUND, it is represented as an additional source of CO_2 emissions. In PAGE, it is a multiplier on CO_2 concentration.

Forcing from CO_2 and non-CO_2 emissions

Radiative forcing, or the change in the earth's heat balance due to increases in atmospheric loading of greenhouse gases relative to pre-industrial, is an intermediate quantity in the translation of emissions to temperature increase. Forcing, measured in watts per square meter, can be calculated for individual gases and other substances and summed to a total forcing level that drives temperature change. For CO_2, forcing has been found to be proportional to the natural log of the atmospheric concentration. Despite a clear central value published by the IPCC, each of the three models in the USG exercise uses a slightly different representation.

Nonetheless, the range of variation in the treatment of non-CO_2 gases and other substances across the three models is far wider. In DICE, there is a single fixed parameter representing all non-CO_2 forcing in each time period. In the USG exercise, this parameter was set equal to the total non-CO_2 forcing as reported in the underlying scenarios, plus a USG estimated trajectory for forcing from aerosols and other non-gas substances, which were excluded from the reporting of results in the EMF-22 study that provided the underlying scenarios. The subtotal of forcing from these substances is subject to large uncertainty, but it is potentially significant and negative in magnitude. In FUND, on the other hand, non-CO_2 forcing is based on native model assumptions for a small set of explicitly modeled agents (CH_4, N_2O, SF_6, and SO_2), with no additional residual radiative forcing category analogous to that included in DICE. In PAGE, SO_2 emissions and forcing are explicitly modeled (but the SO_2 emissions projection is fixed across scenarios and based on the PAGE default SO_2 emissions dynamics not the underlying EMF-22 scenarios). Other non-CO_2 Kyoto forcing, normally modeled by PAGE, is replaced with exogenous forcing trajectories, along with an "other" forcing category. For the scenarios in the USG exercise, projections for these agents in PAGE were based on a combination of reported results from the underlying scenarios and native model assumptions. As shown later, this process results in large differences in the projection of non-CO_2 forcing across the different models for ostensibly the same scenario.

Global mean temperature dynamics

Each of the models has a different formulation for global mean temperature dynamics. The typical formulation in a reduced-form model, such as these, is to specify an equilibrium temperature in each period that is linearly proportional to that period's total forcing, and

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calculate actual temperature as a lagged process starting at an exogenous initial value and approaching the equilibrium temperature at some annual rate. While each of the three models in the USG exercise employs this basic formulation, the parameterization of the lagged process varies. In particular, FUND assumes a much slower lag process than the other two models. However, in both DICE and FUND the lag parameter is a function of the assumed climate sensitivity. Varying the lag whenever the climate sensitivity parameter is varied is to ensure (rough) consistency with historical observations. That is, a higher value for climate sensitivity should be paired with a slower lag process. Only DICE and FUND enforce this condition. Finally, in DICE, ocean temperature rises with atmospheric temperature and moderates the rate of atmospheric temperature increase.[7]

Regional temperatures

FUND and PAGE derive regional mean temperatures from global mean temperatures using unique pattern scaling approaches. The approaches and regional temperature results are discussed further in our climate damage component assessment (Section 6).

2013 modeling revisions

USG (2013) SCC estimates included a number of climate modeling component revisions (Section 2). For DICE, the carbon cycle was revised with weaker ocean uptake. For FUND, the transient temperature response was changed and indirect radiative forcing from methane was added. For PAGE, the carbon cycle land/ocean carbon uptake was revised, as was scaling to regional temperatures. For DICE and FUND, the climate modeling revisions, all else equal, resulted in higher SCC estimates. For PAGE, it is unclear.

Assessment

In this section, we evaluate each of the elements of the USG SCC climate model components using diagnostic scenarios. The USG SCC exercise considers the following uncertainties: future emissions/forcing, climate sensitivity, and model specific parametric uncertainties. We evaluate each of these dimensions as well within our assessment.

Cross model comparison analysis – USG scenarios

We evaluate and compare the climate modeling responses across models using controlled experiments with common inputs. Given our diagnostic objectives to learn about model behavior, we focus on the low and high USG CO_2 emissions projections—USG2 and USG5 (Figure 5-1). For this component assessment, we standardize emissions and forcing inputs to the models to the extent allowed by each model structure and the USG implementation modifications. Thus, we set aside inconsistencies in CO_2 emissions implementation across models and impose the identical CO_2 emissions projections shown in Figure 5-1. Note that the CO_2 projections in the figure are stepwise versions of the smooth projections presented in Section 4. Given model differences in time steps, this representation allows for the greater standardization of the CO_2 inputs for our diagnostics. Each input scenario is a set of CO_2 and non-CO_2 related projections. Our standardized pathways are consistent with EMF-22 decadal

[7] In William Nordhaus' April 2014 version of DICE, there is an additional temperature speed adjustment that is a function of climate sensitivity (http://www.econ.yale.edu/~nordhaus/homepage/).

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results to 2100 and the DICE 2100-2300 implementation. Unfortunately, we are not able to standardize the USG non-CO_2 inputs. Differences in the core modeling structure and USG implementation mean that each model is using a different subset of non-CO_2 related inputs and some inconsistencies persist (Table 5-1). This, of course, contributes to differences in projected climate component outcomes (as illustrated and discussed below).

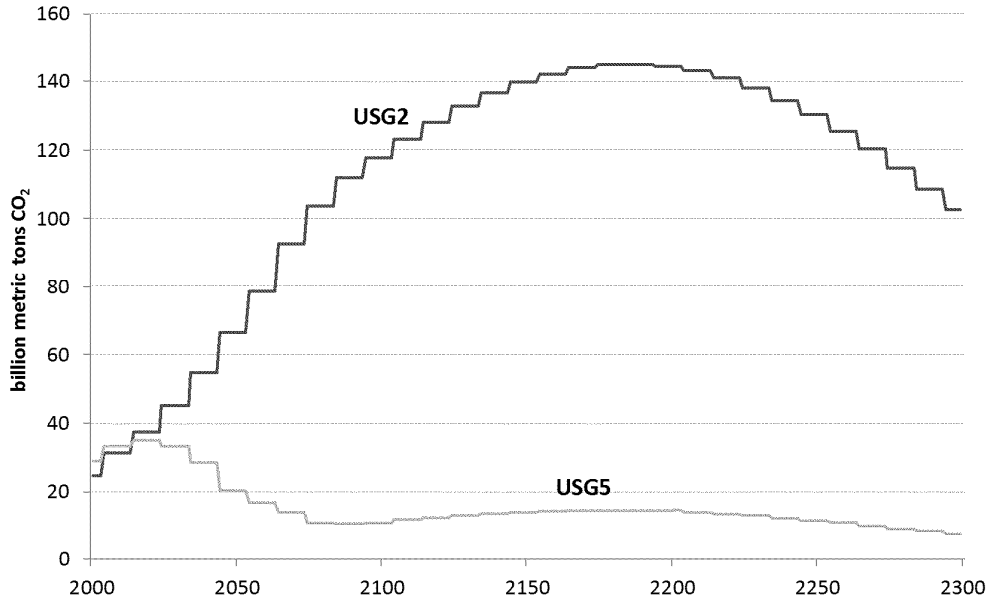

Figure 5-1
Our standardized USG2 and USG5 total global CO_2 emissions inputs to 2300

We run diagnostic scenarios using the standardized inputs to explore total climate responses to climate drivers, as well as "marginal" responses to incremental changes in CO_2 emissions. In each case, we first run deterministic scenarios to evaluate model tendencies with central parameter values for model specific uncertain parameters. We also run deterministic sensitivity scenarios with respect to the climate sensitivity parameter. These sensitivities, in addition to those from the high and low emissions scenarios, provide insights regarding the shape of the climate response functions across models. We then evaluate the role of model specific parametric uncertainties with probabilistic scenarios using random sampling over each model's uncertain parameters. Through this point in our analysis, we focus on results to 2100. However, we conclude this section with an assessment of results through 2300, the full USG analysis time horizon for calculating the SCC estimates. Throughout this assessment, we provide total, as well as incremental climate response results. Total results are important as the reference conditions for the incremental results, as context for thinking about damages, and for direct comparison to other climate models.

Total climate responses

Figure 5-2 shows atmospheric CO_2 concentration results to 2100 for the three models. In the high emissions scenario (USG2), DICE has the highest projected CO_2 concentrations throughout the time horizon, and PAGE has the lowest. In PAGE, atmospheric carbon cycle dynamics are represented more slowly, despite including a temperature feedback. By 2100, variation across the

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models is about 150 ppm CO_2 for the high emissions scenario. The variation is much smaller with the low emissions scenario.

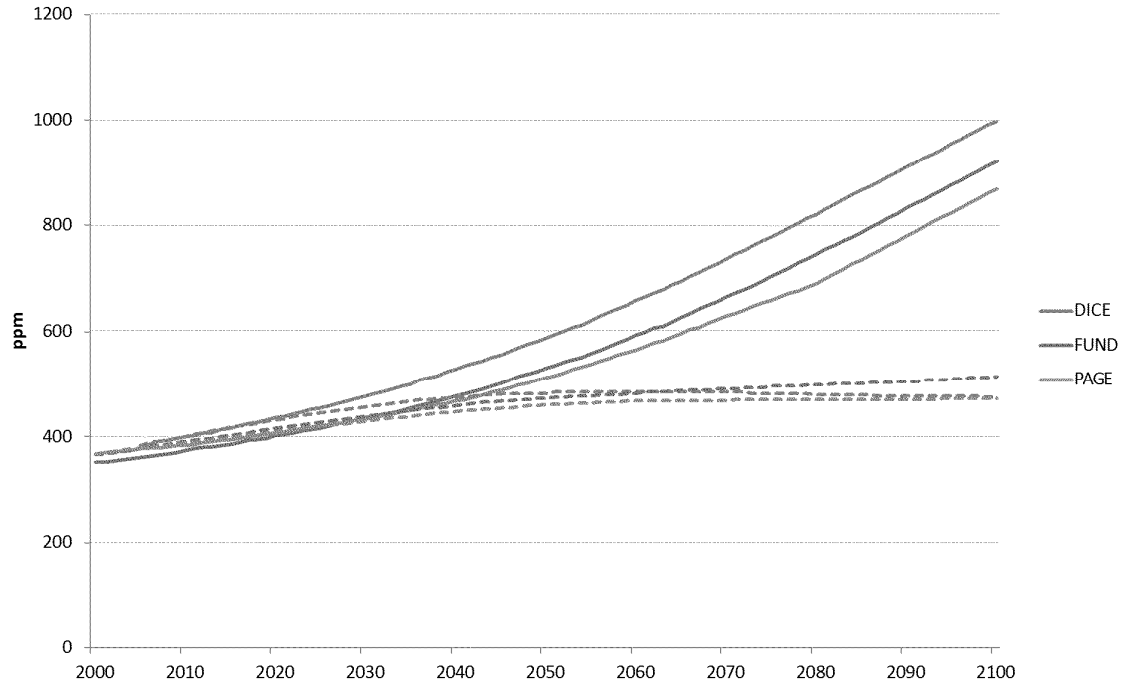

Figure 5-2
CO_2 concentrations in USG2 (solid) and USG5 (dashed) scenarios

DICE CO_2 concentrations are the most sensitive to the assumed emissions scenario, producing the largest difference in CO_2 concentrations in 2100 between the scenarios, as well as the largest difference early in the century. FUND's and PAGE's carbon cycles are equally sensitive.

Figure 5-3 shows CO_2 radiative forcing results for the three models. DICE and PAGE are slightly more responsive to CO_2 concentrations than FUND. FUND uses the IPCC's value of 5.35 as the coefficient between the natural log of concentrations relative to pre-industrial and forcing, DICE uses 5.48 and PAGE uses 5.5. By 2100, for the high emissions scenario, there is variation of about three quarters of a watt per square meter across the three models. For the low emissions scenario, the variation is about a third of a watt per square meter. In terms of CO_2 forcing, DICE is again the most sensitive to the emissions scenario, and FUND and PAGE are similar.

Figure 5-4 shows non-CO_2 radiative forcing for the three models. Non-CO_2 forcing is much smaller in magnitude than CO_2 forcing but still significant. Here we see sharp disparities across the models, which is in large part due to the differences in non-CO_2 forcings included. DICE and PAGE start off with net negative non-CO_2 forcing that rises over time, while FUND's forcing is net positive from the outset. Recall that FUND is computing non-CO_2 forcing from emissions, but only for CH_4, N_2O, SO_2, and SF_6, while PAGE is computing forcing from its own SO_2

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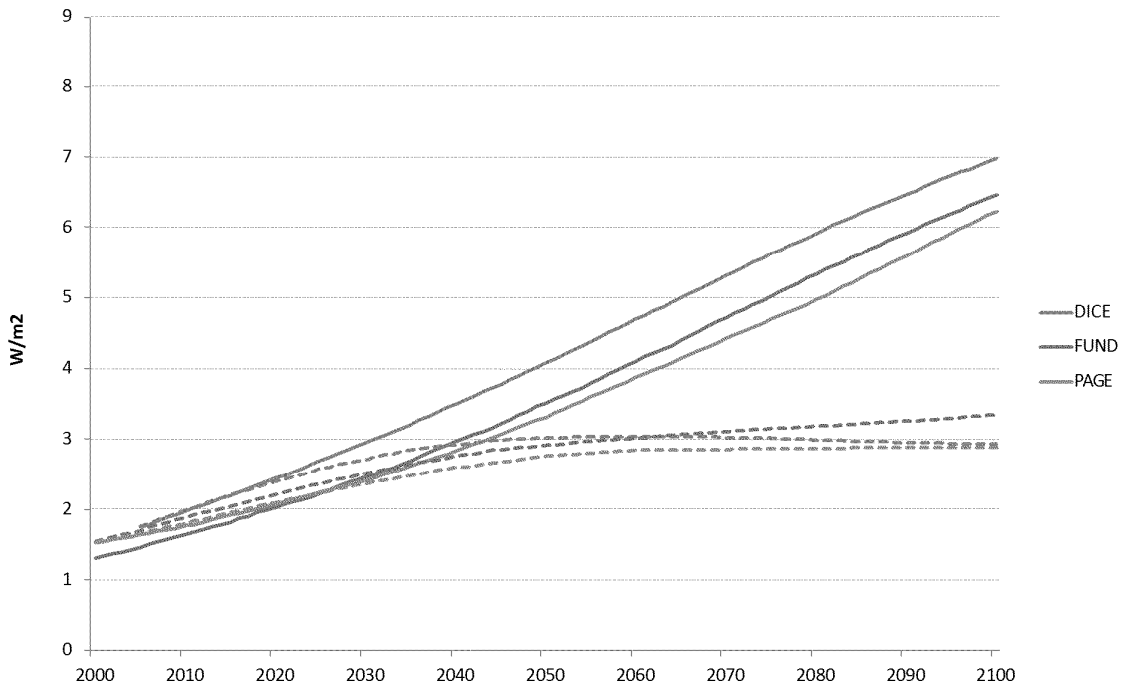

Figure 5-3
CO_2 forcing in USG2 (solid) and USG5 (dashed) scenarios

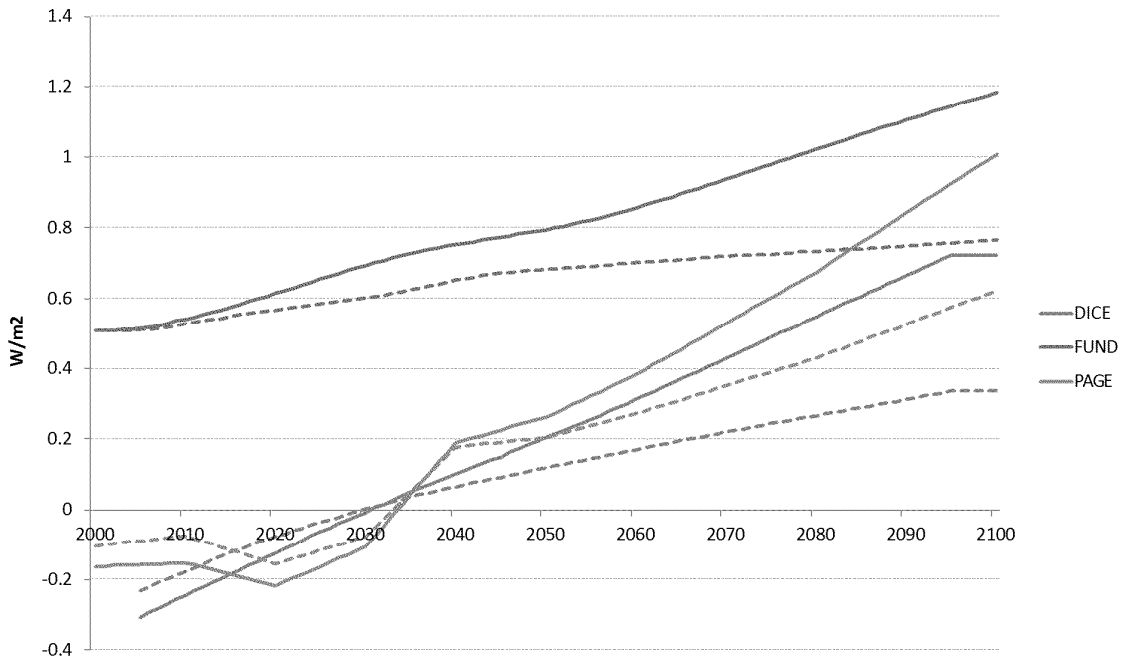

Figure 5-4
Non-CO_2 forcing in USG2 (upper) and USG5 (lower) scenarios

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emissions projections and including an exogenous other forcing that covers more than the non-CO_2 constituents in FUND, and non-CO_2 forcing is entirely assumed in DICE and covers non-CO_2 Kyoto and non-Kyoto constituents. By 2100, there is substantial variation across the models, with 0.4 to 0.5 watts per square meter of variation for a given emissions scenario. Sensitivity to the emissions scenarios is similar across the models, noting however the different starting points in DICE and PAGE.

Figure 5-5 shows total radiative forcing in each model for the two scenarios, illustrating the combined effect of variation in CO_2 and non-CO_2 forcing shown in the previous two figures. PAGE produces much lower total forcing than DICE due to the carbon cycle, but much lower total forcing than FUND due primarily to non-CO_2 forcing. DICE is the most responsive to the emissions scenario due to its carbon cycle. However, the other models are also fairly responsive.

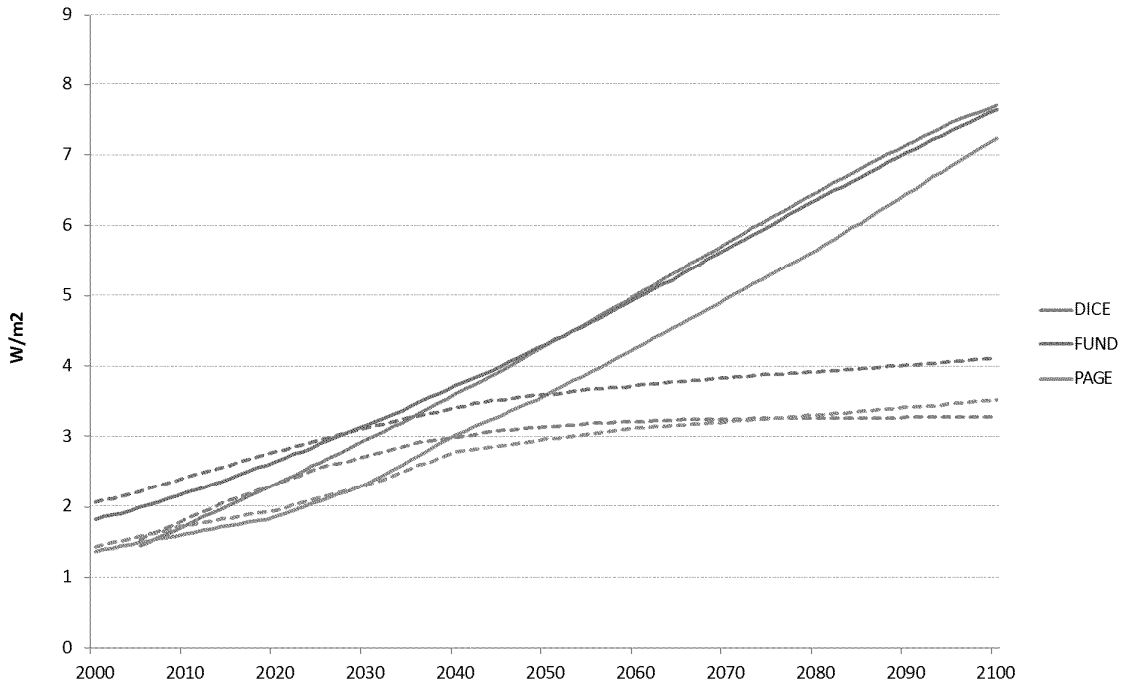

Figure 5-5
Total forcing in USG2 (solid) and USG5 (dashed) scenarios

Figure 5-6 shows temperature change results. In each model, the climate sensitivity parameter is set to three degrees Celsius. Because of its much slower temperature lag process, FUND projects a significantly lower temperature increase in the high emissions scenario. By 2100, there is a sizable 1 degree C difference in the projected increase in temperature across models. For the low emissions scenario, the difference across models is smaller, but significant, at 0.4 degrees C.

Looking across emissions scenarios, we find that there are large differences in the temperature responses between the high and low emissions scenarios. DICE is the most sensitive, producing the largest difference between scenarios, with a deviation that begins earlier in the century than found with the other models. FUND, on the other hand, is far less sensitive to the emissions scenario than the other models due primarily to its slower lag response.

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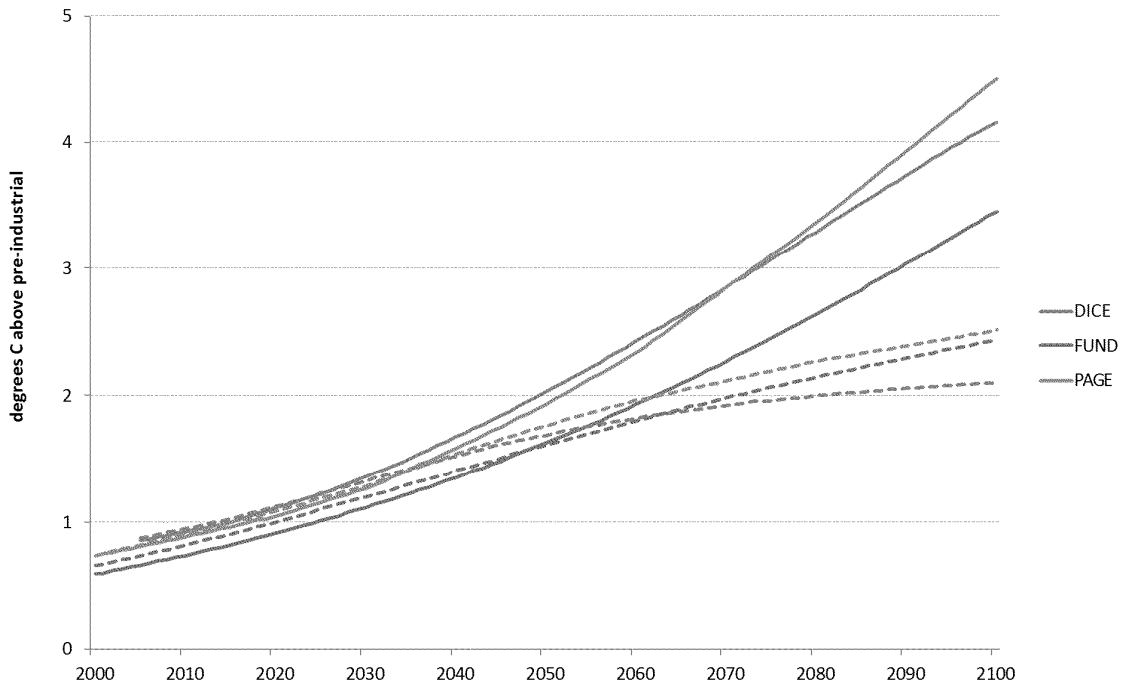

Figure 5-6
Temperature in USG2 (solid) and USG5 (dashed) scenarios

Sensitivity analysis with respect to the climate sensitivity parameter reveals yet another dimension of differences across the models. In Figure 5-7, we see that PAGE is significantly more sensitive than DICE and FUND to the assumed climate sensitivity, and FUND is the least sensitive. For instance, a doubling of climate sensitivity from three to six degrees Celsius, results in a 115% increase in PAGE's projected increase in temperature in 2100 under the high emissions scenario, but DICE and FUND respond with only 38% and 13% increases respectively in the projected temperature increase. This difference in responsiveness is driven by the different temperature lag processes modeled, with the DICE and FUND formulations muting their responses. The result is that we would expect PAGE to produce a broader and more heavily right-skewed distribution of temperature increase than the other models for a given climate sensitivity distribution.

An important modeling issue is highlighted here. Climate sensitivity should not be varied independently. It should be adjusted in concert with the ocean heat uptake and aerosol radiative forcing coefficients to ensure consistency with historical temperature observations (Urban et al., 2014; Forest et al., 2002). For instance, an increase in climate sensitivity should be accompanied by a combination of faster ocean heat uptake and larger negative aerosol forcing. Adjusting for the temperature lag or having increased ocean temperature feedback, as done in FUND and PAGE respectively, are proxies for adjusting ocean heat uptake. However, none of the models currently adjust all three coefficients. Increasing climate sensitivity, without compensating adjustments to the other coefficients, will bias upward the projected temperature increase.

In summary, we find modeling differences in four key elements contributing to differences in projected temperature increase across the three models—carbon cycle modeling, modeling of

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non-CO_2 forcing, translation of forcing to temperature, and climate sensitivity responsiveness. This observation suggests that uncertainties should be considered in each of these dimensions. Some degree of uncertainty is represented with multiple models, and with the model specific parametric uncertainties that are discussed later. However, basic questions arise. Do the differences across models make sense? In other words, are they equally sound and independent reflections of current scientific understanding? If so, the differences across models are important and should be included to capture unique and valuable information regarding uncertainty in the SCC. If not, the differences in results are arbitrary and not informative. The pronounced differences in climate model behavior that we observe should be further assessed and justified, revised, or included as additional standardized uncertainties.

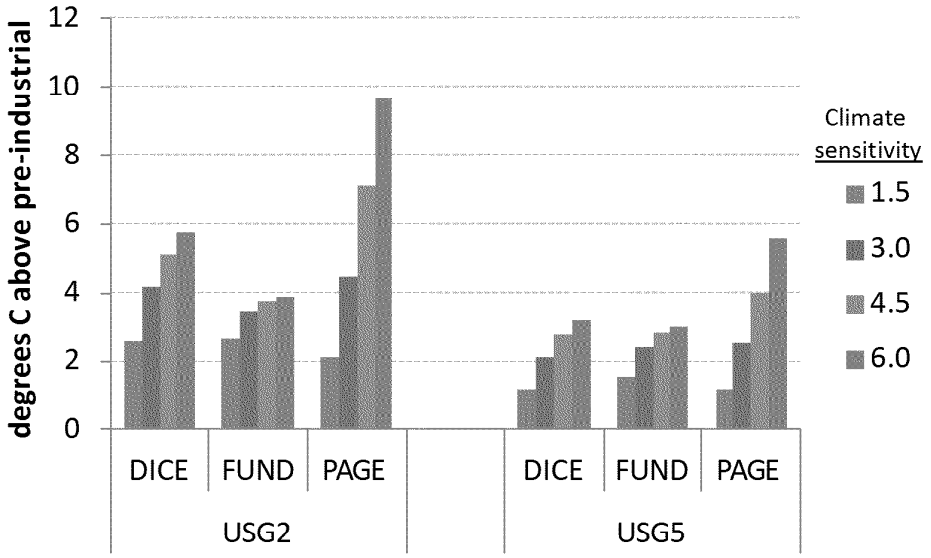

Figure 5-7
Sensitivity of temperature increase in 2100 in USG2 and USG5 to climate sensitivity

Incremental climate responses

Next we explore incremental climate responses. This response feeds directly into the SCC calculation in that it is the incremental increase in temperature in each future year from an incremental increase in emissions in a particular year. Incremental monetary damages reflected in SCC results are driven by the magnitude and timing of the incremental temperature and sea level responses. For our incremental scenarios, we introduce an emissions pulse in 2020 of 1 billion metric tons of carbon, 1 GtC (roughly 10% of current global emissions).[8] Note that in the USG exercise the incremental emissions shocks in a given year t were implemented differently by the three models. In DICE, a 1 GtC shock was added over the decade which straddles year t, in FUND, a 1 million metric ton carbon (1 MtC) shock was added to every year within a decade

[8] One metric ton of carbon (tC) equals 3.667 metric tons of CO_2 (tCO_2). Thus, one billion metric tons of carbon (GtC) equals 3.667 billion metric tons of CO_2 ($GtCO_2$). Our pulse was in carbon units simply for consistency with the standard units of carbon cycle modeling.

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from year t forward, and in PAGE, 100 billion metric tons of CO_2 (100 $GtCO_2$, 27 GtC) was distributed evenly over the decades preceding and subsequent to year t.[9] For our diagnostic purposes, we standardize the pulse size—a 1 GtC pulse—but retain the model specific implementations with respect to time periods.[10] Thus, the additional CO_2 emissions associated with the 1 GtC pulse appear at different times and magnitudes across the models (Figure 5-8).

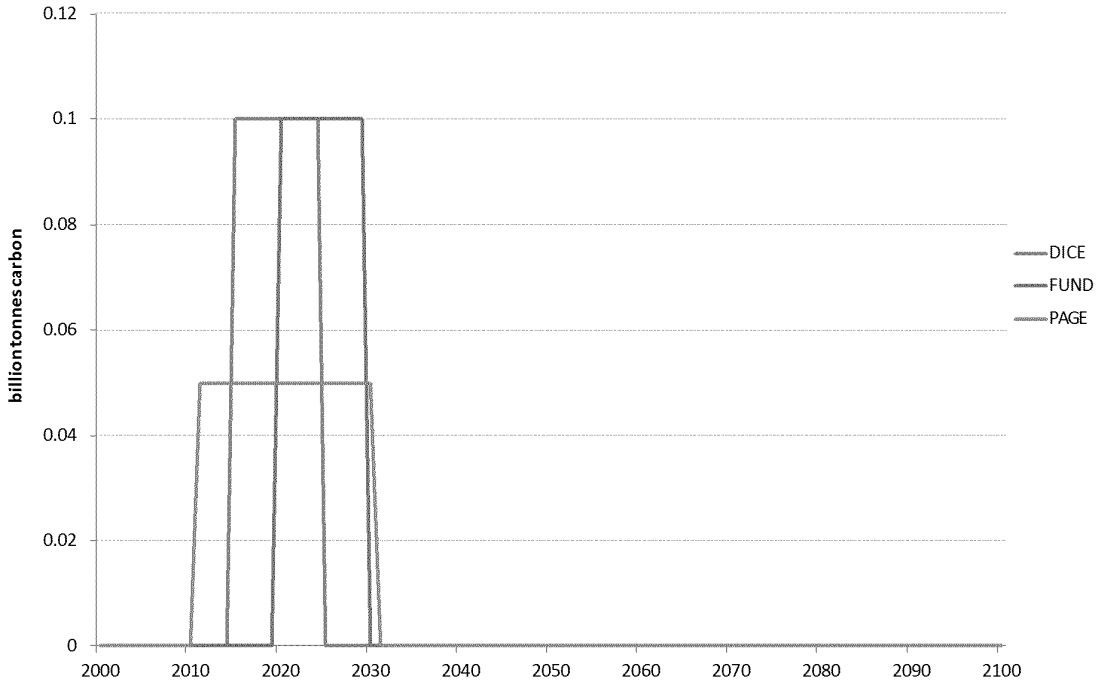

Figure 5-8
Emissions pulse implementation by model of a 1 GtC emissions pulse in 2020

The emissions pulse results in an initial spike in CO_2 concentrations in the atmosphere (Figure 5-9). One billion metric tons of carbon translates to approximately 0.47 parts per million in the atmosphere. However, the initial spikes in CO_2 concentrations do not reach this level, but are instead spread over the first few decades according to the different pulse timing implementations, as well as differences in carbon cycle modeling. For instance, FUND's increase in CO_2

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[9] Note that with PAGE, the emissions pulse is initially introduced as a uniform increase in average annual CO_2 emissions over the given period associated with year t. However, within PAGE's climate model, emissions for years t-1 and t are averaged. Thus, the emissions pulse enters PAGE's carbon cycle as uniform (but half-sized) increases in average annual emissions in both the decades preceding and following year t. In Figure 5-8, we show the pulse as it appears to PAGE's carbon cycle.

[10] A billion tonne increase in carbon is large given that the SCC is the value of an additional tonne of carbon dioxide. With a side analysis, we evaluated the implications of emissions shock size and found that the climate responses scaled proportionally relative to the given reference scenario (i.e., an order of magnitude larger emissions shock produced an order of magnitude larger incremental climate response). We did not evaluate whether the incremental climate damages scaled proportionally. We also evaluated standardizing the pulse time implementation, which could be readily done with FUND, but not with PAGE. With FUND, we implemented a pulse like that in DICE and found a moderate shift in incremental CO_2 concentration response.

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concentration begins later than with DICE or PAGE. Notice however that DICE's CO_2 concentration changes prior to the increase in emissions. This is a modeling artifact. USG DICE is averaging CO_2 concentrations across years, which results in the pulse appearing in the climate model prior to the year of the pulse (2020). The different time accounting is also contributing to differences in the overall shapes of the response functions. Differences in the height of the spikes are associated with differences in carbon cycle modeling. For example, PAGE's significantly lower concentration spike is due to its slower carbon cycle.

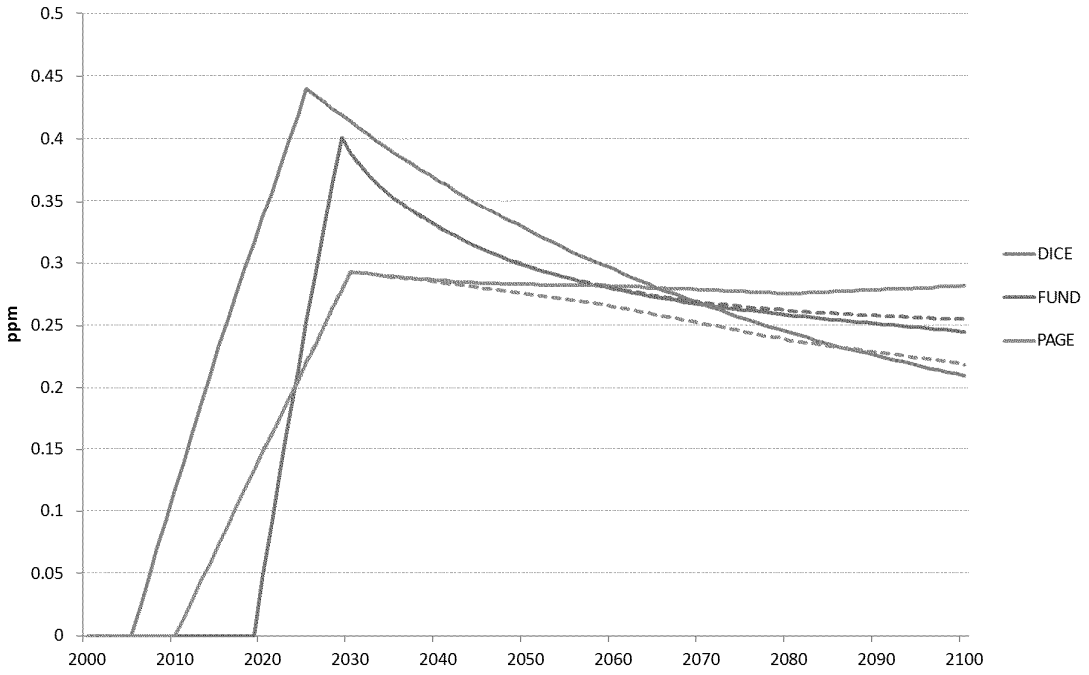

Figure 5-9
Incremental CO_2 concentration response in USG2 (solid) and USG5 (dashed) from a 1 GtC emissions pulse in 2020

After the initial spike, the incremental atmospheric concentration falls in all models as carbon is gradually absorbed by land and ocean sinks. Ignoring climate feedbacks, the response is independent of the emissions scenario pathway, i.e., it is identical for all emissions pathways. This is what we observe from DICE, which has no climate feedback—the incremental CO_2 concentration pathways are identical for the high and low emissions scenarios. However, climate feedbacks are included in FUND and PAGE. For these models, we find differences in the incremental CO_2 concentration response across scenarios. For FUND, the incremental terrestrial carbon feedback is higher at lower temperatures (i.e., off the lower emissions scenario). For PAGE, the incremental terrestrial carbon feedback is higher at higher temperatures (i.e., off the higher emissions scenario). In PAGE, the larger climate feedback off of higher reference temperatures slows the decline in the incremental CO_2 concentration pathway (and may even reverse it as we found in our analysis with other models further below).

Next we evaluate the incremental responses in radiative forcing. The shape of the incremental forcing response over time is similar to the incremental concentration response (Figure 5-10).

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Unlike PAGE, DICE produces a large difference between the two emissions scenarios because it has no compensating climate feedback effect. FUND, on the other hand, also exhibits a large difference between the scenarios because the incremental climate feedback in FUND is reinforcing (working in the same direction).

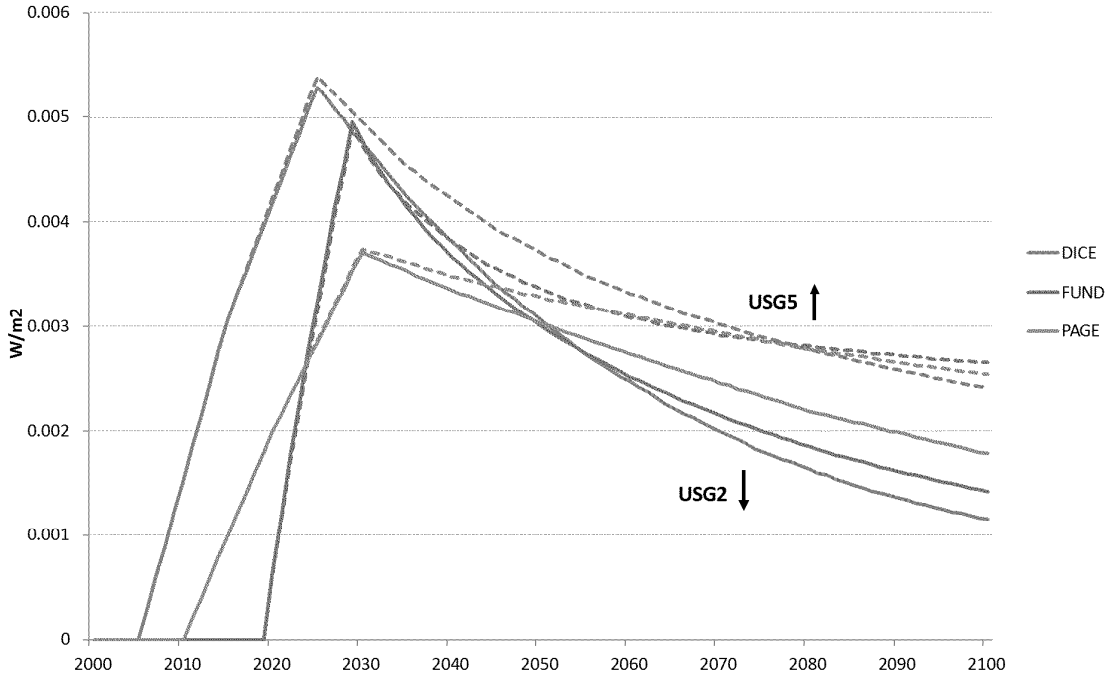

Figure 5-10
Incremental total forcing response in USG2 (solid) and USG5 (dashed) from a 1 GtC emissions pulse in 2020

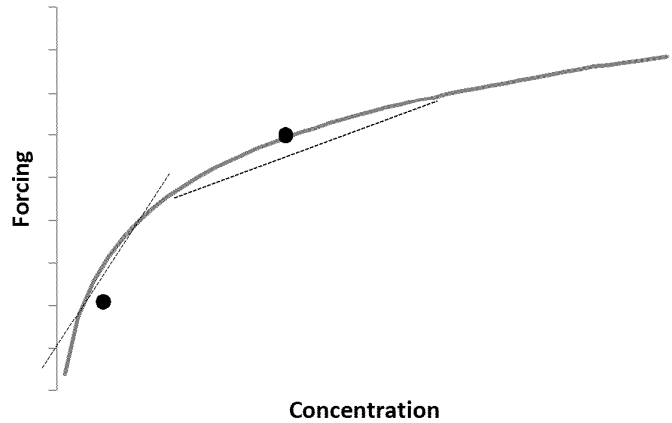

Figure 5-11
Illustrative figure of the logarithmic relationship between radiative forcing of CO_2 and CO_2 concentration

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Another important effect is revealed here. Whereas climate feedbacks caused the incremental concentration response function to vary by emissions scenario, the concave logarithmic function relating CO_2 forcing to CO_2 concentration results in *higher* incremental forcing for scenarios in which emissions are *lower*. This is because the slope of the forcing function is higher for lower concentrations. Figure 5-11 provides a stylized illustration of how the logarithmic function results in a higher marginal forcing from a lower concentration.

The incremental temperature responses are the result of the incremental concentration and forcing responses, as well as the model specific forcing to temperature translations. We find that the incremental temperature pathways are significantly different across models (Figure 5-12). For instance, by 2040, DICE produces an incremental temperature increase that is more than twice that from FUND, with PAGE's response in between but closer to DICE. The slow lag response in FUND is evident: despite having the largest initial forcing response, it has a much lower temperature response for the first half of the century, and indeed the impact on temperature does not peak until nearly the end of the century. By contrast, the DICE response peaks much earlier after the pulse, although the ten-year time step dilutes the pulse response. The PAGE model has similar temperature dynamics but its lower forcing response (due to its slower carbon cycle) leads to an incremental temperature response in the middle. The effect of higher incremental responses with lower emissions scenarios persists in the incremental temperature responses. Also, similar to our observation regarding total temperature, DICE's incremental temperature response is substantially more sensitive than the other models to the emissions scenario through 2100. Beyond 2100, however, it is a different story (discussed later).

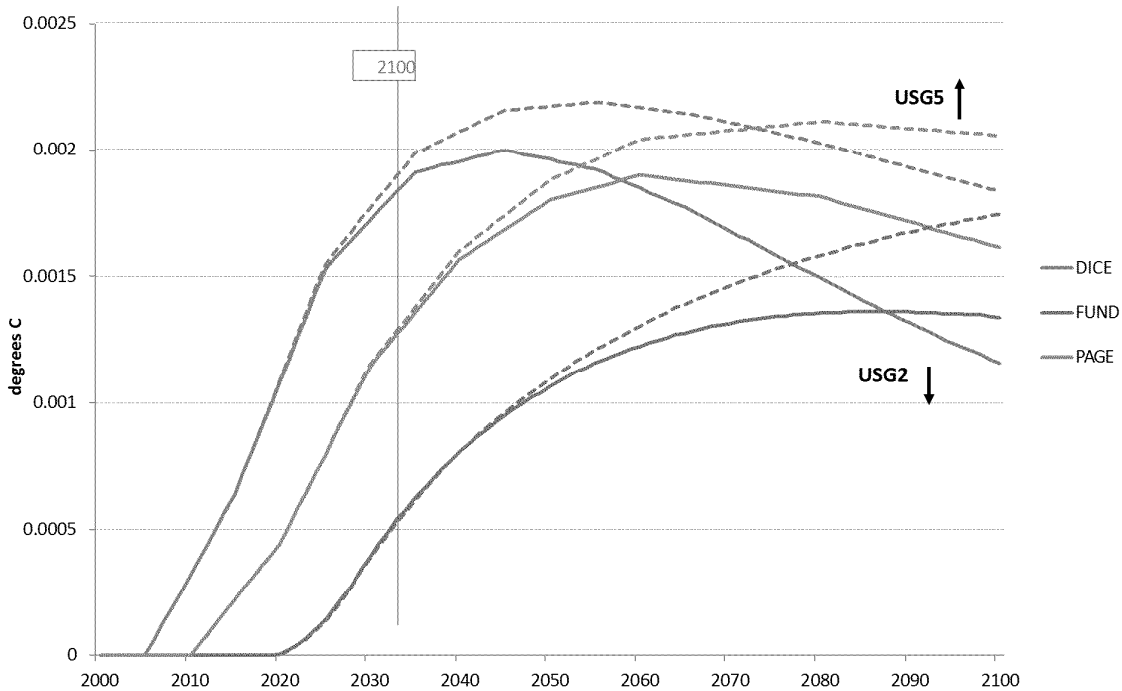

Figure 5-12
Incremental global mean temperature response USG2 (solid) and USG5 (dashed) from a 1 GtC emissions pulse in 2020

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Finally, sensitivity analysis of incremental temperature responses with respect to the climate sensitivity parameter is consistent with our previous finding with respect to total temperature responses that PAGE is significantly more sensitive than DICE and FUND to the assumed climate sensitivity, and FUND is the least sensitive (Figure 5-13). Of course now the larger incremental temperature responses correspond with the lower emissions scenario.

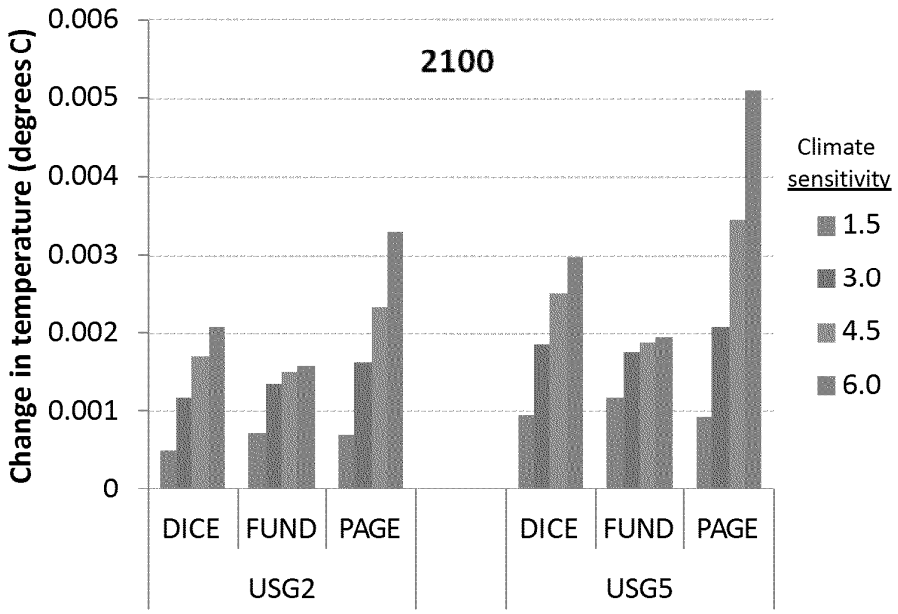

Figure 5-13
Sensitivity of incremental temperature increase in 2100 to climate sensitivity

Overall, we find significant variation in the magnitude and shape of the incremental temperature responses across the three models. These differences have direct implications for SCC estimates and are therefore an important aspect of the modeling that merits further consideration to make sense of the differences, assess their value, and develop an approach for capturing uncertainty. Recall, however, that two of the models included parametric uncertainties in the USG analysis. This dimension is explored next.

Model specific parametric uncertainties

In the USG exercise, the three models entertain different parametric uncertainty in their climate modeling (Table 5-2). FUND and PAGE have 11 and 10 uncertain parameters respectively, while DICE is not considering any model specific uncertainty. For FUND and PAGE, the uncertain parameters vary, as does the uncertainty specifications, in terms of their numerical specification as well as assumed distributions, with FUND using a variety of distributional assumptions, and PAGE using only triangular distributions. Finally, the random sampling schemes differ, with PAGE using Latin Hypercube sampling and FUND using Monte Carlo sampling.

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Table 5-2
Model specific uncertain climate component parameters

Model	# of uncertain parameters	Distribution types	Sampling scheme
DICE	0	n/a	n/a
FUND	11	Normal, Truncated normal, Triangular, Gamma	Monte Carlo
PAGE	10	Triangular	Latin Hypercube

For our analysis, we developed probabilistic versions of each climate model. We then carried out random sampling of the uncertain parameters and ran the relevant models for each sample draw. Specifically, we performed 2,500 random draws, with the model specific uncertain parameters treated as independent, and then ran the FUND and PAGE climate models 2,500 times.[11] Climate sensitivity uncertainty is not included at this point. We want to isolate and elucidate the model specific parametric uncertainties represented within each model.[12]

Total and increment temperature uncertainty results for the USG2 and USG5 scenarios are shown in Figures 5-14 and 5-15. In both figures, means and percentiles are shown (1st, 5th, 25th, 50th, 75th, 95th, and 99th). The deterministic results discussed previously are also shown for comparison. What is immediately evident is the substantially larger uncertainty modeled in PAGE. For instance, in Figure 5-14 by 2050, FUND reflects a third of a degree of uncertainty in its 98% confidence interval (1st to 99th percentiles) in the USG2 scenario, while PAGE reflects 1.8 degrees of uncertainty. By 2100, for the same confidence interval and scenario, FUND's uncertainty is a half degree, while PAGE's is 2.8 degrees. FUND's uncertainty in the USG5 scenario (Figure 5-15) is similar to that in the USG2 scenario, while PAGE's uncertainty is smaller, but still much larger than FUND's. Note that PAGE's uncertainty in the USG5 scenario is not growing over time as it does in the high emissions scenario.

In the incremental temperature results, PAGE's uncertainty is again far greater than that modeled in FUND. However, the largest uncertainty in PAGE is mid-century with a narrowing by 2100. We observe just the opposite from FUND. Note that each figure also includes the deterministic results. The deterministic results can differ from the probabilistic mean due to non-linearities in the climate system modeling.

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[11] The USG exercise also treated the parameters as independent. However, the USG exercise used 10,000 random samples. We use less due to computing constraints. The smaller sampling is inconsequential for PAGE results because of Latin Hypercube sampling. For FUND, however, the tails could be underrepresented by the smaller number of draws because Monte Carlo sampling is used. We overcame this issue by using Latin Hypercube sampling for FUND as well.

[12] Recall that, in the USG SCC exercise, all three models also entertain a standardized climate sensitivity uncertainty. Results associated with this uncertainty are evaluated later.

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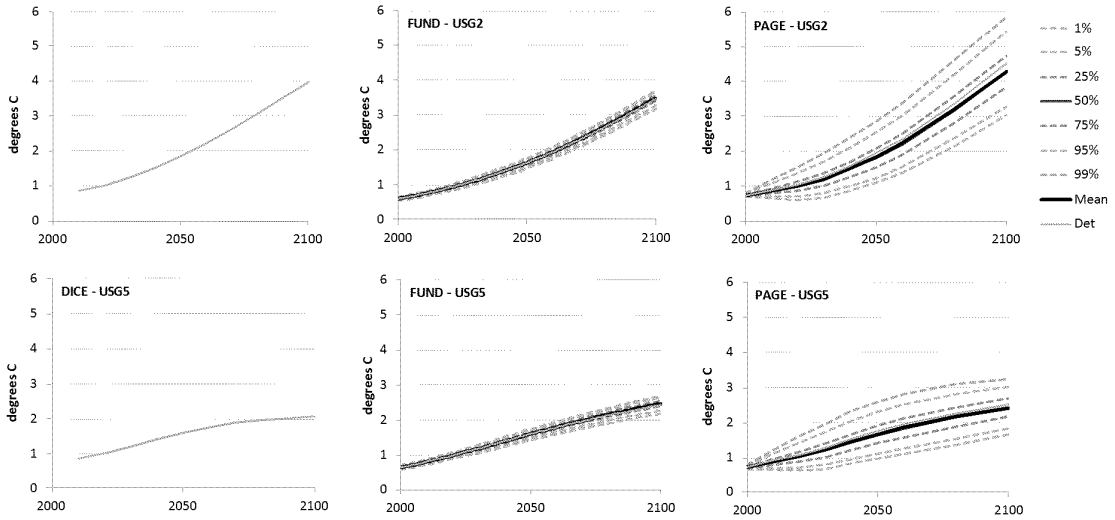

Figure 5-14
Model specific global mean temperature uncertainty to 2100 (percentiles and mean) in USG2 and USG5 scenarios

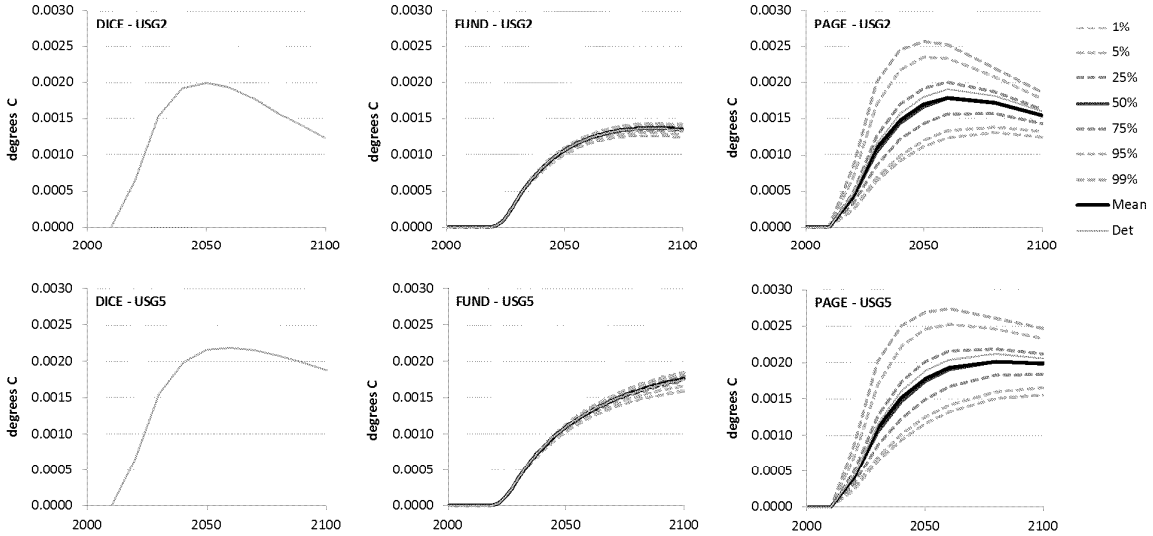

Figure 5-15
Model specific incremental global mean temperature response uncertainty to 2100 (percentiles and mean) in USG2 and USG5 scenarios from a 1 GtC emissions pulse in 2020

A general, but critical, observation here is that the models are considering very different uncertainties—both in type and representation—and, as a result, the models perceive very different potential temperature outcomes, differences that likely affect SCC results. In particular, PAGE's temperature distributions (total and incremental) are broader and right-skewed (i.e., with longer tails towards higher temperatures), while FUND's distributions are tighter and slightly left-skewed. Overall, the models are not modeling the same climate uncertainty space and are therefore unlikely to produce comparable results.

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2100-2300 Results – total and incremental

Results to year 2300 are used in computing the USG SCCs. In this section we therefore analyze climate modeling to 2300. Starting with deterministic results and CO_2 concentrations (Figure 5-16), we find substantially higher concentrations post-2100 and greater differences across models. With the high emissions scenario, DICE and FUND converge and project CO_2 concentrations of over 2000 ppm by 2300. In this scenario, global CO_2 emissions peak in 2200 at almost 40 $GtCO_2$/year and then decline to 28 $GtCO_2$/year in 2300. PAGE concentrations, on the other hand, are well below the other models. This result is due to PAGE's slower carbon cycle, as well as the model's post-2100 emissions implementation (with 100-year time steps post-2100) and emissions averaging across periods. In the low emission scenario, the differences across models are modest through 2100, but post-2100 we find greater separation as FUND's climate feedback accelerates the accumulation of atmospheric carbon. Across scenarios, we see that DICE is still the most sensitive to the emissions scenario post-2100.

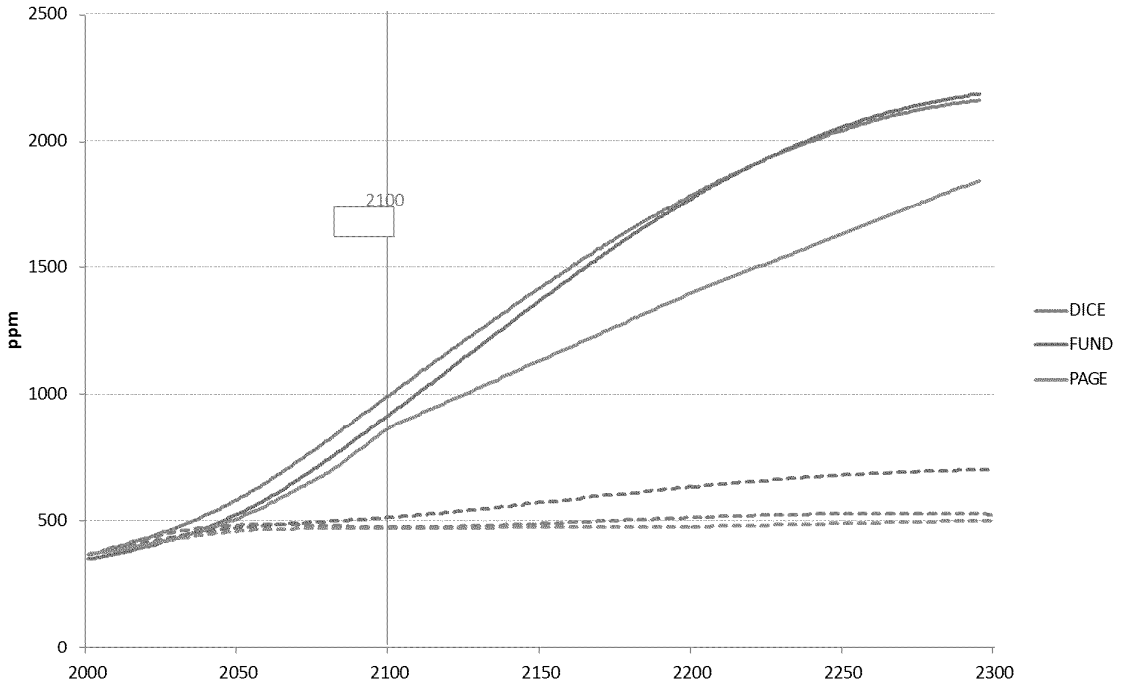

Figure 5-16
CO_2 concentrations to 2300 in USG2 (solid) and USG5 (dashed) scenarios

In Figures 5-17, 5-18, and 5-19, we show radiative forcing to 2300. We find total radiative forcing (Figure 5-19) reaching 12 watts per meter squared in 2300 under the high emissions scenario. The differences in projected forcing across models increase post-2100, driven primarily by differences in carbon cycle modeling and CO_2 forcing (Figure 5-17) that result in lower radiative forcing futures from PAGE and the accelerating total forcing futures from FUND, even in the low emissions scenario. Differences in non-CO_2 forcing post-2100 are present (Figure 5-18) but are somewhat artificial due to the USG exercise assumption of fixed non-CO_2 forcing post-2100 (imposed in DICE and PAGE). Fixed post-2100 non-CO_2 forcing is a clear departure from the rising pre-2100 trends exhibited.

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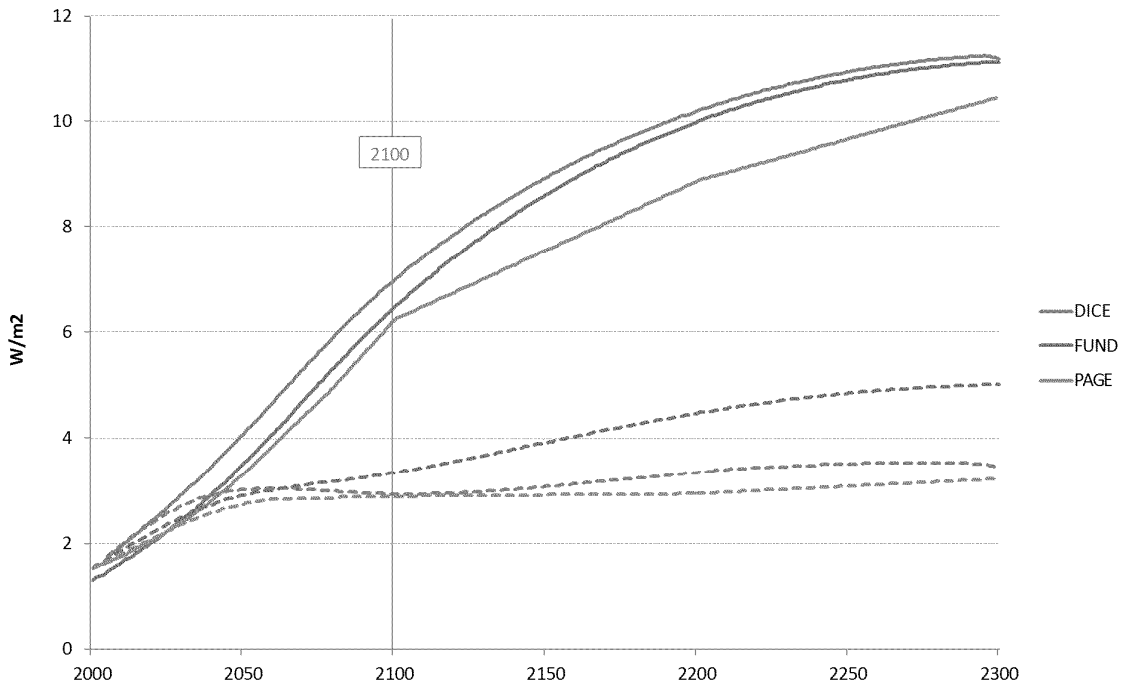

Figure 5-17
CO_2 forcing to 2300 in USG2 (solid) and USG5 (dashed) scenarios

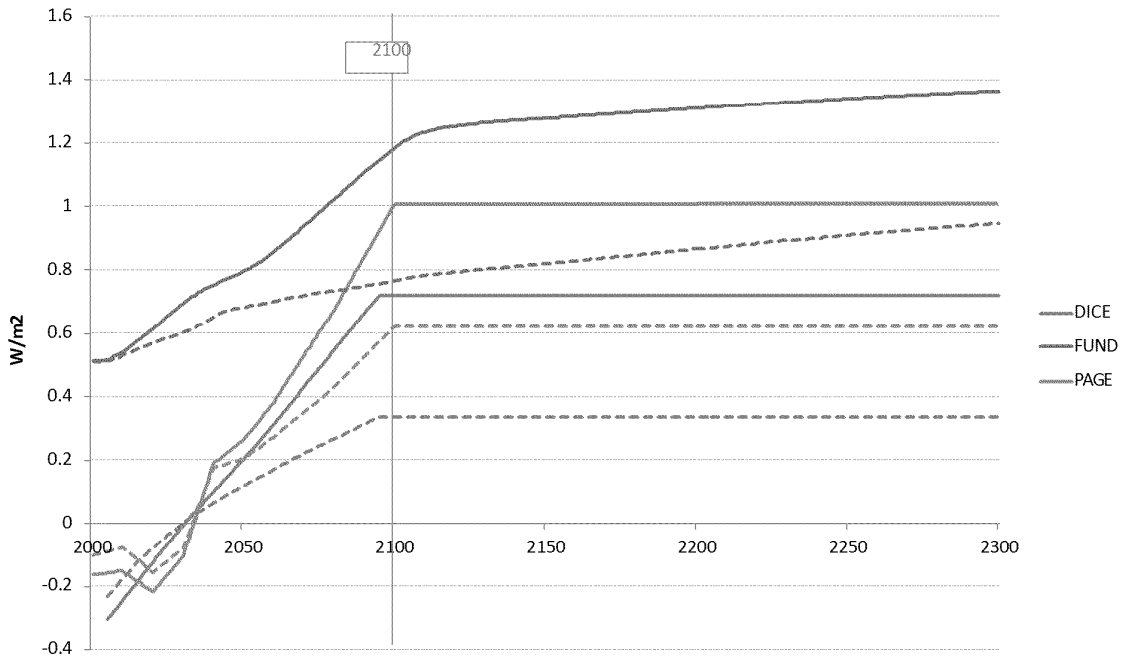

Figure 5-18
Non-CO_2 forcing to 2300 in USG2 (solid) and USG5 (dashed) scenarios

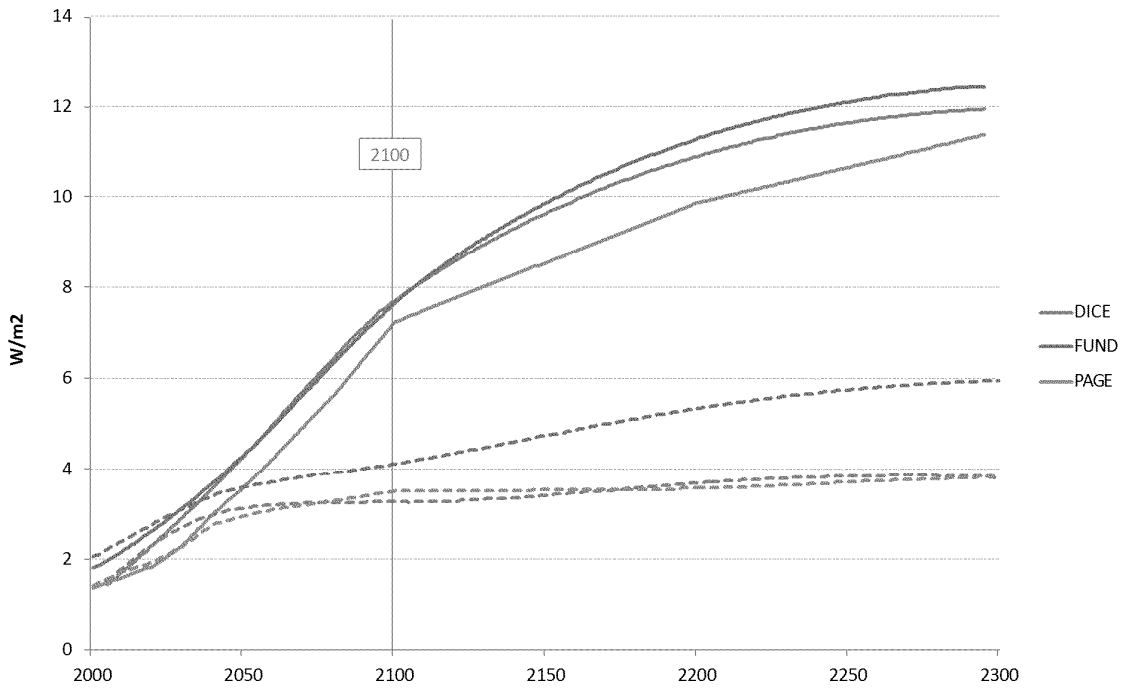

Figure 5-19
Total forcing to 2300 in USG2 (solid) and USG5 (dashed) scenarios

By 2300, we find temperature increases of 8 to 9 degrees Celsius under the high emissions scenario, and an even broader range of 2.8 to 4.5 degrees in the low emissions scenario (Figure 5-20). FUND's climate feedback, in particular, results in temperature growth rates post-2100 that are much greater than those from DICE and PAGE in both the high and low emissions scenarios. And, while there are similar differences in projected temperature increase across models in 2100 and 2300, the ordering has changed, with PAGE projecting the largest temperature increase by 2100, but FUND projecting the largest temperature increase by 2300.

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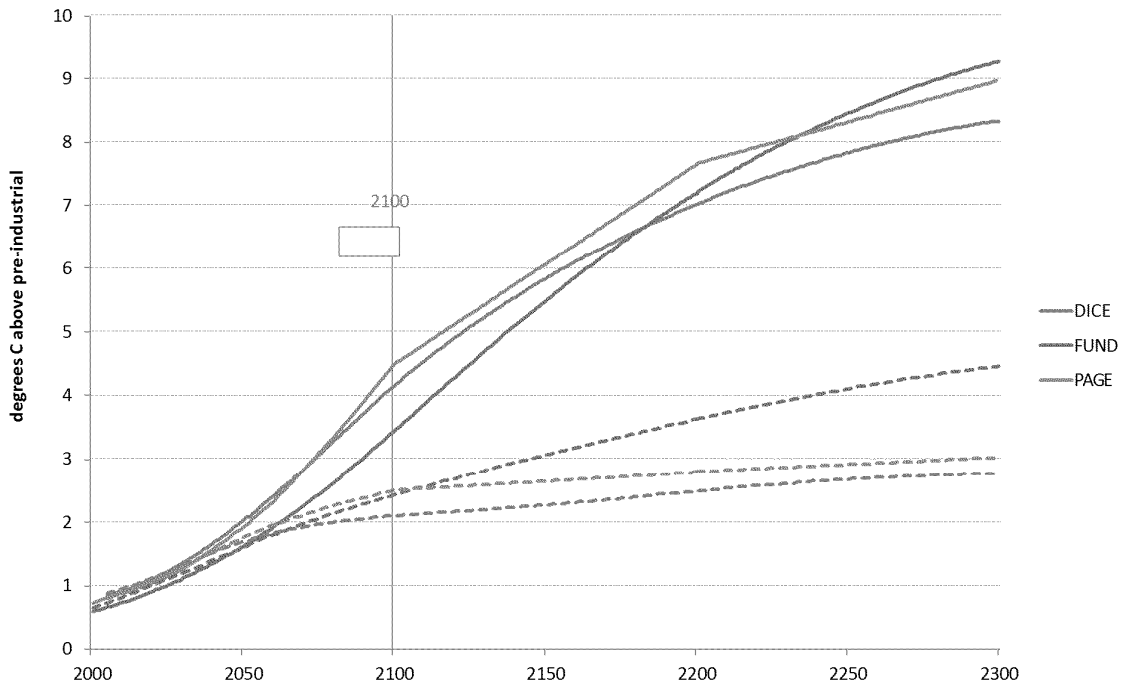

Figure 5-20
Global mean temperature to 2300 in USG2 (solid) and USG5 (dashed) scenarios

Looking at the post-2100 incremental climate responses to the emissions pulse, we find much larger variation in incremental CO_2 concentrations across the three models than observed pre-2100 (Figure 5-21). For instance, the variation across USG2 results is almost twice as large in 2200 versus 2100. Incremental concentration increases generally decline post-2100, but the rates of decline vary significantly. In addition, the differences in carbon cycle feedbacks between the models are even more pronounced in post-2100 concentrations. We also observe that FUND's and PAGE's results post-2100 are much more responsive to the emissions scenarios than they were pre-2100.

In the incremental radiative forcing responses to 2300 (Figure 5-22), we find DICE's forcing declining much more quickly than with FUND and PAGE, and FUND the most sensitive to the emissions scenario. Variation in forcing across models for a given emissions scenario are fairly similar in 2100 and 2300, however there is some re-ranking.

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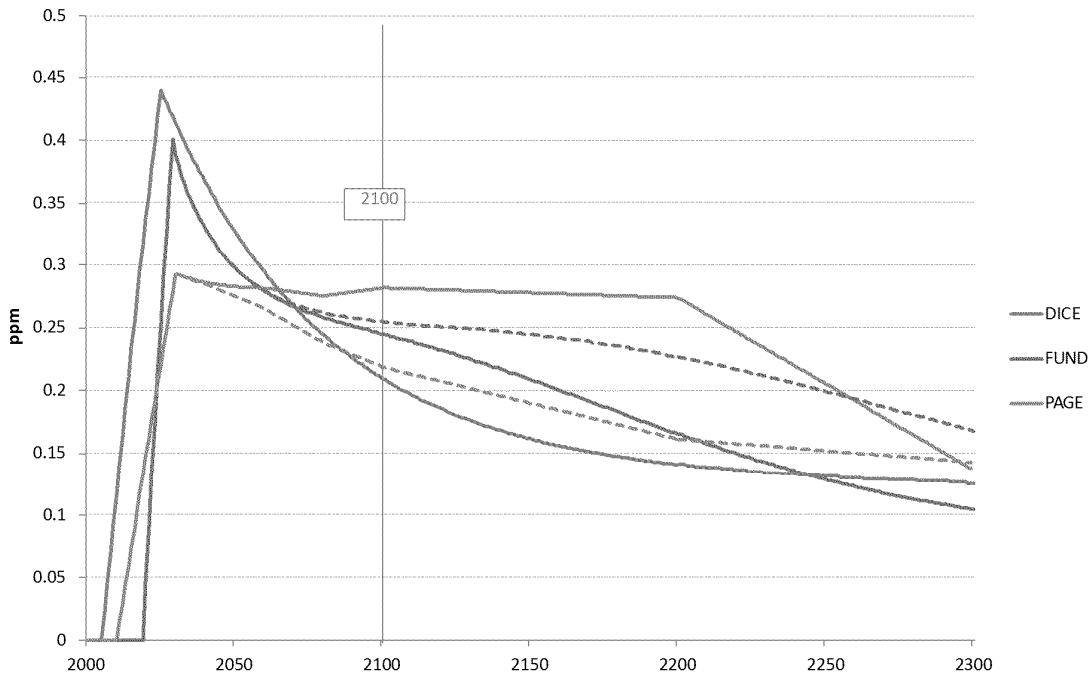

Figure 5-21
Incremental CO_2 concentration response to 2300 in USG2 (solid) and USG5 (dashed) scenarios from a 1 GtC emissions pulse in 2020

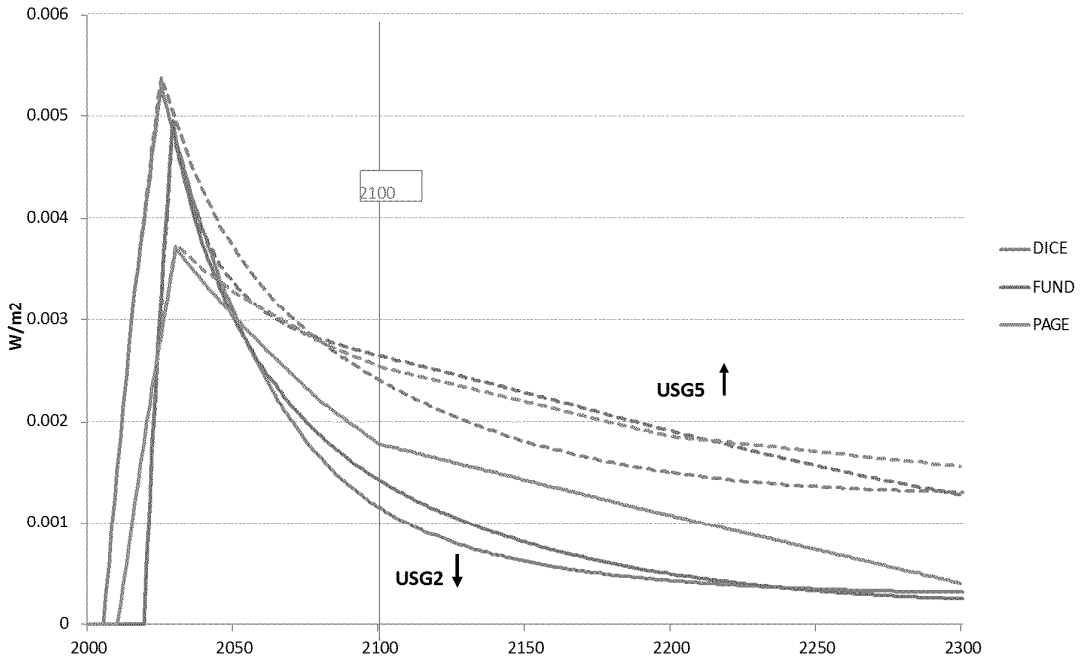

Figure 5-22
Incremental total forcing response to 2300 in USG2 (solid) and USG5 (dashed) scenarios from a 1 GtC emissions pulse in 2020

In the post-2100 incremental temperature responses, we find more pronounced differences across models than we observed pre-2100, including a re-ordering (Figure 5-23). In particular, FUND's incremental temperature responses peak after 2100, while the other models peak before 2100. In the lower emissions scenario, FUND has notably higher incremental temperature change than the other models post-2100.

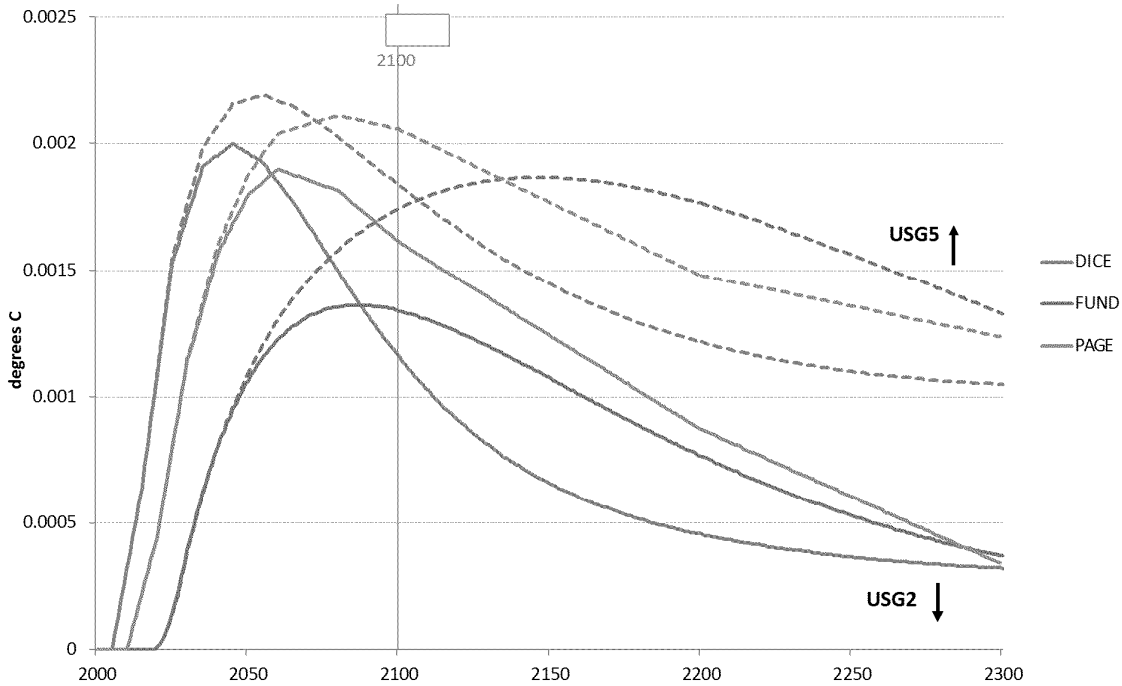

Figure 5-23
Incremental global mean temperature response to 2300 in USG2 (solid) and USG5 (dashed) scenarios from a 1 GtC emissions pulse in 2020

Finally, in the model specific probabilistic incremental temperature change results (Figures 5-24 and 5-25), we see that PAGE is considering substantially more temperature change uncertainty than the other models all the way through to 2300. This is evident in both the total and incremental global mean temperature change results. In the total results, we find the PAGE temperature change distribution in a given post-2100 year to be stable and symmetric, while the FUND distribution is widening over time and slightly left-skewed (i.e., skewed towards lower temperatures). For both models, the distribution is wider under the high emissions scenario. However, the opposite effect is observed in the incremental results—the distributions for incremental temperature change for both PAGE and FUND are broader under the low emissions scenario. In both models the distributions are tightening over time post-2100.

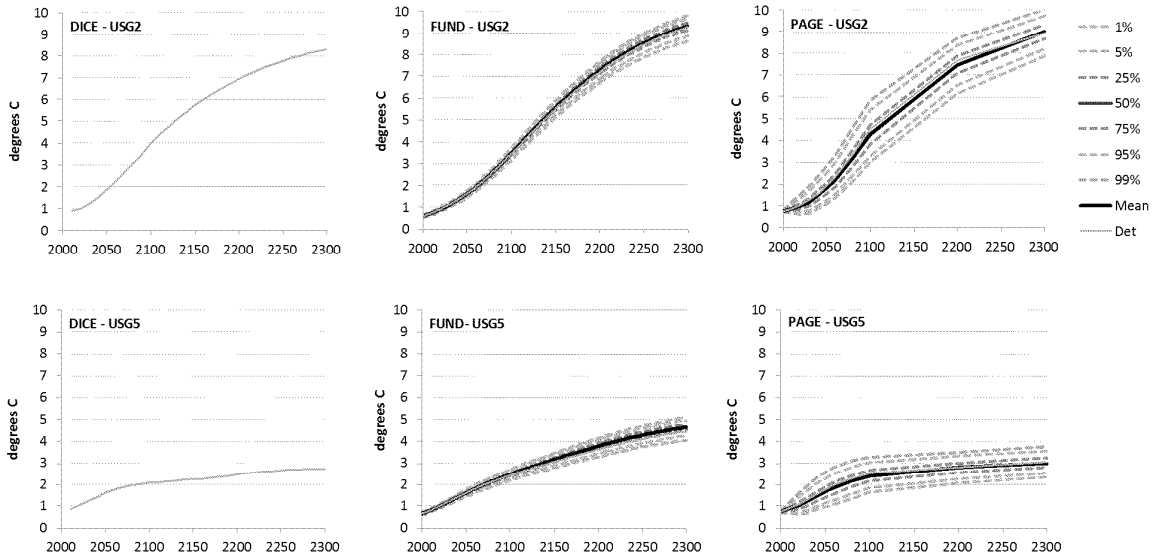

Figure 5-24
Model specific global mean temperature uncertainty to 2300 (percentiles and mean) in USG2 and USG5 scenarios

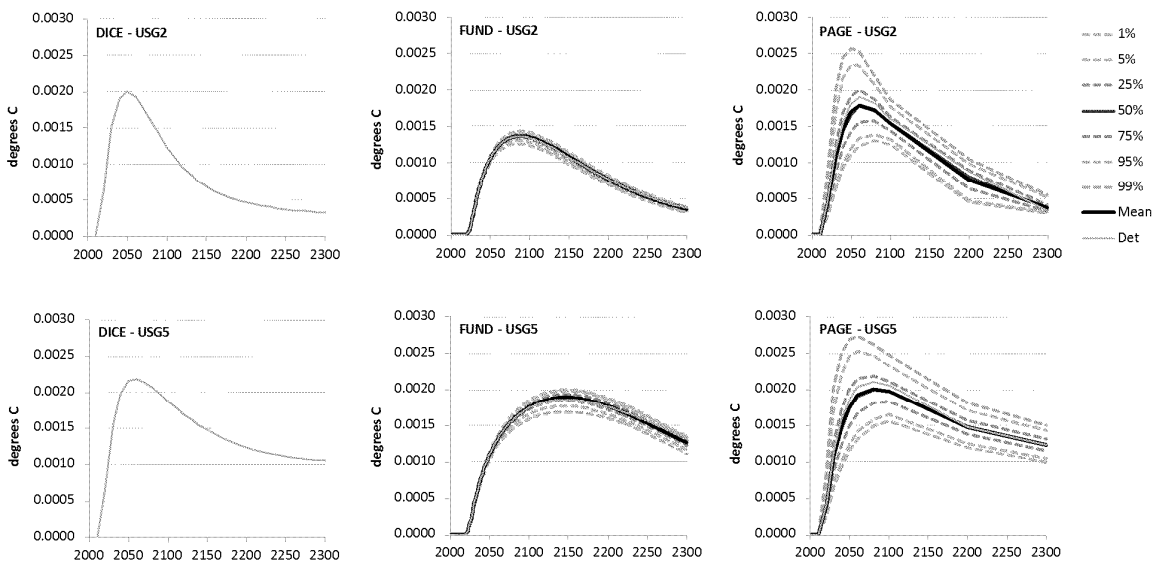

Figure 5-25
Model specific incremental global mean temperature response uncertainty to 2300 (percentiles and mean) in USG2 and USG5 scenarios from a 1 GtC emissions pulse in 2020

Cross model comparison analysis – comparison to other models

In order to better assess the climate outcomes produced by the three USG SCC models, it is helpful to compare with more detailed climate models. Specifically, we compare model responses to an intermediate complexity climate model that is widely used in the literature, the

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Model for Assessment of Greenhouse Gas Induced Climate Change, or MAGICC. While MAGICC is still a reduced-complexity climate model, it has far greater detail of the relevant physical processes than the three USG models and has been calibrated to re-produce the behavior of the much more complex General Circulation and Earth System models (GCMs and ESMs). The most recent version, MAGICC6, is available for public download.[13]

For comparison with MAGICC6, we need common inputs. For this purpose, we turn to the Representative Concentration Pathways (RCPs). The RCPs are alternative sets of consistent radiative forcing related emissions projections developed to be standardized inputs for climate modeling comparison exercises and to facilitate a new generation of scenarios research (Moss et al., 2010; van Vuuren et al., 2011). RCP-based climate projections are now available in the literature (IPCC, 2013; Arora et al., 2013) and we are able to run RCP inputs through the USG SCC climate models, as well as MAGICC6, and make comparisons. We focus on the high and low forcing RCPs—RCP8.5 and RCP3-PD respectively. RCP8.5 is a consistent set of emissions projections that corresponds with a radiative forcing level of 8.5 W/m^2 in 2100, and RCP3-PD is a different consistent set of emissions projections that corresponds with radiative forcing that peaks at 3 W/m^2 mid-century before 2100 and then declines to 2.6 W/m^2 in 2100 (RCP3-PD is sometimes labeled RCP 2.6 in publications). The corresponding RCP radiative forcing levels (and labels) are from the integrated assessment models that originally produced the emissions projections (Moss et al., 2010; van Vuuren et al., 2011). Climate model radiative forcing results running RCP emissions inputs may or may not match these levels.

To implement the RCPs in the USG SCC climate models, we use RCP emissions and MAGICC RCP non-CO_2 forcing where needed for each model. The MAGICC non-CO_2 forcing was developed as part of the original RCP exercise (Meinshausen et al., 2011). Total CO_2 emissions (fossil fuel plus land) for the two RCP scenarios are roughly comparable to the USG2 and USG5 scenarios through 2100 (Figure 5-26). However, beyond 2100, they differ substantially, with RCP8.5 CO_2 far less than USG2, and RCP3-PD CO_2 notably lower (and negative) then the positive annual emissions in USG5. Differences in emissions implementation across models are also shown in Figure 5-26.

[13] See magicc.org. For a model description of MAGICC6, see Meinshausen, Raper, and Wigley (2011).

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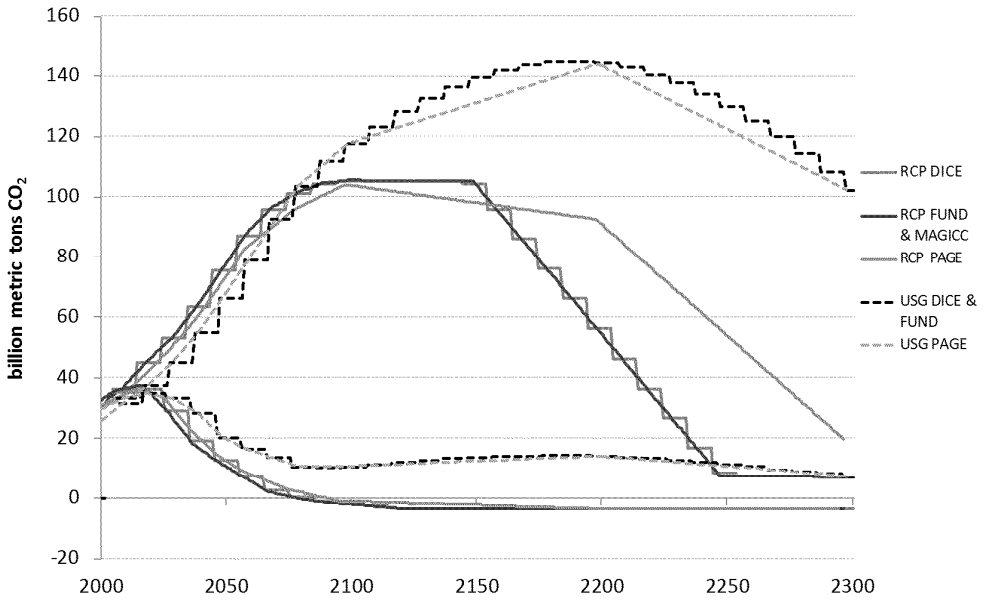

Figure 5-26
Global CO_2 emissions implementation for RCP8.5 (solid colored) and RCP3-PD (dashed colored) scenarios relative to USG2 (solid black/grey) and USG5 (dashed black/grey) scenarios

Total climate responses

Figure 5-27 shows CO_2 concentrations for the two RCP scenarios in MAGICC6 and the three USG models. MAGICC can be configured to emulate different carbon cycle models, in which there is significant variation, particularly with respect to the strength of climate feedbacks. Plotted are MAGICC results for two alternative carbon cycle models, the Bern model, typically used as a default setting for MAGICC6, and the Hadley model, which has one of the largest climate feedbacks through adverse precipitation effects on rainforest carbon stocks. The USG SCC models, in this deterministic mode, produce about 140 ppm of variation in 2100 in the high emissions case. Adding the MAGICC results doubles this range. The MAGICC trajectories are also approaching 2100 with steeper slopes than the USG models. Both observations suggest that there are reasonable alternative carbon cycle representations to those in the USG models and it may be important for the USG exercise to consider these alternatives going forward. Further below, we compare probabilistic results to MAGICC to better gauge the uncertainties being modeled in the USG exercise.

Figure 5-28 shows radiative forcing from CO_2. DICE and FUND have higher mid-century CO2 forcing responses than MAGICC, but MAGICC CO_2 forcing accelerates due to climate feedbacks (Hadley in particular). MAGICC's sensitivity to the emissions scenario is similar to DICE's and FUND's, and PAGE's carbon cycle continues to be the least sensitive.

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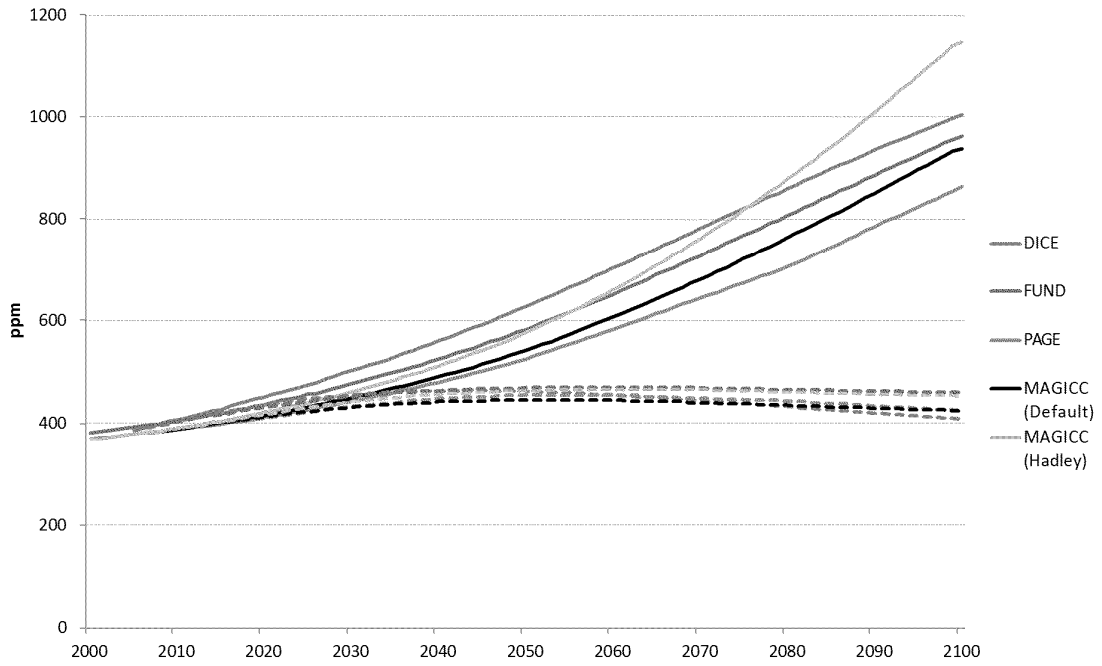

Figure 5-27
CO_2 concentrations in MAGICC vs. the USG models for the RCP8.5 (solid) and RCP3-PD (dashed) scenarios

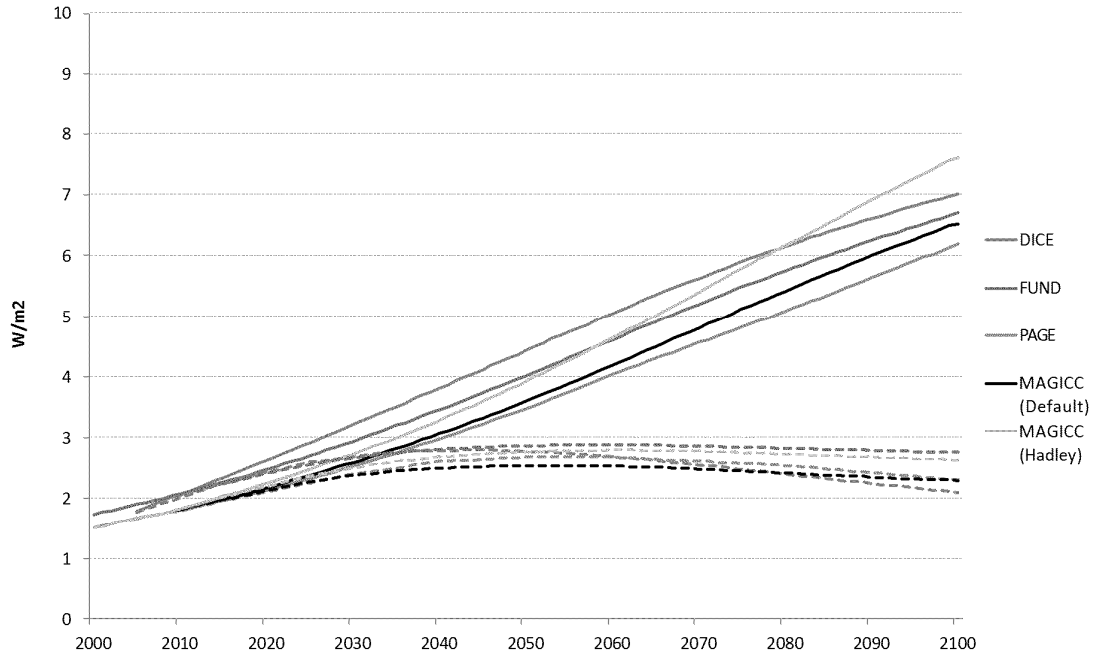

Figure 5-28
CO_2 forcing in MAGICC vs. the USG models for the RCP8.5 (solid) and RCP3-PD (dashed) scenarios

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Figure 5-29 shows non-CO_2 radiative forcing. For this comparison, the MAGICC-derived values for non-CO_2 forcing included with the original RCP emissions projections were used to calculate the residual for DICE. Thus, the DICE non-CO_2 forcing matches MAGICC closely. For PAGE, non-CO_2 forcing is based on a combination of native model calculations driven by the emissions inputs for covered substances and residual forcing in the RCP scenarios. For FUND, non-CO_2 forcing is based strictly on native model calculations, but for the limited number of substances. We find notable discrepancies in non-CO_2 forcing across the models, beginning with one watt per square meter of variation in 2000, and ending with over a watt per square meter of variation by 2100. Excluded forcing categories are defining the FUND results, while SO_2 forcing modeling is distinguishing the PAGE results. For instance, PAGE SO_2 forcing calculations are calibrated to the IPCC's Third Assessment Report (IPCC, 2001), which has a larger negative forcing than suggested by more recent estimates (IPCC, 2007) to which MAGICC is calibrated.

Figure 5-30 shows total radiative forcing. The combination of carbon cycle and forcing differences across models results in about two watts per square meter of variation across models by as early as 2050 with RCP8.5, and one watt per square meter of variation by 2050 with RCP3-PD. By 2100, we observe two watts per square meter of variation under both emissions scenarios.

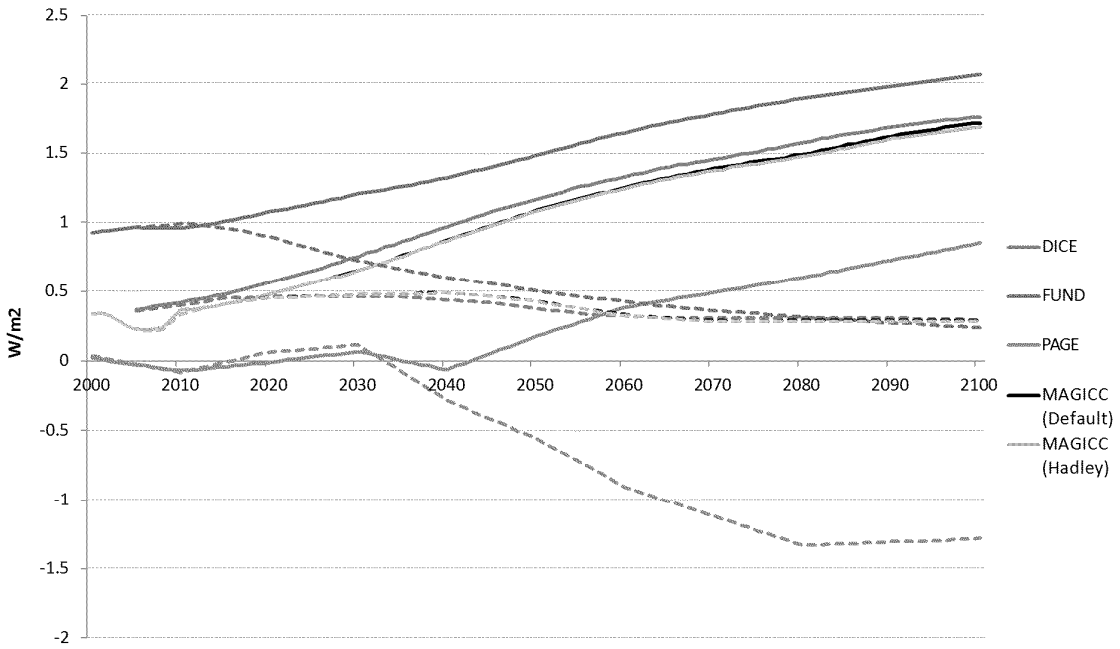

Figure 5-29
Non-CO_2 forcing in MAGICC vs. the USG models for the RCP8.5 (solid) and RCP3-PD (dashed) scenarios

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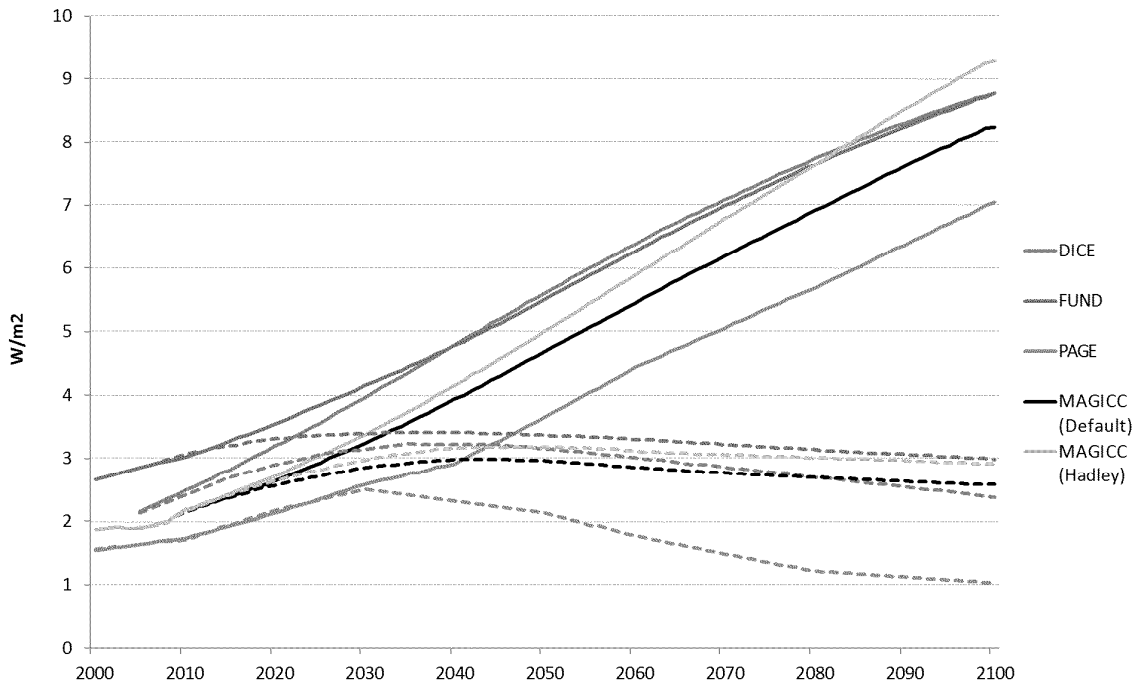

Figure 5-30
Total forcing in MAGICC vs. the USG models for the RCP8.5 (solid) and RCP3-PD (dashed) scenarios

In Figure 5-31, global mean temperature change results are plotted. The FUND model has a slow temperature response relative to MAGICC-Default, starting higher but ending roughly a half degree C lower by the end of the century in the RCP8.5 scenario. The DICE model, which has higher forcing, has a more similar temperature pattern to MAGICC-Default, but higher, while PAGE is initially slower, but faster than MAGICC-Default later. For the lower emissions RCP3-PD scenario, the FUND model's slow response again results in a higher temperature path, and in fact the DICE model also responds slowly to the steep drop in emissions and corresponding peak and decline of forcing. The MAGICC results are lower, but PAGE produces the lowest temperature change projection, one that declines to one degree Celsius by 2100. The MAGICC-Hadley results suggest that there is additional uncertainty to consider beyond the USG models. By 2100, we find about one degree Celsius of variation across models with the high emissions scenario, and about 1.3 degree Celsius of variation with the lower emissions scenario. Comparing the sensitivity of the models to the emissions scenarios, we find MAGICC to be the most sensitive but similar to the sensitivity of DICE and PAGE, with FUND the least sensitive and substantially different than all the other models.

Incremental climate responses

Next, we compare the MAGICC and USG SCC models incremental climate responses to the 2020 1 GtC pulse. MAGICC has annual time steps, so we implemented the emissions pulse in MAGICC as was done in FUND (0.1 GtC per year increase for a decade starting in 2020).

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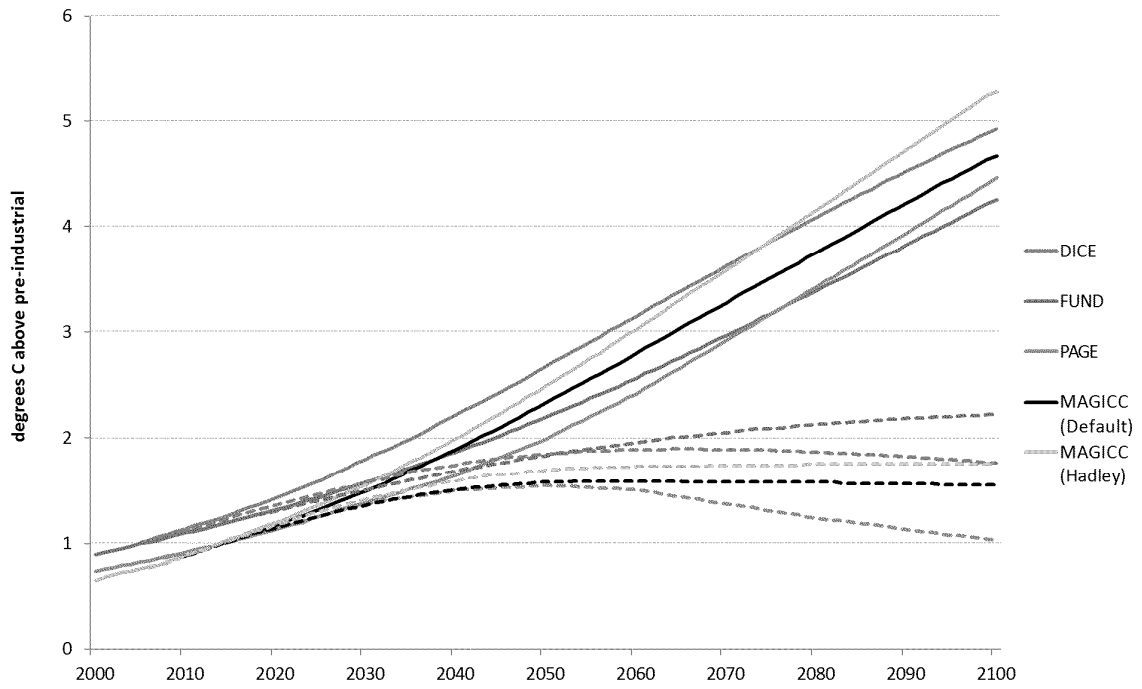

Figure 5-31
Global mean temperature increase in MAGICC vs. the USG models for the RCP8.5 (solid) and RCP3-PD (dashed) scenarios

As with the USG models, MAGICC produces an initial spike in CO_2 concentration (Figure 5-32). MAGICC's peak incremental temperature increase is below the peaks from DICE and FUND, but above PAGE. PAGE and DICE exhibit very different initial dynamics with the carbon cycle representation spreading out the atmospheric response over time, and back in time. Note that for the MAGICC results (along the high emissions RCP8.5 pathway), incremental atmospheric carbon declines but then increases due to climate feedbacks from the incremental temperature increase. In the MAGICC-Hadley results the climate feedback is so strong that, by 2100, atmospheric carbon has increased by more than the 1 billion tonne pulse (0.47 ppm).

MAGICC, like PAGE, but unlike FUND, produces a higher incremental increase in concentrations off the high emissions scenario. And, MAGICC is more sensitive to the emissions scenario than any of the USG models. The MAGICC results broaden the range of possible outcomes substantially for a given emissions scenario. For instance, for RCP8.5, the USG models produce incremental concentration increases of 0.21 – 0.28 ppm in 2100. Including the MAGICC results, expands the range to 0.21 – 0.48 ppm.

The incremental total forcing responses are shown in Figure 5-33. As observed earlier, the shape over time is similar to the concentration function, and the lower emissions scenario generates the higher incremental forcing in all models, including MAGICC. The MAGICC results broaden the range of RCP3-PD and RCP8.5 responses, not just in 2100, but throughout the trajectory. Note that the climate feedbacks in MAGICC imply smaller differences in incremental forcing between the two RCP emissions scenarios as they push the model to higher concentrations and a smaller difference in the incremental logarithmic forcing response.

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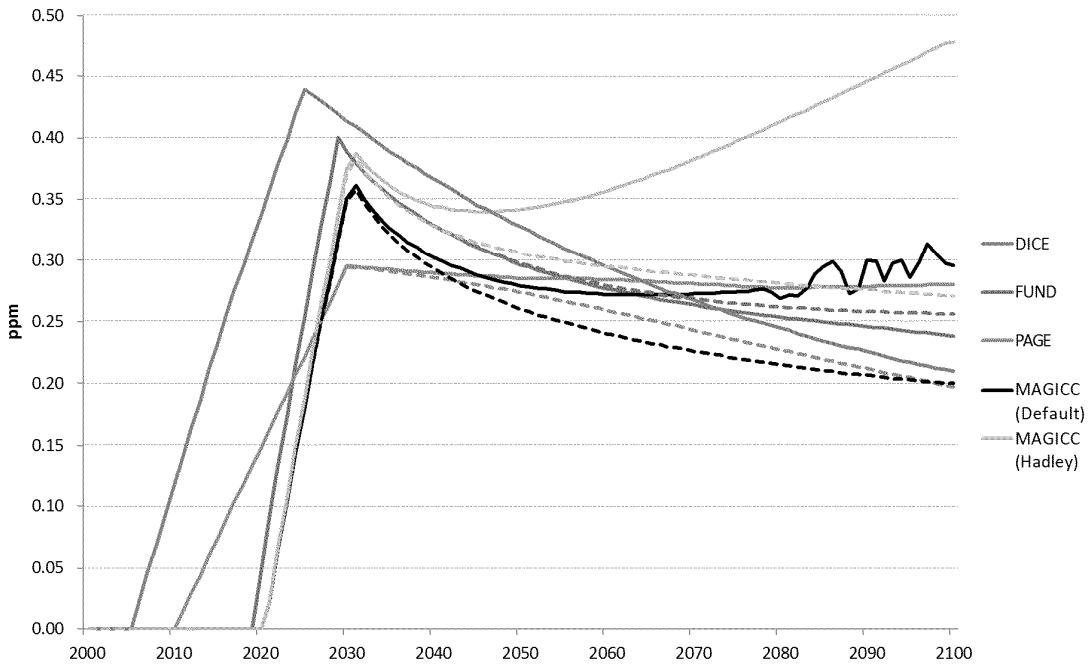

Figure 5-32
Incremental response of CO_2 concentrations for the RCP8.5 (solid) and RCP3-PD (dashed) scenarios from a 1 GtC emissions pulse in 2020

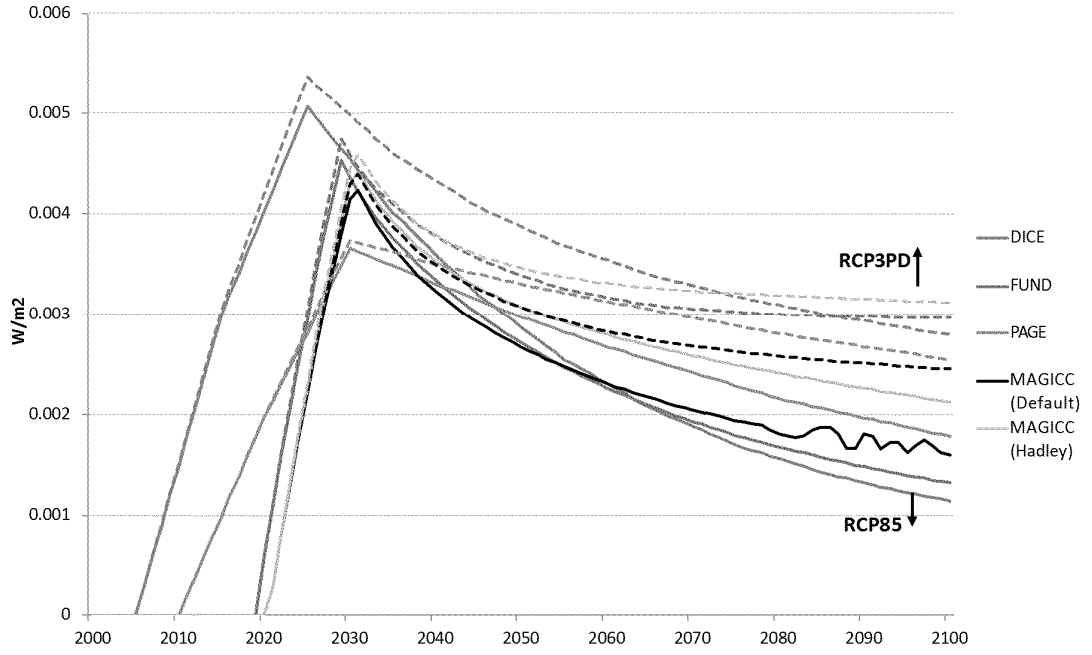

Figure 5-33
Incremental response of total forcing for the RCP8.5 (solid) and RCP3-PD (dashed) scenarios from a 1 GtC emissions pulse in 2020

The incremental temperature responses are shown in Figure 5-34. Like with the USG models, the incremental temperature response in MAGICC is higher for the lower emissions scenario. However, the MAGICC responses exhibit a much earlier and sharper peak and decline than any of the USG models, but MAGICC peaks at a lower level through 2100 than DICE and PAGE. The MAGICC response function peaks in the first decade right after the pulse ceases. The DICE incremental temperature dynamics are closest to MAGICC, although the ten-year time step dilutes the pulse response. The PAGE model has similar temperature dynamics but its lower forcing response (due to its slow carbon cycle) leads to an incremental temperature response in the middle. FUND has the slowest response and not until around 2080 does the annual incremental temperature increase reach that of the other models. Note that the slope of the projections headed into 2100 is an important consideration as well (discussed below).

Overall, the MAGICC incremental climate response magnitudes and shapes over time are so different from those produced by the USG models, especially the carbon cycle and immediate temperature peak following the pulse, that further assessment would be practical.

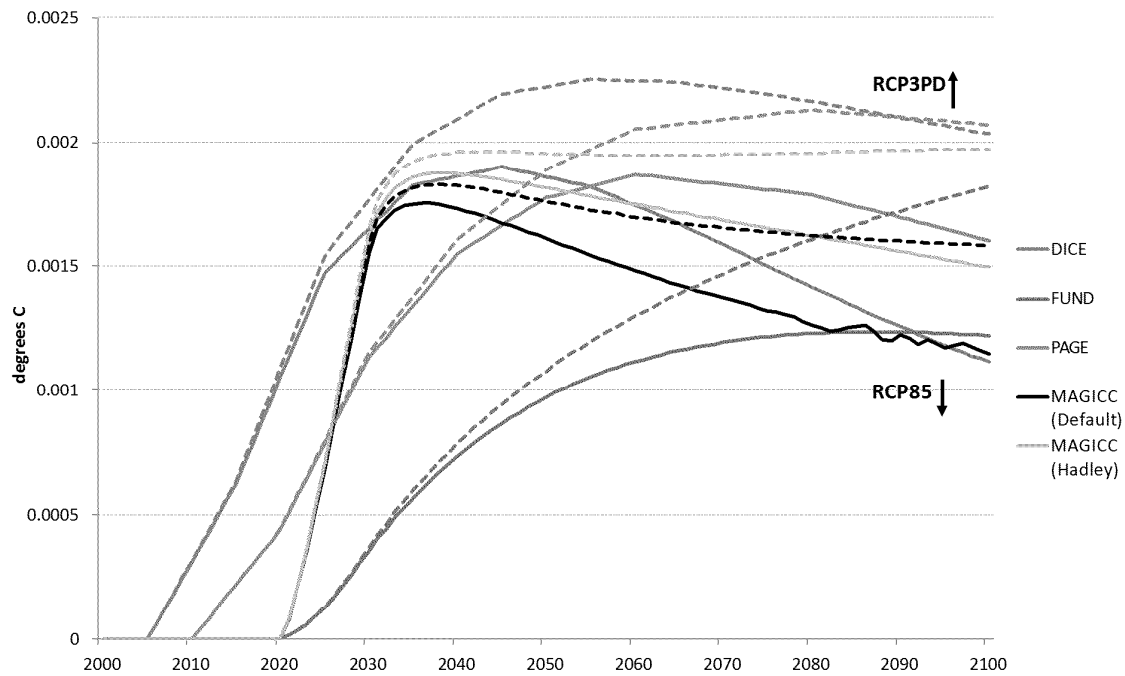

Figure 5-34
Incremental response of Global Mean Temperature for the RCP8.5 (solid) and RCP3-PD (dashed) scenarios from a 1 GtC emissions pulse in 2020

Probabilistic results

The online version of MAGICC also allows for the running of probabilistic scenarios that result in outcome distributions for a limited number of variables—CO_2 concentrations and temperature. The probabilistic runs are based on the model authors' characterization of uncertainty over underlying parameters (Meinshausen et al., 2009). MAGICC's characterization of parametric climate modeling uncertainty differs notably from that represented in the USG models. For instance, MAGICC considers significantly more uncertain parameters (82), versus the USG

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modeling (Table 5-2). Furthermore, MAGICC has different parameter uncertainty specifications. Of particular note, is the specification of climate sensitivity uncertainty, where MAGICC uses a different distribution assumption with a thinner right tail. MAGICC also uses a different probabilistic approach, one that provides limited upfront parameter specification and selects scenarios ex post based on parameter combinations that replicate history and reconcile with climate sensitivity distributional assumptions.

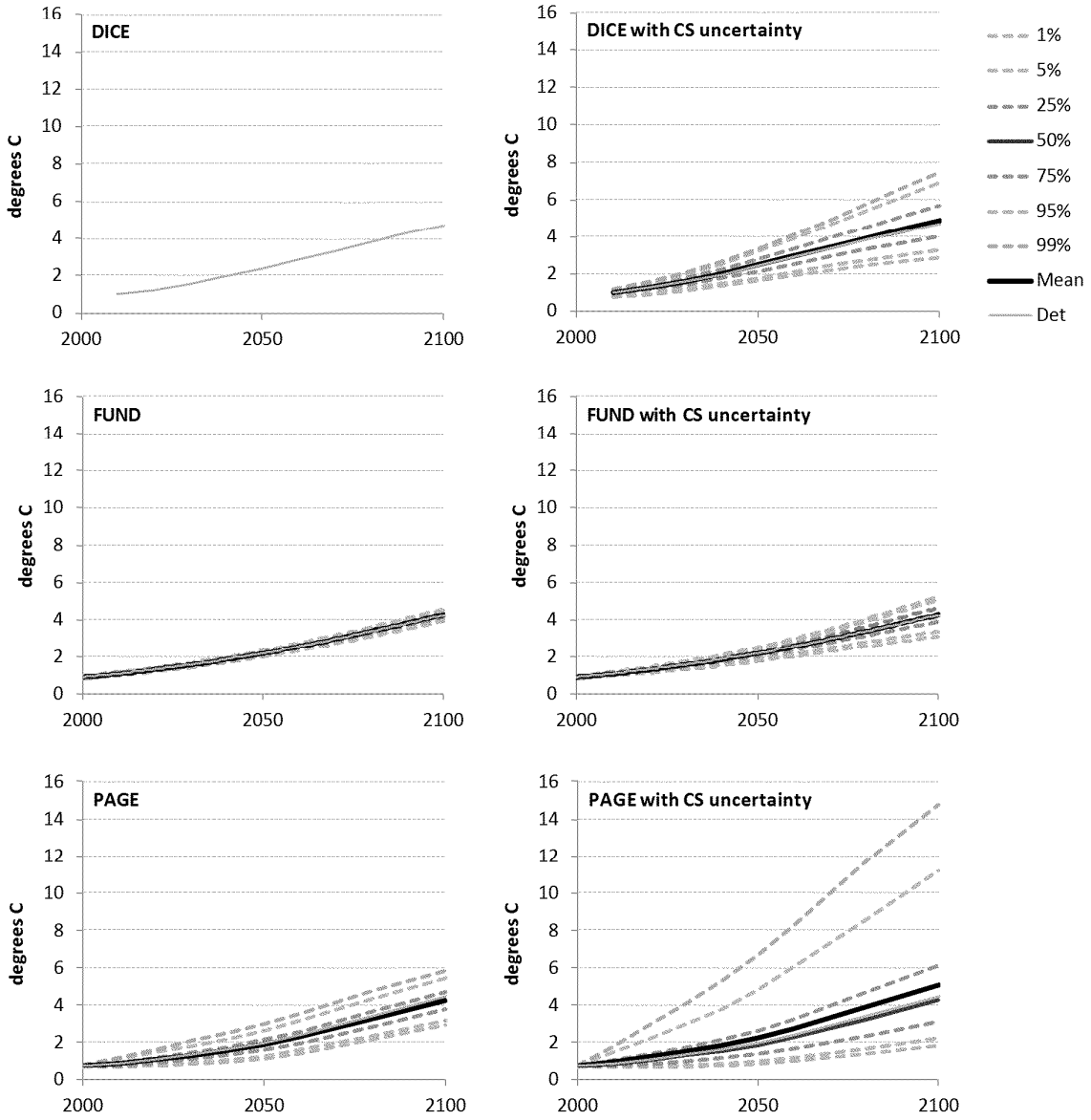

Figure 5-35
RCP8.5 global mean temperature uncertainty for USG models with model specific uncertainty (left) and both model specific and standardized climate sensitivity (CS) uncertainty (right)

Unfortunately, with this version of MAGICC, we are only able to compute probabilistic total climate responses, and not probabilistic incremental climate responses. We run MAGICC and the climate components for the three USG SCC models probabilistically with the RCP8.5 emissions scenario. For comparability with MAGICC's probabilistic results, we now include climate sensitivity as an uncertain parameter in the USG SCC model runs shown in this section. Specifically, we use the USG calibrated Roe and Baker specification for the climate sensitivity uncertainty distribution (USG, 2010). For FUND and PAGE, this implies 12 and 11 uncertain parameters respectively (11 and 10 model specific parameters respectively, plus the USG climate sensitivity uncertainty). For DICE, only climate sensitivity uncertainty is represented. Including the USG climate sensitivity uncertainty expands the uncertainty range of the USG temperature outcomes substantially beyond the model specific parametric uncertainties (Figure 5-35). For instance, the width of the FUND and PAGE 98% confidence intervals (1st to 99th percentiles) in 2100 increases from 0.6 and 2.0 degrees Celsius respectively to 2.2 and 5.5 degrees Celsius.

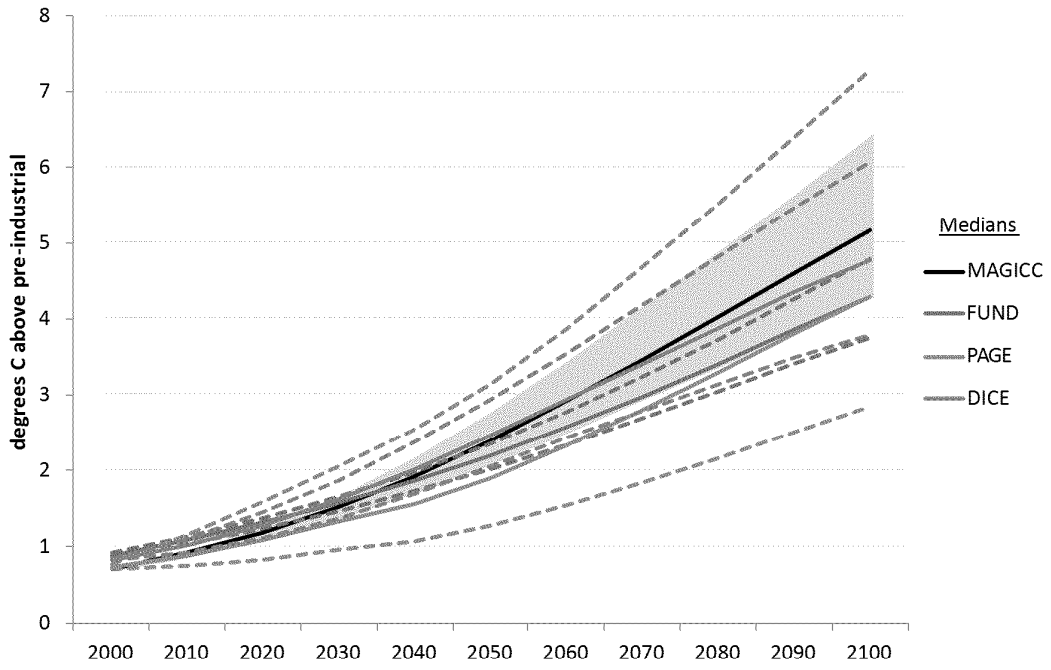

Figure 5-36
RCP8.5 global mean temperature uncertainty comparison with MAGICC to 2100 (solid = median, dashed = USG model 17th-83rd percentile, shaded = MAGICC 17th-83rd percentile)

Figure 5-36 plots the median and the 17th-83rd percentile ranges of the outcome distributions for the RCP8.5 scenario to 2100. While it would be preferable to plot further into the tails of the distributions, the public version of MAGICC restricts results to the 17th-83rd percentiles (the 66% confidence interval). Regardless, we can still meaningfully compare the bulk of the distributions. First, we observe that the MAGICC median lies above the USG medians. Second, we find the DICE distribution to be most closely aligned with the MAGICC distribution. However, keep in mind, that the DICE distribution represents only a single uncertainty. Third, we find that neither the FUND nor PAGE distributions align with the MAGICC distribution. FUND suggests

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significantly less uncertainty and risk than MAGICC, while PAGE suggests significant more uncertainty and risk than MAGICC. More specifically, FUND's distribution is significantly more compact than MAGICC's and lies entirely below MAGICC's median from 2040 on such that the FUND median temperature increase is the MAGICC 17th percentile temperature increase before 2100. PAGE's distribution, on the other hand, is significantly broader than MAGICC's with the entire MAGICC 66% confidence interval lying above the PAGE median, yet still fully within PAGE's 66% confidence interval. The PAGE distribution is also more right-skewed than MAGICC's (and FUND's & DICE's distributions).

In Figure 5-37 we extend the results to 2300. However, MAGICC results are only available through 2100. Nonetheless, the figure gives us some sense of how the distributions evolve. All of the distributions widen over time, with the PAGE distribution enveloping the other distributions throughout the entire 2000-2300 horizon, and the FUND distribution tighter than the others through 2200, but expanding rapidly beyond 2200.

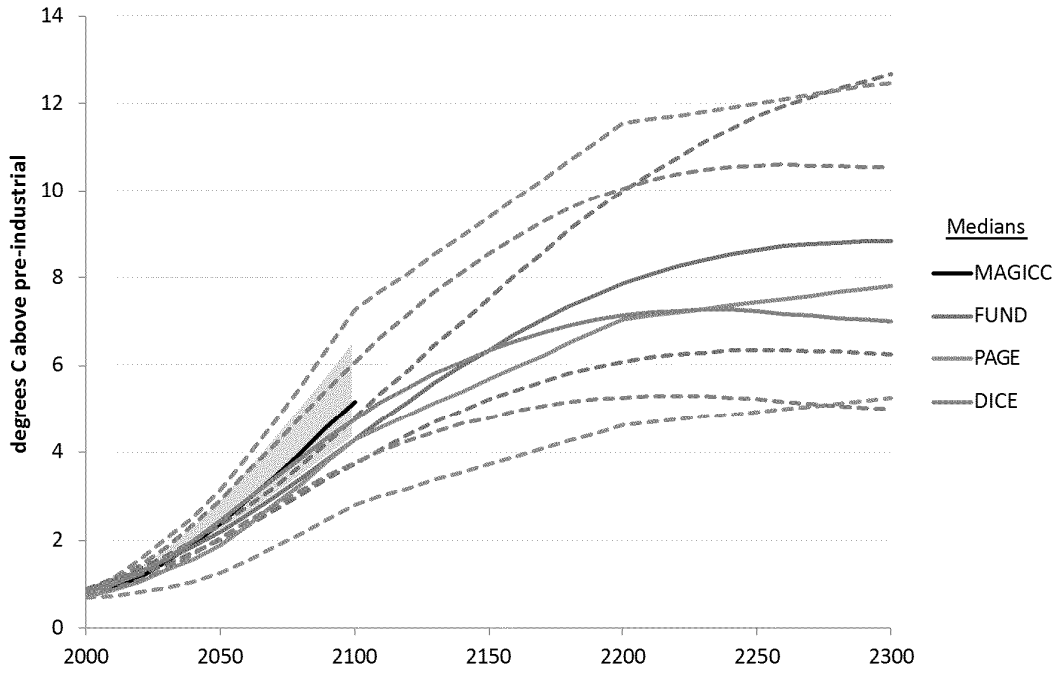

Figure 5-37
RCP8.5 global mean temperature uncertainty comparison with MAGICC to 2300 (solid = median, dashed = USG model 17th-83rd percentile, shaded = MAGICC 17th-83rd percentile)

How much of the difference in uncertainty is derived from differences in carbon cycle uncertainty? Figures 5-38 and 5-39 compare MAGICC CO_2 concentration uncertainty for RCP8.5 to that from FUND and PAGE. DICE is not included because it does not model carbon cycle uncertainty in the USG exercise. We immediately notice that there is less uncertainty represented in the carbon cycle modeling of all the models, including MAGICC, versus the temperature uncertainty shown by each above. In addition, differences in CO2 concentration distributions are not as pronounced. However, the FUND distribution (66% confidence interval) is the tightest, followed by MAGICC, then PAGE. The FUND distribution lies slightly above

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MAGICC's through much of the first century, while the PAGE distribution is almost entirely below MAGICC's. This result is consistent with PAGE's slower carbon cycle. Beyond 2100, FUND and PAGE exhibit very different patterns. FUND's pathway is well aligned with MAGICC's direction coming into 2100, with the distribution rising and gradually expanding before peaking after 2200. PAGE, on the other hand, breaks from its 2100 trend and moves further away from the MAGICC and FUND pathways with the distribution expanding more rapidly and continuing to rise to 2300.

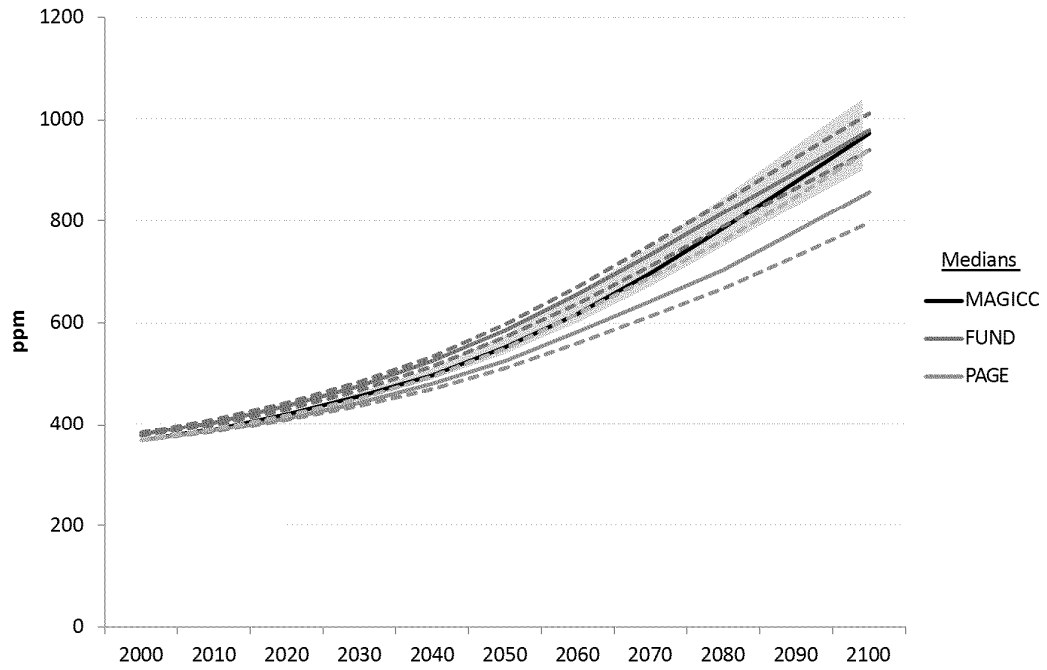

Figure 5-38
RCP8.5 CO_2 concentration uncertainty comparison with MAGICC to 2100 (solid = median, dashed = USG model 17th-83rd percentile, shaded = MAGICC 17th-83rd percentile)

Overall, our comparison of probabilistic results to MAGICC illustrates sharp differences in the modeling of climate change uncertainty versus the USG models. The differences begin with differences in the uncertainty space over which MAGICC and the USG models are sampling as defined by the uncertain parameters considered and their specifications. In the end, the probabilistic results reveal substantial differences in projected carbon cycle and climate uncertainty between MAGICC and the USG models. With such stark differences with MAGICC, and across USG models, the results many not be comparable and re-consideration of the probabilistic modeling in the USG exercise would be practical.

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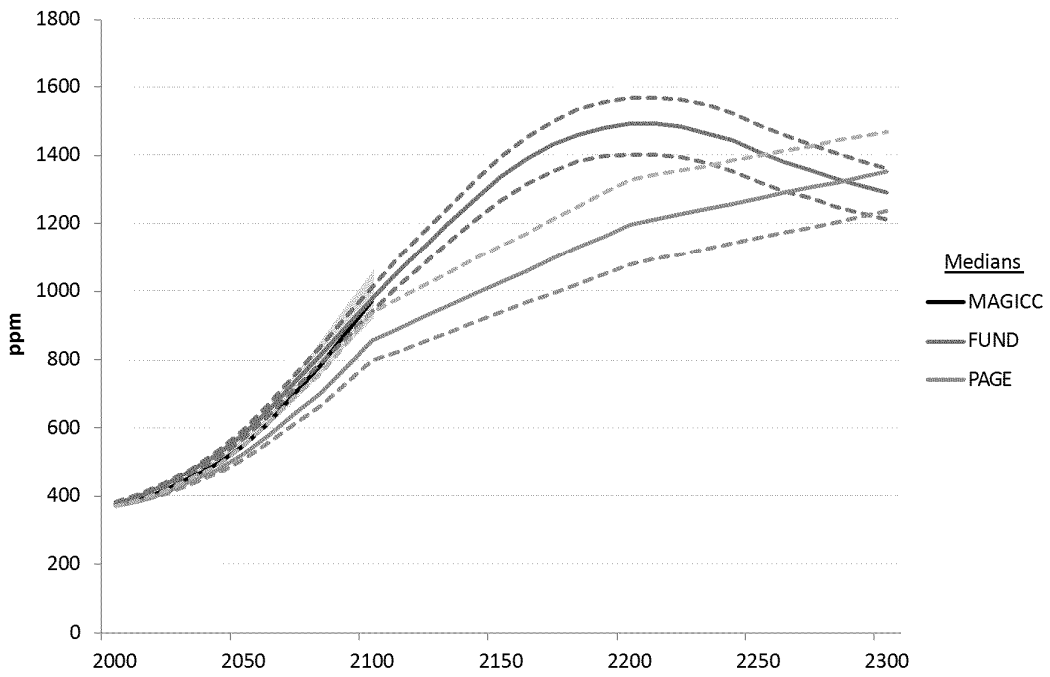

Figure 5-39
RCP8.5 CO_2 Concentration uncertainty comparison with MAGICC to 2300 (solid = median, dashed = USG model 17th-83rd percentile, shaded = MAGICC 17th-83rd percentile)

Implementation

Through our assessment we identify a number of inconsistencies in the climate modeling of the USG SCC analysis that have bearing on the SCC calculations. In this section, we briefly summarize them so that they may be addressed in the future to improve comparability and analyses insights. We note the following inconsistencies:

- *Time step* – The models have different time step formulations that affect emissions representation and concentration calculations
- *Incremental emissions pulse* – The models have different implementations of the incremental CO_2 pulse that affect incremental temperature responses, and therefore incremental damage responses for SCC calculations.
- *Emissions* – Emissions inputs to the climate outcomes were not fully standardized in the USG scenarios. For instance, FUND's fossil fuel and industrial CO_2 emissions are derived, and FUND's CH_4, N_2O, and land CO_2 emissions differ from EMF-22, and therefore differ implicitly (and explicitly in the case of land CO_2) from that represented in DICE and PAGE. In addition, FUND and PAGE differ in their modeling of SO_2 emissions.
- *Non-CO_2* – The non-CO_2 implementation varies in terms of the radiative forcing categories included across models, as well as in the implementation for common elements of forcing. For instance, DICE and PAGE consider broader sets of non-CO_2 radiative forcing constituents than FUND, which only considers non-CO_2 forcing from CH_4, N_2O, SF_6 and SO_2.

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- *Standardized climate sensitivity distribution* – The USG approach implemented a single climate sensitivity distribution assumption (USG, 2010). However, there are plausible alternative distributions as noted in IPCC (2007a), and more recently in IPCC (2013). As such, the distribution assumption is an additional uncertainty of its own that should be evaluated and potentially incorporated into future USG SCC modeling.
- *Uncertainty* – The climate modeling across the three USG models reflects very different uncertainties. The models are sampling from different spaces, which calls into question the comparability of the results across models.

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6
COMPONENT ASSESSMENT 3 – CLIMATE DAMAGE MODELING

What we can learn

A SCC estimate is an aggregate estimate of potential climate damages. As an aggregate metric, SCC estimates themselves are not very intuitive or tractable. A SCC estimate encapsulates damages projected to occur at different points in time, in different regions of the world, and for different types of impacts. The official USG SCCs are not only an aggregation of damages within models, but also an aggregation of damage estimates across the three models. Making sense of and comparing SCC estimates requires understanding of these disaggregated results. However, the raw undiscounted climate damage outcomes over time from the individual USG models, and the many model runs, are not readily available, nor are the contributions of the underlying parts. In addition, and perhaps most importantly, the detailed results have not been directly compared across models. This component assessment therefore explores the following questions:

- What are the detailed damages underlying SCC calculations?
- How sensitive are the damage estimates to alternative assumptions?
- What do the incremental damage responses look like for a marginal change in emissions?

To explore these questions, we code the damage modeling components of each of the USG SCC models and run controlled diagnostic scenarios designed to elucidate and compare the damage responses of each model. For the first question, we undertake a cross model comparison using standardized inputs that isolate damage model behavior. Initially, we use deterministic parameter values to understand the fundamental nature of each damage module. We then perform sensitivity analyses to reveal the shape of the response functions. Next, we evaluate the incremental damage ($/t$CO_2$) responses to a standardized incremental temperature change increase corresponding to a 1 GtC increase in CO_2 emissions. We also explore the probabilistic responses for model specific damage component parametric uncertainties. We conclude with a focused comparison of damages in four regions: Africa, China, the European Union, and the United States. Throughout, we explore results to 2100 and 2300.

Note that the scope of this section includes all modeling driven by projected global mean temperature change. This includes projected damages, but also projected sea level rise (SLR), which drives estimated SLR damages, and projected regional climate change, which drives regional climate damages.

Key observations

- *Overall*: From our assessment, we find stark differences in the approach taken by each model to estimate climate damages, as well as the damage estimates that follow. This section identifies key drivers and elucidates the implications of the current model specifications. However, further assessment of the specifications and uncertainties, and justification or

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reconciliation of differences, is an essential future activity for developing robust estimates. Below, we summarize key individual climate damage modeling observations.

- *Modeling structure and specification*: Across models we find substantial variation in damage component specifications, as well as modes of application within the USG exercise. We also find that the models' damage formulations are based on older climate impacts literature, some dating back to the 1990s, and some formulations are based on those from the other models.
- The damage specifications in each model are based on the climate impacts literature. Table 6-2 summarizes the literature sources for each model. From the table, we make two high-level observations. First, the models draw directly and indirectly on older literature, some dating back to the 1990s. Scientific impacts knowledge has progressed since, as summarized in synthesis products like IPCC (2007b, 2014). However, this knowledge is not reflected in the current SCC model damage formulations, in part because this literature is not in a form readily usable by IAMs. Second, some of the models' damage formulations are based on one another. For instance, DICE non-SLR damages are based on IPCC (2007b) and Tol (2009), both of which summarize past damage estimates (also going back to the 1990s), including estimates from previous DICE, FUND, and PAGE work. Similarly, all four of the PAGE damage categories are calibrated to studies based on output from FUND and DICE, as well as PAGE. Thus, there is some interdependency between the models.
- *2013 revisions*: Uncertainty regarding the damage component model revisions associated with the 2013 USG SCC values was not examined, nor was the potential sensitivity of SCC estimates to these uncertainties. Also, damage component model development was uneven across models, with independent development resulting and contributing to structural differences across models.
- *Damage modeling behavior*: From our deterministic diagnostic analysis, using identical climate and socioeconomic futures, we find significant variation in the behavior across models in projected sea level rise (SLR) and overall climate damages. DICE and PAGE produce substantially higher net climate damages (and percent GDP losses) than FUND, and FUND estimates the potential for net benefits from climate change over much of the next half century while the other models estimate net damages for the entire century. For example, we observe the models producing significantly different annual damages for the same temperature increase, differing by as much as a factor of three over the next century.
- *Sensitivity of damage results*: Damage estimates from PAGE and DICE, are more sensitive than FUND to assumptions regarding the drivers of damages, such as temperature change and income levels. Specifically, damage estimates from DICE and PAGE are more responsive to projected warming, with PAGE the most responsive beyond 3˚C of warming, and FUND estimating net benefits that increase with the size of the economy at lower levels of warming. At higher levels of warming, FUND produces net damages that increase with income, but DICE and PAGE are more responsive to income than FUND, which is assuming increased climate resiliency with income. Damage estimates from all three models are more sensitive to temperature than income. Beyond 2050, the differences in responsiveness are even greater.
- *Regional damages:* Projected regional damages are not equally responsive to temperature change. FUND projects net benefits for a number of regions of the world, even up to about 4.5˚C of global temperature rise, while PAGE projects net damages for all regions and levels

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of warming. DICE does not produce estimates of regional damages. FUND results are dominated by China, while PAGE results are more evenly distributed across regions. However, at lower levels of warming, developing regions in general dominate FUND's damages—China and the Former Soviet Union, while developed regions dominate PAGE's damages—EU, US, and Other OECD. At higher levels of warming, developing region damages continue to dominate in FUND and become more prominent in PAGE, but developed region damages are still a large component of PAGE damages and much larger than developed region damages in FUND. Disaggregated annual damage projections across models are difficult to compare because of different regional and sectoral damage structure across models. For a selection of similar regions, we find FUND and PAGE projecting very different levels of climate damages over time.

- *Sectoral damages:* Across models, projected sectoral damages differ in sign (damage vs. benefit) and responsiveness to warming, with particular sectors driving results. Climate damages in DICE are driven by aggregate non-SLR damages, while damages in FUND are driven by a few damage categories – agriculture, cooling demand, heating demand, and water resources. Damages in PAGE are dominated by sea level rise and non-economic damages at low levels of warming. However, economic and discontinuity damages grow quickly with greater warming and surpass SLR damages. Beyond 2050, the dominance of certain sectors increases—non-SLR damages in DICE, cooling demand and agriculture in FUND, and non-economic and economic damages in PAGE. Aggregating damages into economic and non-economic groupings, we find PAGE's economic and non-economic damages dwarfing FUND's, with non-economic damages similar in sign but economic damages differing in sign for most of this century.
- *Sea level rise damages*: Despite higher projected SLR, FUND projects smaller damages from SLR than the other models, while PAGE with the lowest projected SLR, projects the largest SLR damages. SLR projections in FUND are nearly twice as high as in PAGE for the same amount of warming, yet the coastal damages in PAGE are substantial, dominating the other impact sectors at lower levels of warming, and comprising roughly a third of all damages in 2100. FUND, on the other hand, estimates damages smaller than PAGE by a factor of 3 to 4. Both FUND and PAGE explicitly account for coastal adaptation to minimize SLR impacts, though each in its own way. SLR damages in DICE fall between the other models (and adaptation is implicit).
- *Regional climate*: FUND and PAGE explicitly translate global mean temperature changes into regional mean temperature changes. DICE uses global mean temperature changes only. The FUND and PAGE approaches for downscaling regional temperatures from global temperatures differ, with PAGE producing notably warmer regional temperatures than FUND in many global regions.
- *Specific model drivers*: Some specific features in each model are driving damage results:
  - Net damages in the FUND model are driven by a handful of damage function parameters. The majority of impacts arise in 4 of the 14 impact sectors—damages from increased cooling energy demand, agriculture (both regional net benefits and damages), benefits from avoided heating energy demand, and water resources (both regional net benefits and damages). The largest magnitude of impacts occurs in China, which can be explained by the particular damage coefficient as well as income and population growth. The leading impact sector-region combinations are cooling in China, and agriculture in China and

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South East Asia, water resources in China and the Former Soviet Union, and heating in China.

- PAGE regional damages are scaled off of EU damages. The regional damage functions have been calibrated to impact assessments of the EU region, and this value is adjusted (usually downward) for other regions based on a linear scaling factor (e.g., EU damages scaled by 0.6 for Africa and by 0.8 for the US). The basis for this scale factor is usually explained as the total coastline length relative to the EU.
- PAGE tracks residual damages separate from adaptation costs, and adaptation costs are exogenous, i.e., the costs are associated with a fixed adaptation policy specified at the outset. Thus, adaptation costs (and actions) are not a function of temperature change and identical across alternative climate change scenarios. Total damages include adaptation costs, but only residual damages respond to an additional ton of CO_2 (e.g., the emission pulse used to compute the SCC).
- DICE damages, both SLR and aggregate non-SLR damages, increase quadratically with global mean SLR and global mean temperature respectively.

- *Incremental damage modeling behavior*: Annual incremental damages increase over time in all models. However, for an identical incremental temperature change, we find significant variation in incremental damage responses across models, differing by as much as a factor of four over the next century. The ordinal pattern across models is qualitatively similar to that observed for total damages, with incremental damages growing more quickly over time in DICE and PAGE than in FUND. However, at higher temperatures, PAGE's damage function has a notably steeper slope, which separates PAGE's incremental damages post-2100 from the other models. The drivers of incremental damages vary by model and over time as well. In DICE, non-SLR damages dominate through 2100 and are more evenly distributed with SLR damages after 2100. In FUND, cooling and agricultural damages and benefits dominate results, with China accounting for approximately half of cumulative incremental damage changes, primarily from increased cooling demand. In PAGE, non-economic and economic damages dominate, with a potential incremental increase in the expected value of discontinuity damages towards the end of the first century when the reference temperature change is greater than 3˚C. In PAGE through 2050, 45% of damages are in the EU and US. Beyond 2050, damages in non-OECD regions grow slightly faster than damages in OECD regions. Incremental SLR damages grow most quickly in DICE beyond 2050.
- *Damage results to 2300*: We find significant increases in annual total damages post-2100 from all the models, but also an increase in the range of estimated annual damages, with the steeper slope of PAGE's and DICE's damage formulations resulting in faster total annual damage growth than from FUND for the same climate scenario. China climate damages are prominent in FUND's and PAGE's post-2100 projections, but damages are more equally distributed across regions in PAGE. Post-2100 sectoral damages ramp up quickly in a higher warming scenario—particularly in some sectors. In a lower warming scenario, post-2100 sectoral damage growth is reduced significantly, such that FUND agriculture exhibits increasing net benefits and PAGE economic and discontinuity damages are small fractions of total annual damages. Post-2100 incremental damage results also increase quickly, with a expanding range of estimates, led by faster incremental annual damage growth in DICE and PAGE. Higher post-2100 incremental damages are driven by a growing reference society and projected warming, as well as the incremental temperature response. Post-2100 incremental

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annual damages can stabilize over time to different degrees across models, in part due to the declining annual incremental warming. However, projected annual incremental global damages post-2100 grow most quickly off the lower reference temperature scenario, which has the higher incremental temperature response as well as higher reference income.

- *Model specific parametric uncertainty*: The models are considering very different model specific parametric uncertainties within their damage modeling. DICE is not considering any model specific parametric uncertainty, while FUND and PAGE include approximately 50 uncertain parameters each, which between the two models vary in terms of the specific uncertain parameters and their specification. Through 2100, FUND models substantially more uncertainty in annual damages than PAGE (and DICE of course), with FUND exhibiting a broader distribution and larger tails. Beyond 2100, PAGE's distribution rapidly broadens, but the tails of FUND's distributions are still longer. However, throughout the time horizon, PAGE produces higher annual mean climate damages. The significant differences in the damage uncertainty spaces represented across models may create issues regarding the comparability of results for aggregation, especially where there is clearer overlap in disaggregated damage categories (regions and sectors).
- *Focused regional comparison of damages*: We do a focused comparison of FUND and PAGE damage estimates for Africa, China, the EU, and the US. We observe that FUND damages are below PAGE damages up to 5 degrees of warming in all but China. Damages in PAGE increase much more quickly with greater warming in the EU and US than in FUND, but damages in China grow more quickly in FUND. Damages are similar for Africa. In PAGE, non-economic and economic, and eventually discontinuity, damages accumulate quickly with warming in the EU and US, but accumulate slowly in Africa and China. In FUND, we find stronger damage responses (benefits and damages) in Africa and China versus the EU and US. PAGE and FUND produce regional damage distributions with similar modes for the four regions, but PAGE consistently produces positive and more compact distributions, while FUND consistently produces broader distributions with long tails, a significant amount of mass below the PAGE distribution, and negative and positive net damages possible. PAGE produces tighter distributions for economic damages than FUND, while FUND produces tighter non-economic damage distributions. For both, the mass of the PAGE distributions are well those from FUND for all but China economic damages.

What is done

The climate damage component of each model includes some level of region and damage sector resolution (Table 6-1). A combination of projected climate, sea level-rise (SLR), and socioeconomic projections, as well as adaptation behavior, drive estimated regional and sectoral damages. The models are substantially different in all these dimensions. DICE has a single global region with two damage sectors (SLR and non-SLR, where the latter includes both economic and non-economic damages), while FUND has sixteen regions and fourteen sectors, and PAGE eight regions and four sectors. In DICE, damages are driven by global mean temperature and SLR, and income levels, while in FUND and PAGE damages are driven by regional temperatures and additional drivers. Furthermore, PAGE sectoral damages are scaled across regions from EU damages, while FUND has detailed regional sectoral damage functions calibrated to regional studies when possible and responding dynamically to a larger set of drivers. Finally, the drivers and functional form of damages for each damage sector vary across

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sectors within a model. Also, the functional form for similar damages varies across models (Nordhaus 2010; Anthoff and Tol, 2013a; Hope, 2011a).

Table 6-1
USG SCC climate damage modeling component structural characteristics

	DICE (2010)	FUND (v3.8)	PAGE (2009)
Regions	**1 region:** World	**16 regions:** ANZ, CAM, CAN, CEE, CHI, FSU, JPK, MDE, NAF, SAM, SAS, SEA, SIS, SSA, USA, WEU	**8 regions:** Africa & Middle East, China & CP Asia, EU, FSU & ROE, India & SE Asia, Latin America, Other OECD, USA
Sectors	**2 sectors:** sea level rise (SLR), aggregate non-SLR	**14 sectors:** sea level rise, agriculture, forests, heating, cooling, water resources, tropical storms, extratropical storms, biodiversity, cardiovascular respiratory, vector borne diseases, morbidity, diarrhea, migration	**4 sectors:** sea level rise, economic, non-economic, discontinuity (e.g., abrupt change or catastrophe)
Regional temperature downscaling	n/a	Regional damage parameters calibrated to regional temperatures downscaled based on a linear pattern-scale average of 14 GCMs	Regional temperatures downscaled according to latitude and landmass adjustment
Global mean SLR	Global mean SLR components (thermal expansion, glacier and small ice cap melt, GIS melt, WAIS melt) computed as functions of temperature and lagged temperature	Global mean SLR computed as a function of temperature and lagged temperature	Global mean SLR computed as a function of temperature and lagged temperature
SLR damage specification	Quadratic function of global SLR (e.g., $DF=\alpha SLR^2$)	Additive functions for coastal protection costs, dryland loss, and wetland loss, based on an internal cost-benefit rule for optimal adaptation	Power function of global SLR (e.g., $DF=\alpha SLR^{0.7}$)
SLR damage drivers	Global mean SLR (driven by temperature), income	Global mean SLR, dryland value, wetland value, topography (elevation, coast length), protection cost, population density, income density, per capita income	Global mean SLR, regional coast length scaling factor relative to EU, adaptation capacity and costs, per capita income, income
Non-SLR damage specification	Quadratic function of global temperature (e.g., $DF=\alpha T^2$)	Uniquely formulated by sector	Power function of regional temperature (e.g., $DF=\alpha T^2$)
Non-SLR damage drivers	Global mean temperature, income	Global mean temperature, CO_2 concentrations, ocean temperature (for storms), population, income, per capita income, technological change	Regional temperature, regional scaling factor relative to EU, adaptation capacity and costs, per capita income, income

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Table 6-1 (continued)
USG SCC climate damage modeling component structural characteristics

	DICE (2010)	FUND (v3.8)	PAGE (2009)
Adaptation	Implicit (damages net of adaptation)	Explicit for agriculture & SLR, implicit otherwise (econometric studies of net response to warming)	2 types of exogenous fixed adaptation policy (i.e., fixed irrespective of level of climate change and socioeconomics) that that reduce impacts for a cost
Climate benefits	Implicit (damages net of benefits)	Explicit outcome of certain sectoral damage functions (e.g., avoided heating demand, agriculture benefits from CO_2 fertilization)	Assumes small economic benefits at low levels of warming
Catastrophe	Implicit (via calibration to an expected value of catastrophic loss)	Represented in probabilistic mode via extreme tails of parameter distributions	'Discontinuity' impact occurs with a positive probability linked to temperatures over 3°C
Other features		"Dynamic vulnerability" (climate resiliency increases with per capita income)	

The damage specifications in each model are based on the climate impacts literature. Table 6-2 summarizes the literature sources for each model. Unfortunately, literature details do not reside in single document for each model so constructing such a table is challenging. Instead, this information is spread across peer reviewed and other publications going back in time. From the table, we make two high-level observations. First, the models draw directly and indirectly on older literature, some dating back to the 1990s. Scientific impacts knowledge has progressed since, as summarized in synthesis products like IPCC (2007b, 2014). However, this knowledge is not reflected in the current SCC model damage formulations, in part because this literature is not in a form readily usable by IAMs. Second, some of the models' damage formulations are based on one another. For instance, DICE non-SLR damages are based on IPCC (2007b) and Tol (2009), both of which summarize past damage estimates (also going back to the 1990s), including estimates from previous DICE, FUND, and PAGE work. Similarly, all four of the PAGE damage categories are calibrated to studies based on output from FUND and DICE, as well as PAGE. Thus, there is some interdependency between the models.

The USG SCC exercise did not modify the native damage modules. However, a number of damage component revisions to the native modules were included in the updated 2013 USG SCC estimates (Section 2). These include changes or fixes to SLR damage estimation in all three models, a fix to heating demand in FUND and overall GDP loss estimation in PAGE, as well as a variety of revisions in PAGE—regional temperature change, regional damage scaling factors, the probability of a discontinuity damage, and revised adaptation assumptions. As noted previously, in general, uncertainty regarding these revisions was not evaluated, but would be practical.

Finally, we note that standardized uncertainties regarding climate change and socioeconomic futures were considered via the five alternative socioeconomic and emissions futures (important implementation differences aside). However, standardized damage component specific uncertainties were not a part of the USG SCC exercise. Model specific damage uncertainty was considered within FUND and PAGE via parameter uncertainty and probabilistic modeling. As

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part of our component assessment we evaluate the probabilistic damage modeling below. Key features of each model's damage modeling component are summarized in Table 6-1.

Table 6-2
Literature sources for model damage specifications

Model (version)	Damage type	Study	Basis	Links to SCC models
DICE (2010)	Aggregate non-SLR	IPCC (2007b), Tol (2009)[14]	Calibration	DICE, FUND, PAGE
	SLR coastal impacts	Undocumented		
FUND (v3.8)	Agriculture	Kane et al. (1992), Reilly et al. (1994), Morita et al. (1994), Fischer et al. (1996), Tsigas et al. (1996)	Calibration	
		Tol (2002b)	Income elasticity	
	Forestry	Perez-Garcia et al. (1995), Sohngen et al. (2001)	Calibration	
		Tol (2002b)	Income elasticity	
	Energy	Downing et al. (1995), (1996)	Calibration	
		Hodgson and Miller (1995)	Income elasticity	
	Water resources	Downing et al. (1995, 1996)	Calibration	
		Downing et al. (1995, 1996)	Income elasticity	
	Coastal impacts	Hoozemans et al. (1993), Bijlsma et al. (1995), Leatherman and Nicholls (1995), Nicholls and Leatherman (1995), Brander et al. (2006)	Calibration	
	Diarrhoea	WHO Global Burden of Disease (2000)[15]	Calibration	
		WHO Global Burden of Disease (2000)	Income elasticity	
	Vector-borne diseases	Martin and Lefebvre (1995), Martens et al. (1995, 1997), Morita et al. (1995)	Calibration	
		Link and Tol (2004)	Income elasticity	
	Cardiovascular and respiratory mortality	Martens (1998)	Calibration	
	Storms	CRED EM-DAT database,[16] WMO (2006)	Calibration	
		Toya and Skidmore (2007)	Income elasticity	
	Ecosystems	Pearce and Moran, (1994), Tol (2002a)	Calibration	
PAGE (2009)	SLR	Anthoff et al. (2006)[17]	Calibration & income elasticity	FUND
	Economic	Warren et al. (2006)[18]	Calibration	DICE, FUND, PAGE
	Noneconomic	Warren et al. (2006)	Calibration	DICE, FUND, PAGE
	Discontinuity	Lenton et al. (2008), Nichols et al., (2008), Anthoff et al. (2006), Nordhaus (1994)[19]	Calibration	DICE, FUND
	Adaptation costs	Parry et al. (2009)	Calibration	

[14] Tol 2009 is a meta analysis of global damage studies some of which report impacts estimated by earlier versions of the SCC models, specifically DICE-94, RICE-96, RICE-99, DICE-99, PAGE95, PAGE2002, and FUND1.6.

[15] http://www.who.int/health_topics/global_burden_of_disease/en/.

[16] http://www.emdat.be/.

[17] Anthoff et al. (2006) is a study of coastal impacts that uses an earlier version of the FUND model (v2.8).

[18] Warren et al. (2006) is a review of damage modeling in earlier versions of four integrated assessment models: DICE/RICE-1999, MERGE 1995 and 2004, PAGE2002, and FUNDv2.9.

[19] Nordhaus (1994) is an expert elicitation on climate catastrophes, and is also used as the basis for catastrophic impacts in DICE prior to 2010.

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Assessment

For this assessment, we decipher and code the model damage formulations and then evaluate and compare the climate damages modeling across models using controlled experiments with common inputs. Given our diagnostic objectives to learn about model behavior, we continue to focus on the low and high USG emissions projections—USG2 and USG5. However, to isolate damage responses and differences in damage responses alone across models, we standardize the climate change and socioeconomic inputs to 2100 and 2300, i.e., the same climate and socioeconomic projections are inputs to all three models (Figures 6-1 and 6-2 respectively). Thus, we ignore variation in climate damages across models (and SCC outcomes) that would result from the differences in the climate modeling identified in the previous section.

Specifically, we use the DICE USG2 and USG5 total and incremental climate projections from our climate component diagnostic analysis, combined with the corresponding EMF-22 socioeconomic projections. The standardized set of inputs includes projections to 2300 for global mean temperature, CO_2 concentrations, population, and GDP. Population and GDP are regionally disaggregated to the FUND and PAGE regions, with non-OECD regions growing much faster than OECD regions.[20] Both climate scenarios begin with initial temperature change in year 2000 of about 0.8°C over pre-industrial, and then rise to 4.0°C and 2.1°C in 2100 in USG2 and USG5 respectively, and 8.3°C and 2.8°C in 2300.

Using a variety of diagnostic scenarios, we evaluate total SLR and damage responses over time. We begin with deterministic scenarios to evaluate model tendencies with central parameter values for uncertain damage component parameters. In this context, we can learn about model responses over time—in terms of aggregated and disaggregated damages. We also run deterministic sensitivity scenarios with respect to temperature and income to elucidate and compare the shapes of the damage functions. Total results are important as the reference conditions for the incremental results, and context for thinking about damages.

We then shift our attention to an explicit evaluation of the incremental damage responses over time to incremental climate change. Through this point in our analysis, we focus on results to 2100. Next, we consider damage responses to 2300, the full USG analysis time horizon for calculating the USG SCC estimates. We then evaluate the role of model specific parametric uncertainties with probabilistic scenarios using random sampling over each model's uncertain damage component parameters. Finally, we conclude with a focused comparison of estimated damages for four regions (Africa, China, EU, and the US).

[20] FUND also requires energy efficiency improvement assumptions for the cooling and heating demand damage calculations. The FUND USG SCC assumptions were used.

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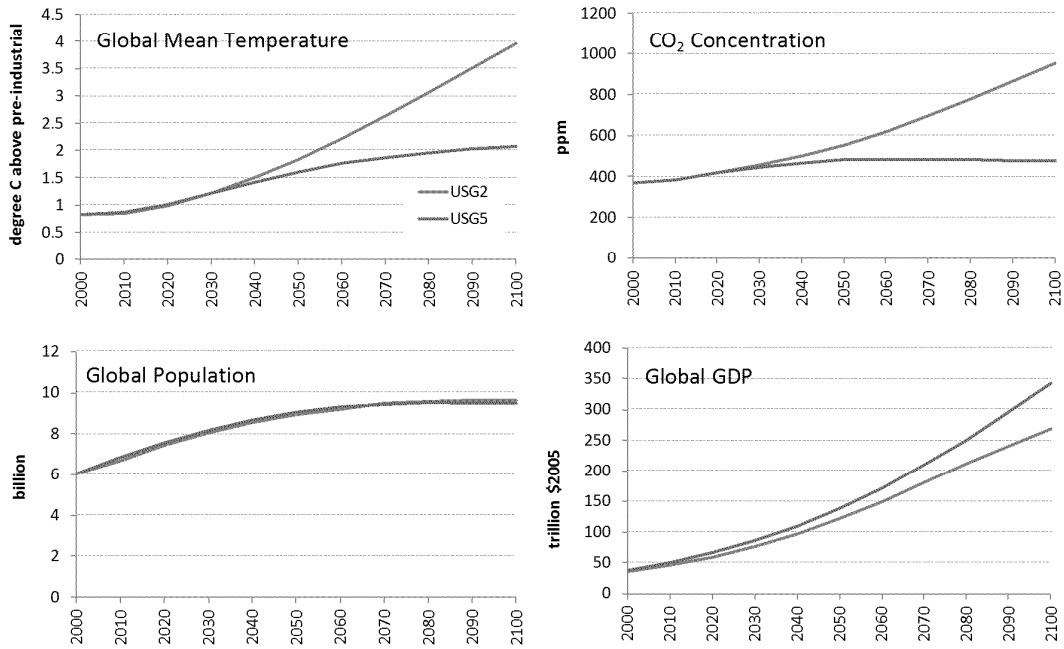

Figure 6-1
Standardized reference climate & socioeconomics inputs to 2100

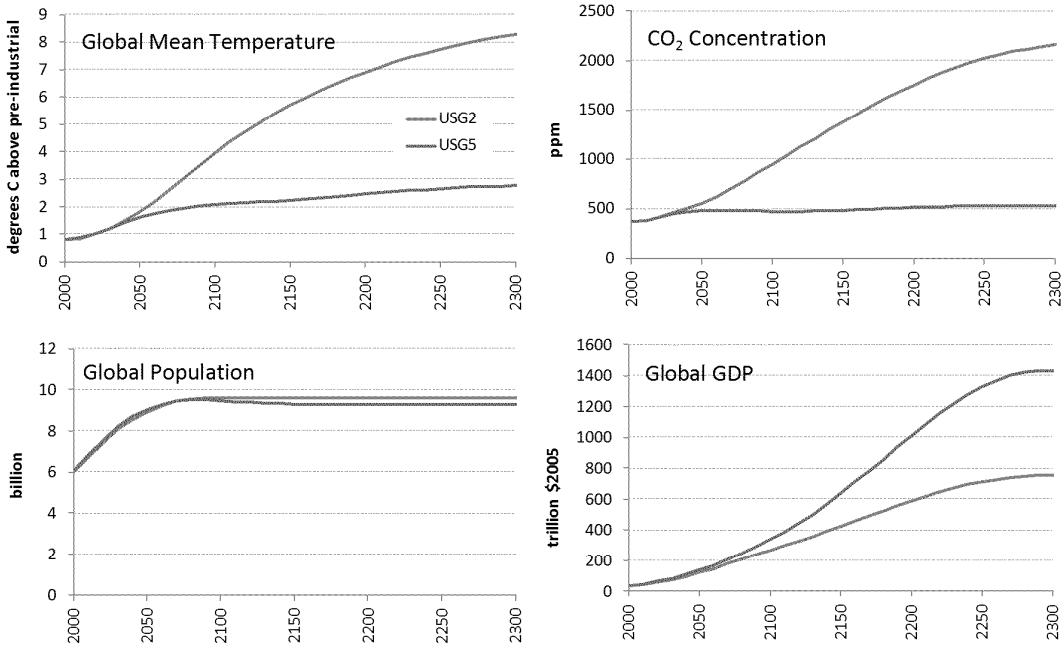

Figure 6-2
Standardized reference climate & socioeconomics inputs to 2300

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Total damages over time

Sea Level Rise

Global mean SLR projections are derived from the global mean temperature pathways corresponding to the two socioeconomic and climate scenarios. Our results show that SLR increases most rapidly in FUND, with FUND projecting twice the SLR projected by PAGE in 2050 and 2100, and DICE in between (Figure 6-3).[21]

FUND and PAGE produce the smooth curves shown in Figure 6-3 because they have similar formulations in which equilibrium SLR is a linear function of temperature, but the equilibrium is reached slowly over a number of centuries. DICE, on the other hand, develops SLR projections from four independent components—thermal expansion, glaciers and small ice cap melt, Greenland Ice Sheet melt, and West Antarctic Ice Sheet (WAIS) melt. WAIS melt is assumed to only occur after 3°C of warming, which produces the slight kink around 2080 in the DICE USG2 SLR projection. Not visible in Figure 6-3 is the fact that SLR will slow post-2100 in DICE due to the depletion of meltwater from glaciers and small ice caps. This is discussed latter.

The average annual rate of SLR implied by a given level of warming can be computed and is a useful way to summarize the average difference between the model SLR projections: PAGE assumes about 2mm/yr/°C, DICE about 3mm/yr/°C, and FUND about 4mm/yr/°C.

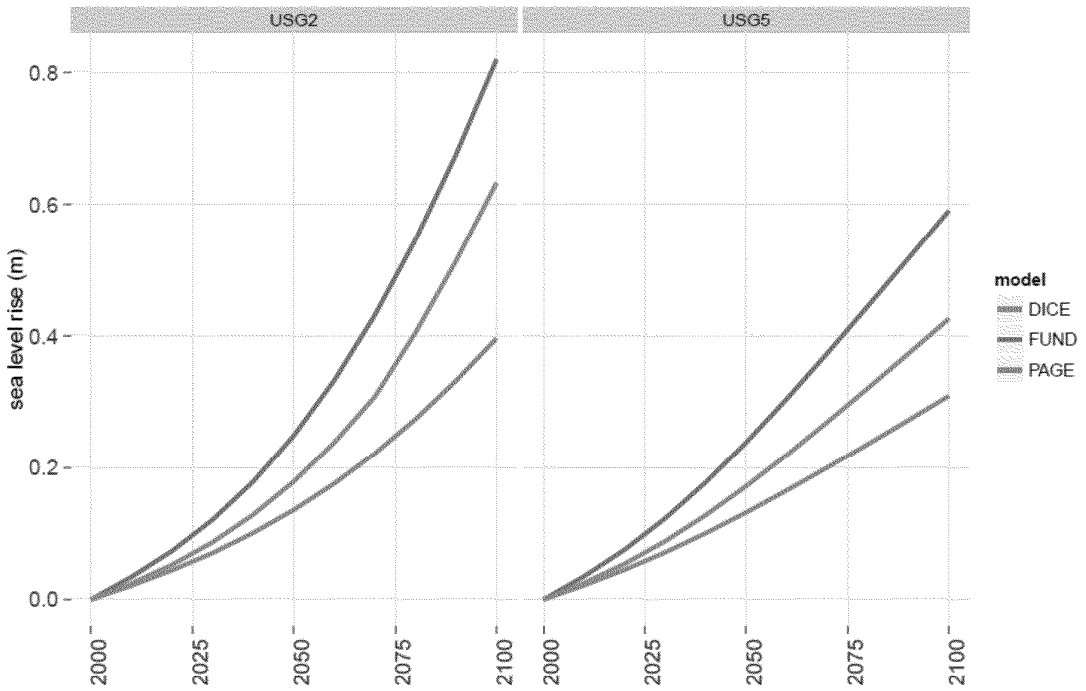

Figure 6-3
Sea level rise from 2000 to 2100

[21] Note that the figure portrays SLR since 2000. Thus, the figure does not include the approximately 12 cm of rise that has occurred since pre-industrial. We normalized SRL to 2000 for comparison across models. SLR damages in DICE and PAGE are a function of SLR since pre-industrial.

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Regional temperature downscaling

In FUND and PAGE, regional temperatures are inferred from the global mean temperature projection in order to drive the regionally-disaggregated damage functions. FUND uses a linear pattern scale based on the average response of 14 global circulation models (GCMs) while PAGE applies two scaling factors to adjust for warming by latitude and landmass.[22] In FUND, regional damage parameters are calibrated to regional temperatures. In both models, the regional temperature scaling patterns are fixed for all levels of warming.

As shown in Figures 6-4 and 6-5, and Table 6-3, for a given global mean temperature change (e.g., 4˚C in 2100 in Figure 6-4), PAGE projects notably warmer regional temperatures than FUND in many global regions (e.g., North America, Europe, Latin America, Africa, and Asia). Since DICE does not disaggregate into regions, temperature downscaling is unnecessary and the map reflects the global mean temperature used to compute aggregate damages. In addition, regional temperatures in PAGE are much higher than the global mean, while regional temperatures in FUND are both warmer and cooler than the global mean.

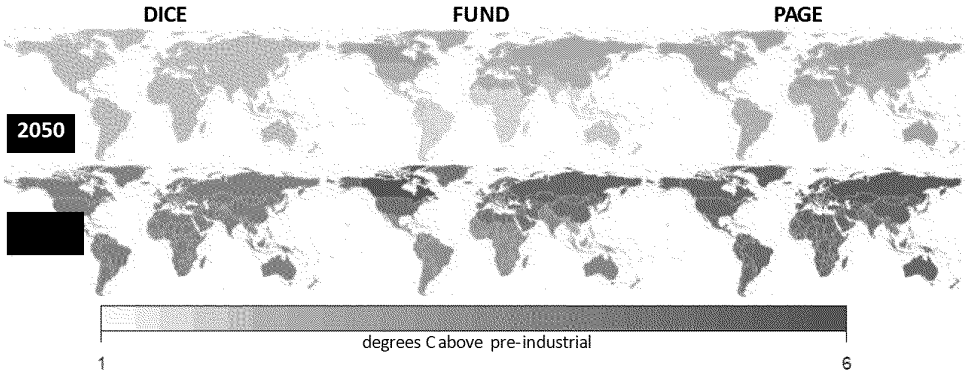

Figure 6-4
Regional average temperature change by 2050 and 2100 for standardized USG2 climate

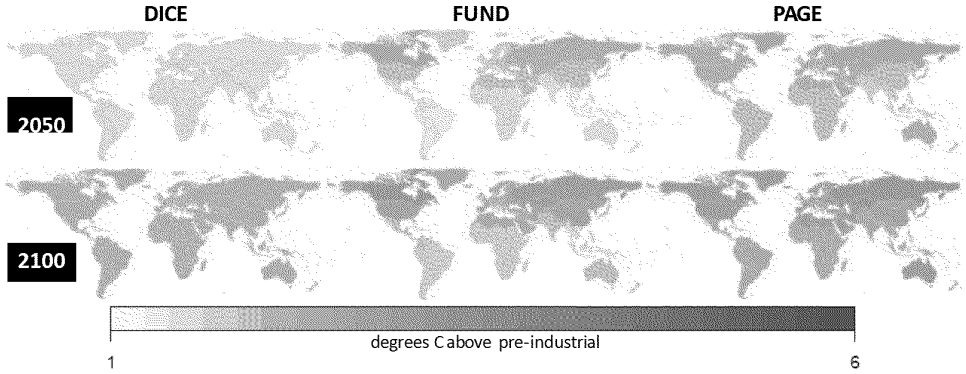

Figure 6-5
Regional average temperature change by 2050 and 2100 for standardized USG5 climate

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[22] The latitude adjustment accounts for polar amplification (i.e., relatively more warming will be experienced at the poles), while the landmass adjustment reflects the fact that land warms more the oceans.

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Table 6-3
Regional average temperature change by 2050, 2100, 2200, and 2300 for standardized USG2 and USG5 climates

FUND								
	USG2				USG5			
Region	2050	2100	2200	2300	2050	2100	2200	2300
ANZ	1.8	3.8	6.7	8.0	1.6	2.0	2.4	2.7
CAM	1.6	3.5	6.1	7.3	1.4	1.8	2.2	2.4
CAN	2.7	5.8	10.2	12.2	2.4	3.1	3.6	4.1
CEE	2.2	4.6	8.1	9.7	1.9	2.4	2.9	3.2
CHI	2.2	4.7	8.2	9.8	1.9	2.5	2.9	3.3
FSU	2.4	5.1	8.9	10.7	2.1	2.7	3.2	3.6
JPK	1.9	4.2	7.3	8.8	1.7	2.2	2.6	2.9
MDE	2.1	4.6	8.0	9.6	1.9	2.4	2.9	3.2
NAF	2.1	4.5	7.9	9.5	1.9	2.4	2.8	3.2
SAM	1.6	3.4	5.9	7.1	1.4	1.8	2.1	2.4
SAS	1.7	3.6	6.3	7.5	1.5	1.9	2.2	2.5
SEA	1.3	2.8	4.9	5.9	1.1	1.5	1.8	2.0
SIS	1.4	3.0	5.2	6.2	1.2	1.6	1.9	2.1
SSA	1.6	3.5	6.1	7.3	1.4	1.8	2.2	2.4
USA	2.2	4.7	8.3	9.9	1.9	2.5	3.0	3.3
WEU	2.1	4.5	7.8	9.3	1.8	2.3	2.8	3.1

PAGE								
	USG2				USG5			
Region	2050	2100	2200	2300	2050	2100	2200	2300
AF	2.2	4.8	8.5	10.3	1.9	2.5	2.9	3.3
CA	2.3	5.0	8.7	10.4	2.0	2.6	3.1	3.5
EE	2.7	5.4	9.1	10.9	2.5	3.0	3.5	3.9
EU	2.6	5.2	9.0	10.7	2.3	2.9	3.4	3.7
IA	2.1	4.7	8.5	10.2	1.8	2.4	2.9	3.2
LA	2.2	4.8	8.5	10.3	1.9	2.5	2.9	3.3
OT	2.5	5.1	8.9	10.6	2.2	2.8	3.3	3.6
US	2.5	5.1	8.9	10.6	2.2	2.8	3.3	3.6

DICE								
	USG2				USG5			
Region	2050	2100	2200	2300	2050	2100	2200	2300
World	1.8	4.0	6.9	8.3	1.6	2.1	2.5	2.8

See Appendix A for region definitions.

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Total damages

All of the models project rising annual damages over time during the 21st century. However, the sign, magnitude, and rates of changes are very different across models (Figure 6-6). DICE and PAGE have similar total damage projections, but FUND projects very different impacts from climate change, with net benefits from lower levels of warming for most of the century, and total damages in 2100 that are less than a third of those from DICE and PAGE.

Damages across the two scenarios (USG2 and USG5) are very similar up to 2050 due to similar climate and socioeconomic assumptions. Beyond 2050, warming occurs much more quickly in USG2 and leads to greater damages than with USG5 (although there is an offsetting effect of higher GDP in USG5). By the end of the century, projected damages from DICE and PAGE are substantially higher than those from FUND in both scenarios.

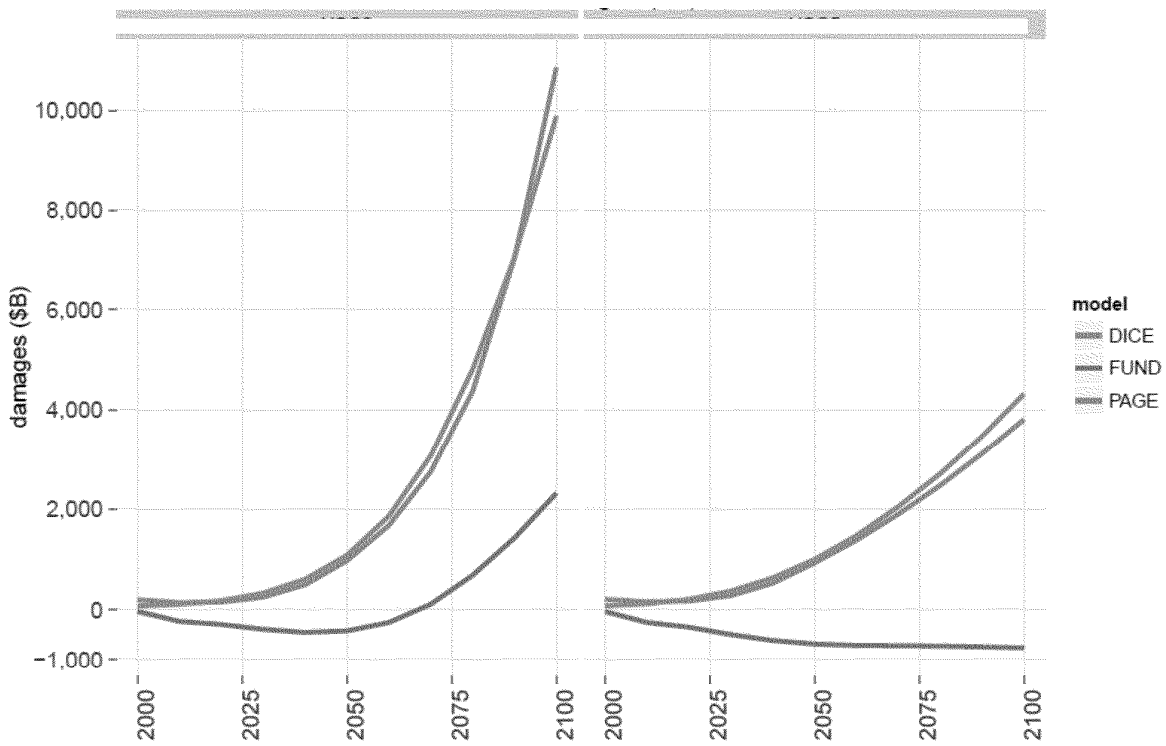

Figure 6-6
Total global climate damages to 2100

Figure 6-7 presents total damages in terms of percentage loss of global GDP (Figure 6-7). Thus, the pattern across models is similar to that just discussed. Damages in 2100 in the USG2 scenario are about 4% of GDP from the DICE and PAGE models, and about 1% of GDP from the FUND model. With less warming in the USG5 scenario, damages in 2100 are about 1.2% of GDP from DICE and PAGE, with net benefits of about 0.25% of GDP from FUND. Note that damages in PAGE in Figures 6-6 and 6-7 are initially higher due to un-adapted coastal impacts from SLR, which then subside after adaptation investments in the model have had time to ramp up. What's

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underlying the different total damage projections, and are DICE and PAGE really similar? Next we explore the relative contributions of the disaggregated regional and sectoral damages.

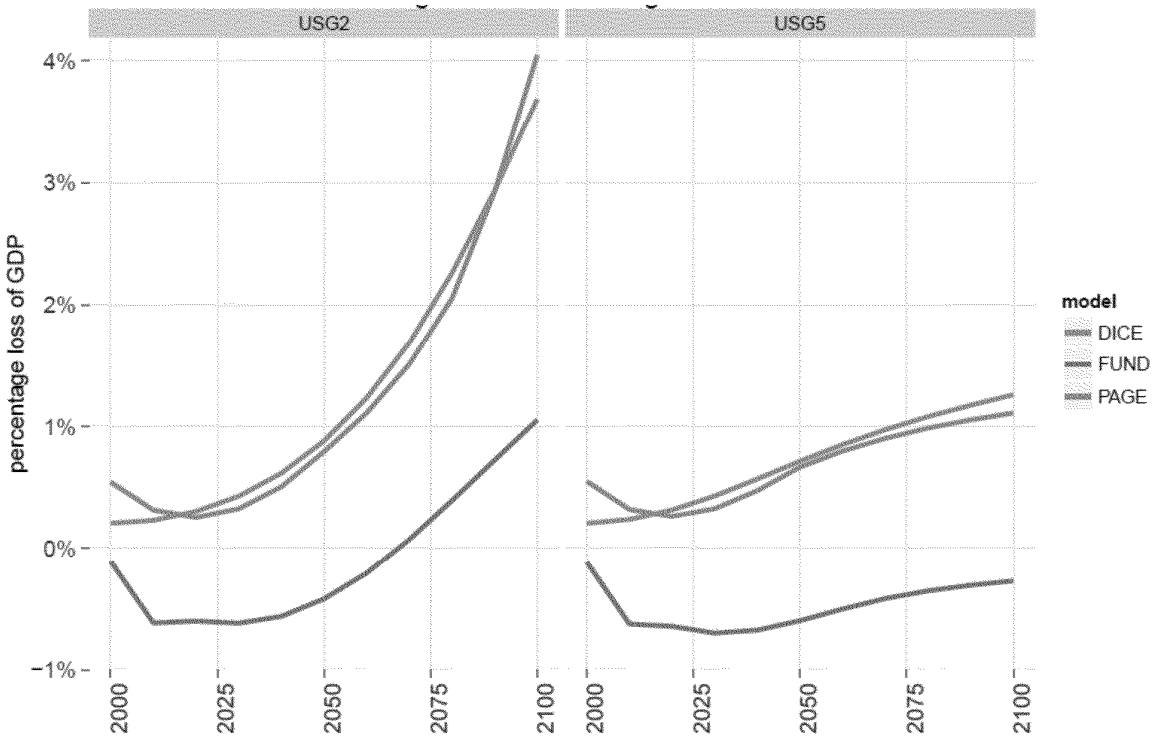

Figure 6-7
Total climate damages as a percent of global GDP to 2100

Figure 6-8 shows the regional decomposition of damages from the two models with regional detail, FUND and PAGE. In the higher warming scenario, FUND projects net benefits in several regions, most notably China, as well as the Middle East and Japan-South Korea, while the United States, Europe, Latin America, and the Former Soviet Union experience net negative effects from any amount of warming. PAGE, on the other hand, projects damages in all regions for the entire century. For similarly defined regions, we find PAGE projecting substantially more damages than FUND, e.g., United States (US, USA), the European Union (EU, WEU), and China (CA, CHI). We discuss this further at the end of this section in our focused comparison of select regions. With FUND, in the lower warming scenario, we observe smaller regional net damages, and larger net benefits for regions projected to benefit from moderate levels of climate change. In PAGE, on the other hand, we only observe reductions in annual damages across regions.

We also observe that regional damages in PAGE grow (and shrink) together in a balanced, linear pattern over time and across scenarios. The stable regional distribution of damages in PAGE is a direct result of PAGE's scaling of regional damages off of EU damages. FUND, on the other

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hand, models regions independently, and therefore damages grow at different rates across regions.

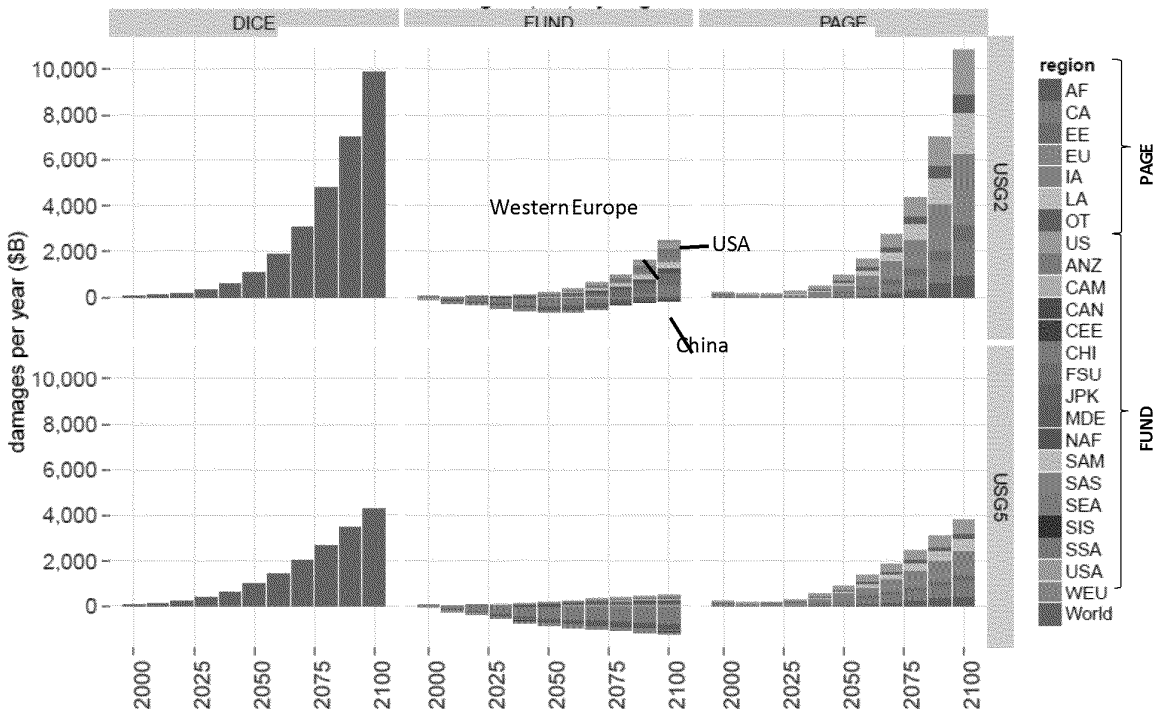

Figure 6-8
Total regional climate damages to 2100

Figure notes: See Appendix A for region definitions.

Figure 6-9 shows the sectoral decomposition of damages. A number of insights leap out. First, net benefits in terms of increased agricultural productivity due to CO_2 fertilization and reduced heating demand (i.e., avoided energy) are prominent in FUND, and dominate FUND's aggregate results discussed previously. Until warming reaches about 2.5°C after mid-century, benefits from low levels of warming in agriculture and heating outweigh the damages in other sectors. Second, increased cooling demand damages grow rapidly in FUND and eventually, combined with a variety of smaller damages (SLR, biodiversity loss, cooling demand, migration costs, and water resources) lead to net damages. Third, PAGE damages through 2050 are dominated by non-economic and SLR damages. Beyond 2050, to 2100, damages grow rapidly in all categories, but non-economic damages are the dominant damage. PAGE economic damages can be avoided by adaptation for low levels of warming, while non-economic sectors have less capacity for adaptation. PAGE's discontinuity shows up after crossing a threshold of 3°C, which occurs in USG2 before 2100, but not in USG5 at all. Fourth, only one damage sector, SLR, is represented in all three models. SLR damages are the highest in PAGE and the lowest in FUND, despite PAGE having the lowest projections for SLR and FUND having the highest (Figure 6-6). FUND has an explicit representation of adaptation options in the coastal sector, and the ability to build sea walls for protection helps lower the net cost of SLR impacts.

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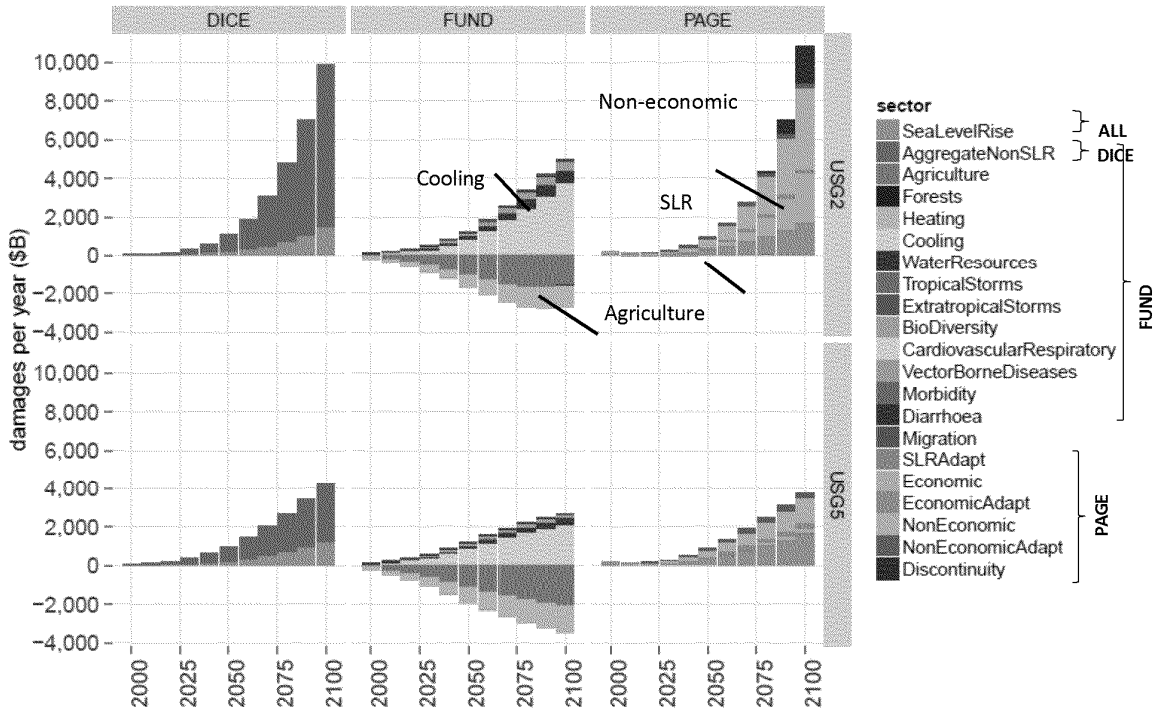

Figure 6-9
Total sectoral climate damages to 2100 (native sectors)

In Figure 6-10, we aggregate FUND & PAGE's damages into more comparable groupings, that we label "economic," "non-economic," and "discontinuity."[23] We find PAGE's economic and non-economic damages dwarfing FUND's, with non-economic damages similar in sign across the two models but economic damages different in sign for most of this century.

In Figure 6-11, we compare SLR damages (% GDP loss) per meter of projected rise and find PAGE SLR damages increasing most quickly for SLR up to about 1.5 meters, after which DICE damages increase most quickly and accumulate quadratically through to 5 meters of SLR. FUND SLR damages, on the other hand, are relatively insensitive to the amount of SLR, staying around 0.025% of global GDP.

[23] The description of PAGE's discontinuity is vague that we therefore are not able to clearly characterize the damages as "economic" or "non-economic." For FUND, "economic" damages include SLR, agriculture, forests, heating demand, cooling demand, water resources, and physical storm damage (tropical and extratropical). For PAGE, "economic" damages include SLR, and PAGE's economic damage category, as well as the corresponding adaptation costs. For FUND, "non-economic" damages include storm deaths (tropical and extratropical), biodiversity, cardiovascular & respiratory health, vector borne disease, morbidity, diarrhoea, and migration. For PAGE, "non-economic" damages include PAGE's non-economic damage category and corresponding adaptation costs.

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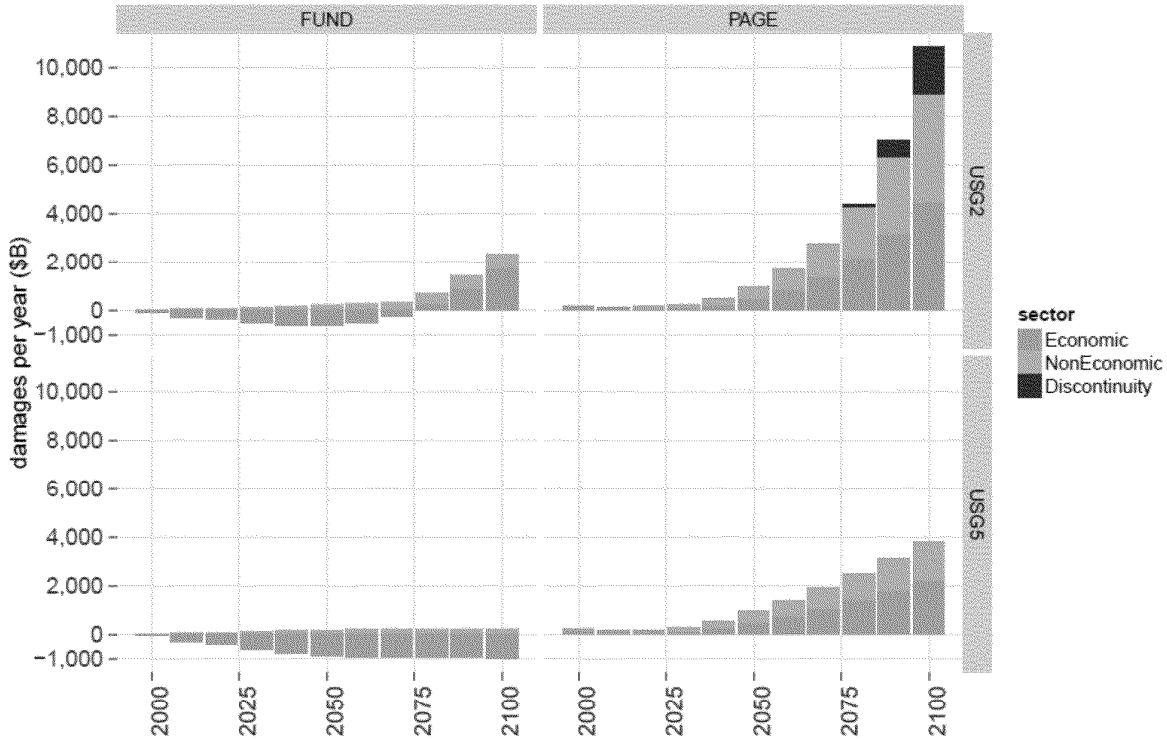

Figure 6-10
Total sectoral climate damages to 2100 (harmonized sectors)

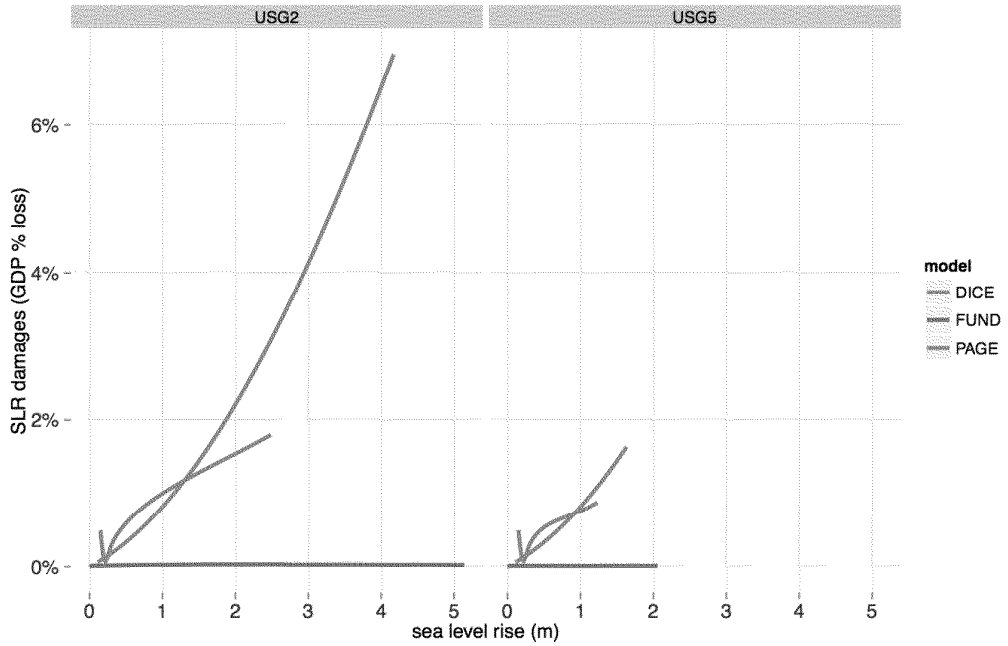

Figure 6-11
Sea level rise climate damages per projected level of sea level rise

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Damage function shapes

Sensitivity analyses

The previous results report damages for two socioeconomic scenarios that vary in emissions (and thus temperature) as well as slight differences in GDP and population. In order to understand the importance of these distinct drivers we perform independent sensitivity analyses.

First, we examine the responsiveness of damages to temperature, all else unchanged. We designate the USG2 scenario as our reference scenario, and design four sensitivity cases with linear temperature projections (Figure 6-12). USG2 socioeconomics are used for all the sensitivity runs. While a linear temperature pathway is not realistic, it is parsimonious and serves our diagnostic objective. The scenarios are numbered to indicate the level of global warming reached in 2300, ranging from 3°C to 13°C. In 2100, warming along these paths ranges from 1.4°C to 4.7°C. Our reference scenario USG2, is labeled TempRef. Higher (lower) temperature pathways are representative of higher (lower) climate sensitivity, higher (lower) emissions futures due to higher (lower) energy intensive societies, as well as other possible conditions.

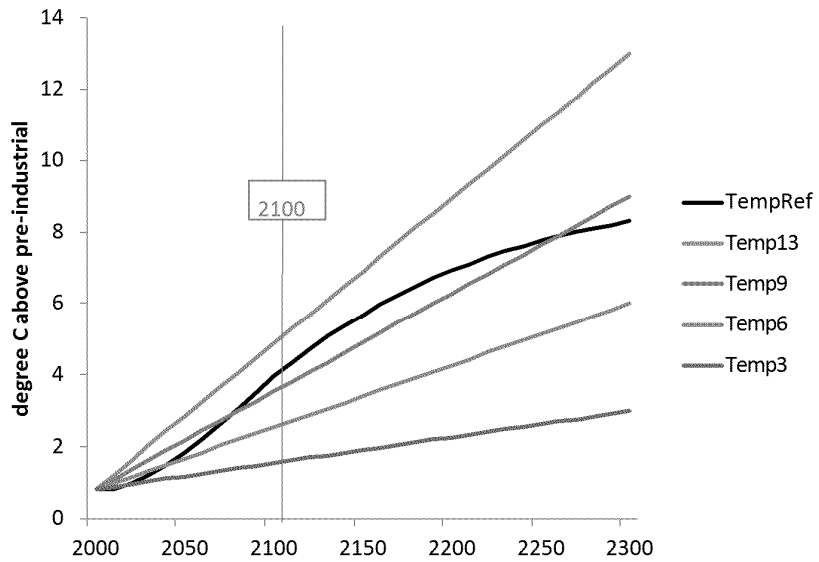

Figure 6-12
Temperature sensitivity scenario assumptions

Figure 6-13 elucidates the temperature sensitivity of physical SLR. SLR is a function of temperature and time (lagged temperature) in all three models. FUND, in the middle panel, is the most sensitive to the warming signal, with projected SLR ranging from just above 0.4m to 1.1m of SLR in 2100. PAGE is the least responsive, with projected SLR ranging from just below 0.3 to 0.5m in 2100.

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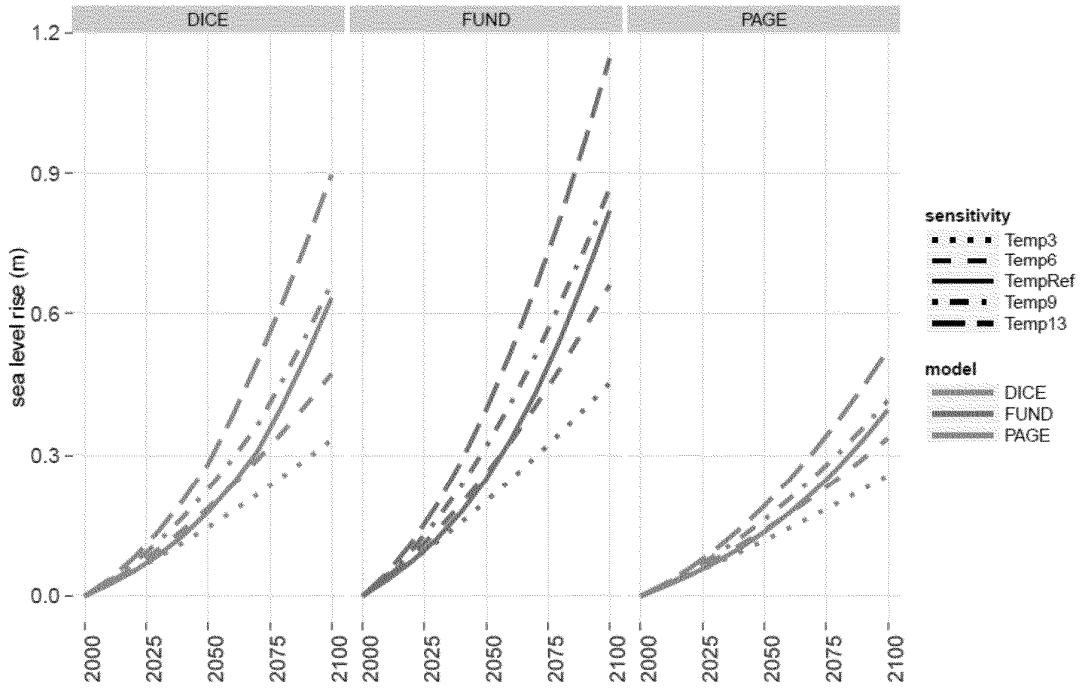

Figure 6-13
Sea level rise to 2100 for temperature sensitivity scenarios

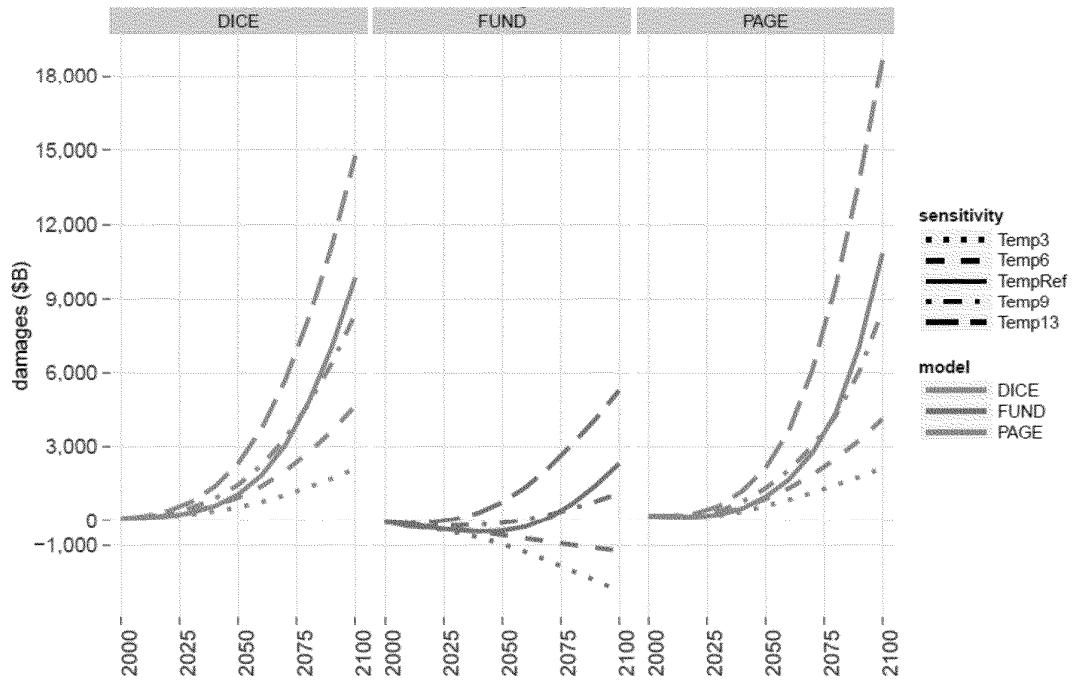

Figure 6-14
Total climate damages to 2100 for temperature sensitivity scenarios

Next, we consider the temperature sensitivity of damages. Total damages vary widely across the sensitivity cases (Figure 6-14). PAGE's damages are the most sensitive, while FUND's damages are the least sensitive (a point reinforced later in our exploration of functional relationships). DICE has the most predictable response because damages are specified as a quadratic function of warming. Since temperature increase is linear over time, each of the total damage projections from DICE are quadratic in time, resulting in annual damages of $2 to $15 trillion in 2100. FUND has a much more nuanced response to temperature. Warming ramps up slowly in the Temp3 and Temp6 cases, staying below 2.5°C in the 21st century and results in net benefits that increase with income growth over time. The net benefits become net damages over time in FUND with greater warming. PAGE, like DICE, has well behaved damage functions that are power functions of temperature. Damages in PAGE increase substantially in the highest warming case, Temp13, after 3°C of warming of around 2050.

Figure 6-15 shows the native sectoral composition of damages across temperature sensitivities. In DICE, non-SLR damages are the most responsive and the main driver of aggregate damage responsiveness. The responsiveness in the FUND model can be attributed to different sectoral damage functions, with very large damages in the Temp13 case from increased cooling load (and smaller offsetting benefits in agriculture and heating) and very large net benefits in the Temp3 case due to agriculture (note this is not from CO_2 fertilization because the sensitivity scenario design only alters the temperature path, not CO_2 concentrations). The PAGE damages in the Temp3 case reflect adaptation costs that avoid most negative impacts. In contrast, the Temp13 case invests in the same level of adaptation, but at such high levels of warming, the adaptation is only partially effective and the damages in the economic and non-economic sector accumulate, and expected discontinuity damages increase with a higher probability of a discontinuity occurring.

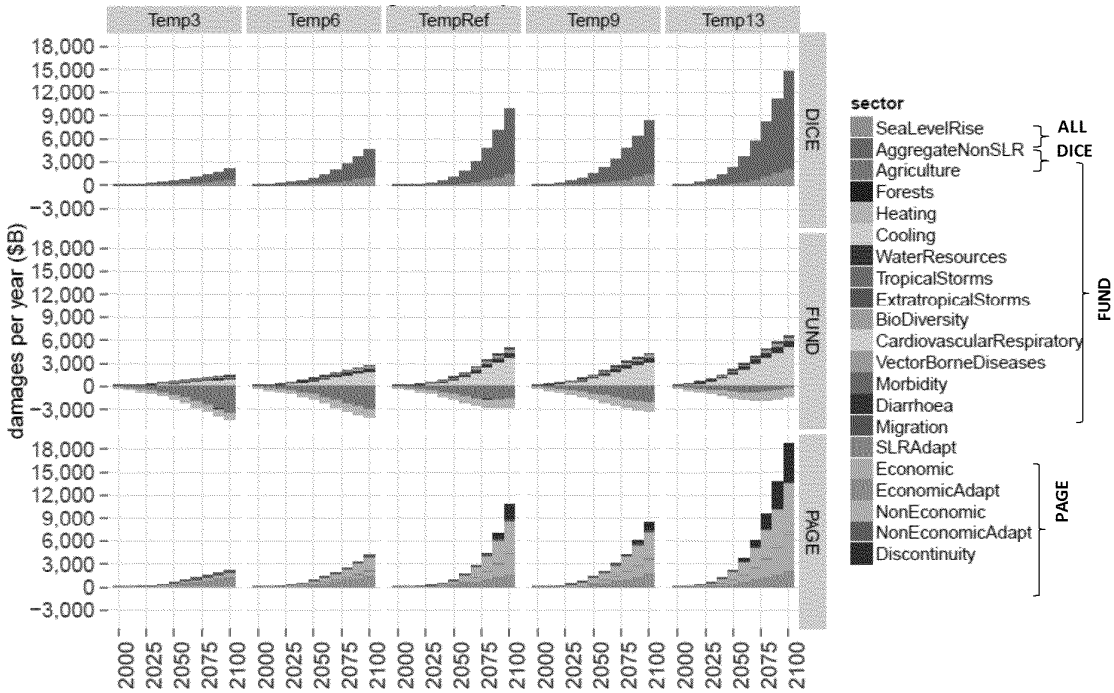

Figure 6-15
Total sectoral climate damages to 2100 for temperature sensitivity scenarios (native sectors)

Looking at our harmonized aggregated sector groupings (Figure 6-16), we find economic damages in FUND to be more sensitive to temperature than in PAGE. In PAGE, non-economic and discontinuity damages are more responsive to temperature.

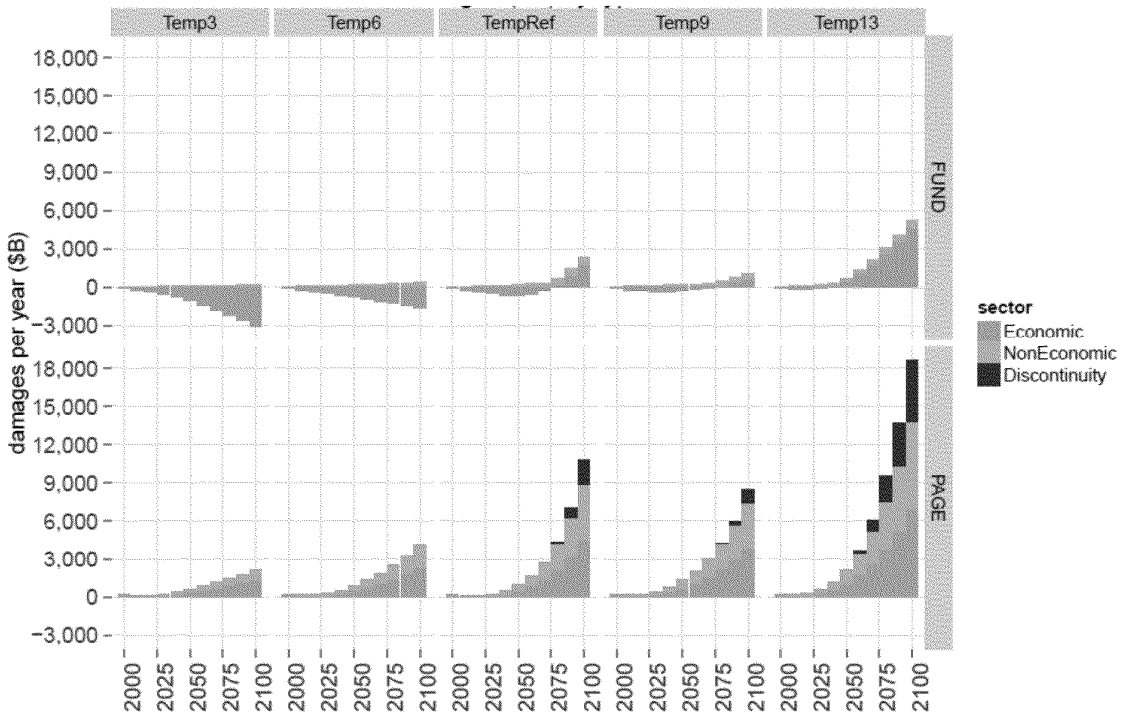

Figure 6-16
Total sectoral climate damages to 2100 for temperature sensitivity scenarios (harmonized sectors)

Regionally, we find that the gradual, low levels of warming in Temp3 and Temp6 produce net benefits, or near-zero to zero net damages, in all regions in FUND, while in PAGE, we find damages in all regions (Figure 6-17). We also see a relatively stable regional distribution of damages in PAGE regardless of the level of warming. Regional damages in PAGE respond similarly with temperature due to PAGE's regional scaling of damages. In FUND, however, the regional distribution of damages changes with the level of warming, but China is the largest regional contributor regardless of the level of warming.

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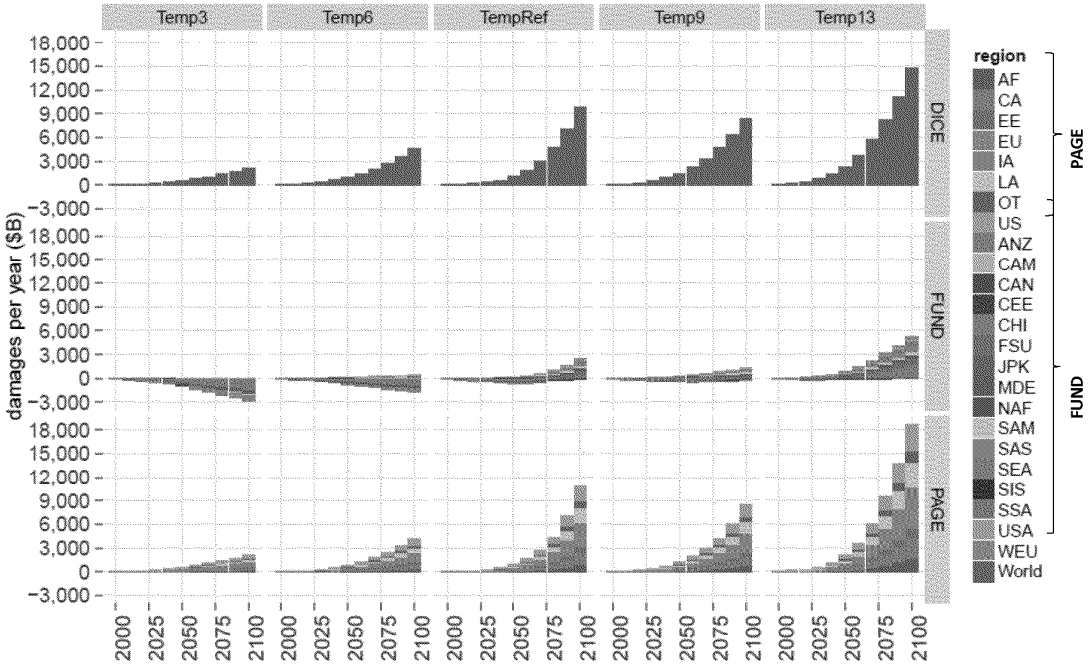

Figure 6-17
Total regional climate damages to 2100 for temperature sensitivity scenarios

We design a second set of sensitivity cases to evaluate the responsiveness of damages to income, with all else unchanged from the reference USG2 projection, including temperature (Figures 6-1 and 6-2). We develop sensitivity cases using high and low GDP projections from the recent EMF-27 study (Kriegler et al., 2014) to evaluate damage sensitivity to OECD and non-OECD income growth (Figure 6-18). To isolate the effect of income growth in an income group, we combine the low and high income growth case for each group with the reference income growth of the other regional group. The result is five sensitivity scenarios (Table 6-4).

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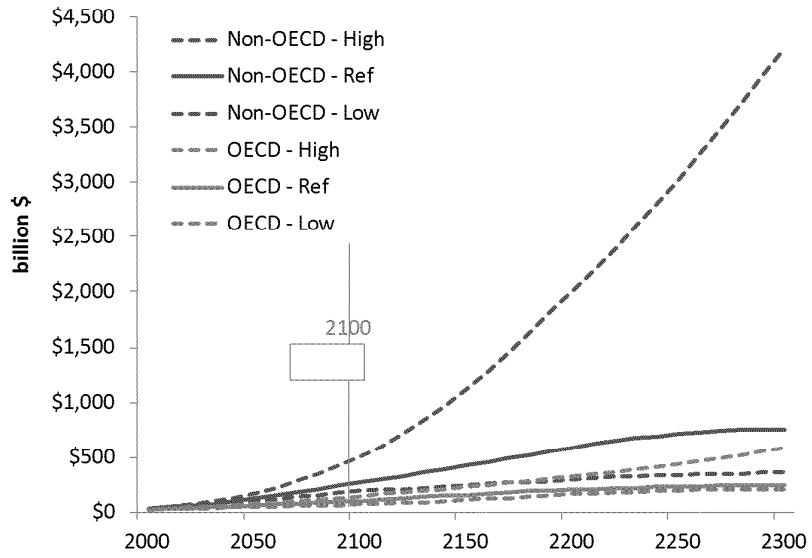

Figure 6-18
Income growth sensitivity scenario assumptions

Table 6-4
Income growth sensitivity scenarios

Scenario	OECD income growth	Non-OECD income growth
Ref GDP	Reference (USG2)	Reference (USG2)
NonOECD high	Reference	High
NonOECD low	Reference	Low
OECD high	High	Reference
OECD low	Low	Reference

We find the damage projections from all the models, including DICE, to be more responsive to non-OECD income growth variation (Figure 6-19). Although DICE does not have regions, the non-OECD cases produce larger swings in global GDP levels that result in larger swings in total damages in DICE (although the percentage loss of GDP is the same across all five cases, equal to what was shown in Figure 6-7). FUND, however, is not very responsive to income until temperature exceeds 2.5°C after 2050. At that point, net benefits change to net damages. The OECD sensitivity cases do not have much bearing on overall damages in FUND, while damages are more responsive to non-OECD income assumptions (a result strengthened in our functional relationships discussion later). PAGE is structurally similar to DICE in that damages are expressed as a percent of GDP so much of the responsiveness shown is simply driven by the different levels of global GDP. However PAGE does have an additional damage adjustment based on the elasticity of per capita income, which means that non-OECD regions will experience slightly less (more) damages due to their higher (lower) income respectively.

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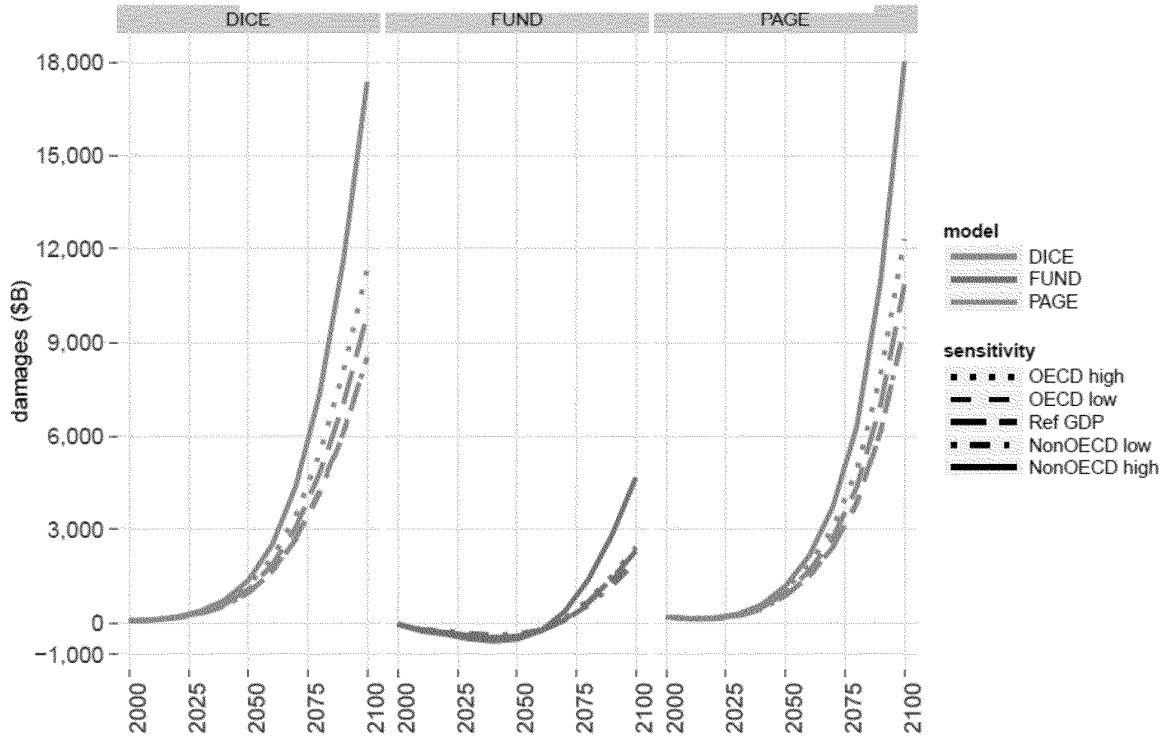

Figure 6-19
Total climate damages to 2100 for income sensitivity scenarios

Figure 6-20 shows the regional composition of FUND and PAGE damages across income growth sensitivities. In general, higher income implies larger estimated damages. However, in FUND, higher regional income can also imply larger regional net benefits for regions estimated to have net benefits in the reference income scenario (e.g., China)—i.e., the higher the income in region *x*, the larger the magnitude of the absolute value of damages in *x*, regardless of the sign. FUND damages are highest in the non-OECD high GDP case, particularly in the Former Soviet Union and Latin American regions, and damages are lowest when the non-OECD has low GDP levels. Many regions still have net benefits and this result is robust over the socioeconomic cases. In PAGE, the OECD sensitivity cases show larger damages for the US, EU, and OT (other OECD) regions under high OECD GDP. Similarly the same type of responsiveness is seen in Africa, China, Eastern Europe, India, Asia and Latin America, with increased damage with higher non-OECD income.

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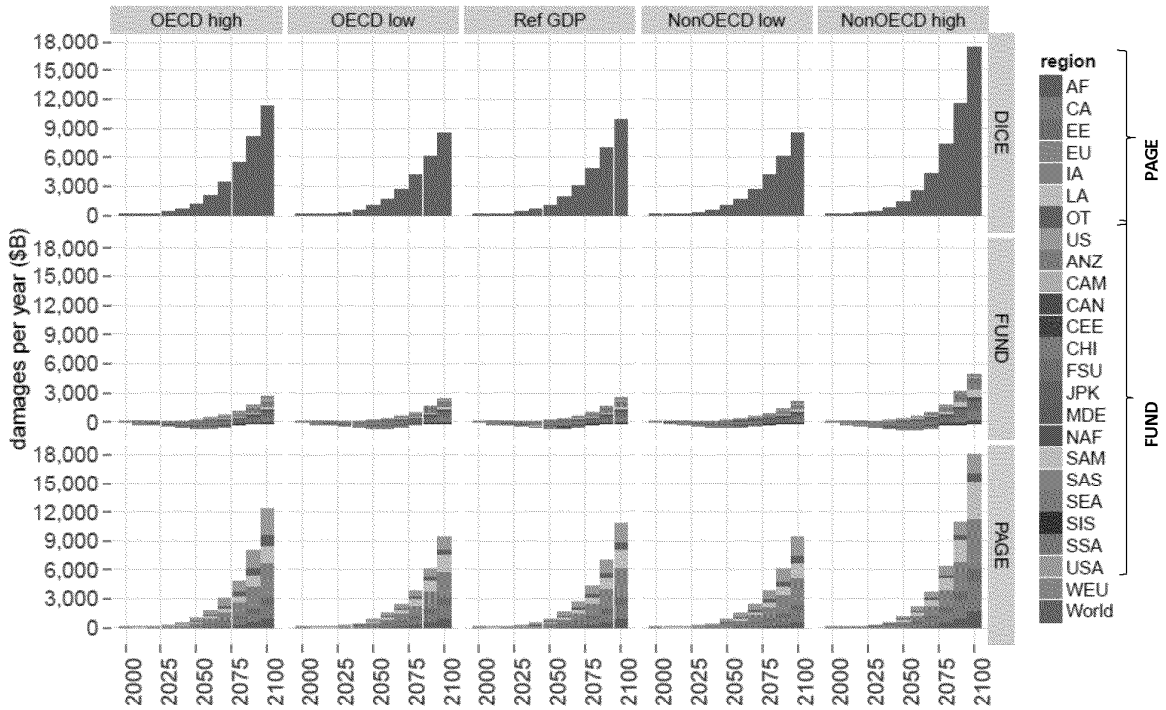

Figure 6-20
Total regional climate damages to 2100 for income sensitivity scenarios

Sectorally, we find that damages within and across models are not equally responsive to income (Figure 6-21). In DICE, for instance, non-SLR and SLR damages are equally responsive to changes in income in terms of percent change since both damage functions are defined as percent losses in income. In FUND, the sectors are not equally responsive to income. In PAGE, economic and non-economic damages are more responsive to income than SLR and discontinuity damages.

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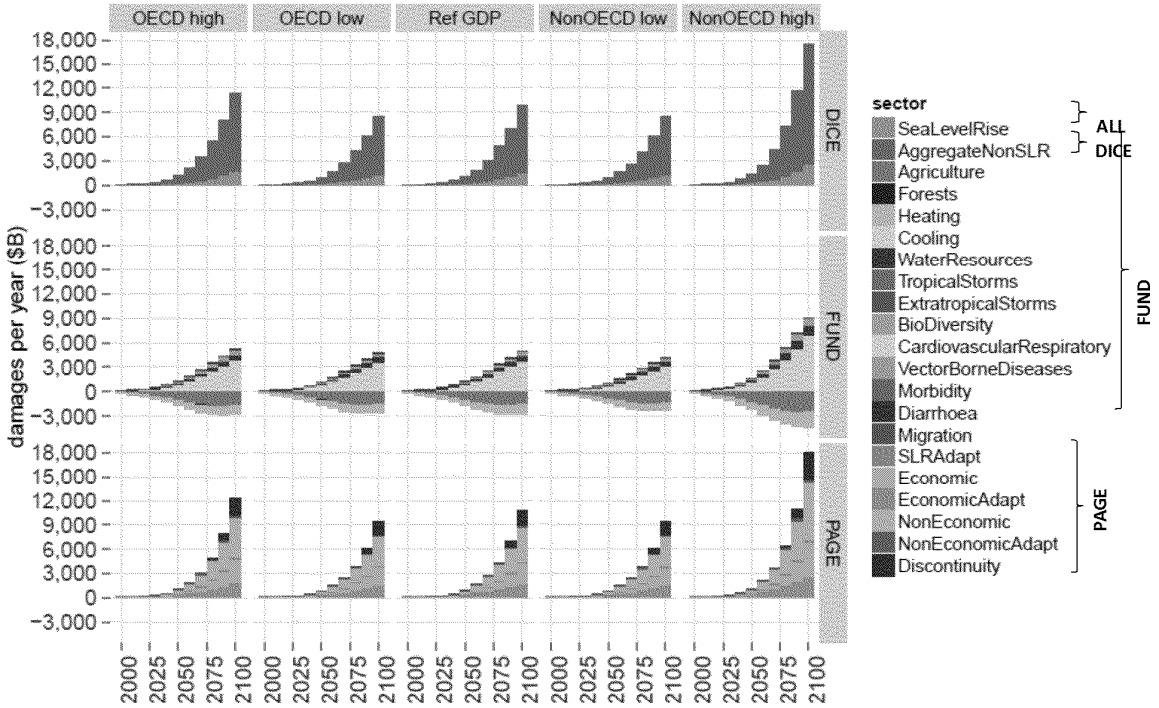

Figure 6-21
Total sectoral climate damages to 2100 for income sensitivity scenarios (native sectors)

Does it matter where income growth occurs? In other words, are damages equally sensitive to OECD and non-OECD income growth? We find that only FUND's aggregate damages respond differently depending on where income growth occurs. Specifically, we find FUND's aggregate damages to be more responsive to non-OECD income growth, and DICE and PAGE's damages to be indifferent to where income growth occurs in the world.

Functional relationships

As shown, the three model's damage modules respond differently to climate and socioeconomic drivers. Looking across and expanding our scenarios, we can derive functional relationships with respect to temperature and income. This is a useful perspective for summarizing and comparing damage responses. It also provides insights regarding marginal damage responses—a topic we explore explicitly in the next section. These relationships are presented graphically in the figures below.

In Figure 6-22, we present temperature damage response functions for 2050, 2100, and 2200. For each year, we can clearly illustrate how damages respond to temperature. Across years, however, the curves shift with the changing socioeconomic condition. For instance, due to economic growth in the USG2 scenario, a warming of 5°C in 2050 results in $3.5 to $7 trillion of total damages, but $5 to $20 trillion of damages in 2100.

In Figure 6-22, we observe that the PAGE damage module is most responsive to warming with the slope increasing substantially after 3°C of warming. DICE damages increase smoothly with warming, reflecting the two quadratic damage functions of temperature and SLR. FUND, on the

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other hand, estimates net benefits below 2.5°C in 2100. Overall, FUND is the least responsive to warming, as demonstrated by the flatter slope of FUND's curve. We also observe that PAGE's damage growth rate continues to increase until beyond 15°C of warming before slowing down, while DICE's damage growth rate is relatively constant beyond 5°C of warming.

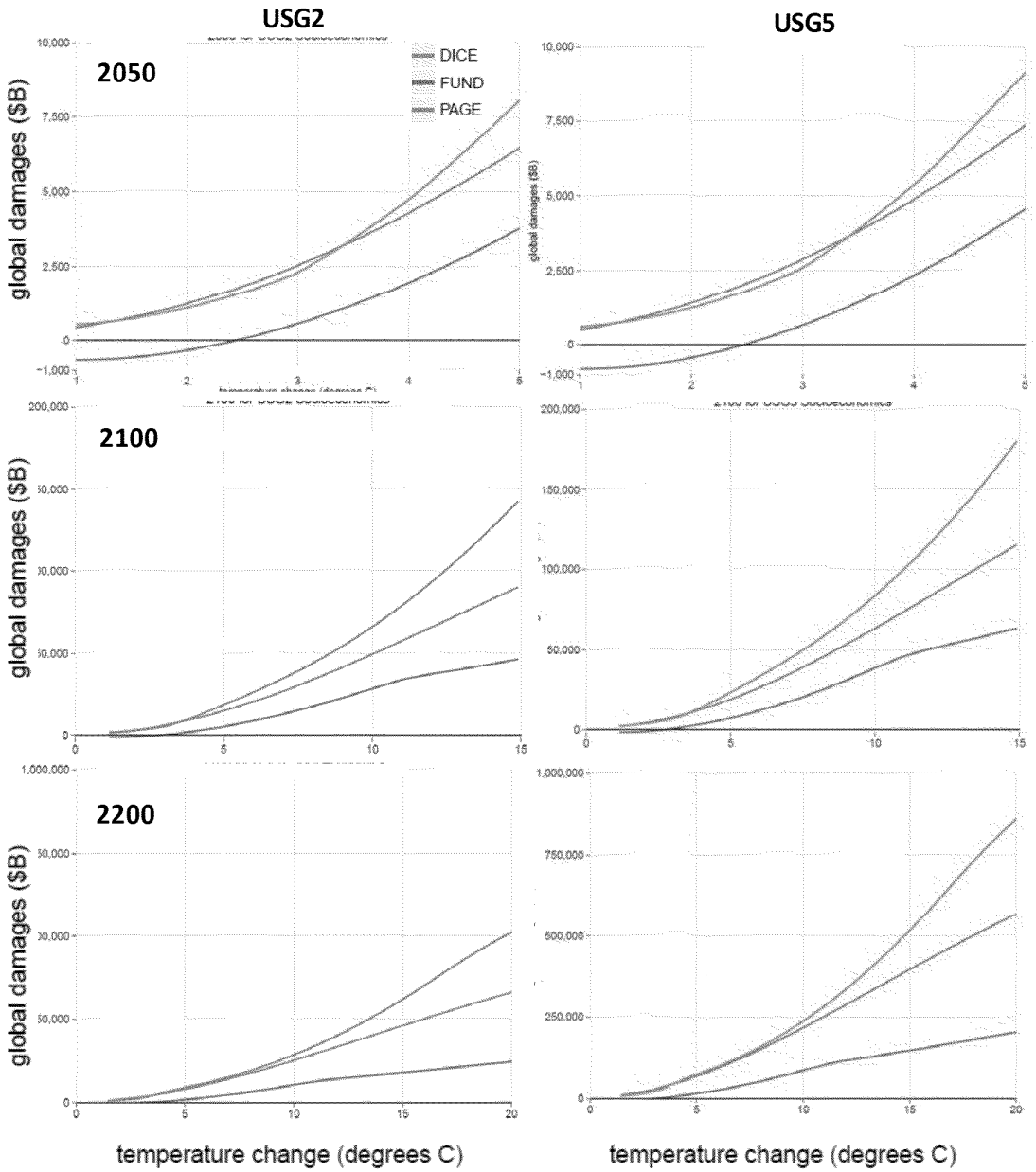

Figure 6-22
Total climate damages as a function of temperature for 2050, 2100, and 2200 with USG2 & USG5 socioeconomics

Figure note: x-axis' & y-axis' scales vary

Aggregate damages as a function of temperature can be decomposed into sectoral and regional temperature response functions for each model. Sectoral response functions for 2050 and 2100 are shown in Figure 6-23. From the figure, we immediately see how each sector responds to warming. In DICE, non-SLR damages are most responsive. In FUND, cooling damages increase dramatically with warming, while heating benefits increase with initial warming and then begin to slow, reflecting limits on how much heating can be avoided. Agriculture produces net benefits until about 5°C, while water resource damages increase linearly with warming and are of similar magnitude as SLR damages. In PAGE, all four damage sectors respond to warming, but the cost of adaptation remains constant (and small) for all levels of temperature by assumption. SLR and non-economic damages dominate at low levels of warming, and non-economic, economic and discontinuity damages accumulate quickly with greater warming. The expected value of a discontinuity impact is zero until 3°C and then increases linearly with a steep slope. Finally, in all three models, SLR damages have a roughly linear response to temperature.

Regional response functions are shown in Figure 6-24 for FUND and PAGE. The figure highlights key regional drivers of aggregate total damages. First, in FUND, we see how damages in China influence the aggregate damages storyline, switching from large net benefits to large net damages, with both potentially far greater in absolute magnitude than other regions depending on the warming level. The Former Soviet Union region also stands out with net damages across warming levels and the next largest damages after China at higher temperatures. Second, in the PAGE results we more clearly see how regional damages grow together with warming as damages in every region are a fixed fraction of EU damages (EU damages are the purple line).

Next we decompose the FUND and PAGE damage functional responses into sector-region combinations (Figure 6-25). We see that, for all regions, FUND damages are concentrated in same four sectors—agriculture, cooling demand, heating demand, and water resources. China damage responses (in blue) clearly stand out in each of these four sectors, but the next most prominent region varies by sector (e.g., South Asia in agriculture and cooling, and the Former Soviet Union in water resources with net damages instead of net benefits as shown for China, and a number of regions with similar smaller damages in cooling and heating demand). Increased cooling load and agricultural impacts in China explain the majority of FUND's damages (and thus its SCC values). Interestingly, in PAGE, regional damage responses never intersect with increasing temperature in any of the four damage sectors. The stable sectoral pattern across regions reflects the EU pattern due to PAGE's regional scaling, with some adjustments for adaptation and income levels.

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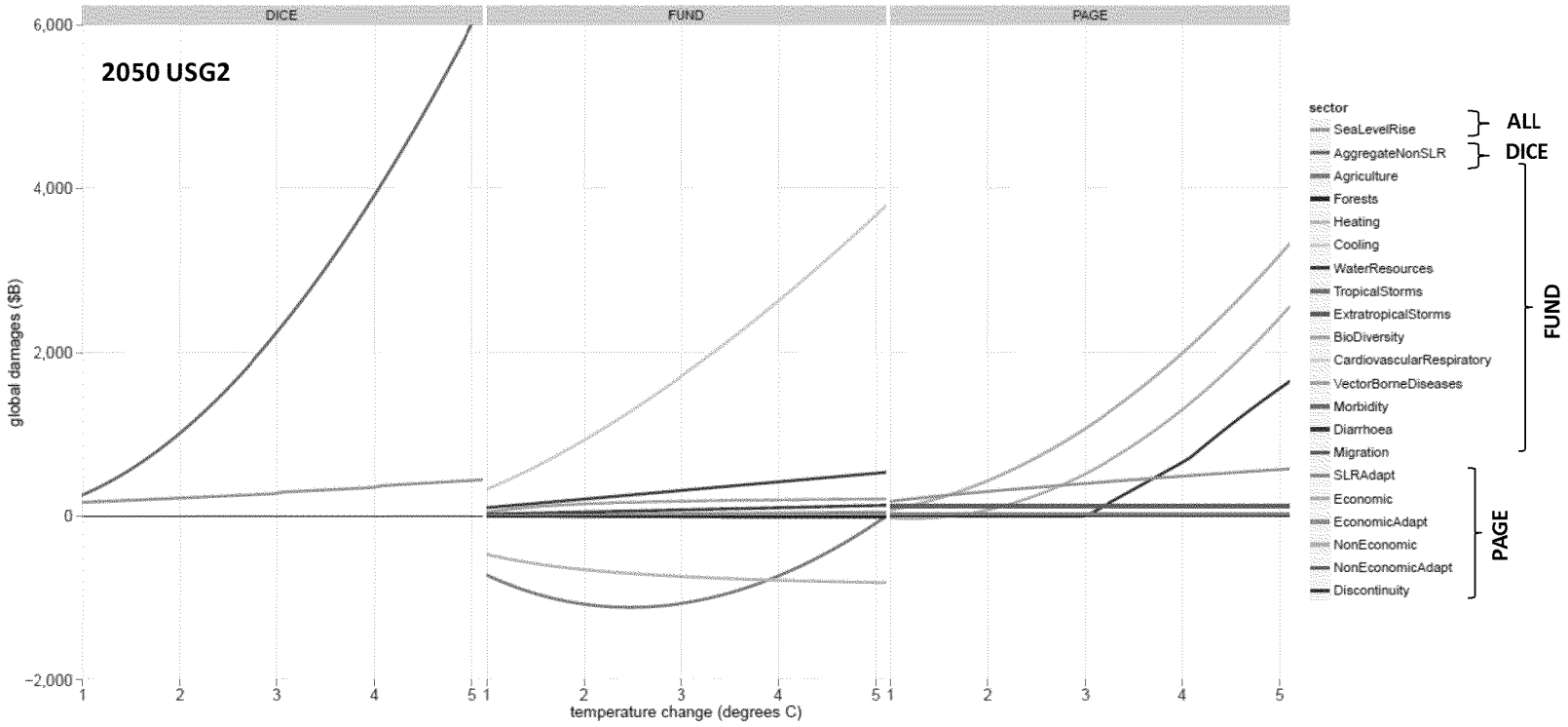

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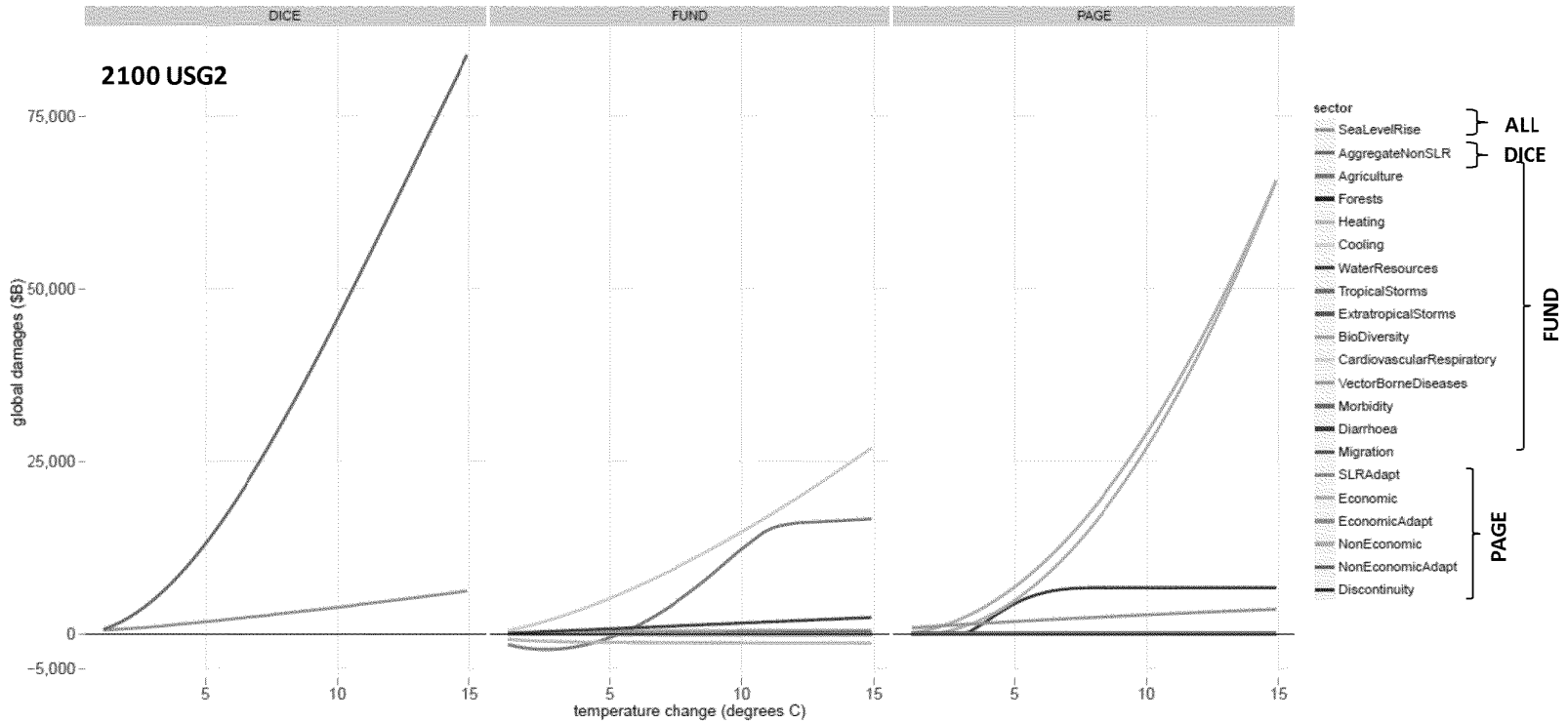

Figure 6-23
Total sectoral climate damages (native sectors) as a function of temperature for 2050 and 2100 with USG2 socioeconomics

Figure note: y-axis' scales vary between 2050 and 2100

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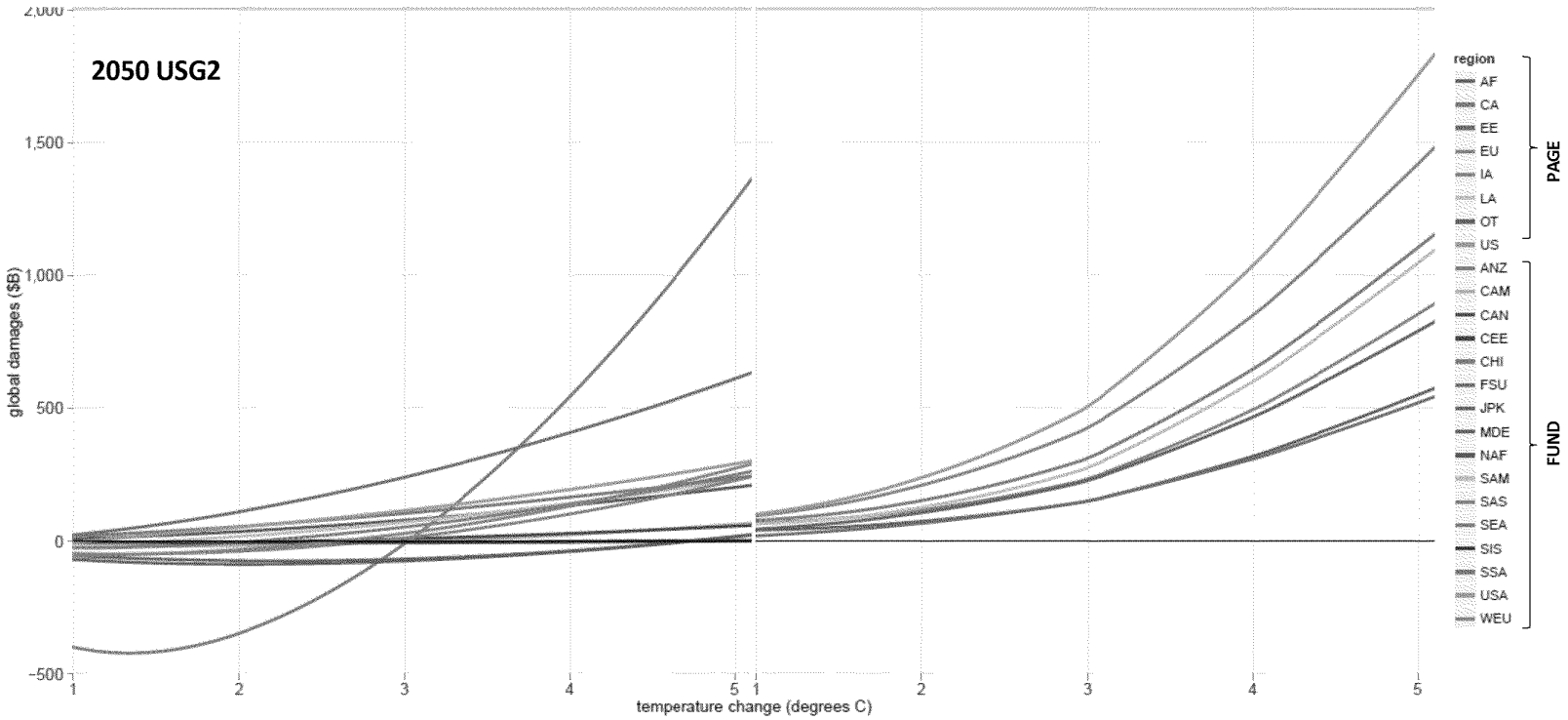

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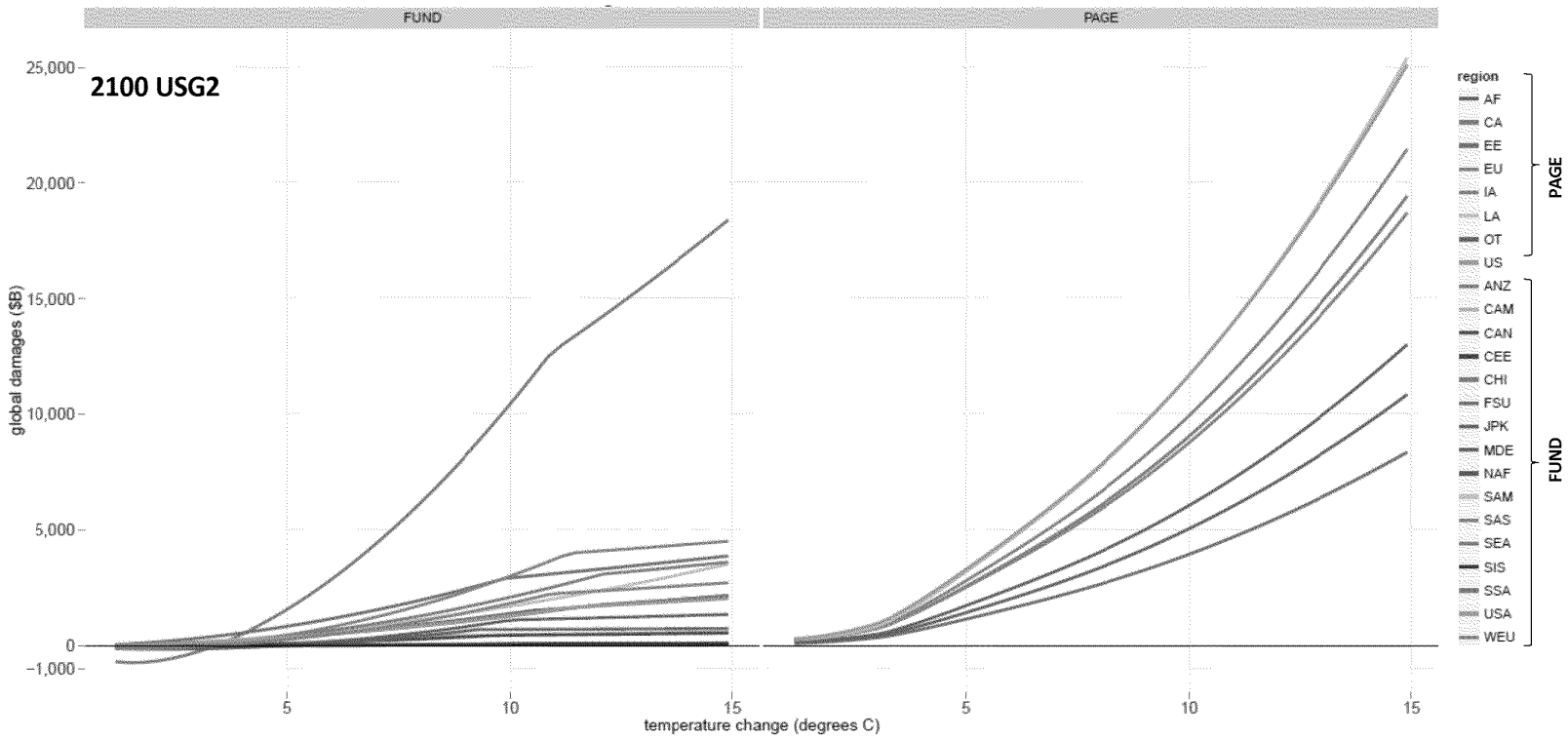

Figure 6-24
Total regional climate damages as a function of temperature for 2050 and 2100 with USG2 socioeconomics

Figure note: y-axis' scales vary between 2050 and 2100

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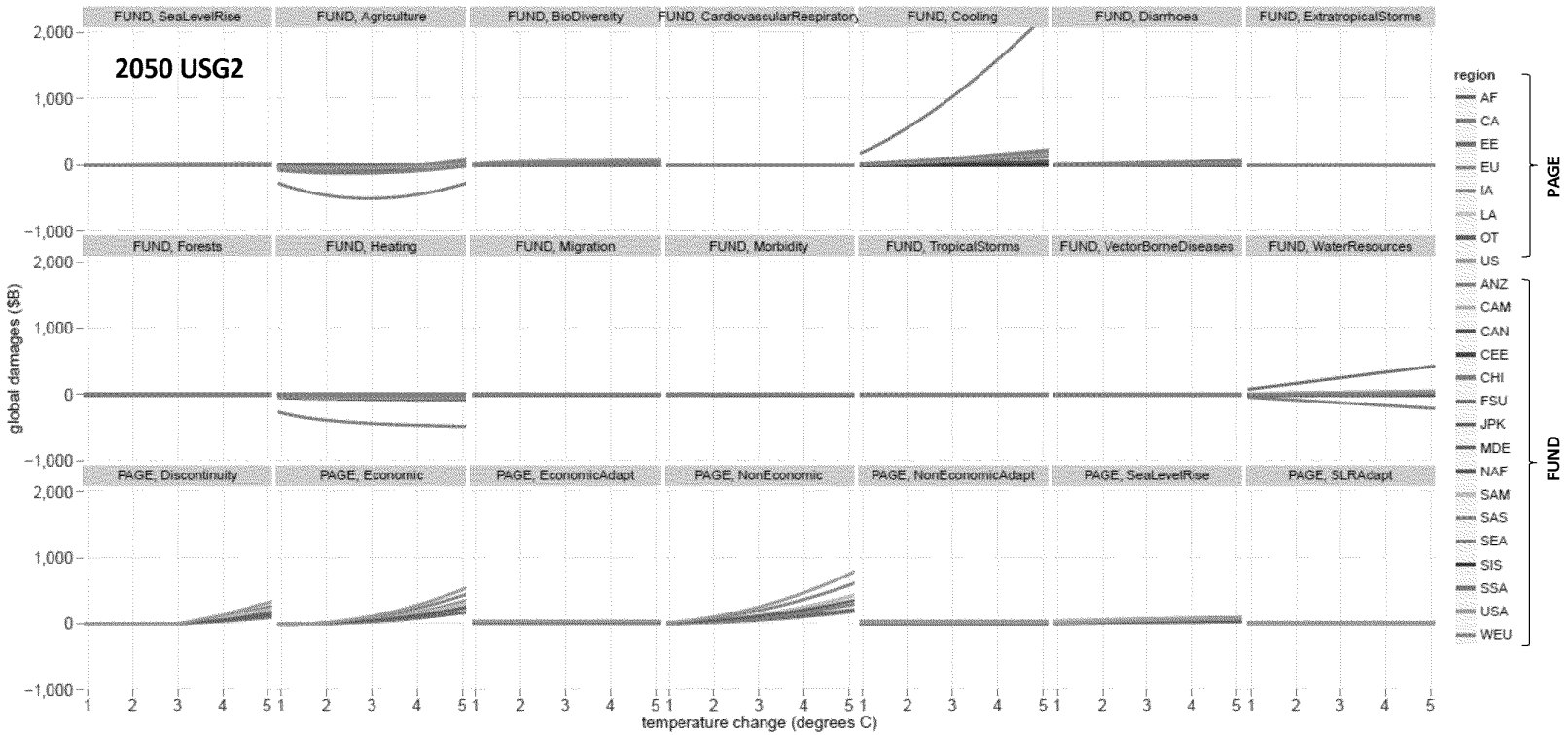

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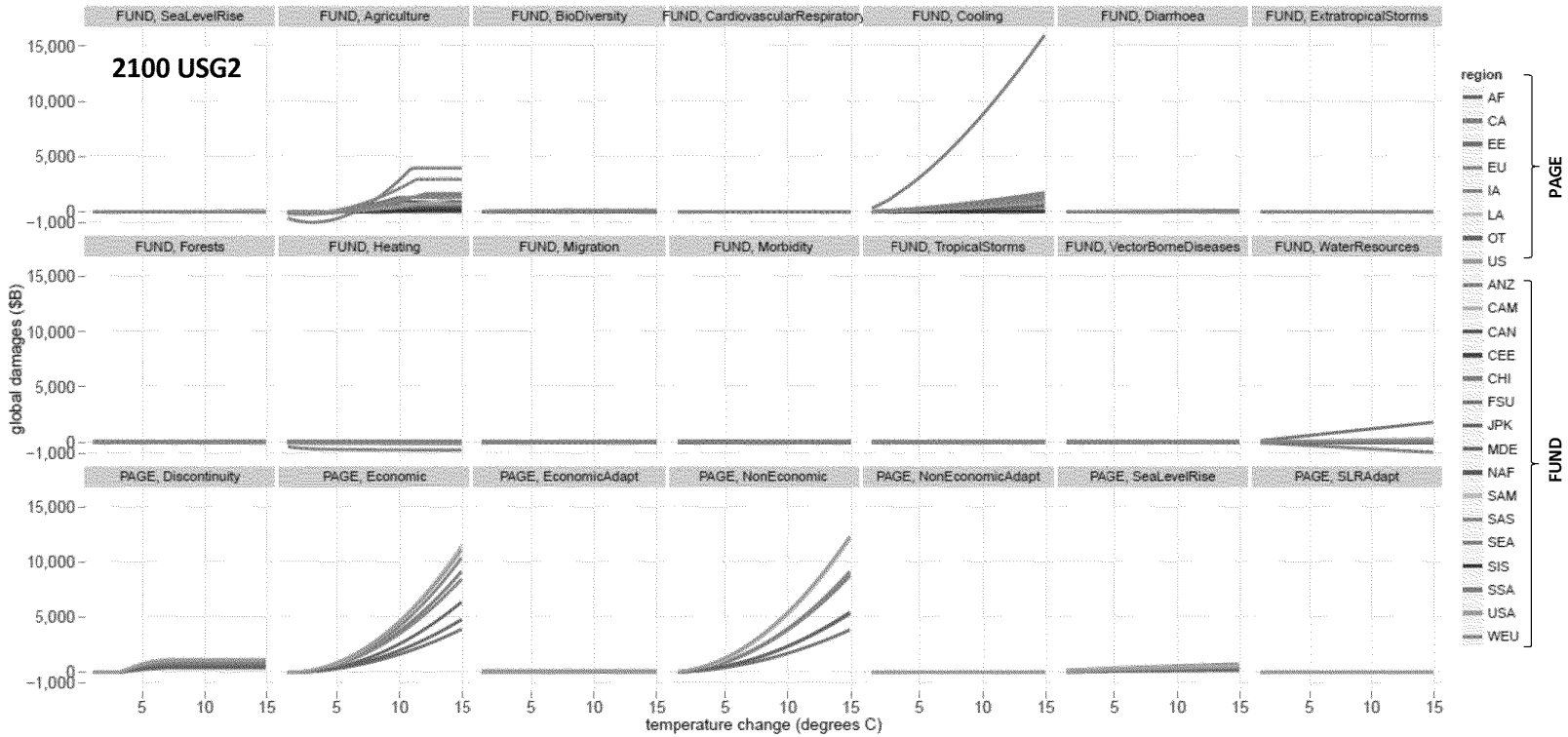

Figure 6-25
Sectoral regional climate damages (native sectors) as a function of temperature for 2050 and 2100 with USG2 socioeconomics

Figure note: y-axis' scales vary between 2050 and 2100

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Although warming is the primary diver of damages, socioeconomic assumptions matter as well. This discussion briefly illustrates the extent to which damages respond to income (GDP).

DICE and PAGE are both formulated as a fractional loss of GDP, and are substantially more responsive to OECD and non-OECD income levels than FUND (Figure 6-26). As income increases in FUND, damages increase due to the larger affected income level but damages are moderated by the resilience mechanism in FUND described as "dynamic vulnerability". As noted, FUND's aggregate damages are more responsive to non-OECD income growth, while DICE and PAGE are indifferent to where income growth occurs.

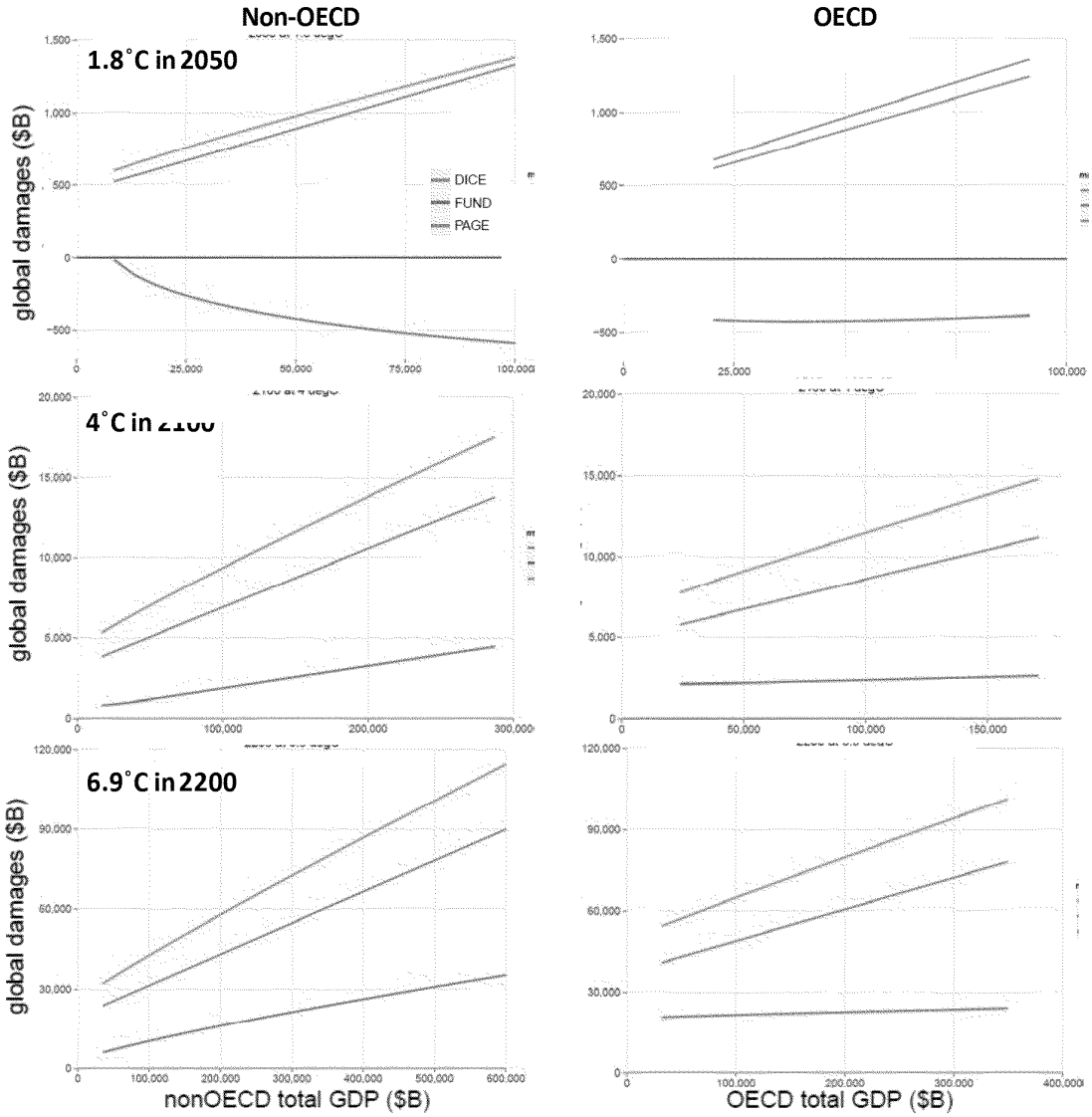

Figure 6-26
Total climate damages as a function of non-OECD (left) and OECD (right) income for 2050, 2100, and 2200 with USG2 climate

Figure note: x-axis' & y-axis' scales vary

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Incremental damages over time

In order to understand the behavior of damages in a setting that is most relevant to the SCC, we examine how each model's damage functions respond to an incremental pulse of emissions. For this task we first run each model's damage component with our standardized diagnostic reference inputs (climate and socioeconomics)—USG2 and USG5. We then re-run each damage component with a standardized perturbed climate projection from a 1 GtC incremental increase in global CO_2 emissions in 2020. Finally, we compute the annual differences in damages between the reference and perturbed scenarios, with additional damages from 2020 to 2300 attributed to the emissions pulse. Socioeconomics are unchanged between the reference and perturbed climate scenarios. Figures in this section present undiscounted incremental annual damages over time in terms of $ per ton CO_2. They are not net present value SCC estimates.

The standardized incremental climate responses we use are shown in Figure 6-27. For consistency with our standardized USG2 and USG5 reference climate inputs presented earlier, we use the incremental climate responses that we generated with the DICE climate module. As a result, there is no difference in the incremental CO_2 concentration changes across the scenarios because DICE does not model climate system feedbacks (Figure 6-27). Incremental CO_2 concentrations are nonetheless necessary inputs as a climate driver for FUND's agriculture and forestry damage sectors.

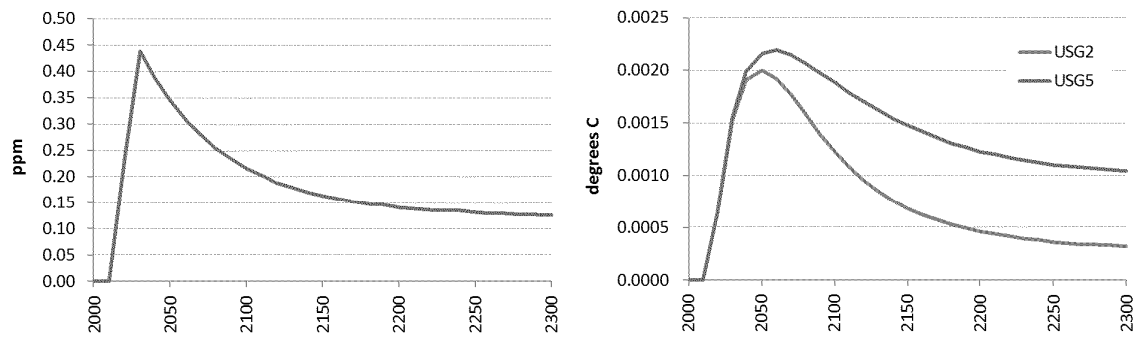

Figure 6-27
Standardized USG2 and USG5 Incremental global mean temperature (left) and CO_2 concentration (right) inputs

Aggregate incremental damages to 2100 are shown in Figure 6-28. The ordinal pattern across models is qualitatively similar to that observed for total damages, with incremental damages growing more quickly over time in DICE and PAGE than in FUND. However, at higher temperatures, recall that PAGE's damage function has a notably steeper slope, which separates PAGE's incremental damages from the other models. Also, the near-term net benefits are far less prominent in FUND's incremental responses compared to its total damage responses (Figure 6-6).

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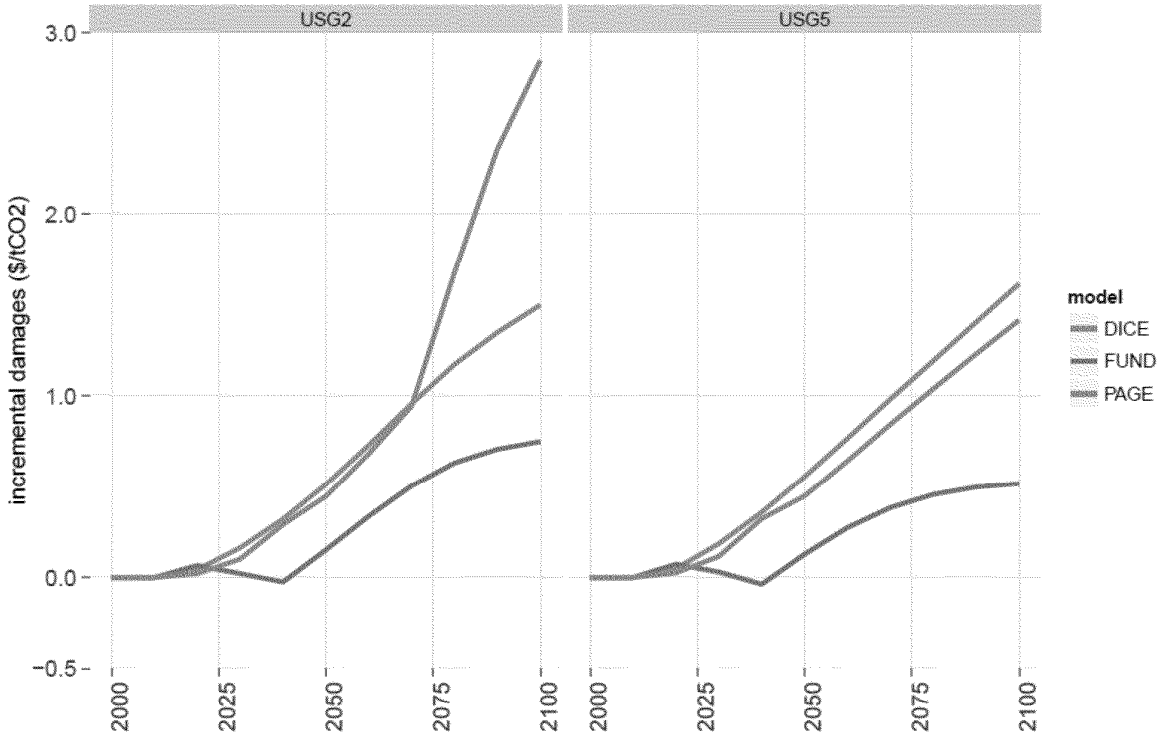

Figure 6-28
Incremental climate damages to 2100

Incremental damages from DICE are smooth due to its quadratic functional form. PAGE's incremental damages are also smooth due to its power functional form up until the reference temperature change is greater than 3˚C. At this point, the incremental increase in temperature triggers an incremental increase in the expected value of discontinuity damages. In contrast, the incremental damage response in FUND has kinks because of the nature of certain discontinuous functions for impacts and adaptation for sea level rise that lead to jumps from one period to the next.

Overall, the figure demonstrates a fundamental insight regarding how damages respond to an emissions pulse. Even though the annual incremental temperature response declines over time in any given scenario (Figure 6-27), we see that the annual incremental damages from the elevated temperature path continue to increase over time. This result derives from rising reference temperatures and income levels over time. Thus, annual incremental damages increase with elevated climate and socioeconomic conditions.

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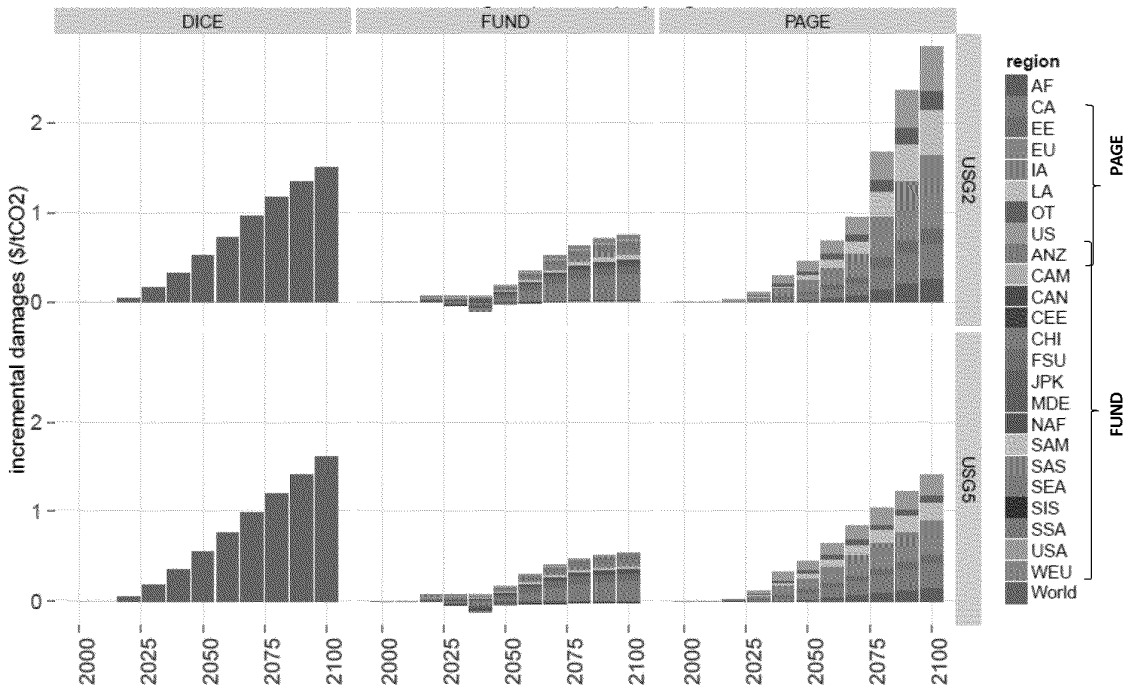

Figure 6-29
Incremental regional climate damages to 2100

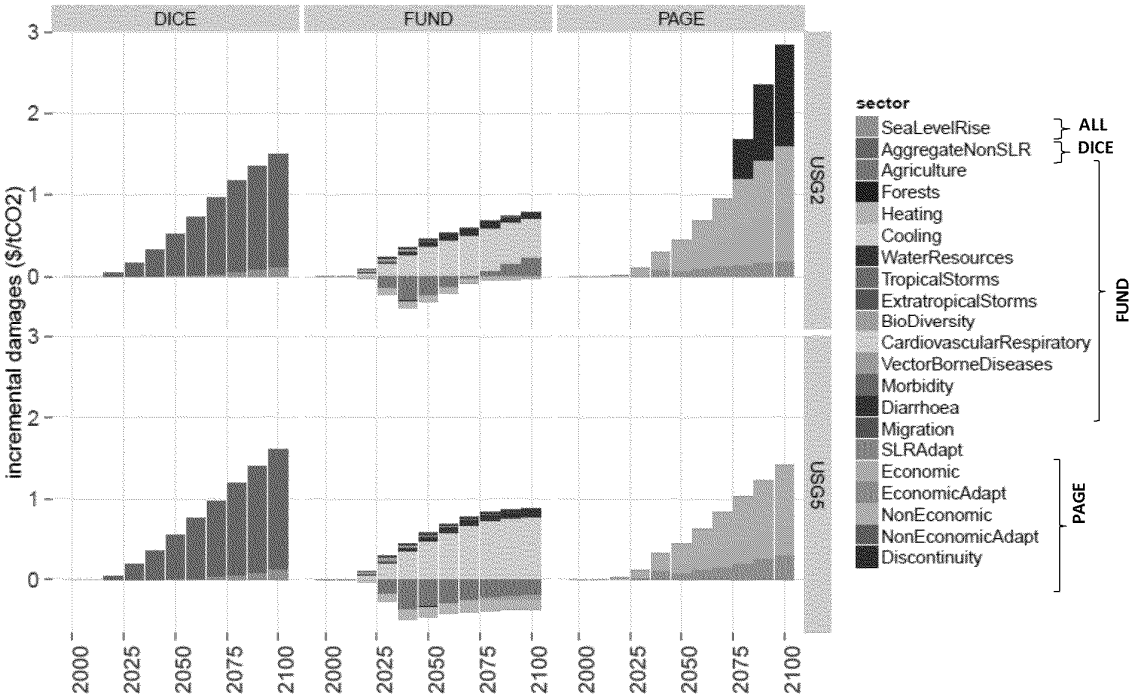

Figure 6-30
Incremental sectoral climate damages to 2100 (native sectors)

The distribution of incremental damages regionally and sectorally within FUND and PAGE are shown in Figures 6-29 and 6-30. Incremental damages in FUND are more heavily concentrated in China than we observe with total damages. This result appears in the FUND incremental responses off both the high (USG2) and low (USG5) temperature scenarios. In PAGE, on the other hand, the regional distribution of incremental damages is similar to the distribution observed with total damages. Meanwhile, incremental sectoral damages in FUND are more heavily concentrated in increased cooling demand than we observe with total damages, with coinciding smaller incremental benefits from heating reductions and improved agricultural productivity. From PAGE, off the high temperature scenario (USG2), we find that the discontinuity has a larger role in the incremental damages through 2100 than we observe in total damages, while SLR has a smaller role, and non-economic and economic damages are the primary incremental damages in the near-term but SLR and non-economic damages are the primary near-term total damages.

2100-2300 damages—total & incremental

In this section, we assess the total and incremental damage responses beyond 2100, to 2300. Overall, we find significant increases in annual damages post-2100 with all the models and clearly see the effects of the steeper slope of PAGE's and DICE's total damage formulations, as their total and incremental damage responses pull away from FUND's, and are substantially more sensitive to warming and income assumptions. In the discussion that follows, we explore total annual damage responses in detail, and then incremental annual damages.

Post-2100, we find the models projecting five times as much SLR in 2300 versus 2100 in the higher warming scenario, and 2-4 times as much in the lower warming scenario (Figure 6-31). Total climate damages rise by an even greater degree, over an order of magnitude in all the models with both warming scenarios (Figure 6-32). However, DICE and PAGE exhibit significantly faster, yet similar, increases in annual damages post-2100 compared to FUND in the higher warming scenario. In the lower warming scenario, annual total damages rise most quickly with DICE, with DICE projecting about 50% more annual damages than PAGE in 2300, while FUND rises from net benefits in 2100 to relatively moderate net damages post-2100. As a fraction of the economy, annual climate damages rise from about 1% to 4% of global GDP in 2100 to 7% to 19% in 2300 with the higher warming scenario, and from approximately -1% to 1% in 2100 to 1% to 3% in 2300 with the lower warming scenario (Figure 6-33).

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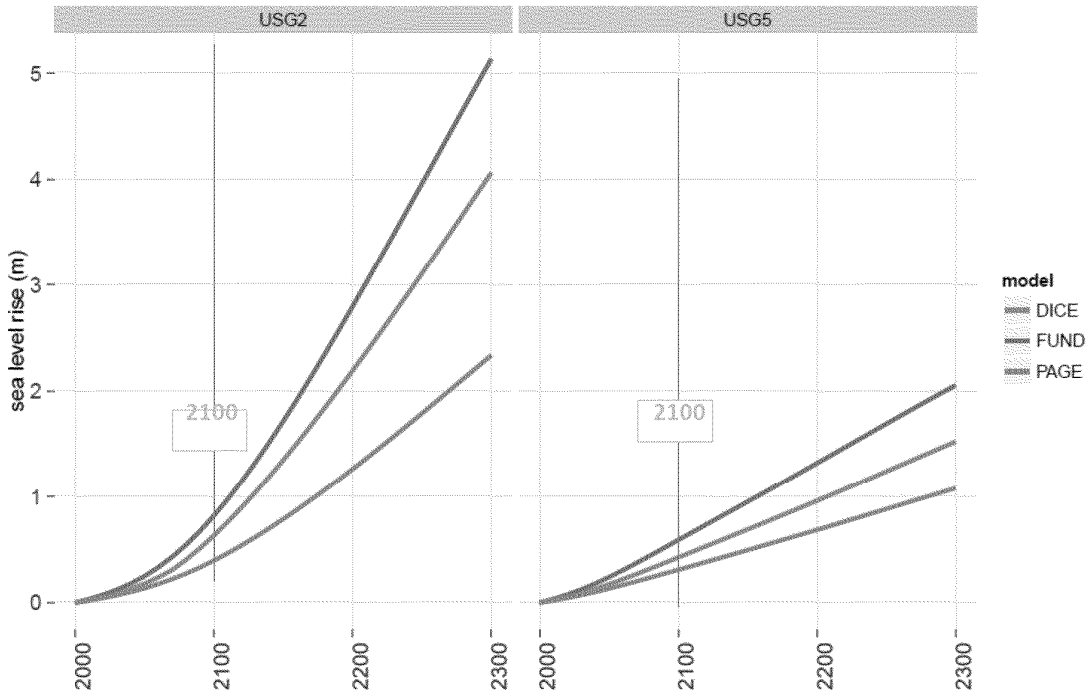

Figure 6-31
Total sea level rise from 2000 to 2300

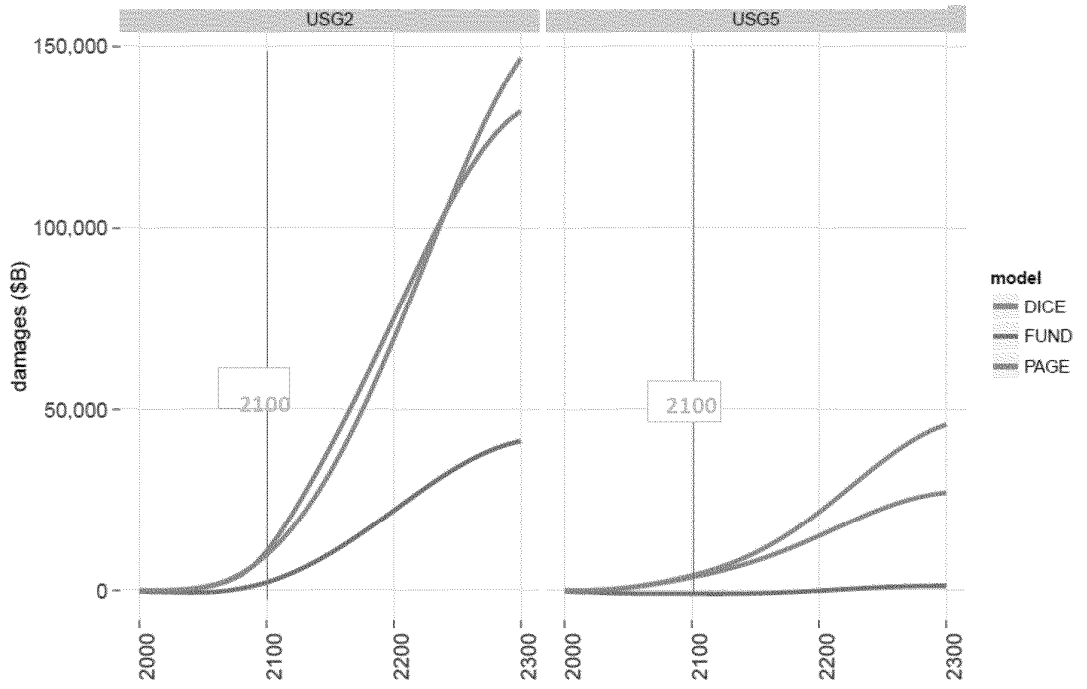

Figure 6-32
Total climate damages to 2300

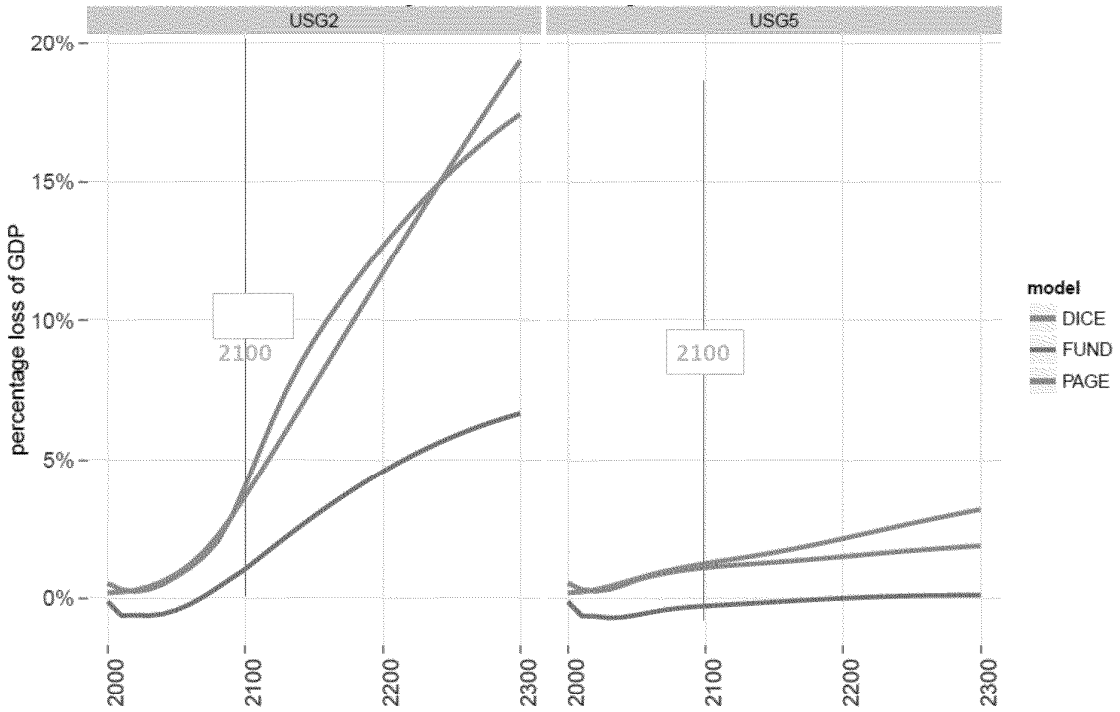

Figure 6-33
Total climate damages to 2300 as a fraction of GDP

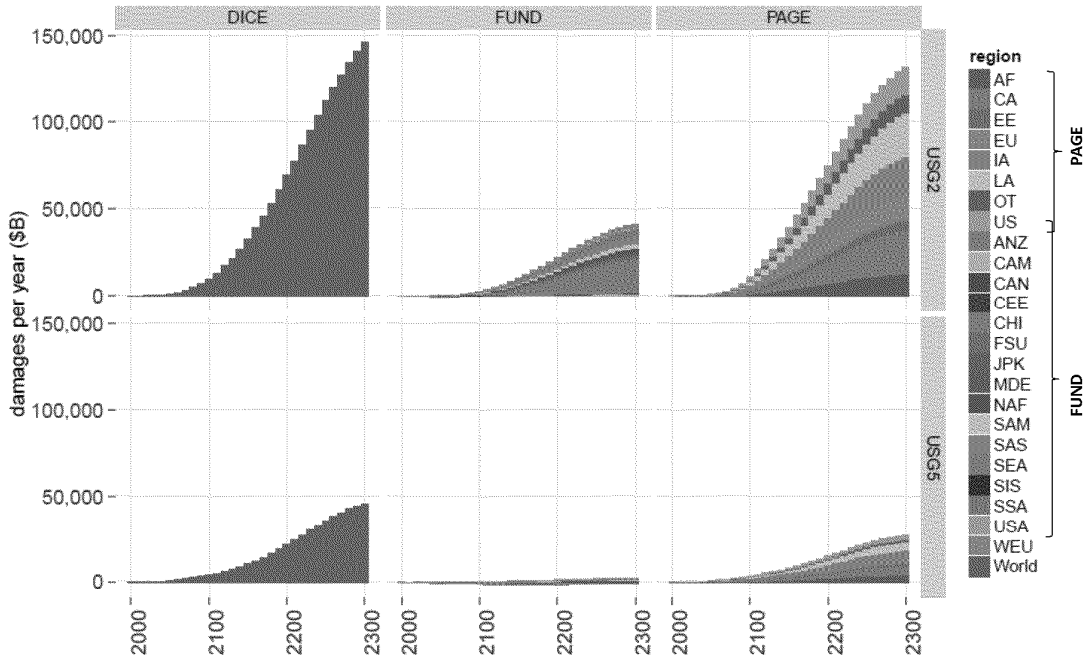

Figure 6-34
Total regional climate damages to 2300

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Post-2100, net damages are projected in all regions in FUND with both warming scenarios, with annual damages in China growing most quickly (Figure 6-34). China damages are also prominent in PAGE's post-2100 results, but damages are more equally distributed across regions as damages grow together due to the regional scaling.

In the higher warming scenario, post-2100 sectoral damages ramp up quickly—particularly in some sectors (Figure 6-35). In DICE, both annual non-SLR and SLR damages grow quickly. In FUND, increased cooling demand grows quickly, followed by agriculture, which shifts from a net benefit in 2100 to relatively rapidly growing net damages. In PAGE, growth in annual economic and non-economic damages is far greater than growth in the other sectors. In the lower warming scenario, post-2100 sectoral damage growth is reduced significantly, such that FUND agriculture exhibits increasing net benefits and PAGE economic and discontinuity damages become small fractions of total annual damages. Note that, under both warming scenarios, DICE annual SLR damages post-2100 grow much more quickly than the SLR damages in FUND and PAGE.

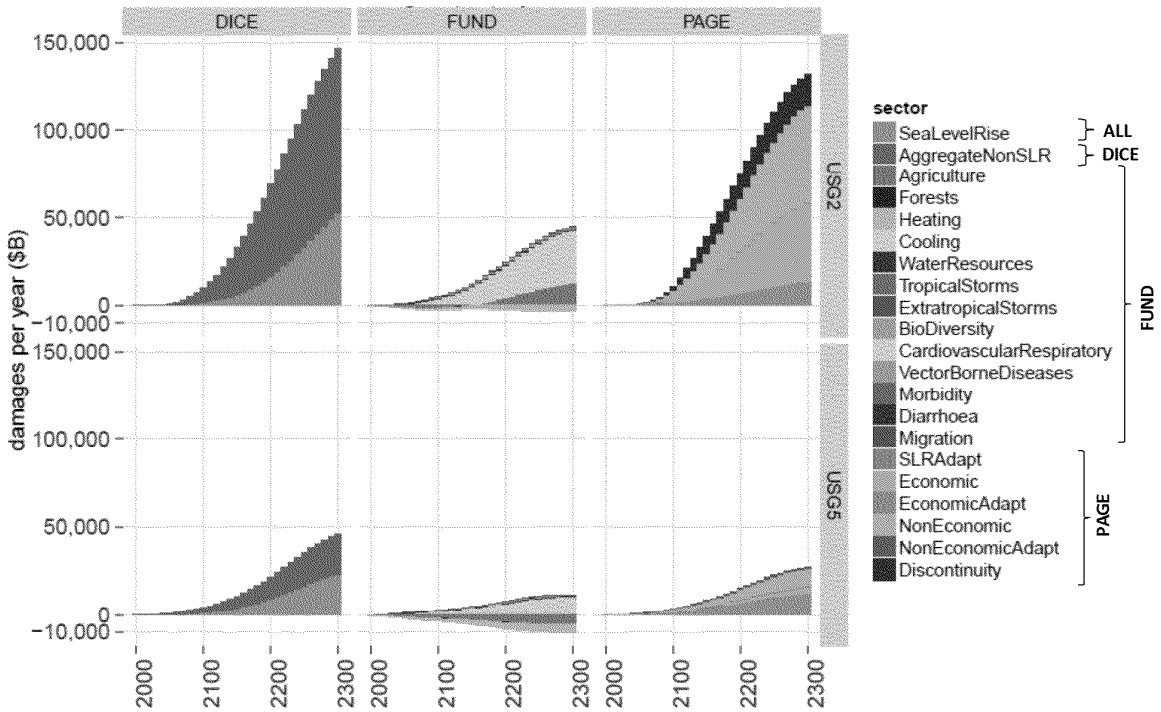

Figure 6-35
Total sectoral climate damages to 2300 (native sectors)

Moving away from native sectors, to harmonized aggregated sectors, we see that FUND and PAGE produce somewhat similar annual economic damages post-2100 in the higher warming scenario, but that's where the similarities end (Figure 6-36). Post-2100 annual economic damages are very different in the lower warming scenario, and annual non-economic and discontinuity damages are clearly the primary difference in annual total damages between the models post-2100.

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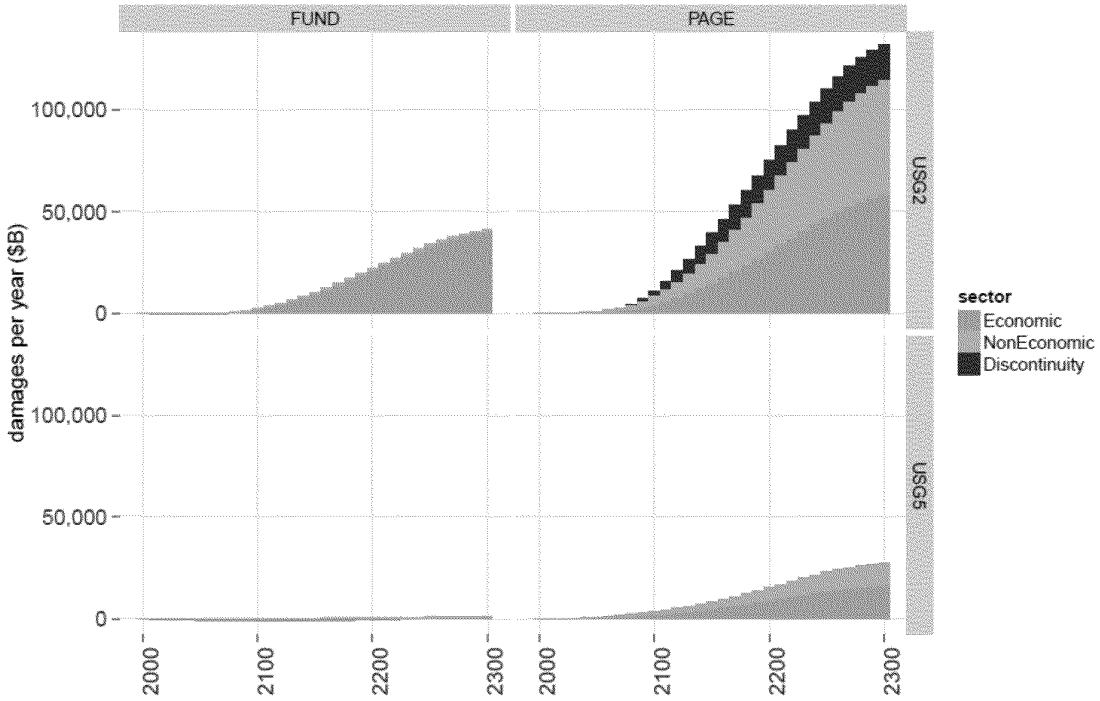

Figure 6-36
Total sectoral climate damages to 2300 (harmonized sectors)

PAGE post-2100 total annual damage responses are the most sensitive to the assumed warming projection (Figure 6-37). However, both FUND and PAGE exhibit approximately a doubling of total annual damages in 2300 between the reference warming and the highest warming sensitivity (just above 8˚C versus 13˚C of warming by 2300). DICE post-2100 total annual damages are the most responsive to the assumed income projection (Figure 6-38), followed by PAGE, with FUND significantly less responsive.

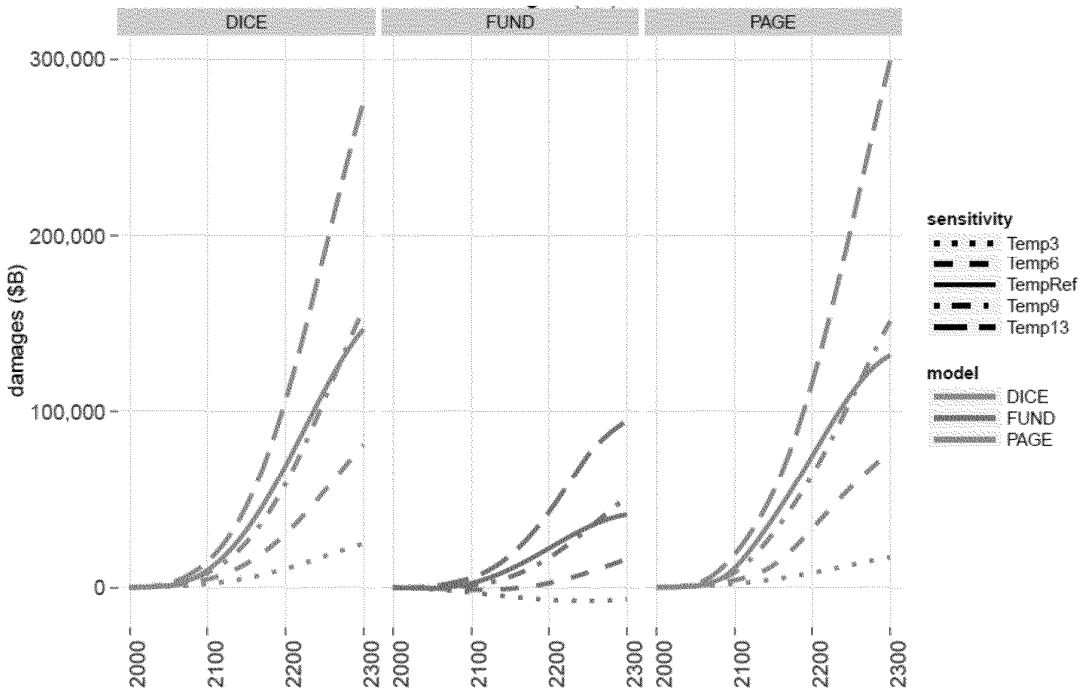

Figure 6-37
Total climate damages to 2300 for temperature sensitivity scenarios

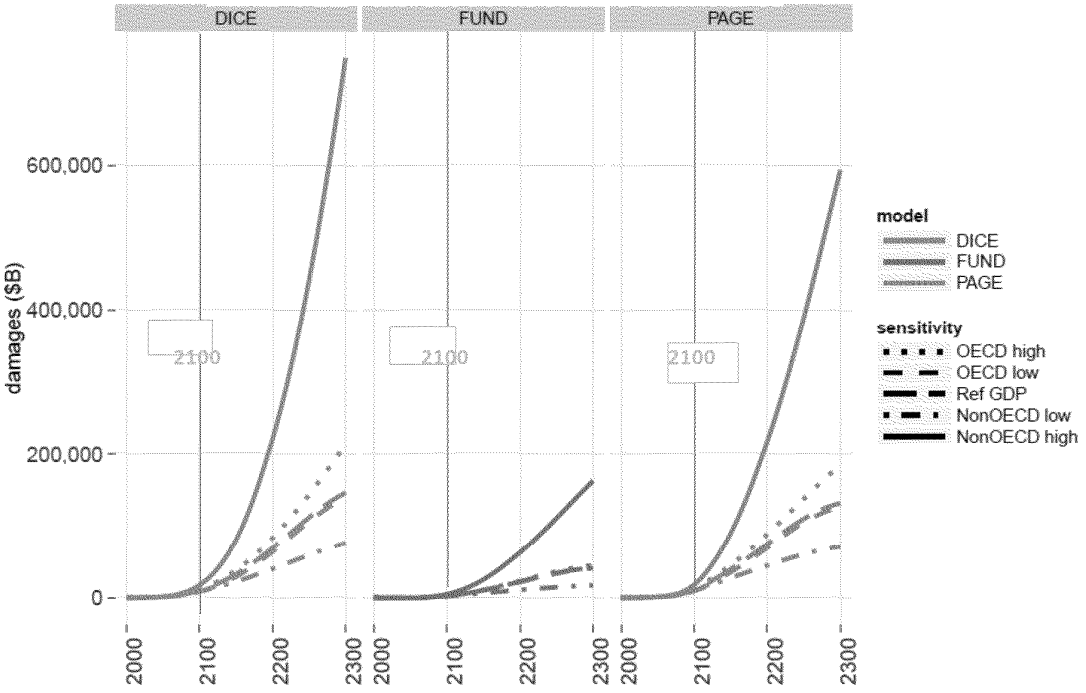

Figure 6-38
Total climate damages to 2300 for income sensitivity scenarios

In post-2100 incremental annual damages, we find incremental annual damages continuing to grow through 2300 (Figure 6-39). We again find DICE and PAGE annual damages rising more quickly than FUND's, similar to what we observe with total annual damages. However, unlike total annual damages, incremental annual damages are growing at a declining rate. Recall that the projected annual incremental temperature increase diminishes over time. At the same time, higher future incomes reduce vulnerability in FUND, while PAGE damages can saturate. Together, these effects moderate post-2100 growth in incremental annual damages, such that they begin to stabilize, an overall outcome that is more pronounced in FUND and PAGE, then DICE.

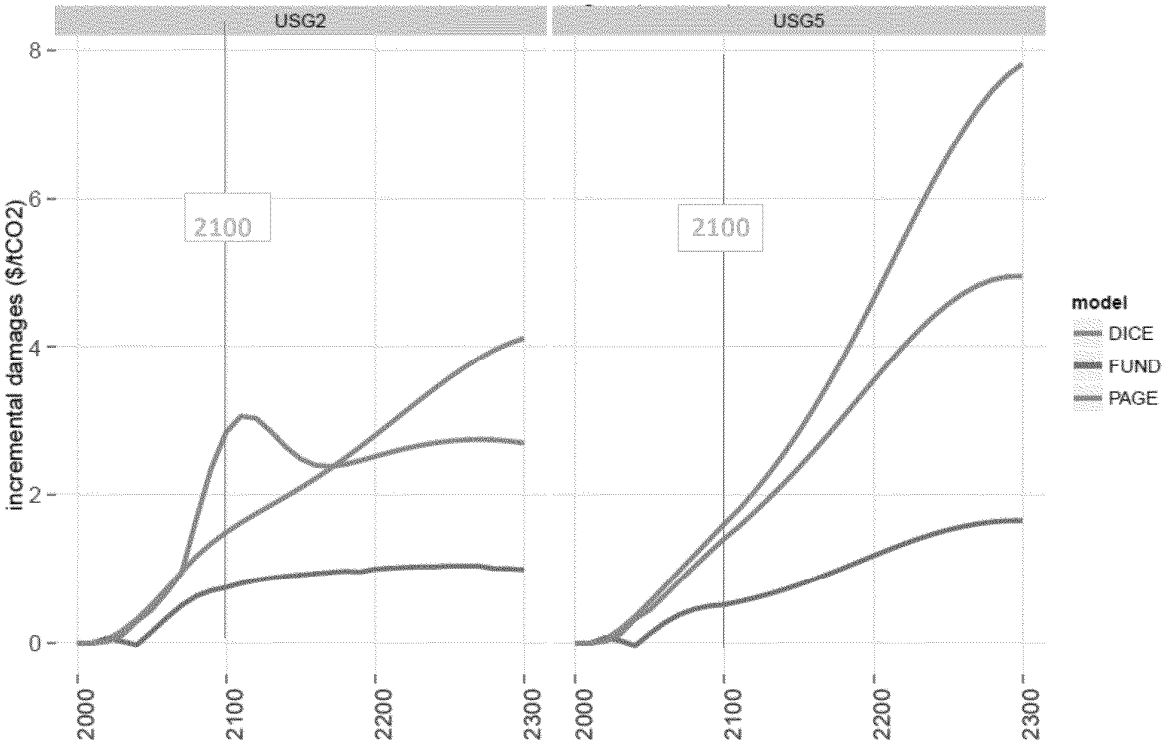

Figure 6-39
Incremental climate damages to 2300

Comparing the USG2 and USG5 results, we find higher post-2100 incremental damages with the lower temperature pathway (USG5) from all the models. Two effects are contributing to this outcome—higher incremental temperature responses in USG5 due to the logarithmic forcing response discussed in the climate component assessment (Section 5), and the higher future income levels in the USG5 scenario (Figure 6-1).

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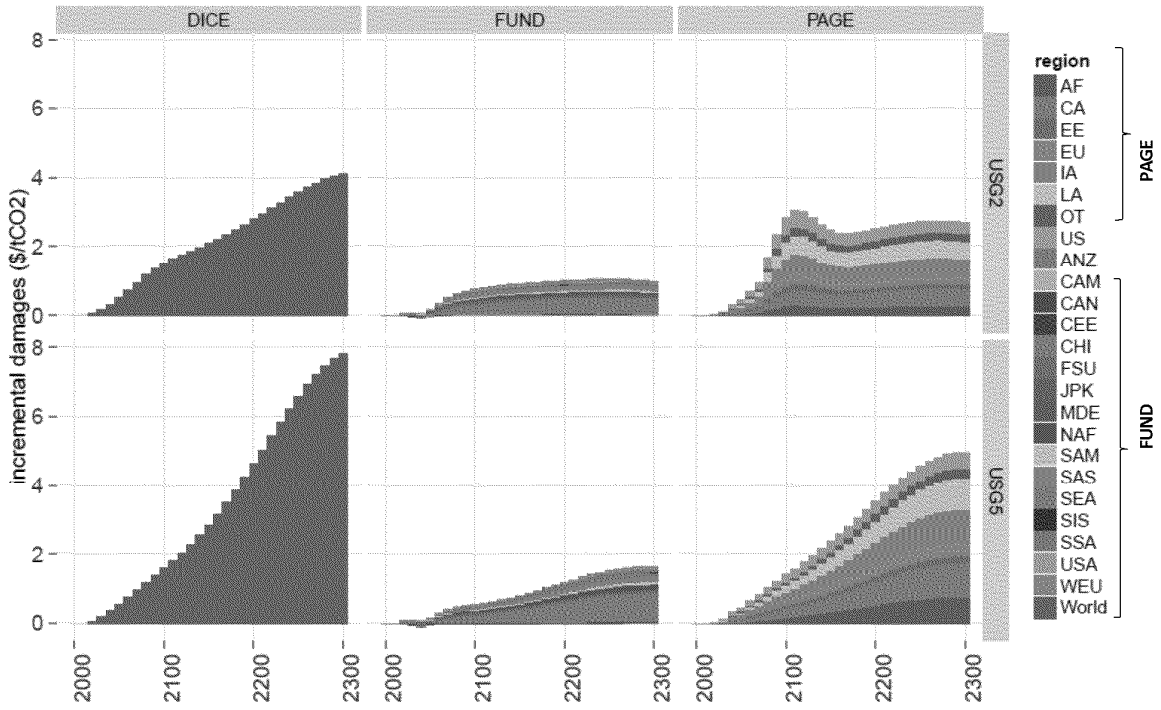

Figure 6-40
Incremental regional climate damages to 2300

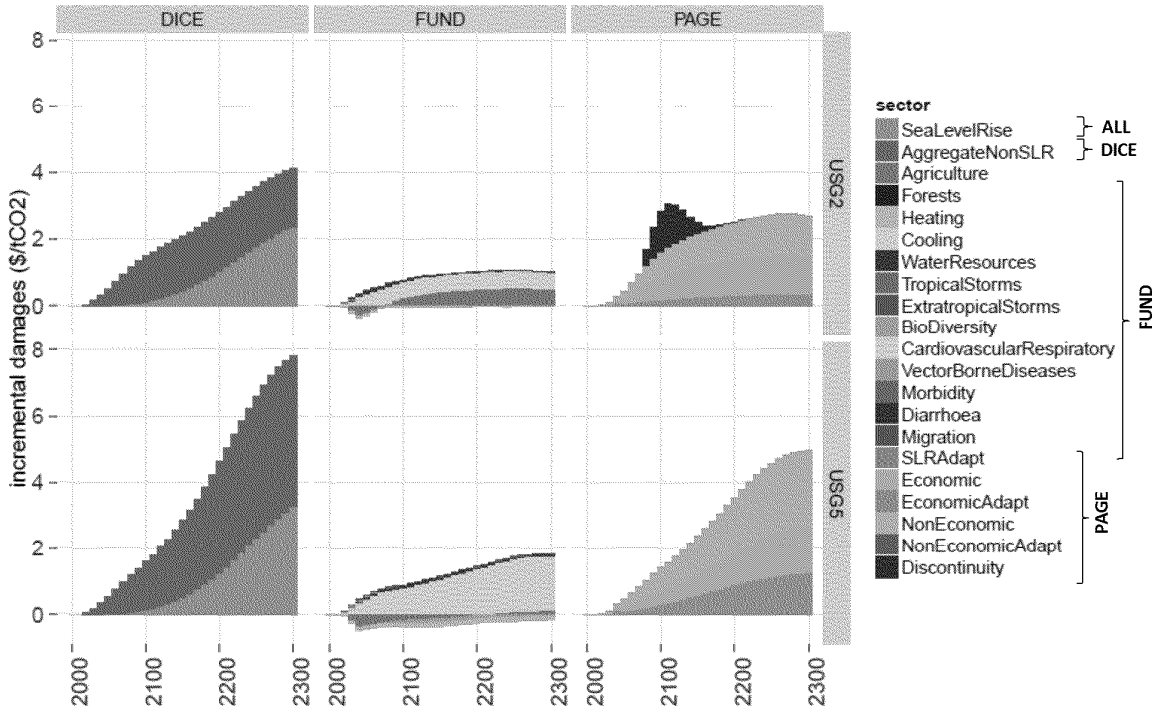

Figure 6-41
Incremental sectoral climate damages to 2300 (native sectors)

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Post-2100 incremental damages are distributed across regions in FUND and PAGE in a pattern somewhat similar to what we observe in the distribution of total damages post-2100 (Figure 6-40). In FUND, post-2100 incremental damages are dominated by damages in China, with damages in South Asia, Southeast Asia, and the Former Soviet Union having distant 2nd through 4th place contributions. PAGE incremental damages continue to be more balanced, with the share of damages in non-OECD regions growing post-2100. The sectoral distribution of post-2100 incremental damages however varies from the sectoral distribution we observe in the post-2100 total damages (Figure 6-41). In FUND, we find net agricultural damages having a much larger share of the overall outcome to 2300, while cooling and heating have smaller roles. In PAGE, we find the discontinuity to be less important post-2100, while economic damages are slightly more important.

Figure 6-42 provides a summary of the cumulative contributions of individual sector and region combinations to the incremental damages through 2050, 2100, and 2300 for the high temperature scenario (USG2). The values in the figure are the shares of total absolute impacts, which is the sum of the absolute values of damages and benefits. The bottom row and last column of each grid are the share for the overall region and sector, respectively. The color shading indicates the net impact, with net benefits shaded blue and net damages shaded red, and the color gradient indicating the net impact as a fraction of the absolute impact, i.e., the darkest shade indicates that the net impact is equal to the numerical absolute impact. For instance, through 2050, Chinese (CHI) cooling is responsible for 22% of the incremental damage changes that occur in FUND, and China overall is responsible for 45% of the incremental damage changes. However, China has cumulative incremental net damages of approximately zero during this time due to offsetting cooling damages and heating and agricultural benefits.

In DICE, with only sectoral resolution, we see in Figure 6-42 the story we observe in our previous figure (Figure 6-41). Non-SLR incremental damages dominate through 2050 and 2100, but incremental SLR damages come on strong post-2100.

In FUND, we clearly see China cooling dominating the incremental response through 2050, followed by China agriculture, heating demand and water resources. Incremental damages in the Former Soviet Union (FSU), Western Europe (WEU), and USA are contributing as well, but at a significantly lower level, with incremental damages in these regions concentrated in the same sectors but allocated differently, and biodiversity damages evident. By 2100, FUND's incremental changes are more heavily concentrated in China cooling. By 2300, agricultural net damages are prominent and appear across regions, but are more heavily distributed in non-OECD regions.

In PAGE, incremental damages to 2050 are most heavily concentrated in European Union (EU) and United States (US) non-economic damages, but non-economic damages appear in other regions as well. Economic and SLR damages are also concentrated in the EU and US. By 2100, incremental damages have spread across sectors and regions, with the US the region with the largest cumulative incremental damages to date that are balanced across the discontinuity, non-economic, and economic sectors. Post-2100 incremental damages are concentrated in the non-economic and economic sectors, with non-OECD regions dominating slightly.

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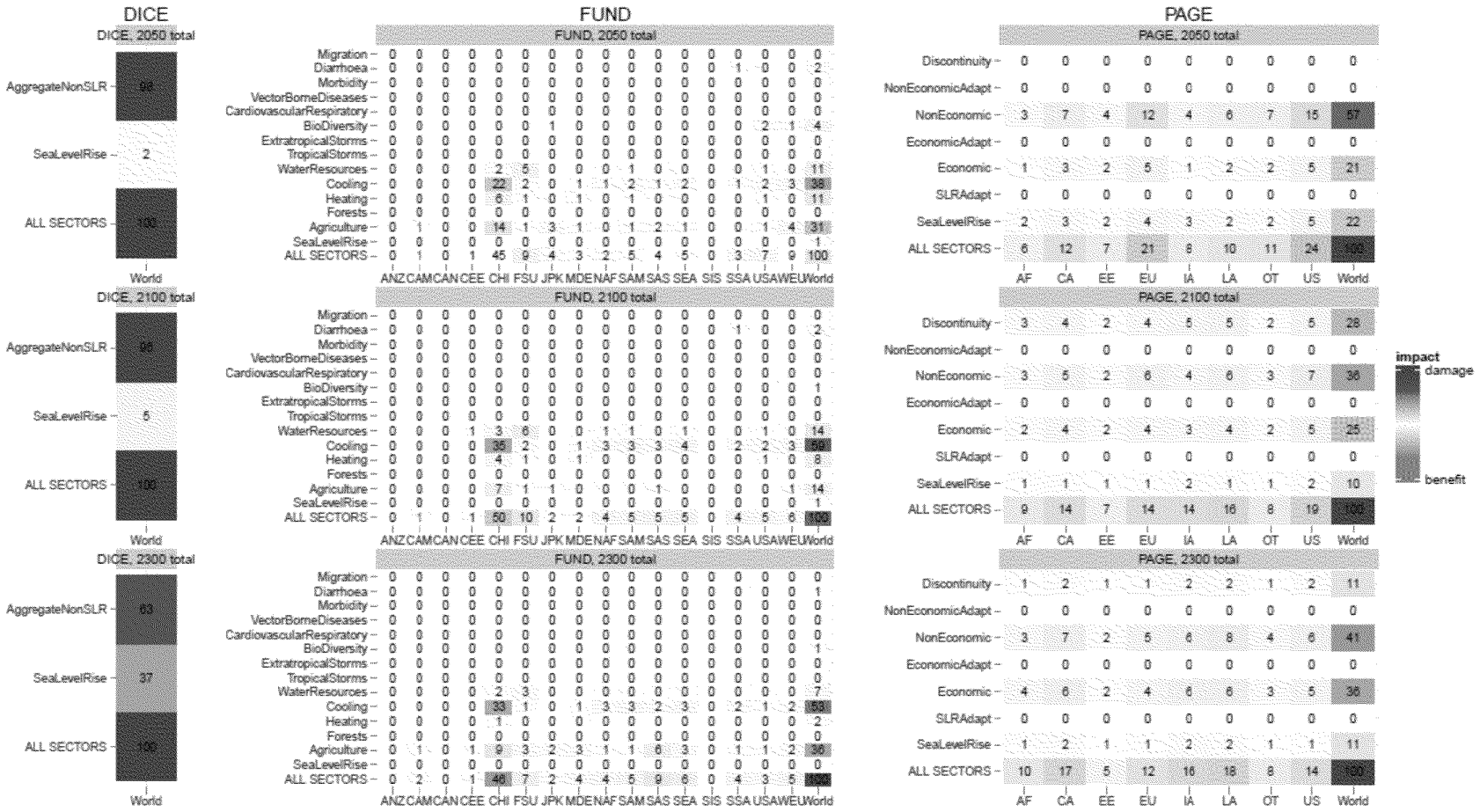

Figure 6-42
Shares of cumulative undiscounted incremental damages off of the USG2 scenario by sector (row) and region (column) for each model through 2050, 2100, and 2200

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Probabilistic damages

In addition to the USG standardized uncertainties, FUND and PAGE in the USG approach are run with additional damage component specific uncertain parameters, e.g., the exponent on the temperature term the in damage function (temperature squared versus cubed), the rate of SLR, and the elasticity of damages to income levels. Table 6-5 summarizes the extent and treatment of the uncertain damage component parameters in the USG exercise. As we observed in the climate modeling, the models are entertaining very different uncertainty spaces. DICE considers no damage specific uncertainty, while FUND and PAGE consider 50 and 46 independent uncertainty parameters respectively, and the specific uncertain parameters and specifications are not readily comparable across FUND and PAGE given the differences in damage modeling structure. We note however that FUND uses tailed distributions for many of its uncertainty specifications, versus PAGE's triangular distributions, which have a minimum and maximum. Probabilistic results in this section are expressed in terms of the 1st, 5th, 25th, 50th, 75th, 95th, and 99th percentiles, and mean. For comparison, DICE is shown with its single deterministic result. The deterministic results for FUND and PAGE are also included for comparison to each model's probabilistic results, especially the means, which are the values used in the USG SCC calculations.[24] Keep in mind that the results shown here do not fully reflect uncertainties elsewhere in the causal chain of estimating climate impacts, such as in socioeconomics and emissions, and climate change. The results here simply illustrate the damage component specific uncertainties modeled.

For our analysis, we developed probabilistic versions of the FUND and PAGE damage components. We perform 2500 random draws from the specified distributions, and run the models 2500 times. Like in the USG exercise, we treat the uncertain parameters as independent.[25]

Table 6-5
Model specific uncertain damage component parameters

Model	# of uncertain parameters	Distribution types
DICE	0	None
FUND	50	Normal, Truncated normal, Triangular, Gamma
PAGE	46	Triangular

FUND and PAGE respectively have two and three uncertain parameters that affect the rate of sea level rise. In Figure 6-43, we observe that FUND projects a very different distribution of SLR than PAGE to 2100 and 2300—one that is much wider, with the mass to the right of PAGE's

[24] To be precise, the USG exercise uses the means from the full probabilistic runs across all aspects of the modeling (socioeconomics, climate, and damages), including standardized and model specific parametric uncertainties. Here we are only showing probabilistic results from the model specific damage component uncertainties.

[25] As noted in Section 2, the USG exercise performed 10,000 random samples and runs. We use 2,500 due to computing constraints. The smaller sampling is inconsequential for PAGE results because of Latin Hypercube sampling. For FUND, however, the tails could be underrepresented by the smaller number of draws because Monte Carlo sampling is used in the USG modeling. We overcame this issue but using Latin Hypercube sampling for FUND as well.

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(i.e., higher), and more heavily skewed towards higher SLR. In general, FUND projects substantially more SLR uncertainty than PAGE (and DICE). The risk of higher SLR notably declines in both FUND and PAGE with the USG5 scenario, as the mass of the overall distributions shift down slightly.

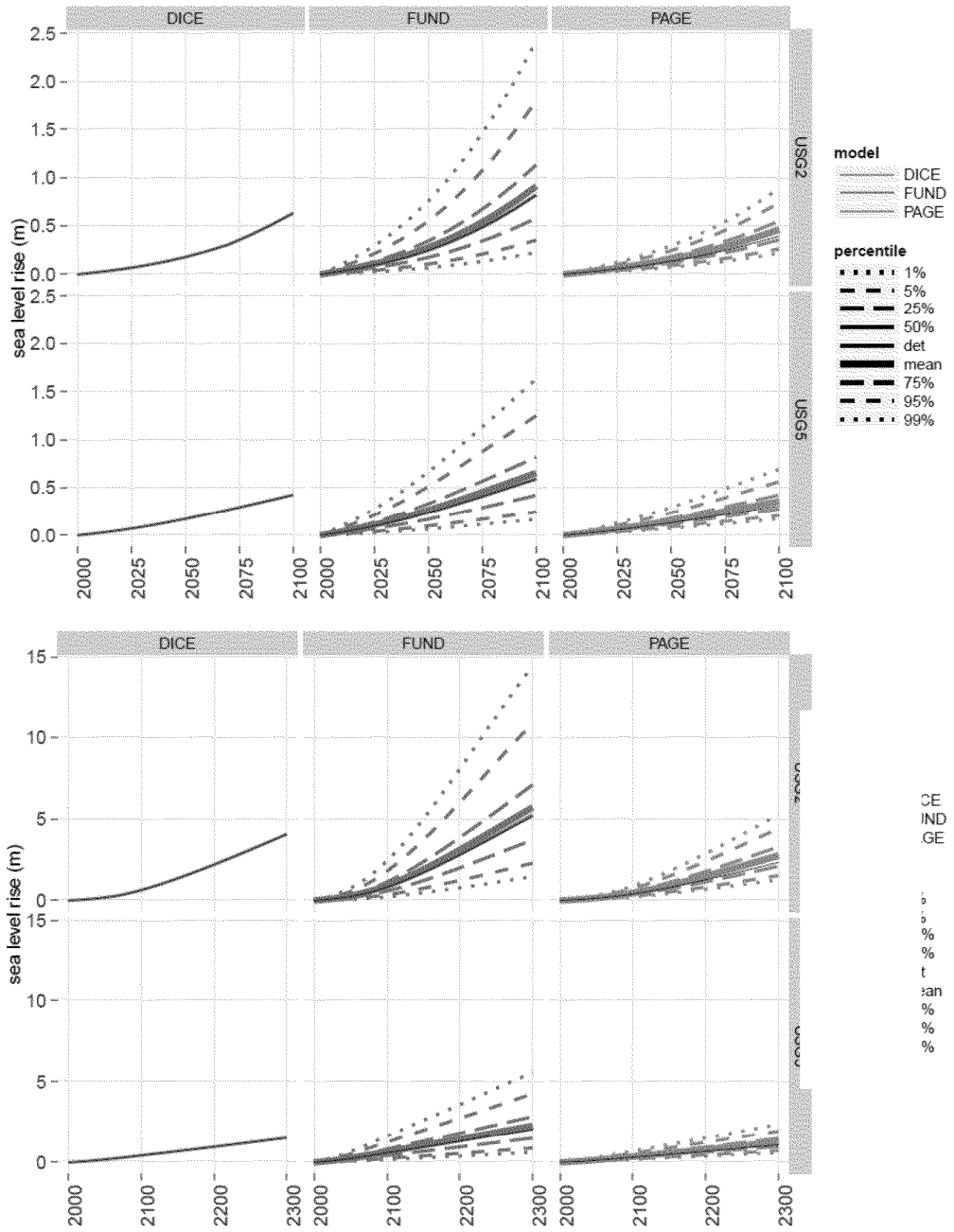

Figure 6-43
Model specific sea level rise uncertainty to 2100 (top) and 2300 (bottom) – percentiles and means

Figure note: y-axis' vary

Overall, in the subsequent figures, we find that the resulting distributions for total and incremental damages have some similar traits, with FUND producing much wider distributions than PAGE that are heavily skewed towards higher damages. FUND's uncertain parameters for damages are drawn mostly from distributions with tails, which contributes to the wide distribution. However, the mass of FUND's damage distributions lie to the left of PAGE's, have extremely long right tails, and include a sizable probability of net benefits, as well as the possibility of net damages throughout the time horizons. Also, while FUND's damage distributions are much wider than PAGE's during the 21st century, PAGE's distributions broaden quickly with time post-2100. In the discussion that follows, we work our way through our results—from uncertainty in total annual damages to uncertainty in incremental annual damages.

The distribution of FUND's total annual damages exhibits significantly more uncertainty than that from PAGE, with the uncertainty right-skewed but with substantial tails towards both negative and positive net damages (Figures 6-44). However, while PAGE has relatively modest damage uncertainty compared to FUND, it produces a higher mean. The lower warming scenario (USG5), on the other hand, results in significantly less uncertainty in both FUND and PAGE, with the risk of higher damages most affected. As a matter of fact, the probability of net negative damages in FUND is only slightly affected. Post-2100 model specific climate damage uncertainty is over an order of magnitude greater than during the first century, with PAGE's mean growing faster than FUND's.

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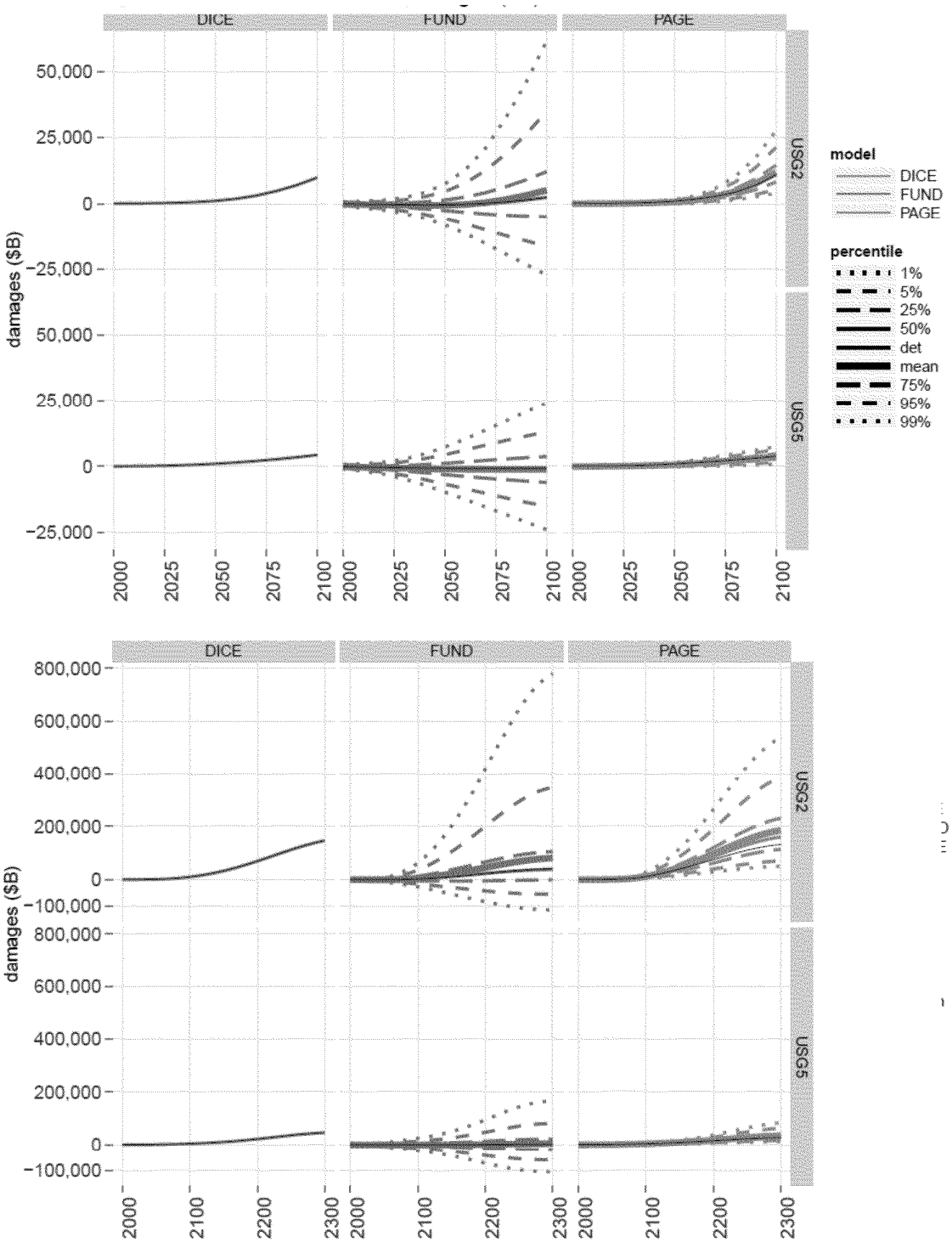

Figure 6-44
Model specific total damages uncertainty to 2100 (top) and 2300 (bottom) – percentiles and means

Figure note: y-axis' vary

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To get a better feel for the differences in the location and shape of the modeled total annual damage uncertainty and risk, we construct damage distributions for specific points in time—2050, 2100, and 2200 (Figure 6-45). We immediate notice the substantially wider distribution from FUND in 2050, with most of the mass below zero (net benefits), while all of the PAGE mass is above zero (net damages). The distributions of total annual damages in both models through 2050 are fairly similar across scenarios. However, by 2100, the distributions separate as the damage distributions for the higher climate scenario (USG2) shift out and spread faster than with the lower warming scenario, with FUND developing a longer and longer right tails. Note that FUND still allows for the possibility of net benefits in 2200.

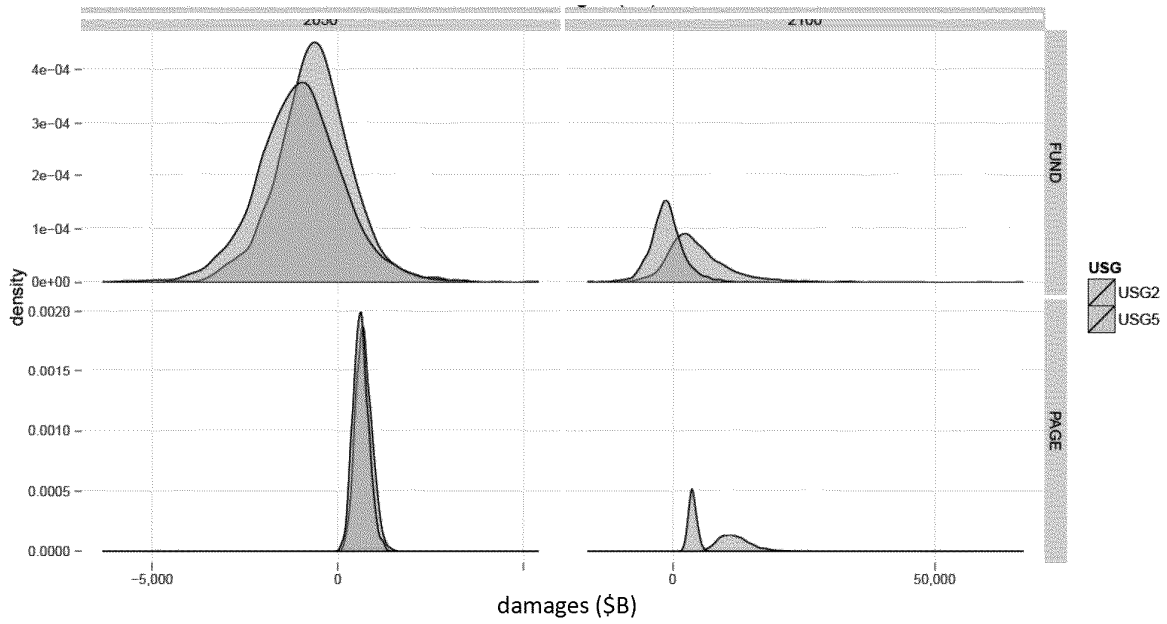

Figure 6-45
Model specific total damage distributions in 2050 and 2100

We can then look at regional distributions in a particular year to identify the regional sources of climate damage uncertainty in FUND and PAGE. In Figure 6-46, we observe that China is clearly the most conspicuous contributor to overall uncertainty in FUND (CHI), followed by the Former Soviet Union (FSU) and Southeast Asia (SEA). China continues to be the key source of uncertainty in FUND through 2200. In PAGE, China (CA) is also a prominent contributor to uncertainty, but the Europe Union (EU) and the United States (US) are the primary sources early on (Figure 6-47). Over time, however, China becomes the main source of uncertainty, followed by the Latin America, EU, and India & SE Asia (IA). Note that in PAGE, we find a much more pronounced separation of the regional damage distributions associated with the two scenarios than we find with FUND.

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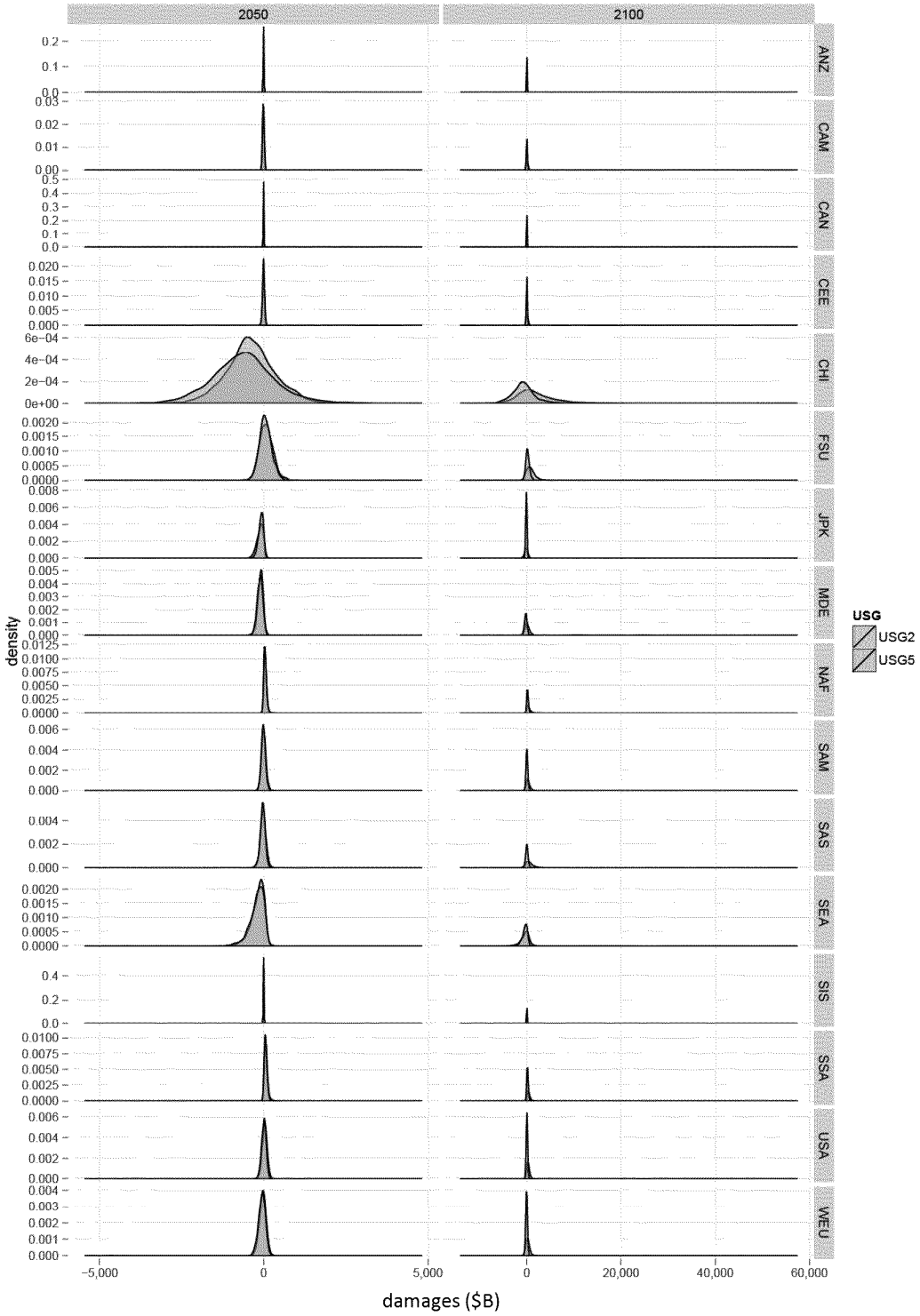

Figure 6-46
FUND regional damage distributions in 2050 and 2100.

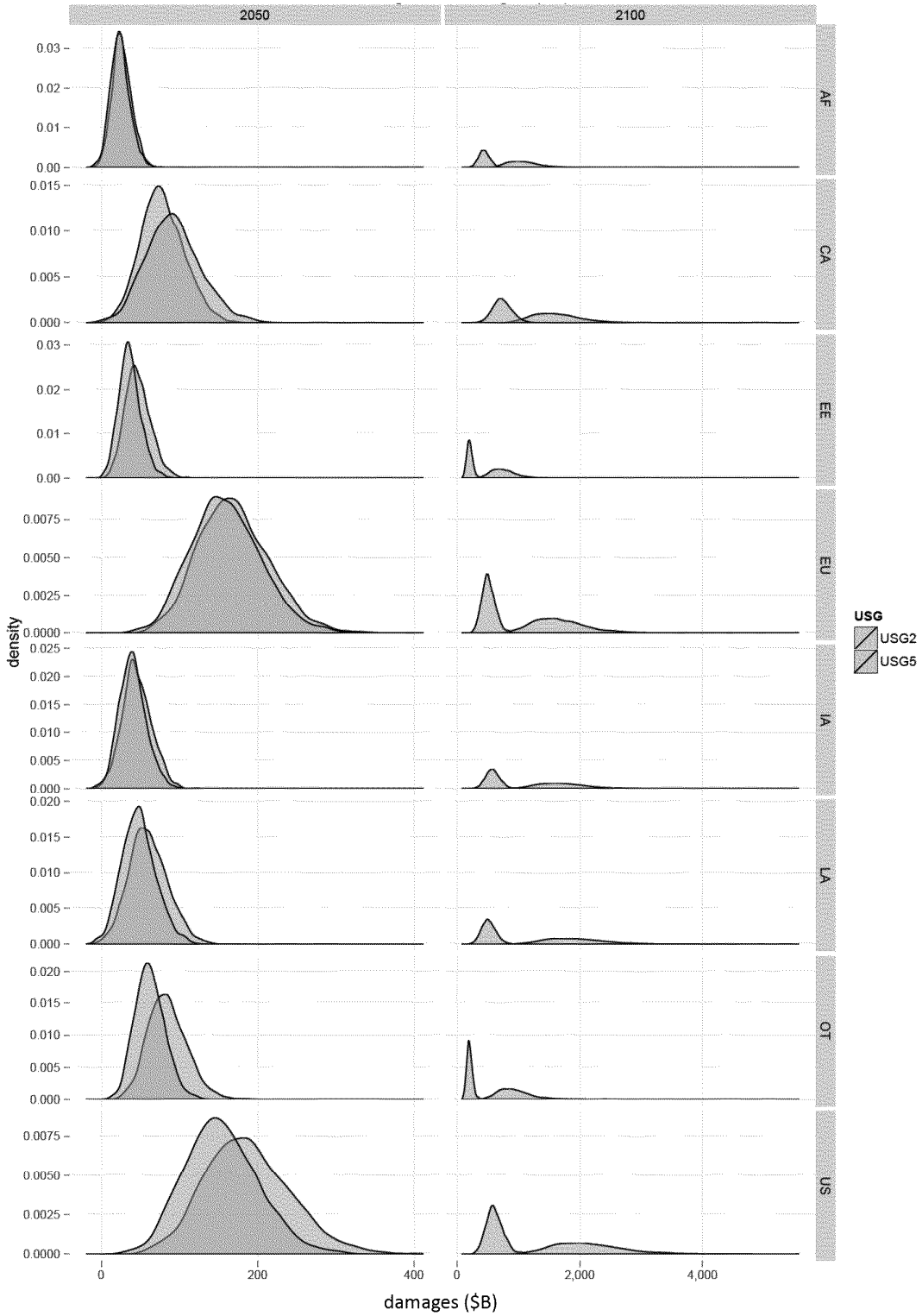

Figure 6-47
PAGE regional damage distributions in 2050 and 2100.

Sectorally, we find most of the uncertainty in FUND concentrated in agriculture, cooling demand, and heating demand, with heavily left-skewed agricultural and heating demand damage distributions, and right-skewed damage distributions for everything else, but more so for increased cooling demand, sea level rise impacts, and water resource damages (Figure 6-48). Over time, all the FUND sectoral damage distributions shift right and become more right skewed. From PAGE, we find most of the uncertainty in 2050 associated with non-economic damages, followed by economic damages and adaptation costs, and non-economic adaptation costs (Figure 6-49). Note that PAGE includes the possibility of economic or non-economic net benefits through 2050, with a larger likelihood of economic net benefits. Over time, only net damages are possible from all the PAGE sectors, with non-economic damages the primary source of uncertainty, followed by economic damages, and then discontinuity damages.

Differences in uncertainty across models regarding *incremental* damages has many similarities with the uncertainty we observe for total damages—significantly wider distributions from FUND that are right-skewed with negative and positive tails, but a lower mean than PAGE (Figure 6-50). Note, of course, that there is *more* uncertainty and risk of higher incremental damages off of the lower temperature scenario, USG5. The result is higher mean damages. This is a consequence of the higher incremental warming from a lower emissions scenario (Figure 6-27). Finally, despite the uncertain parameters, the FUND and PAGE incremental damage distributions stabilize post-2100, as the annual incremental temperature increase wanes, higher incomes reduce vulnerability (FUND), and damages can saturate (PAGE).

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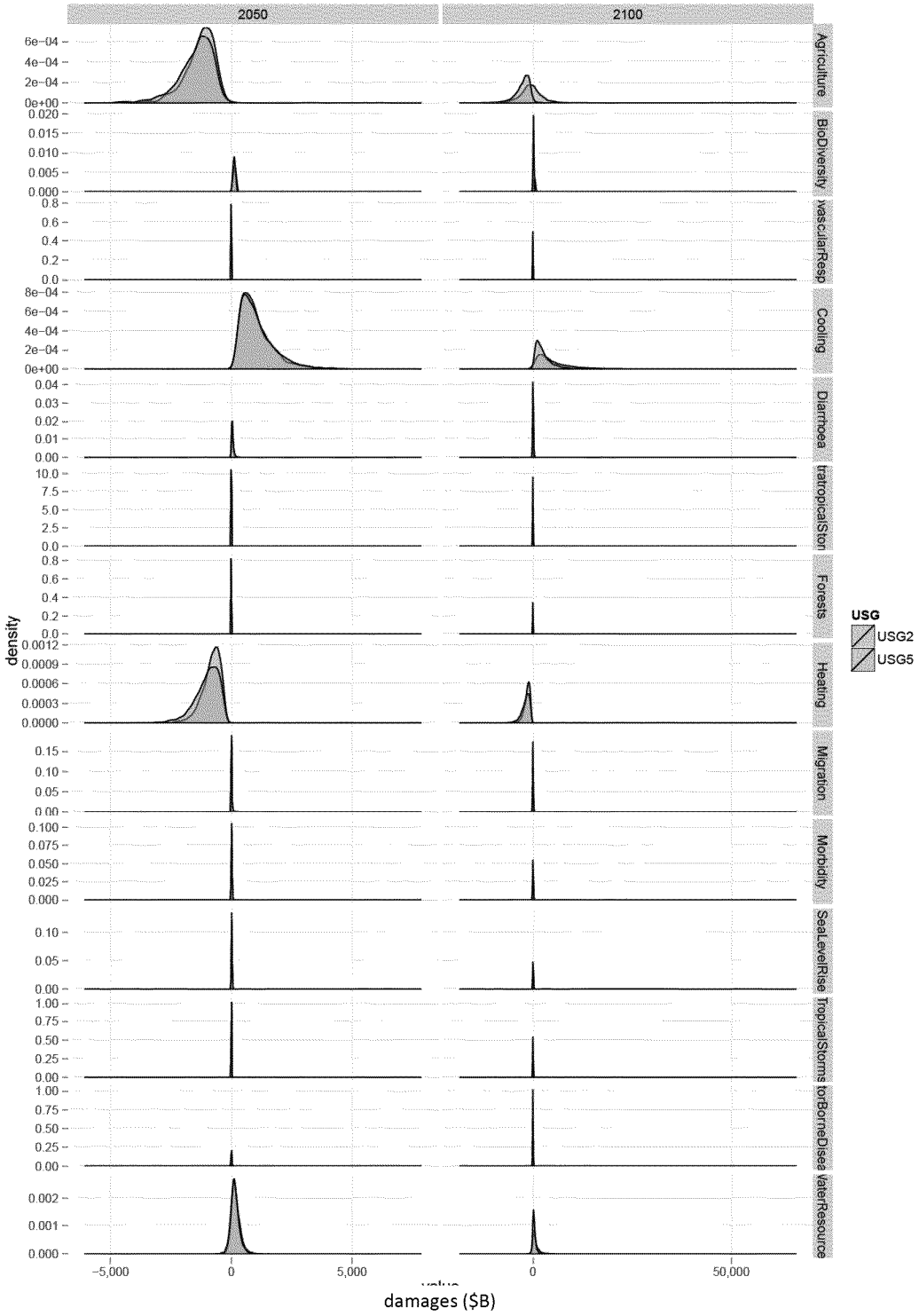

Figure 6-48
FUND sectoral damage distributions in 2050 and 2100

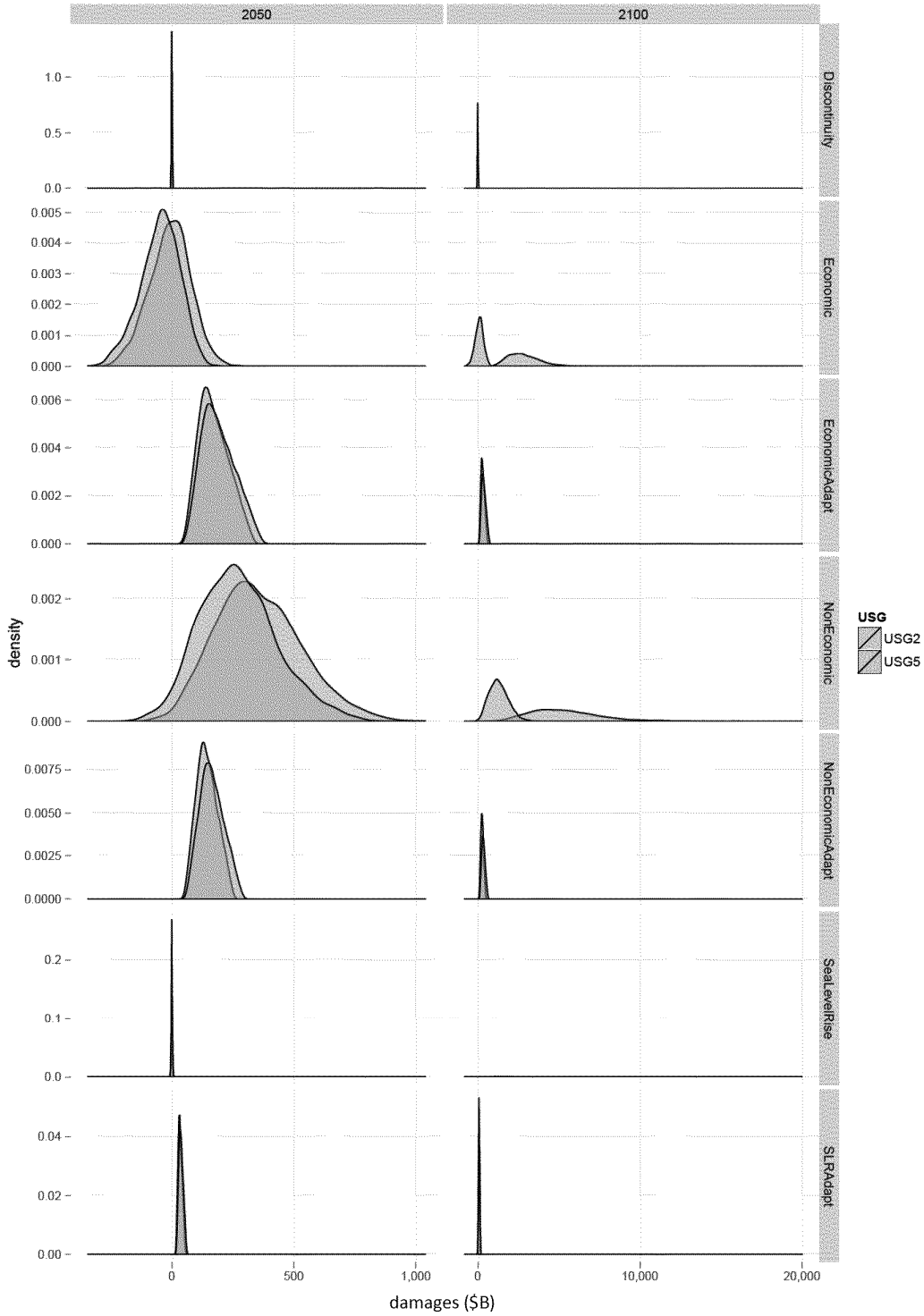

Figure 6-49
PAGE sectoral damage distributions in 2050 and 2100

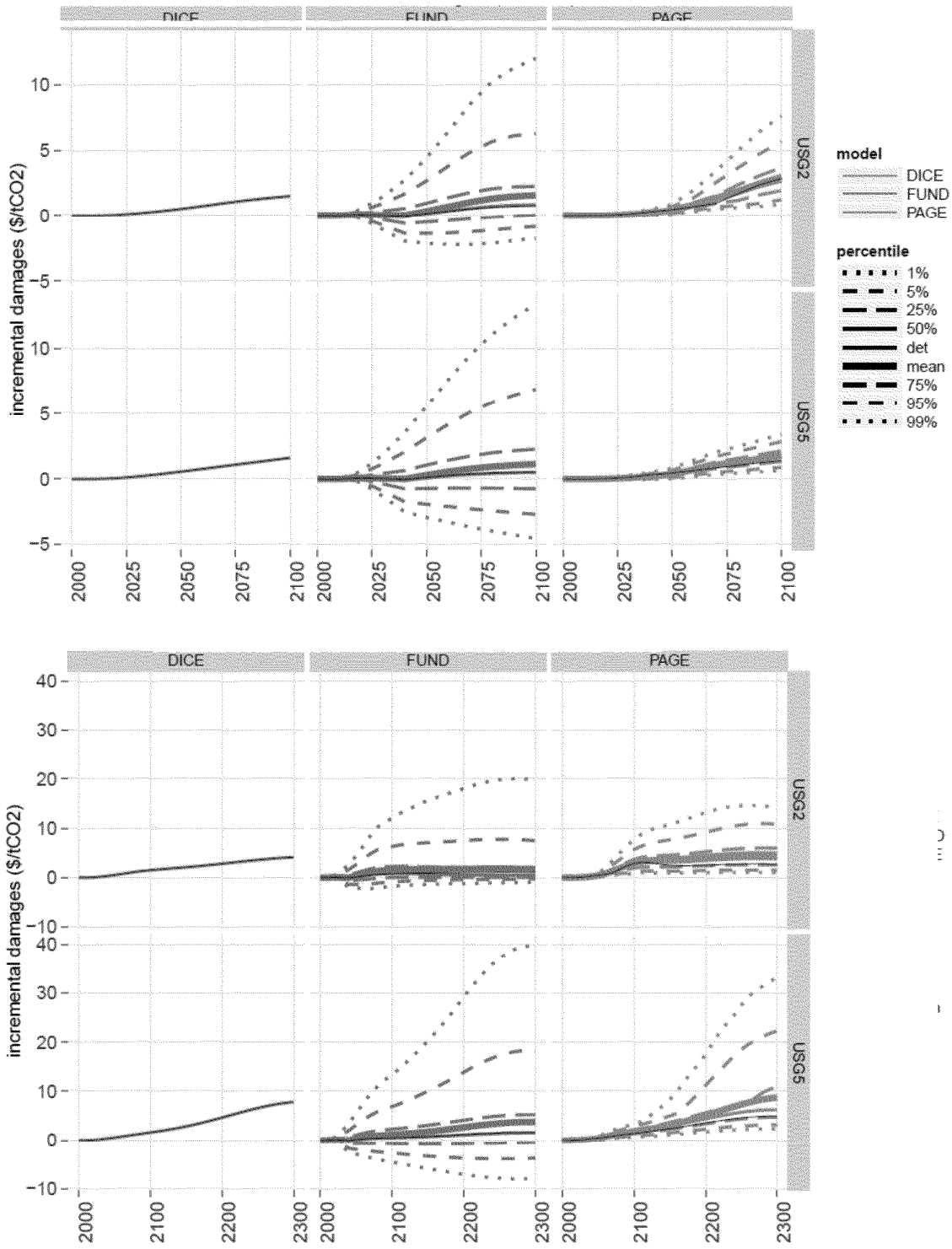

Figure 6-50
Model specific incremental damages uncertainty to 2100 (top) and 2300 (bottom) – percentiles and means

Figure note: y-axis' vary

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Lastly, we review the incremental damage distributions in 2050, 2100, and 2200. We find the expected rightward shifting over time of the incremental damage distributions from both models (Figure 6-51). However, because of the larger incremental temperature response off of the lower warming scenario, we find more overlap of the USG2 and USG5 distributions than we observe in the total damage distributions, and even observe the FUND USG5 distribution shifting right faster than the USG2 distribution over time.

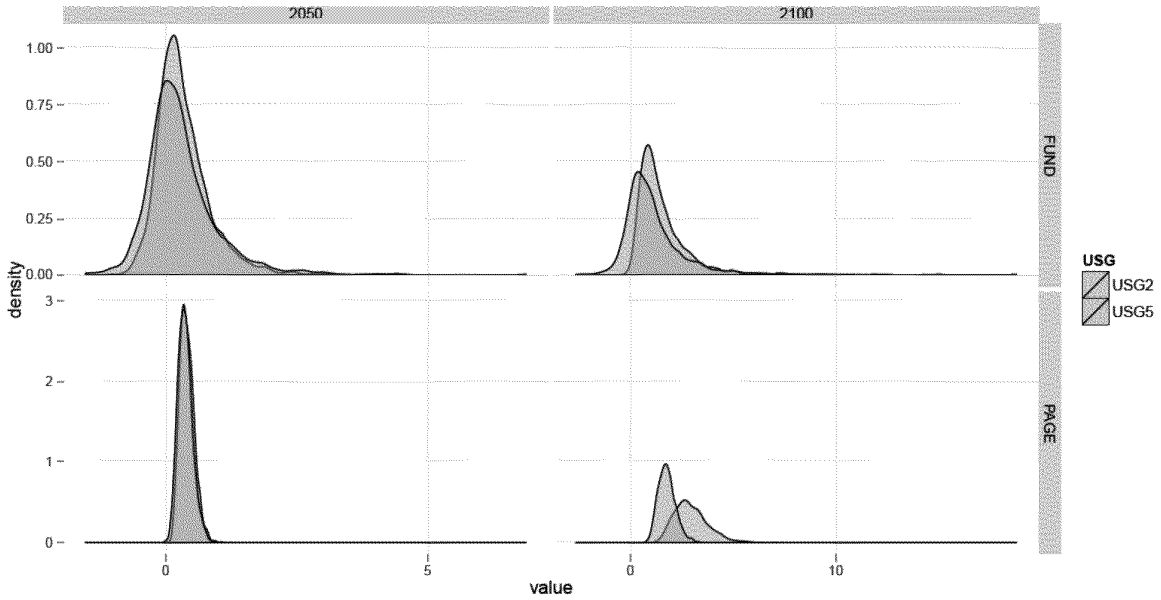

Figure 6-51
Model specific incremental damage distributions in 2050 and 2100

Focused regional assessment – Africa, China, Europe, and the United States

In this section, we focus on a select number of comparable regions in the USG FUND and PAGE models. Specifically, we compare the damage responses for Africa, China, Europe (Western Europe), and the United States.[26] We have already seen that the two models project dramatically different climate damage implications for these regions. In this section we explore those differences further with novel comparisons, and we focus on potential nearer-term damages (2050), which are more tangible. However, we do not try to reconcile or justify the differences we observe. Further analysis along those lines would be practical. Of particular value, would be a comparison to recently completed regional climate damage assessments (e.g., IPCC, 2014; Ciscar et al., 2014; Melillo et al., 2014; Kopp et al., 2014; Waldhoff et al., 2014).

[26] For FUND, damages for Africa are an aggregation of estimated damages in Middle East (MDE), North Africa (NAF), and Sub-Saharan Africa (SSA). For PAGE, Africa is already a separate region (AF). For China, from FUND and PAGE, we use CHI and CA respectively. For Europe we use WEU and EU respectively. For the United States we use USA and US respectively.

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We begin with a comparison of deterministic aggregate regional damages with respect to temperature change. In Figure 6-52, we observe that FUND damages are below PAGE damages up to 5 degrees of warming in all regions but China, with PAGE estimating significantly more damages in the EU and USA, and in China up to about 4.5 degrees of warming. FUND, on the other hand, estimates net benefits at lower levels of warming in all the regions (but only for one degree of warming in the USA). Damages in PAGE increase much more quickly with greater warming in the EU and USA than in FUND, but damages in China grow more quickly in FUND.

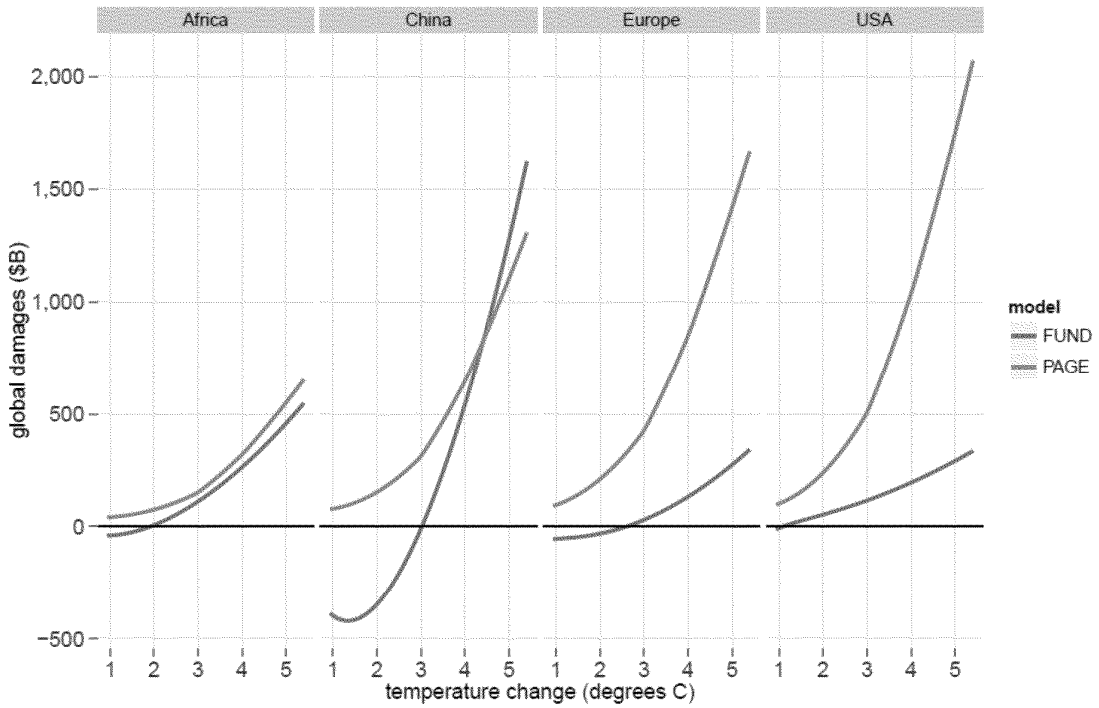

Figure 6-52
Comparison of aggregate climate damages as a function of temperature for Africa, China, EU, and USA for 2050 with USG2 socioeconomics

The sectoral damage responses within each of the four regions reveals that PAGE estimates similar patterns across regions for increasing sectoral damages with greater warming, while FUND's sectoral pattern has more variation across regions (Figure 6-53). In the EU and USA, non-economic and economic, and eventually discontinuity, damages accumulate quickly with warming in PAGE, while more moderate cooling demand increases in FUND are offset by heating reductions and improvements in agricultural productivity. In Africa and China, we see a reversal, with PAGE exhibiting weaker non-economic, economic, and discountinuity damage responses, and FUND producing stronger benefit and damage responses in cooling, heating, agriculture, and water resources. Note that FUND estimates water resource net benefits in China, but net damages in other regions.

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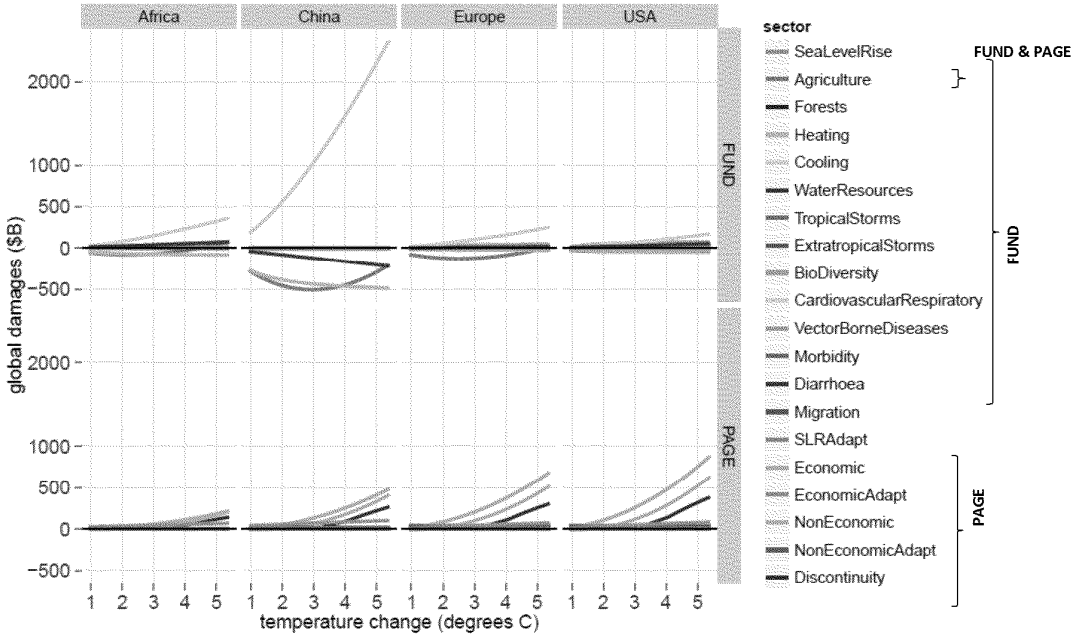

Figure 6-53
Comparison of sectoral climate damages as a function of temperature for Africa, China, EU, and USA for 2050 with USG2 socioeconomics

From our probabilistic damage component modeling, we find PAGE consistently producing positive and more compact regional aggregate damage outcome distributions for the four regions, while FUND consistently produces broader distributions with negative and positive net damages possible (Figure 6-54). Interestingly, the distribution modes are similar across models, but FUND has very long and thick tails and, in the case of the EU and USA, a significant amount of the mass below the PAGE distribution.

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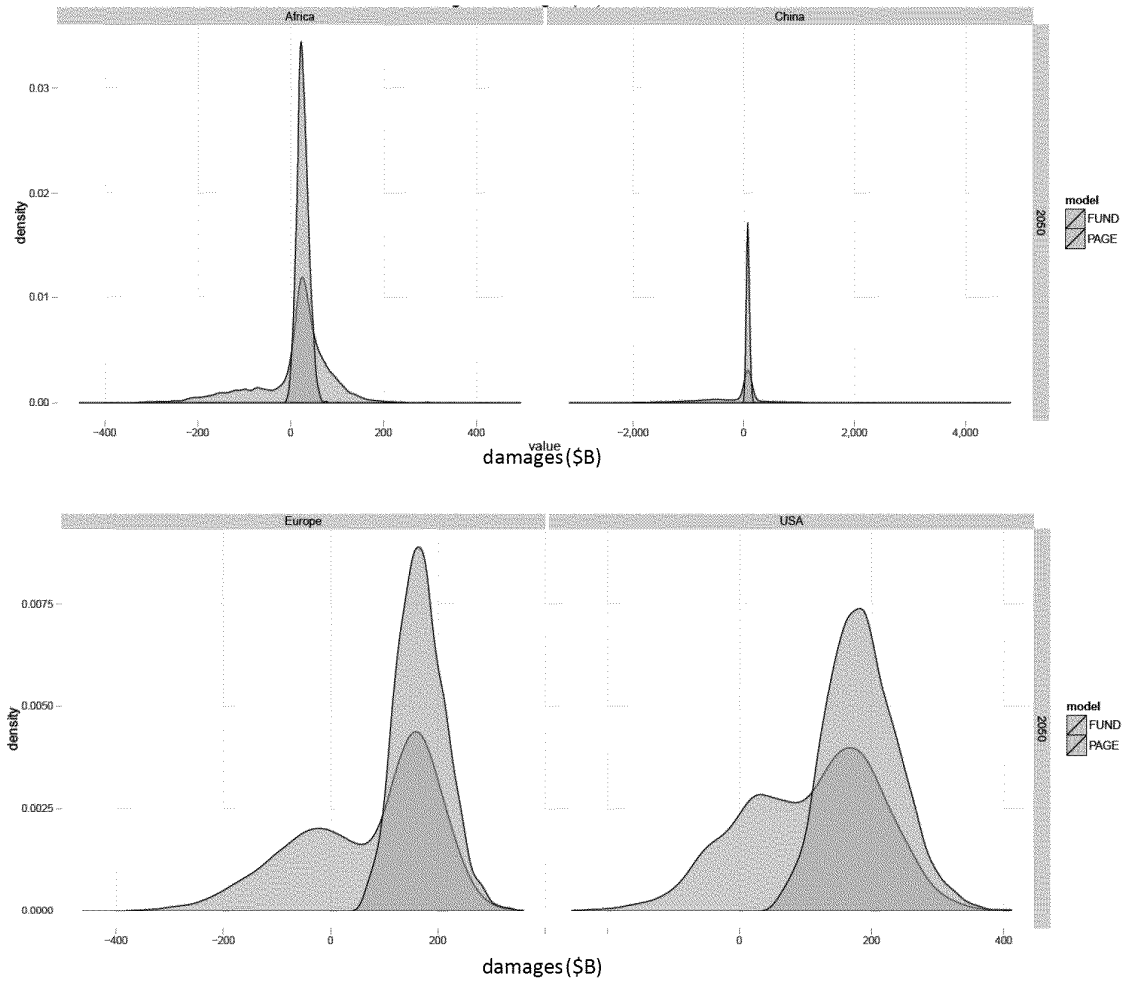

Figure 6-54
Comparison of model specific total damage distributions for Africa, China, EU, and US for 2050 with USG2 socioeconomics

Sectorally, with our harmonized economic and non-economic aggregation, we find PAGE producing tighter economic damage distributions than FUND, but the opposite for non-economic damages, with FUND producing much tighter non-economic damage distributions (Figures 6-55 through 6-58). However, for both economic and non-economic damages, the mass of PAGE distributions are well above those from FUND in all regions, except for China economic damages. Note that both models estimate only positive non-economic damage possibilities, while economic damages could be positive or negative in FUND but only positive in PAGE.[27] Only PAGE produces explicit discontinuity damages, which could include economic and/or non-economic damages. Unfortunately, it is difficult tell from the documentation.

[27] PAGE does produce the possibility of negative and positive net damages from its native "economic" damage sector. Recall that our aggregated economic sector includes both PAGE economic and SLR damages and adaptation costs for both sectors.

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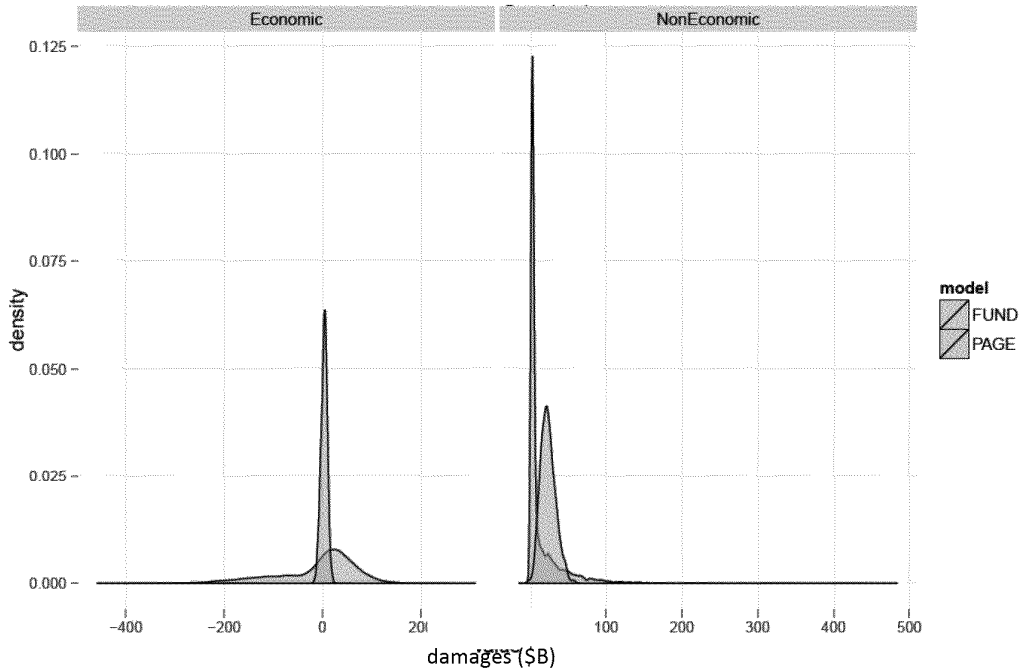

Figure 6-55
Comparison of model specific damage distributions for harmonized sectors for Africa for 2050 with USG2 socioeconomics

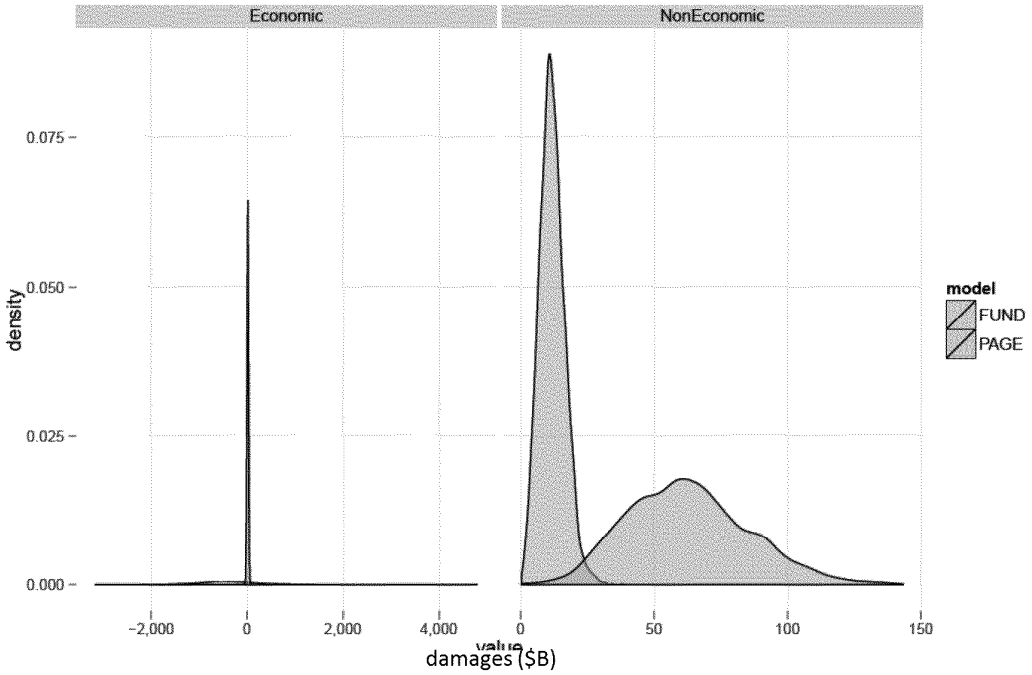

Figure 6-56
Comparison of model specific damage distributions for harmonized sectors for China for 2050 with USG2 socioeconomics

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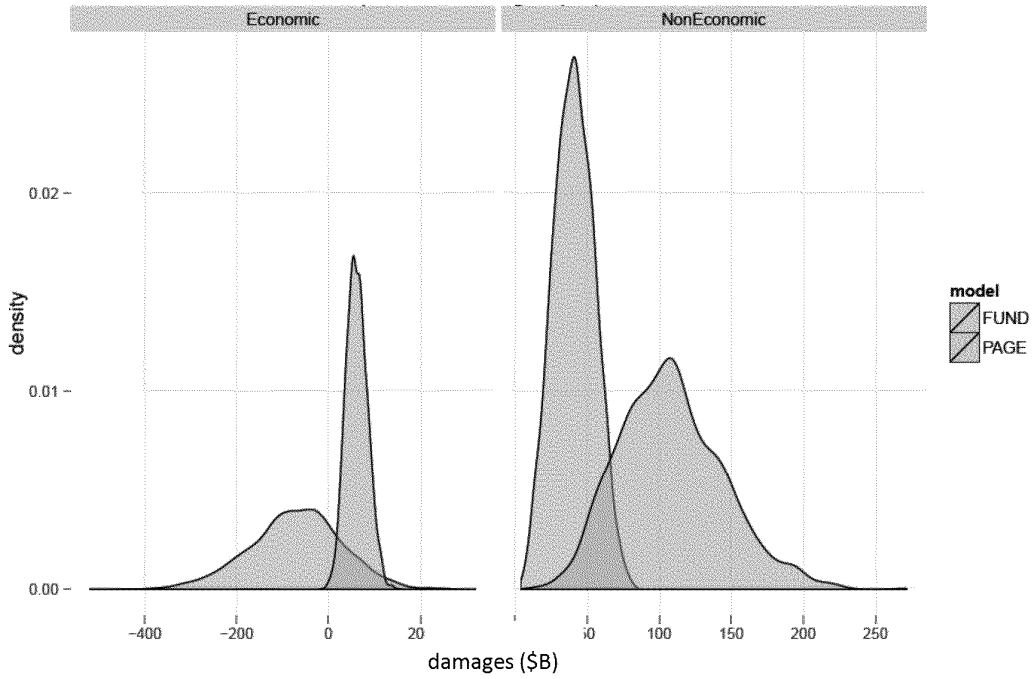

Figure 6-57
Comparison of model specific damage distributions for harmonized sectors for EU for 2050 with USG2 socioeconomics

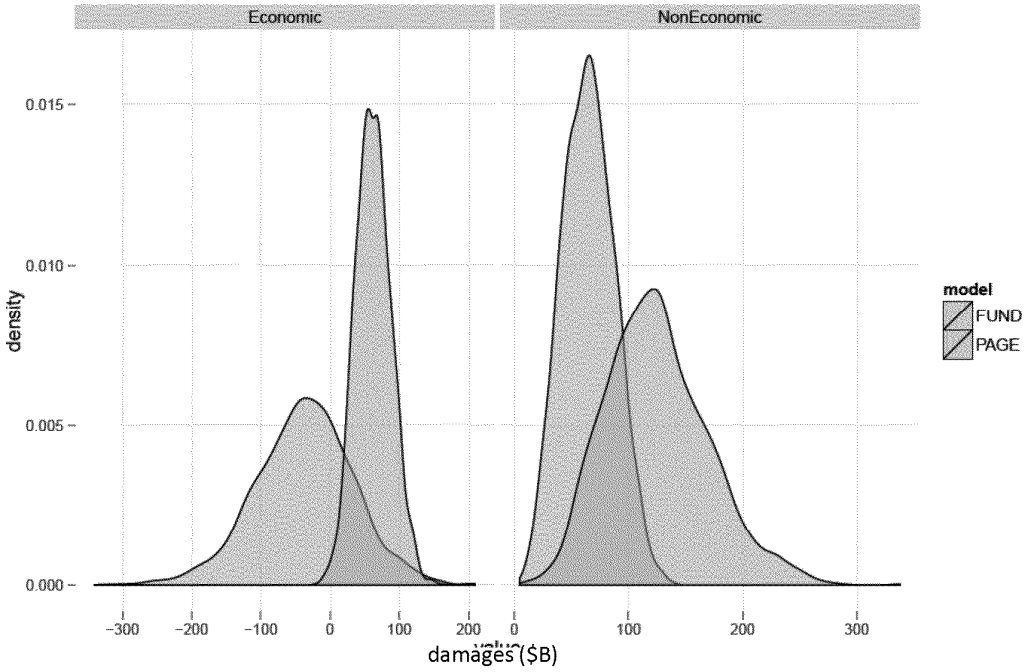

Figure 6-58
Comparison of model specific damage distributions for harmonized sectors for USA for 2050 with USG2 socioeconomics

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EXPERIMENTAL DESIGN ASSESSMENT

Previous sections explored the individual components of the USG SCC modeling. As such, they had a narrow focus within the overall USG approach. The overall USG approach has an overarching experimental design that prescribes how the models are run and how the results from the individual models are used. The experimental design has specific features, which reflect methodological choices that have implications for the final USG SCC estimates. Recall, that the USG experiment design is defined by the following key features (Section 2):

1. Use of multiple models
2. Running the models with two standardized uncertainties – socioeconomic & emissions assumptions, climate sensitivity distribution assumption
3. Running two of the models with model specific parametric uncertainty distributions
4. Using standardized constant discount rates to compute net present values
5. Producing 150,000 SCC results for each discount rate/SCC year combination (50,000 SCC estimates per model)
6. Aggregation of the 150,000 results to create a single USG SCC estimate for a discount rate and SCC year.

This experimental design is unique relative to the SCC literature with its multi-model approach, standardized and model specific parametric uncertainties, probabilistic modeling, and aggregation procedure. This approach is novel because, to date, SCC estimates in the literature have been generated by individual models with non-standardized uncertainties (e.g., Hope, 2013; Nordhaus, 2010; Anthoff and Tol, 2013b, 2013c). The approach is also novel because U.S. regulatory analyses typically use individual models (e.g., the Integrated Planning Model used at the U.S. EPA, and the CAFE Compliance and Effects Model used at the U.S. National Highway Traffic Safety Administration).

The USG experimental design was used to generate both the initial and revised USG SCC estimates in 2010 and 2013 respectively (USG, 2010; USG, 2013). The design reflects a number of considerations, in particular the desire to capture uncertainty (by including alternative models and assumptions). However, the design creates challenges, especially for its implementation and communication. From our assessment, we have identified a number of design challenges and some explicit issues in the current implementation. These represent areas for potential improvement in future SCC development and estimation.

Multi-model approach

Using multiple models is a means for accounting for differences in expert opinion about the structure of social, economic, and physical processes. However, using multiple models creates a comparability challenge since one needs to assure that the results from the different models are truly comparable and providing unique, and independent, valuable information. From our assessment, we find inconsistencies in the current implementation and fundamental differences

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in modeling that call into question the comparability of results. We also find interdependence between the models.

- *Implementation inconsistency* – We find inconsistencies across models in how different standardized elements were implemented in the USG SCC modeling, such as in the implementation of the standardized socioeconomic and emissions inputs, non-CO_2 emissions and radiative forcing, and the incremental CO_2 emissions shock used to estimate the incremental damages for the SCC calculations (Sections 4, 5, and 6). These inconsistencies introduce artificial variation in the results across models.
- *Intermodel uncertainty inconsistency* – In the USG exercise, the models are considering very different parametric uncertainty within their climate change and climate damage modeling (Sections 5 and 6). FUND and PAGE have model specific uncertain parameters, but with specifications that differ between the two, and DICE is not considering model specific parametric uncertainty at all. The models are therefore representing different uncertainty spaces, which implies that results from the individual models are not derived from the same statistical population, and therefore not comparable.
- *Model structural differences* – We observe significant differences in the climate change and climate damage modeling structures that raise questions about the comparability of the results being produced (Sections 5 and 6). Do these structural differences reflect differences in expert scientific opinion? Or, are they differences to resolve, or uncertainties to be explicitly evaluated in the overall approach? For instance, the models consider different sets of emissions and radiative forcing categories—the drivers for projected temperature. The models also have stark differences in key pieces of the climate modeling (e.g., the carbon cycle, climate sensitivity, climate feedbacks, and projected climate change uncertainty), with some elements excluded entirely from some models. Furthermore, unique model specific factors dominate results in the damage components and therefore raise questions about their representation within each model and across models—e.g., agricultural CO_2 fertilization, cooling energy demand, global damages dominated by China, regional scaling of damages, rapidly growing global non-economic damages, potential discontinuity damages, and damages that increase quadratically with temperature. Finally, we find dramatic differences in estimated damages across models for comparable regions and sectors that are not explored or explained. Differences in modeling, such as these, need to be reviewed to resolve or justify the differences, or potentially develop a new standardized uncertainty to consider in all models. That review should consider the importance of different uncertainties as well through sensitivity analyses.
- *Model interdependence* – We find that the damage formulations across models are not fully independent in that some damage formulations are based on previous results from the other models (Section 6).

Consideration of uncertainty

There are two main challenges to considering uncertainty within this modeling: fully capturing uncertainty and consistently capturing uncertainty across models. Not all uncertainties need to be incorporated—only those relevant to the SCC estimates. The sensitivity of SCC estimates to alternative and additional uncertainties should be evaluated to determine importance. Important uncertainties should be included as explicit uncertainties in future SCC estimation. Also, uncertainties should be standardized to the extent possible (given the unique model structures) to

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increase comparability of results. We found a number of opportunities for improving the representation of uncertainty in USG SCC estimation:

- *Current uncertainties* –We found that the current standardized uncertainties are not capturing known uncertainty in the two domains considered—socioeconomics/emissions and climate sensitivity. There are legitimate alternatives, as well as constraints on what is reasonable and comparable, that need to be considered. (Sections 5 and 6).
- *Additional uncertainties* – We found that there are additional uncertainties to consider (e.g., socioeconomic structure, alternative 2300 extrapolations, alternative climate modeling and uncertainty specifications, and alternative specifications for 2013 revisions). (Sections 4, 5, and 6).
- *Parametric uncertainty* – As discussed, parametric uncertainty differs across models to the extent that it threatens the comparability of results across models. To the extent possible, parametric uncertainty should be quantified as part of methodological development and standardized across models. This is likely easier with climate modeling where there is a substantial scientific literature from which to draw.

Robustness

The robustness of the USG SCC estimates is potentially an issue. Robustness refers to whether results are insensitive to reasonable alternative assumptions and modeling. Robustness is potentially an issue for the USG SCC estimates because we find that there are alternative and additional uncertainties to consider, key model differences that need to be evaluated and potentially modified, and model results that are sensitive to alternative assumptions and modeling. Thus the results may not be stable and could change with reasonable alternatives. Robustness was not evaluated in the USG SCC exercise, but would be useful to do to provide greater confidence in final SCC estimates. Such an evaluation would test the sensitivity of results to alternatives and develop an experimental design that produces results that are robust to alternatives not considered. Robustness, of course, will be contingent on the state of scientific knowledge at the time.

Discounting

Constant standardized discount rates, as currently used in the USC SCC modeling, are problematic for two reasons. First, they are inconsistent with the economic growth models being used for the analysis, which have dynamic economic growth and therefore should have dynamic discount rates that are a function of growth. Dynamic discount rates are typical in this type of modeling and have been used in each of the models outside the USG SCC exercise in published applications (e.g., Anthoff et al., 2009; Hope, 2013; Nordhaus, 2013). Second, standardized discount rates are inconsistent with differences in economic growth rates across models, primarily due to different regional structures.

Aggregation of results

The USG approach aggregates 150,000 estimates by averaging across standardized assumption scenarios, model specific parametric uncertainties, and the three models to create a single USG SCC estimate for a particular discount rate and year. Averaging results requires that the results be comparable and independent. Comparability insures that the results are from the same statistical population. Independence insures that the results are providing unique information and

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deserve equal weight. However, our observations regarding socioeconomic assumptions and differences in modeling, implementation, and application suggest that the experimental design should be re-evaluated to determine whether it is meeting these requirements.

Considering an alternative framework

Ensuring comparable and independent results across models is challenging, and may be difficult to overcome. Consideration of alternative approaches with greater control and transparency would be practical. In particular, in this context, one could design a framework component by component, choosing the best approach for each causal component and entertaining uncertainty through a single structure within each component. Such an approach offers full experimental control, statistically comparable results, and greater transparency regarding modeling and uncertainty.

Documentation

It is difficult to understand and interpret elements of the USG SCC modeling from the current documentation. Additional modeling details and results, as well as justification for modeling choices is needed to facilitate interpretation and provide confidence in the methods and estimates. For instance, there is very little quantitative detail about climate and damage modeling and differences, justification for differences in responses, justification for experimental design choices (e.g., average 550 ppm scenario, constant discount rates, EMF-22 versus other published scenarios, FUND and PAGE probabilistic modeling), or discussion of 2013 revision alternatives and justification for the choices implemented.

Regarding 2013 revisions, updating the modeling with improved information is a scientifically laudable goal. However, the description and discussion of the 2013 revisions is insufficient for understanding and interpreting the changes in the USG SCC results. Additional justification for many of the revisions would be helpful (e.g., space heating expenditure reductions, transient temperature responses, constant indirect methane radiative forcing effect, saturation, regional scaling factors, probability of a discontinuity, adaptation, CO_2 absorption, regional climate modeling). Discussion of uncertainty regarding the revisions would also be helpful. At a minimum, it would be reasonable to explain differences across models for similar components (e.g., sea level rise, transient temperature response, saturation, adaptation). Finally, it is unclear which revised elements were peer reviewed. Part of the confusion is that the technical support documents ("TSD") have references to previous model versions, websites, and working papers. A clear citation for each of the revisions in each model would be useful.

Peer review

The USG SCC approach is a novel application and, as such, would benefit from external peer review. External review from qualified scientific experts would provide valuable feedback regarding the modeling framework (models, runs, aggregation), uncertainties (standardized, model specific, and specifications), and other elements. The review would lead to improved methods and provide the public with greater confidence in the resulting estimates.

Model peer review might also be considered. This would be a separate but related activity that explicitly reviews the individual models for regulatory application. Such a review is common for models regularly used for regulatory purposes.

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In addition to providing peer review, there is an opportunity to assess the climate literature and for improve damage modeling in general through engaged participation with scientific experts.

SCC application guidance

Very little guidance is provided regarding application of the USG SCC estimates. Technical documentation advises that regulatory analyses consider all the USG SCC estimates. However, there are a number of issues were clear guidance on the proper application of the USG SCC estimates will help avoid misapplication and increase consistency across regulatory applications. These include (but are not limited to) the following:

- Estimation of net changes in global CO_2 emissions,
- Valuation of non-CO_2 GHG emissions changes (e.g., changes in methane, nitrous oxide, or fluorinated gas emissions),
- Problems for SCC use with non-incremental changes in global emissions, and
- Consistency across benefit and cost estimation and use.

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CONCLUSION

The SCC is a metric used in U.S. regulatory analyses to value potential changes in CO_2 emissions associated with proposed and final rules—primarily the benefits of estimated CO_2 emissions reductions resulting from rules. The SCC is also in broader use domestically in local and non-regulatory applications. The SCC is a monetary estimate of the climate change damages to future societies over hundreds of years from an additional metric ton of carbon dioxide emitted to the earth's atmosphere today. With a global and multi-century scope, the SCC is complicated to compute and is surrounded by a great deal of uncertainty.

The USG developed SCC estimates, most recently in 2013, with each USG SCC estimate the result of significant aggregation—across models, over time, across regions and impact categories, and across 150,000 scenarios. However, the USG SCC estimates are difficult to interpret, discuss, and evaluate in terms of the societal risks they do and do not represent, and how well they reflect current scientific knowledge, because little is known about the disaggregated modeling.

This study elucidates and assesses the modeling and raw detailed results underlying USG SCC estimation. Our primary goal is to improve understanding of SCC modeling and estimates to inform public discussion and future applications and climate research. We model and assess the individual components of the USG SCC modeling with diagnostic analyses and consideration of alternatives. We also evaluate the overall USG SCC experimental design. Through our multiple assessments, we observe significant variation across models in structure, implementation, and underlying model behavior and results, and identify fundamental issues with and opportunities for improving the USG SCC approach and increasing confidence in future results.

Given our goal of improving understanding of modeling and estimates, we likely stimulate more questions than we answer. By providing a richer technical foundation and identifying issues and opportunities, we hope to encourage discussion and facilitate improved SCC analyses and climate change research broadly (climate change impacts analyses in general, climate science, climate economics, and integrated assessment). Through this topic there is a tremendous opportunity for taking stock and assessing the literature on socioeconomic development, climate change and climate impacts that can improve SCC and damage modeling in general through engaged participation with scientific experts.

Finally, we acknowledge that a variety of other SCC issues have been discussed by others recently that are beyond the scope of this study, including omitted impacts categories (e.g., Howard, 2014; Tol, 2009; IPCC, 2007), USG SCC development process (e.g., U.S. GAO, 2014), and equity weighting and low intergenerational discount rates (e.g., Johnson and Hope, 2012). Our focus was instead on understanding, evaluating, and improving the modeling currently in place, which is a requisite first step before many of these issues can be broached.

We conclude by noting that this study focuses on SCC estimation. SCC application is a separate, but important, topic that also needs consideration to insure appropriate application of SCC estimates. Overall, the USG is confronted by two key SCC technical challenges: robustness and

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application. The former refers to establishing public confidence by developing estimates that are robust to reasonable alternative assumptions. This study was designed to help with this issue. The latter refers to using the SCC estimates properly in a way that is consistent with what they represent and how they are computed.

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MODEL REGIONS

Model	Region	Name
FUND	USA	United States of America
	CAN	Canada
	WEU	Western Europe
	JPK	Japan and South Korea
	ANZ	Australia and New Zealand
	CEE	Central and Eastern Europe
	FSU	Former Soviet Union
	MDE	Middle East
	CAM	Central America
	SAM	South America
	SAS	South Asia
	SEA	Southeast Asia
	CHI	China plus (Hong Kong, North Korea, Macau, Mongolia)
	NAF	North Africa
	SSA	Sub-Saharan Africa
	SIS	Small Island States
PAGE	EU	European Union
	US	United States of America
	OT	Other OECD countries
	EE	Former Soviet Union & Rest of Europe
	CA	China & Centrally Planned Asia
	IA	India & Southeast Asia
	AF	Africa & Middle East
	LA	Latin America

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To: Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]
Cc: McGartland, Al[McGartland.Al@epa.gov]
From: Langdon, Robin
Sent: Mon 8/24/2015 5:39:12 PM
Subject: RE: Refinery rule - Follow up on natural gas prices
Refinery GHG Valuations June 2015 Values.xlsx

Hi Elizabeth,

Below is a draft footnote for the Refinery EIA. I was thinking I could insert it at the end of the sentence **Non-Responsive**

Non-Responsive

Also, attached is a worksheet that summarizes the methane and CO2 emissions decreases and increases associated with the DCU and flare requirements. Based on our discussion with Brenda, I kept the estimates separated by DCU and flare requirements to more easily reflect them in the analysis.

Please let me know if you have any questions.

Robin

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From: Kopits, Elizabeth
Sent: Monday, August 24, 2015 11:11 AM
To: Langdon, Robin
Cc: McGartland, Al
Subject: Refinery rule - Follow up on natural gas prices

Hi Robin,

I just looked at the natural gas prices from EIA. The industrial natural gas price in EIA's AEO 2015 is $5.35 ($2013 $/mill Btu) for 2018 (http://www.eia.gov/beta/aeo/#/?id=3-AEO2015), (which converts to $5.4998/thousand cubic feet according to conversions given in http://www.eia.gov/tools/faqs/faq.cfm?id=45&t=8). (The latest STEO only reports an industrial natural gas price out to 2016 - $4.33 ($/thousand cubic feet) - http://www.eia.gov/forecasts/steo/report/natgas.cfm).

Non-Responsive

along with an explanatory footnote in the EIA.

Thanks,

Elizabeth