Ocean Ecosystem Indicators of Salmon Marine Survival in the Northern California Current

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January 2012

ED_002660K_00011990-00001

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Project Summary

Ocean Ecosystem Indicators of Salmon Marine Survival in the Northern California Current

As many scientists and salmon managers have noted, variations in marine survival of salmon often correspond with periods of alternating cold and warm ocean conditions. For example, cold conditions are generally good for Chinook and coho salmon, whereas warm conditions are not.

These pages are based on our website of how physical and biological ocean conditions may affect the growth and survival of juvenile salmon in the northern California Current off Oregon and Washington. We present a number of physical, biological, and ecosystem indicators to specifically define the term "ocean conditions." More importantly, these metrics can be used to forecast the survival of salmon 1–2 years in advance, as shown in Table 1. This information is presented for the non–specialist; additional detail is provided via links when possible.

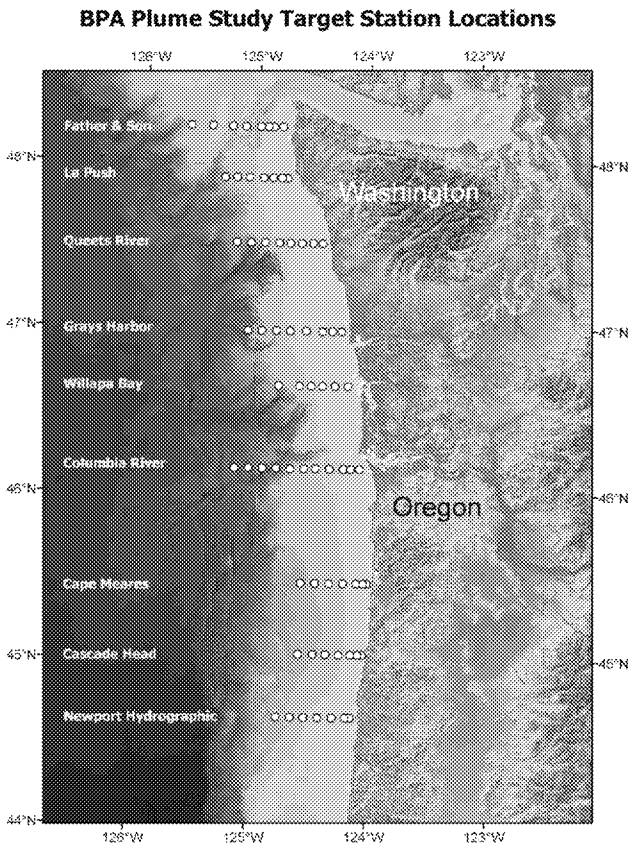

Figure 1. Transects sampled during trawling surveys off the coast of Oregon and Washington.

Material presented in this report has two sources. One is the World Wide Web, from which we have drawn values for the Pacific Decadal Oscillation, Multivariate ENSO index, Upwelling Index, and sea surface temperatures. Links and references to these sources are given in the respective sections that deal with these four physical variables. All other data are from our direct observations during a) biweekly oceanographic sampling along the Newport Hydrographic Line and b) annual juvenile salmonid surveys conducted in June and September. Survey station locations are shown in Figure 1; sampling and survey methods are presented in "Ocean Sampling Methods."

Using all of these data, we developed a suite of ocean ecosystem indicators upon which to base forecasts of salmon returns. These forecasts are presented as a practical example of

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how ocean ecosystem indicators can be used to inform management

decisions for endangered salmon. At this time, the forecasts are qualitative in nature: we rate each in terms of its "good," "bad," or "neutral" relative impact on salmon marine survival (Table 1).

We use this suite of indicators to complement existing indicators used to predict adult salmon runs, such as jack returns, smolt–to–adult return rates (Scheuerell and Williams 2005), and the Logerwell production index.

The strength of this approach is that biological indicators are directly linked to the success of salmon during their first year at sea through food–chain processes. These biological indicators, coupled with physical oceanographic data, offer new insight into the mechanisms that lead to success or failure for salmon runs.

In addition to forecasting salmon returns, the indicators presented here may be of use to those trying to understand how variations in ocean conditions might affect recruitment of fish stocks, seabirds, and other marine animals. We reiterate that trends in salmon survival track regime shifts in the North Pacific Ocean, and that these shifts are transmitted up the food chain in a more–or–less linear and bottom–up fashion as follows:

upwelling → nutrients → plankton → forage fish → salmon.

The same regime shifts that affect Pacific salmon also affect the migration of Pacific hake and the abundance of sea birds, both of which prey on migrating juvenile salmon. Therefore, climate variability can also have "top down" impacts on salmon through predation by hake and sea birds (terns and cormorants). Both "bottom up" and "top down" linkages are explored here.

2011 Annual Update

The trend of cold ocean conditions that started in September 2007 was interrupted by a moderately strong El Niño event in mid 2009: this warming event continued from August 2009-May 2010 and had a negative influence on productivity in the coastal waters of the northern California Current.

However, in June 2010 La Niña (cold ocean) conditions returned and have continued throughout 2011. Should these conditions persist into spring 2012, ocean conditions will be the best observed in the past few decades for Pacific salmon juveniles that enter the sea during spring (spring Chinook, coho, and steelhead). Juvenile migrants entering the ocean in spring 2012 would have very high ocean survival.

There is some uncertainty in this outlook: some NOAA forecast models predict a weakening La Niña, whereas others predict a strengthening. Regardless, cold ocean conditions will likely prevail through spring.

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Here we discuss each of our indicators in the context of how our measurements in 2011 compare to those made by our research team since 1998. Annual values for each indicator from 1998 until present are listed in Table 3.

Pacific Decadal Oscillation—The PDO is now once again negative (Figure 5); values have been strongly negative since July 2011 (> -1.3). In fact, the PDO value for November 2011 (-2.33) was the lowest observed since the early 1950s and 1960s and ranks as the 13th lowest since 1900.

The Oceanic Niño Index (ONI)—The ONI has a value of –0.7 as of November 2011; although not strongly negative, it should be noted that this value has become more negative each month since July 2010 (Figure 4).

Sea Surface Temperature (SST)—In winter 2010-2011, SST values were colder than usual, at -0.5°C below normal (Figure 7). In summer 2011, SST values were also cooler than normal, at -0.66°C below normal (Figure 7).

Coastal Upwelling—Upwelling in 2011 was initiated on 13 April (day 105), near the average start date, and continued until mid-September (day 256). Thus, upwelling ended nearly a month earlier than the 10 October average (day 283). The upwelling season was initially weak in April and May and did not begin to strengthen until early June (Figure 10), resulting in a negative upwelling anomaly for April-May (Table 3). This was the 3rd worst start to the upwelling season observed in the past 14 years.

Physical Spring Transition—The spring transition date in 2011 came on day 105 (13 April); however, northerly winds were weak and inconsistent until day 160 (9 June). Thus, even though the strong winter storms ended in early April, consistent upwelling winds did not commence until early June, after which they were quite strong. The upwelling season ended early, on 13 September.

Deep Water Temperature and Salinity—As a result of relatively weak upwelling in spring 2011, deep waters on the continental shelf were not as cold as they have been in years of stronger upwelling. This pattern continued through summer 2011, when deep water temperature ranked 6th. Overall, the upwelling season of 2011 would be categorized as moderate (Figures 16 and 17).

Length of the Upwelling Season—Even though the strong winter storms ended in early April, and the first puff of upwelling winds was seen on 13 April (day 105), as noted above, significant amounts of upwelling did not begin until 9 June (Figure 10). The season ended early, on 13 September, resulting in an upwelling season that was 161 days in length, or 20% shorter than the climatological average.

Copepod Biodiversity (Species Richness)—Species richness is the number of copepod species in plankton samples. Monthly averaged values of copepod species composition continue to track the PDO and SST quite closely (Figure 21). When the PDO is negative, surface waters are cold (see Figure 5), and the copepod community is dominated by only a few cold–water, subarctic

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species; however, when the PDO is positive, SSTs are warm, and the community is dominated by a greater number of warm–water, subtropical copepod species. We found low values of species–richness values throughout 2011, an indication of improving ocean conditions.

Northern Copepod Anomalies—Copepods are transported to the Oregon coast, either from the north/northwest or from the west/south. Copepods that arrive from the north are cold–water species that originate from the coastal Gulf of Alaska; these are referred to as the "northern copepods." The "northern copepod index" is the log biomass anomaly of three species of cold–water copepods: Calanus marshallae, Pseudocalanus mimus, and Acartia longiremis. This index tracks closely with the PDO (Figure 24). This index was especially significant in summer 2011 because the log of the northern copepod biomass anomaly was the highest we have seen in recent years (Table 2 and 3), indicating "good ocean conditions" in 2011.

Biological Spring Transition—The biological spring transition is defined as the date when the zooplankton community has transitioned from a warm–water "winter" community to a cold–water "summer" community. During 2011, the biological transition came early, on day 82 (21 March), as shown in Table 3. This is another indicator of improving ocean conditions. Several methods are used to calculate dates of the spring and fall transition, and a compilation of the different methods (including our "biological transition") is available from Columbia River DART (Data Access in Real Time), a project of the University of Washington School of Aquatic and Fishery Sciences (http://www.cbr.washington.edu/data/trans.html).

Winter Ichthyoplankton—Annual abundance estimates of key salmon prey in winter and early spring provide an indicator of survival in the months before juvenile salmon enter the sea because these estimates reflect the feeding conditions they will potentially encounter. Data from January-March 2011 (winter) indicate below average feeding conditions for salmon that entered the sea in spring 2011.

Catches of Spring Chinook in June—Pelagic trawl surveys have been carried out for 14 years, since 1998. In recent June surveys (2008 2010) catches of spring Chinook have been high, with record high catches in 2008. However, catches in June 2011 were poor, ranking 10th among the 14 years of surveys (Figure 36).

Catches of Coho in September—Catches of juvenile coho salmon in our September trawl surveys have been a fairly good indicator of rates of return of coho the following year (Figure 37). Catches over the past few years have been among the lowest since 1998 (Figure 36); however, numbers of coho in the September 2011 survey ranked 5th overall.

Overall Summary—When all of the indicators are taken as a whole (Table 2), the year 2011 has a rank of 6 out of 14, suggesting average returns of coho in 2012 and Chinook in 2013. However, similar to the past 2 years, individual indicators have sent a mixed message. Certain indicators suggest the potential for above average returns: persistence of strong La Niña conditions, a negative PDO, positive copepod anomalies from May-September, and reasonably high catches of coho in the September survey. However, negative indicators include relatively warm surface waters on the continental shelf, weak upwelling in spring, a short upwelling season, and low

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abundances of ichthyoplankton during January-March. Because of these mixed signals, we are less certain of our prediction for coho in 2012 and Chinook in 2013.

Positive Signs for 2012

- Strong negative values of the PDO were observed in autumn 2011; if these values persist through winter and early spring 2011-2012, they could result in the best ocean conditions observed in decades. This is the first indication that 2012 could result in some of the highest returns of Columbia River coho salmon in 2013 and spring Chinook in 2014.
- Negative ONI values indicate cold La Niña conditions at the equator. These negative values are expected to continue into spring 2012, which suggests that the northern North Pacific Ocean will also remain cold through spring 2012, giving rise to continuation of good ocean conditions.
- Northern copepod biomass in 2011 has been the highest in recent years, indicating improved ocean conditions compared to the past few years. This suggests good feeding conditions for the baitfish upon which juvenile salmon feed (however see "ichthyoplankton" below).
- Catches of coho in the September 2011 survey were relatively high, ranking 5th overall among 14 annual surveys.

Negative Signs for 2012

- Even though the spring transition occurred near the date of the climatological average (early April), upwelling from April through early June was relatively weak. Another negative indicator is that upwelling ceased very early, in mid-September.
- Throughout 2011 we found low values of copepod species–richness values, an indication of improving ocean conditions; however, these low anomalies were less negative than in other "good" years.
- Ichthyoplankton biomass in January-March 2011 (winter) was among the lowest values in our time series, indicating poor feeding conditions for salmon that entered the sea in spring 2011.
- Catches of juvenile spring Chinook in the June surveys were poor, ranking 10th of 14 years.

Forecast of Adult Returns for Coho and Chinook Salmon

2011 was characterized by the continuation of La Niña conditions that were initiated in July of 2010. Combined with persistently negative PDO values throughout the year and a high biomass of lipid-rich northern copepods supporting the base of the food-chain, 2011 had the potential to be a good year for supporting juvenile salmon entering the ocean. However, this positive bio-physical outlook is tempered by observations of low winter-time ichthyoplankton (larval stages of fish-prey for salmon) abundance and poor upwelling (both in terms of the total amount and duration) throughout the year. Considering the previous two years (2009 and 2010) were characterized by below-average ocean conditions, we suggest that 2011 was an intermediate year

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with the foundation to support a rich biological community if the ocean conditions remain positive in 2012.

As 2012 begins to unfold, all signs are that ocean conditions will be among the best observed in recent years. Our annual update of ecosystem indicators during 2011 is here, and our "stoplight" rankings and predictions are shown below in Table 1, Table 2, and Figure A.

Table 1. Ocean ecosystem indicators of the Northern California Current. Colored squares indicate positive (green), neutral (yellow), or negative (red) conditions for salmon entering the ocean each year. In the two columns to the far right, colored dots indicate the forecast of adult returns based on ocean conditions in 2011.

					Forecast of adult returns	
	2008	2009	2010	2011	Coho 2012	Chinook 2013
Large–scale ocean and atmospheric indicators						
PDO	■	□	□	■	●	●
ONI (Jan-Jun)	■	□	■	■	●	●
Local and regional physical indicators						
Sea surface temperature anomalies	■	□	□	□	□	□
Coastal upwelling	■	□	■	■	●	●
Physical spring transition	□	■	□	□	□	□
Deep water temperature and salinity	■	□	□	■	□	□
Local biological indicators						
Copepod biodiversity	□	□	■	■	●	●
Northern copepod anomalies	■	□	■	■	●	●
Biological spring transition	■	■	□	■	●	●
June spring Chinook	■	■	□	□	—	□
September Coho	□	■	■	□	□	—

Key
■ good conditions for salmon
□ intermediate conditions for salmon
■ poor conditions for salmon
● good returns expected
— no data
● poor returns expected

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Table 2 shows rank scores for the color-coding in Table 1. Scores were assigned based on their effect on juvenile salmonids. We show variables that are correlated with returns of coho salmon after 1 year and of Chinook salmon after 2 years. For example, positive PDO values (and red colors) indicate poor ocean conditions in coastal waters off the northern California Current. Similarly, higher sea surface temperatures in summer are a negative indicator for salmon, but particularly so for resident coho. Table 3 shows the values of each variable shown by rank in Table 2.

Table 2. Rank scores upon which color-coding of ocean ecosystem indicators is based. Lower numbers indicate better ocean ecosystem conditions, or "green lights" for salmon growth and survival, with ranks 1-4 green, 5-10 yellow, and 11-14 red. 14 years of sampling data were compared across years (within each row), and each year received a rank between 1 and 14.

	Year of Samples													
Ecosystem Indicators	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
PDO (December-March)	13	5	2	9	6	14	8	12	10	7	4	1	11	3
PDO (May-September)	8	3	5	4	9	12	13	14	10	11	1	7	6	2
ONI Jan-June	14	1	1	5	10	11	9	12	6	8	3	7	13	4
SST at 46050 (May-Sept)	12	8	3	4	1	7	13	11	5	14	2	9	6	10
SST at NH 05 (May-Sept)	8	4	1	6	2	5	14	11	7	13	3	12	10	9
SST winter before (Nov-Mar)	14	11	3	5	7	10	12	9	8	2	1	4	13	5
Physical Spring Trans (UI Based)	3	6	11	12	4	9	13	14	9	1	5	2	7	8
Upwelling Anomaly (Apr-May)	7	1	12	3	6	10	9	14	7	2	4	5	11	13
Length of upwelling season	6	2	11	9	1	10	8	14	5	3	7	3	11	13
Deep Temperature at NH 05	14	4	6	3	1	9	10	11	12	5	2	8	7	6
Deep Salinity at NH05	14	3	6	2	5	12	13	8	7	1	4	10	11	8
Copepod Richness Anomaly	14	2	1	5	4	10	9	13	11	8	6	7	12	3
N.Copepod Anomaly	13	9	5	6	3	12	10	14	10	8	2	7	4	1
Biological Transition	14	9	6	5	7	12	8	13	11	2	1	4	10	3
Copepod Community structure	14	4	3	6	1	10	11	13	12	8	2	5	9	7
Winter Ichthyoplankton	14	6	2	4	5	13	12	8	11	10	1	7	3	9
Catches of salmon in surveys														
June-Chinook Catches	12	2	3	14	7	9	13	11	8	6	1	4	5	10
Sept-Coho Catches	10	2	1	4	3	6	13	14	8	9	7	11	12	5
Mean of Ranks	11.3	4.6	4.8	5.7	4.6	10.2	10.8	12.3	8.8	6.5	3.1	6.5	9.0	6.5
RANK of the mean rank	13	2	4	5	2	11	12	14	9	6	1	6	10	6

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Table 3. Data for rank scores of ocean ecosystem indicators.

	Year of Samples													
Ecosystem Indicators	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
PDO (Sum Dec-March)	5.07	-1.75	-4.17	1.86	-1.73	7.45	1.85	2.44	1.94	-0.17	-3.06	-5.41	2.17	-3.65
PDO (Sum May-September)	-0.37	-5.13	-3.58	-4.22	-0.26	3.42	2.96	3.48	0.28	0.91	-7.63	-1.11	-3.53	-6.45
ONI Jan-June (Average)	1.20	-0.98	-0.98	-0.32	0.35	0.45	0.32	0.47	-0.25	0.17	-0.95	-0.22	0.88	-0.70
SST 46050	13.66	13.00	12.54	12.56	12.30	12.92	14.59	13.56	12.77	13.87	12.39	13.02	12.92	13.06
SST NH 05 Summer	11.26	10.79	10.64	11.08	10.73	10.91	13.11	12.00	11.11	12.08	10.74	12.00	11.50	11.27
SST NH 05 Winter Before (Nov-Mar)	12.00	10.80	9.96	10.04	10.11	10.78	11.02	10.74	10.47	9.84	9.36	10.03	11.28	10.04
Physical Spring Trans UI Based	83	88	134	120	84	109	113	142	109	70	87	82	95	105
Upwelling Anomaly (April-May)	-14	19	-36	2	-12	-34	-27	-55	-14	9	0	-5	-35	-36
Length of upwelling season (UI Based)	191	205	151	173	218	168	177	129	195	201	179	201	161	153
NH 05 Deep T (May-Sept)	8.58	7.51	7.64	7.50	7.38	7.75	7.88	7.91	7.92	7.55	7.46	7.70	7.67	7.57
NH 05 Deep S (May-Sept)	33.51	33.87	33.83	33.87	33.86	33.70	33.66	33.79	33.82	33.88	33.87	33.73	33.71	33.8
Copepod richness anomaly	4.81	-2.92	-3.61	-1.17	-1.45	1.58	0.98	3.94	2.68	-0.82	-1.04	-0.92	2.93	-2.41
Northern Copepod Biomass	-0.58	0.10	0.19	0.15	0.28	-0.07	0.06	-0.77	0.10	0.14	0.31	0.14	0.26	0.43
Biological Transition	209	134	102	93	120	156	132	230	150	81	64	83	135	82
Copepod Community structure	0.76	-0.84	-0.84	-0.78	-0.99	-0.18	-0.13	0.57	0.03	-0.67	-0.94	-0.79	-0.20	-0.70
Winter Ichthyoplankton	0.12	0.90	1.80	1.25	1.05	0.53	0.58	0.83	0.59	0.60	1.84	0.89	1.65	0.61
June-Chinook Catches	0.26	1.27	1.04	0.44	0.85	0.63	0.42	0.13	0.69	0.86	2.56	0.97	0.89	0.46
Sept-Coho Catches	0.11	1.12	1.27	0.47	0.98	0.29	0.07	0.03	0.16	0.15	0.27	0.01	0.03	0.30

Figure A shows correlations between adult Chinook and coho salmon counts at the Bonneville Dam and coho salmon smolt to adult survival versus a simple composite integrative indicator — the mean rank of all indicators (the second line from the bottom) in Table 2. This index explains about 50% of the variance in adult returns. A weakness of this simple non-parametric approach is that each indicator is given equal weight, an assumption that may not be true, thus Brian Burke (NWFSC/FE) has begun to explore a more quantitative analysis of the ocean indicators shown in Table 3, using principal component analysis (PCA). PCA was run on the indicator data, a procedure which reduces the number of variables in a dataset as much as possible, while retaining the bulk of information contained in the data (a sort of weighted averaging of the indicators). Another important feature of PCA is that the principal components (PCs), which are the new, rotated data, are uncorrelated. This eliminates one of the original problems with the indicator data set (i.e., multi co-linearity). We used the PCs obtained from the PCA as new predictor variables in a linear regression analysis of adult salmon returns (this process is termed principal component regression, or PCR) and results are shown below in Figure B.

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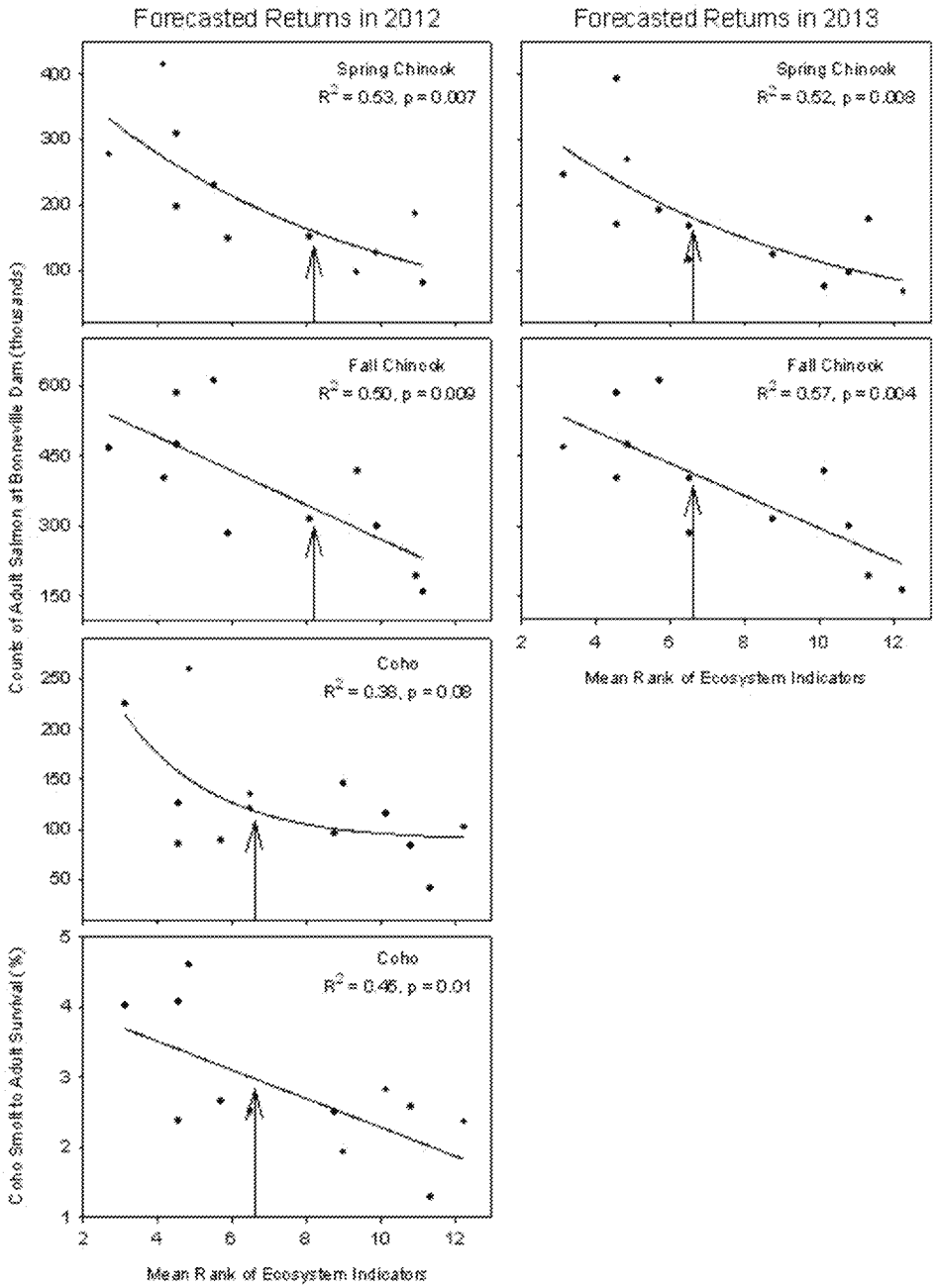

Figure A. Salmon returns versus the mean rank of ecosystem indicators. Arrows show the forecasted returns of Chinook salmon in 2012 and 2013 (upper four panels) and Coho salmon in 2012 (lower left two panels). With a mean rank of the ecosystem indicators of 8.1 in 2010, the spring and fall Chinook salmon forecast for 2012 (top left two panels) is 160,000 and 325,000 adults returning to the Bonneville dam respectively. With a more favorable mean rank (6.5) of the ecosystems indicators in 2011, the forecasted adult returns of spring and fall Chinook are expected to be slightly higher at 177,000 and 400,000 adult fish returning to the Bonneville dam in 2013 (upper right two panels). Coho adult returns to the Bonneville Dam in 2012 are expected to be approximately 119,000 fish and the smolt to adult survival of coho to Oregon coastal streams is expected to be approximately 2.9% in 2012 (lower left two panels).

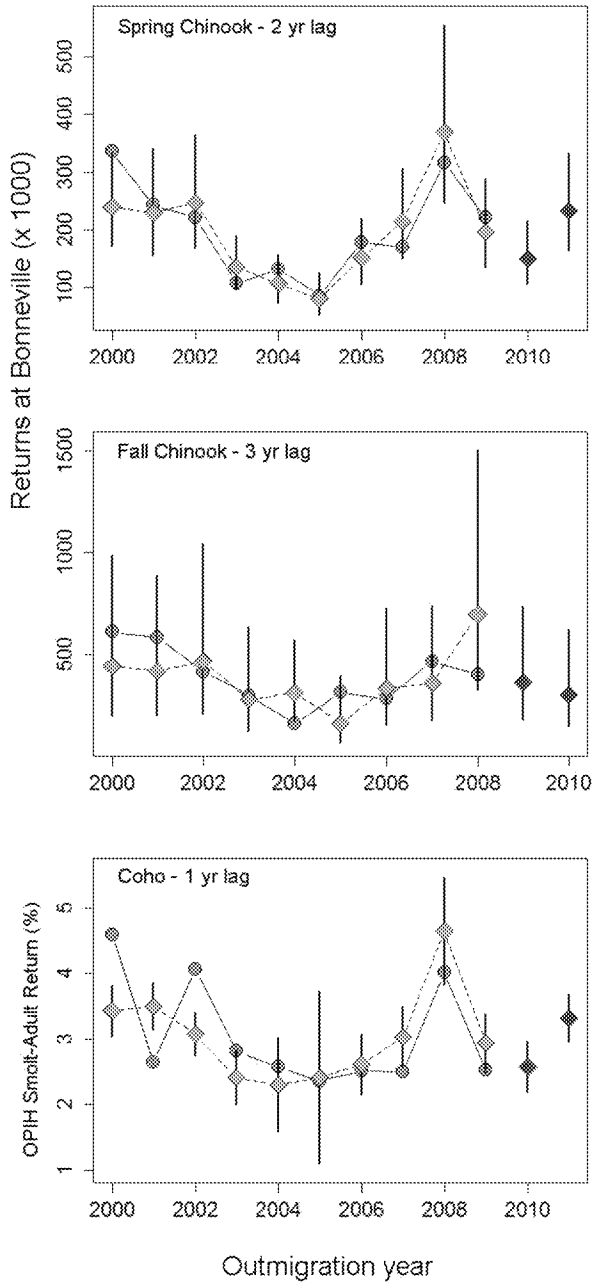

Figure B. Comparison between adult salmon returns to Bonneville Dam and the smolt to adult survival rate (OPIH, blue circles) of coho and the predicted returns calculated from a principal components regression analysis (yellow diamonds). The x-axis indicates the out-migration year that corresponds to the year we characterize with ecosystem indicators (e.g. mean rank of ecosystem indicators). Predicted returns (purple diamonds) for spring Chinook in 2012 and 2013 are 150,000 and 233,000 (top panel) and the predicted returns for fall Chinook in 2012 and 2013 are 364,000 and 302,000. The predicted smolt to adult survival rate (OPIH) of coho salmon to Oregon coastal streams in 2011 is 2.58%, and for 2012 it is 3.31%. Results are from work done by Brian Burke (NWFSC/FE).

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In summary, we have received mixed signals from ocean ecosystem indicators over the past three years and the variable ocean conditions in 2011 made our forecasts less certain for returns of coho salmon in 2012 and Chinook salmon in 2013. Our best guess is to expect average to above-average returns of coho in 2012 and Chinook in 2013. Based on a simple comparison to adult counts at Bonneville (Figure A), this translates to 177,000 spring Chinook, 400,000 fall Chinook, and 119,000 coho. Perhaps the most positive sign is that the ocean became very cold (and the PDO signal strongly negative) in summer 2010 and has remained so to date. If the cold conditions continue to persist into 2012, we may be seeing some of the better ocean conditions among the past 15 years.

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Adult Returns of Chinook and Coho Salmon

For specific stocks of Chinook and coho, the proportion of adult returns from a particular year class is not often known. This proportion, or escapement, is the number of juvenile salmon that survive to the smolt stage, migrate to the ocean, and return to spawn as adults after several months or years (Healy 1991).

Ordinarily, the proportions of fish that die in freshwater vs. those that die in the ocean can only be estimated. Thus adult return data, such as counts at dams or traps, can be used only as an index or surrogate measure of ocean survival. With these caveats in mind, we present adult data from various sources with which we compare forecasts based on ocean indicators.

The table below (Table 4) is color-coded according to ranks of adult return data from each year for which we have corresponding ocean indicator data. Adult data are lagged behind ocean entry by 1 year for coho and 2-3 years for spring and fall Chinook salmon; therefore, as of 2011, we have 14 years of indicator data but only 11 - 13 years of adult return data.

Table 4. Ranks among years for adult returns by year of ocean entry, 1998-present. Colors represent high (green), intermediate (yellow) and low (red) returns.

Adult returns by Year of Ocean Entry[1]

	OPIH Coho (adults:smolts)	Bonneville spring Chinook (n)	Bonneville fall Chinook (n)	Klamath River fall Chinook (n est.)
1998	13	5	7	2
1999	10	1	3	3
2000	1	2	1	1
2001	5	4	2	8
2002	2	6	5	10
2003	4	11	9	11
2004	6	10	11	4
2005	11	12	8	7
2006	8	8	10	6
2007	9	9	4	8
2008	3	3	6	5
2009	7	7	--	--
2010	12	--	--	--

[1] Counts of spring and fall Chinook are lagged by 2 and 3 years, respectively. Return ratios for coho are lagged by 1 year.

[2] Estimate based on jack returns.

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Data used in the rank scores above are shown in the chart below. Again, counts of spring and fall Chinook salmon at Bonneville Dam are shown lagged by 2 and 3 years, respectively. For example, for fish that entered the ocean in 1998, the number listed for spring Chinook indicates adults that returned in 2000, while the number for fall Chinook indicates adults that returned in 2001. For Chinook salmon, return numbers may also change during the 2-5 years of adult returns due to the different age classes of returning adults. For example, spring Chinook that entered the ocean in 2000 may return to spawn in 2002, 2003, or 2004.

Table 5. Adult-return data used for ranking among years, as shown in Table 4. Again, the full data set for the year of ocean entry requires a lag time of at least 3 years: thus though we have 14 years of ocean ecosystem indicator data, we have only 13 years of adult-return data.

Adult returns by Year of Ocean Entry[1]

	OPIH Coho (adults:smolts)	Bonneville spring Chinook (n)	Bonneville fall Chinook (n)	Klamath River fall Chinook (n est.)
1998	0.0128	177,741	400,205	187,333
1999	0.0238	391,367	473,786	160,788
2000	0.0459	268,813	610,075	191,948
2001	0.0265	192,010	583,754	78,944
2002	0.0407	168,656	417,057	65,227
2003	0.0282	74,038	299,161	61,374
2004	0.0257	96,456	161,415	132,131
2005	0.0236	66,624	315,279	92,758
2006	0.0251	124,334	283,691	100,644
2007	0.0250	114,525	467,524	90,860
2008	0.0402	244,384	401,576	103,005[2]
2009	0.0253	167,097	—	—
2010	0.0193[2]	—	—	—

[1] Counts of spring and fall Chinook are lagged by 2 and 3 years, respectively. Return ratios for coho are lagged by 1 year.

[2] Estimate based on jack returns.

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Age at maturity of Chinook salmon may differ depending on genetics, stream of origin, migration timing, and a number of other factors (Myers et al. 1998). Therefore, lag times for spring and fall Chinook may vary: those used here were selected based on age–class of the largest proportion of runs for which we had corresponding information (Whiteaker and Fryer 2007). For coho salmon, age at maturity is more constant within a given area and varies within a shorter time frame (Sandercock 1991; Weitkamp et al. 1995). Lag times for coho will likely remain at 1 year.

Estimates of SARs for OPIH coho and adult counts for Klamath River fall Chinook were provided by the Pacific Fishery Management Council. Counts of spring and fall Chinook at Bonneville were provided by the Columbia River DART project. These sources are publicly available via the internet.

Note also that these estimates were not adjusted for catch in fisheries, which can have a major impact on adult numbers. For example, ocean fisheries for Chinook salmon off California and most of the Oregon coast were closed in 2008 and 2009; these fisheries typically catch hundreds of thousands of Chinook salmon annually (PFMC 2011). Consequently, adult returns to basins most impacted by this closure (e.g., Klamath River) in those years reflect both substantially reduced harvest rates and the influence of ocean conditions on marine survival. Accordingly, direct comparisons of adult abundances across years should be made with considerable caution due to this high variation in harvest rates.

Large–scale Ocean and Atmospheric Indicators

Pacific Decadal Oscillation (PDO)

The Pacific Decadal Oscillation is a climate index based upon patterns of variation in sea surface temperature of the North Pacific from 1900 to the present (Mantua et al. 1997). While derived from sea surface temperature data, the PDO index is well correlated with many records of North Pacific and Pacific Northwest climate and ecology, including sea level pressure, winter land–surface temperature and precipitation, and stream flow. The index is also correlated with salmon landings from Alaska, Washington, Oregon, and California.

The PDO is highly correlated with sea surface temperature in the northern California Current (CC) area; thus we often speak of the PDO as being in one of two phases, a "warm phase" and a "cool phase," according to the sign of sea–surface temperature anomalies along the Pacific Coast of North America. These phases result from the direction of winter winds in the North Pacific: winter winds blowing chiefly from the southwest result in warmer conditions in the northern CC. The CC warms at such times due to onshore transport of warm waters that normally lie offshore. Conversely, when winds blow chiefly from the north, upwelling occurs both in the open ocean and at the coast, leading to cooler conditions in the northern CC.

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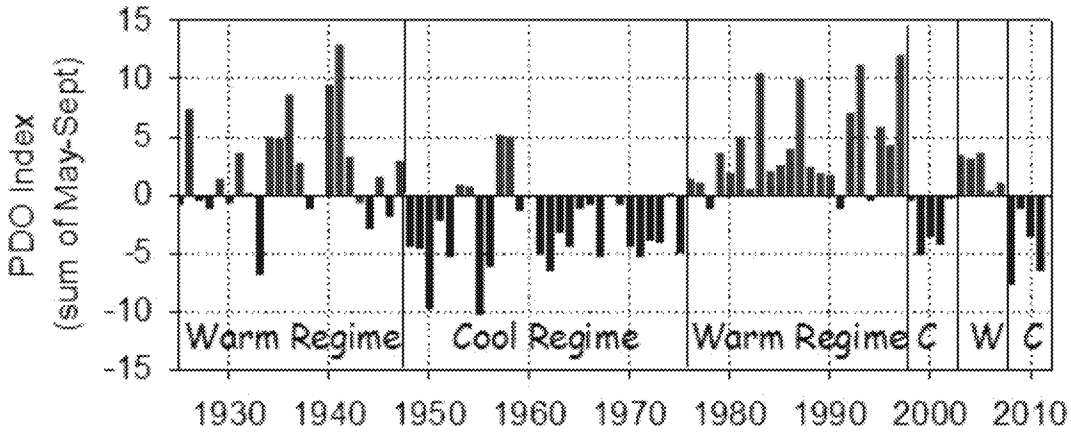

Figure 2. Time series of shifts in sign of the Pacific Decadal Oscillation (PDO), 1925 to 2010. Values are averaged over the months of May through September. Red bars indicate positive (warm) years; blue bars negative (cool) years. Note that 2008 was the most negative since 1956.

Warm and cold phases can persist for decades. For example, a warm phase continued from 1925 to 1946 (red bars in Figure 2), and a cool phase from 1947 to 1976 (blue bars). From 1977 to 1998, another 21–year warm phase occurred. However, these decadal cycles have recently broken down: in late 1998, the PDO entered a cold phase that lasted only 4 years followed by a warm phase of 3 years, from 2002 to 2005. The PDO was in a relatively neutral phase through August 2007, but abruptly changed in September 2007 to a negative phase that lasted nearly 2 years, through July 2009. The PDO then reverted to a positive phase in August 2009 (Figure 5) because of a moderate El Niño event that developed at the equator during fall/winter 2009–2010. This positive signal continued for 10 months (August 2009–May 2010) until June 2010, when persistently negative values of the PDO initiated and have remained strongly negative through autumn 2011.

Dr. Nathan Mantua and his colleagues were the first to show that adult salmon catches in the Northeast Pacific were correlated with the Pacific Decadal Oscillation (Mantua et al. 1997). They noted that in the Pacific Northwest, the cool PDO years of 1947–1976 coincided with high returns of Chinook and coho salmon to Oregon rivers. Conversely, during the warm PDO cycle that followed (1977–1998), salmon numbers declined steadily.

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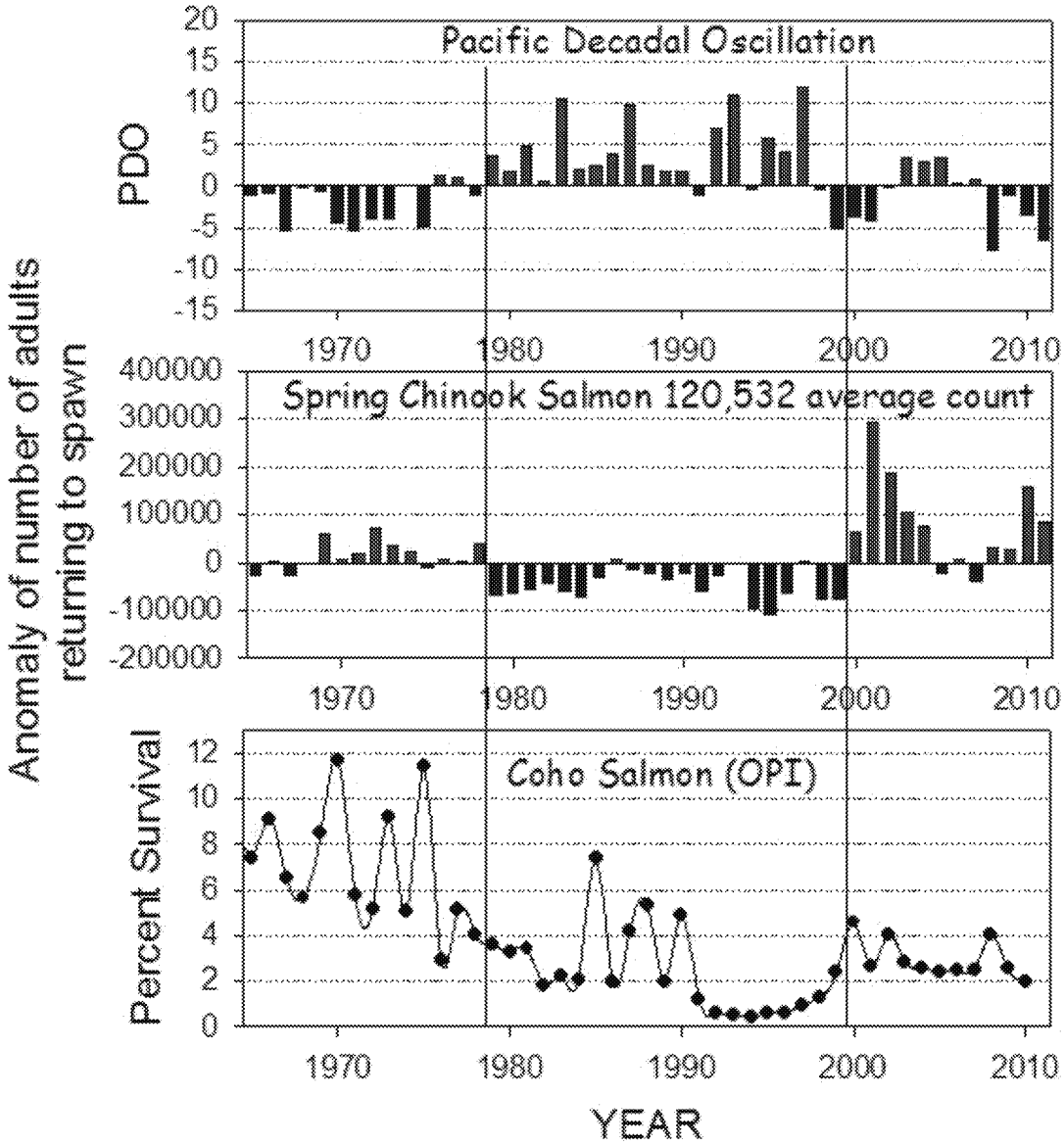

Figure 3. Upper panel shows summer average PDO, 1965–present; middle panel shows anomalies in counts of adult spring Chinook passing Bonneville Dam for the same period; lower panel shows survival of hatchery coho salmon from 1965–present. Vertical lines indicate climate shift points in 1977 and 1998.

The listing of several salmon stocks as threatened or endangered under the U.S. Endangered Species Act coincides with a prolonged period of poor ocean conditions that began in the early 1990s. This is illustrated in Figure 3, which shows average PDO values in summer vs. anomalies in counts of adult spring Chinook at Bonneville Dam. Also shown are percentages of

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hatchery juvenile coho salmon that returned as adults to hatcheries in SW Washington and NE Oregon during this period. These percentages have been recorded since 1961 as the Oregon Production Index, Hatchery (OPIH).

The OPIH includes fish taken in the fishery as well as those that returned to hatcheries. Figure 3 shows a clear visual correlation between the PDO, adult spring Chinook counts and hatchery coho adult returns. Note that during the 22–year cool phase of the PDO (1955 to 1977), below–average counts of spring Chinook at Bonneville Dam were seen in only 5 years (1956, 1958-60, and 1965).

In contrast, below–average counts were common from 1977 to 1998, when the PDO was in warm phase: below–average counts were observed in 16 of these 21 years. The dramatic increase in counts from 2000 to 2004 coincided with the return to a cool–phase PDO in late 1998. Note also from Figure 3 that a time lag of up to 2 years exists between PDO phase changes and spring Chinook returns: Chinook runs remained above average in 1977 and 1978, 2 years after the 1976 PDO shift. Similarly, increased returns of spring Chinook adults in 2000 lagged 2 years behind the PDO shift of 1998.

Adult spring Chinook runs declined again, beginning with fish that had entered the sea in 2003 and had experienced poor conditions associated with the positive PDO signal in that year. This decline continued for 3 years, until 2008 and 2009, when returns began to increase, as we predicted based on ocean conditions during 2006–2007. With the strongly negative PDO in effect for juvenile Chinook that entered the ocean in spring 2008, we predicted high adult returns of these fish in 2010. In fact, the third highest returns on record were recorded in 2010.

Oceanic Nino Index (ONI)

Coastal waters off the Pacific Northwest are influenced by atmospheric conditions not only in the North Pacific Ocean (as indexed by the PDO), but also in equatorial waters, especially during El Niño events. Strong El Niño events result in the transport of warm equatorial waters northward along the coasts of Central America, Mexico, and California and into the coastal waters off Oregon and Washington.

These events affect weather in the Pacific Northwest as well, often resulting in stronger winter storms with southwesterly winds that drive the transport of warm, offshore waters into the coastal zone. The transport of warm waters toward the coast, either from the south or from offshore, also results in the presence of unusual mixes of zooplankton and fish species.

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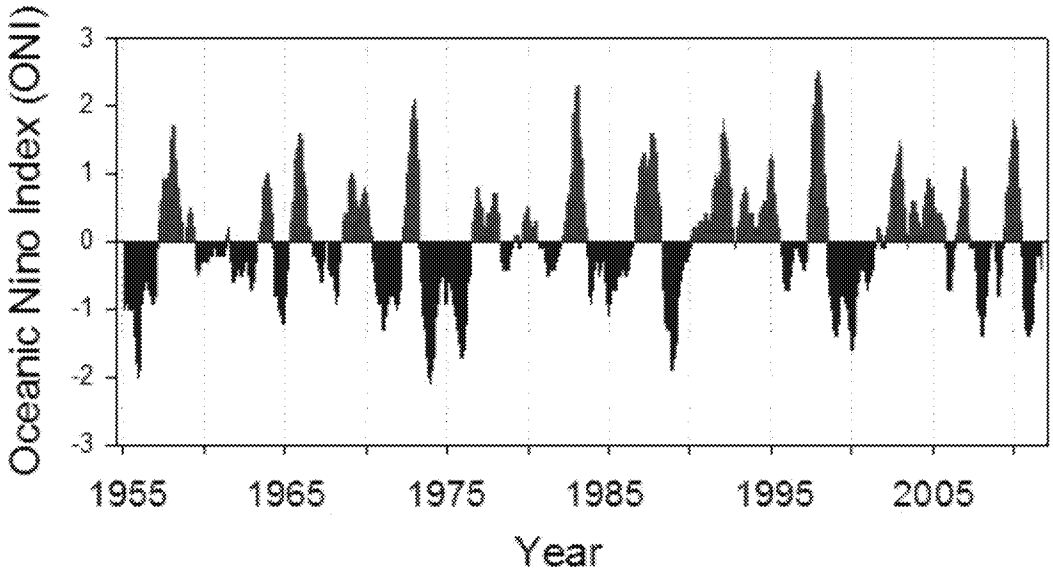

Figure 4. Values of the ONI, 1955 - present. Red bars indicate warm conditions in the equatorial Pacific, blue bars indicate cool conditions in equatorial waters. Large and prolonged El Niño events are indicated by large, positive values of the index: note the > +2 value associated with the 1972, 1983 and 1998 events. Note cool anomalies (La Niña) during 1999-2002 and 2007-spring 2009. A La Niña event developed in equatorial waters in mid-2010 and remained in effect from June 2010 through June 2011, weakening to near-neutral values towards the end of the year.

El Niño events have variable and unpredictable effects on coastal waters off Oregon and Washington. While we do not fully understand how El Niño signals are transmitted northward from the equator, we do know that signals can travel through the ocean via Kelvin waves. Kelvin waves propagate northward along the coast of North America and result in transport of warm waters from south to north.

El Niño signals can also be transmitted through atmospheric teleconnections in that El Niño conditions can strengthen the Aleutian Low, a persistent low–pressure air mass over the Gulf of Alaska. Thus adjustments in the strength and location of low–pressure atmospheric cells at the equator can affect our local weather, resulting in more frequent large storms in winter and possible disruption of upwelling winds in spring and summer.

Since 1955, the presence/absence of conditions resulting from the El Niño Southern Oscillation (ENSO) has been gauged using the Oceanic Niño Index, or ONI. A time series of the ONI is shown in Figure 4. Prior to 1977 (during the cool phase of the PDO), El Niño conditions were observed infrequently (note the predominance of blue bars prior to 1977).

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During these 22 years, cool conditions were observed in only 98 of 266 months. During this same warm phase of the PDO, both the equatorial and northern North Pacific oceans experienced two very large El Niño events (1983-1984 and 1997-1998). There were also two smaller events in 1986 and 1987 and a prolonged event from 1990 to 1995.

Beginning in September 1998, ONI values turned negative and remained so for nearly 4 years, similar to the trend observed in the PDO. The ONI returned to positive in April 2002 and remained so through September 2005, after which negative values returned. Positive values were seen once again, beginning in spring 2009 and remaining through May 2010. In June 2010, negative values became established and persisted into mid 2011 before becoming near-neutral.

Both the PDO and ONI can be viewed as "leading indicators" of ocean conditions, since after a persistent change in sign of either index, ocean conditions in the California Current soon begin to change. The ONI is a good index of El Niño conditions, and one can find information on the status of both El Niño and La Niña at the Climate Prediction Center and other websites maintained by the NOAA National Weather Service. Following the relatively strong El Niño during the winter of 2009-2010, the northern California Current experienced a rapid switch to La Niña conditions. The switch was reflected in both a drop in sea surface temperatures (Figure 5) and a later decrease in copepod biodiversity (Figure 21).

Local and Regional Physical Indicators

Sea Surface Temperature Anomalies

Given that the Pacific Decadal Oscillation is a basin–scale index of North Pacific sea surface temperatures (SST), how closely does the PDO match local sea surface temperatures off the Pacific Northwest? We examined this question using data from the NOAA Marine Environmental Buoy Database. Data were taken from NOAA Weather Buoy 46050, located 22 miles off Newport, Oregon.

Figure 5 shows monthly PDO values vs. monthly average sea surface temperatures at Buoy 46050 from 1996 through 2011. This is the period during which we have been measuring local ocean conditions.

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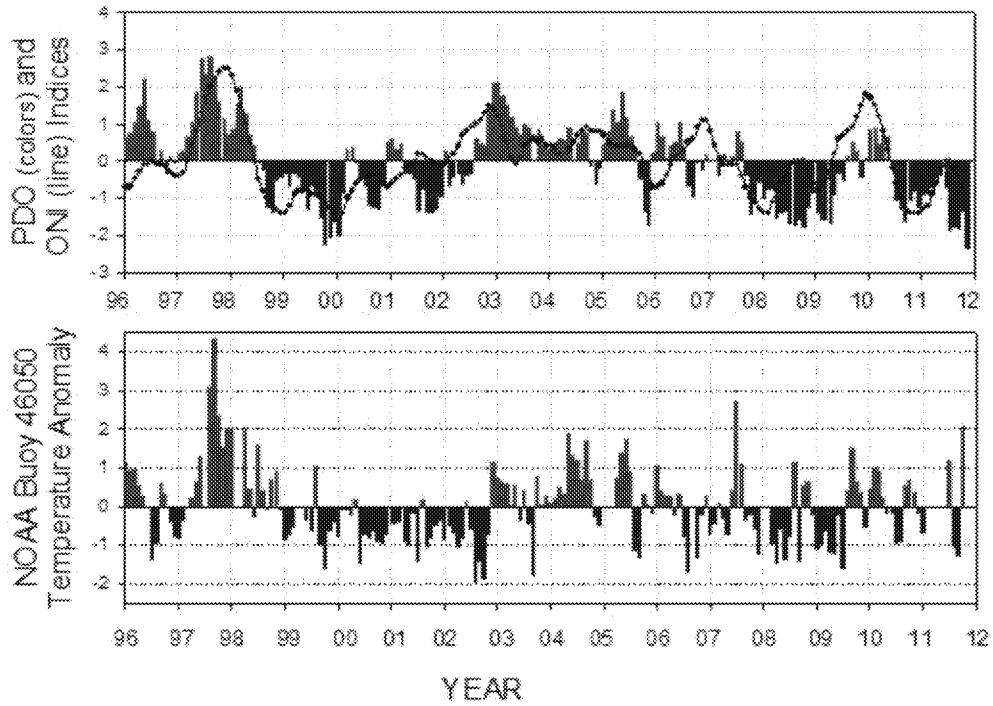

Figure 5. The PDO and monthly sea surface temperature anomalies at NOAA Buoy 46050, 22 miles west of Newport OR.

Correspondence between the PDO and local temperature anomalies is very high. For example, the 4 years of negative PDO values from late 1998 until late 2002 closely match the negative SST anomalies measured off Newport. Timing of the positive PDO values also matches that of the positive SST anomalies.

This suggests that changes in basin–scale forcing results in local SST changes, and that local changes may be due to differences in transport of water out of the North Pacific into the northern California Current. The data also verify that we can often use local SST as a proxy for the PDO. However, there are periods in which local and regional changes in the northern CC may diverge from the PDO pattern for short periods (usually less than a few months).

Buoy temperatures clearly identify warm and cold ocean conditions. During the 1997–1998 El Niño event, summer water temperatures were 1–2°C above normal, whereas during 1999–2002, they were 2°C cooler than normal (Figure 5). The summers of 2003–2005 were again warm, and some months showed positive SST anomalies that exceeded even those seen during the 1998 El Niño event. Some marine scientists refer to 2003–2005 as having "El Niño–like" conditions. In contrast, summertime SSTs were cooler than normal during summer 2006 and 2008 and during winters of 2006–2008. Cool temperatures persisted from mid–2007 through mid–2009, with only a few months of warmer–than–average temperatures (autumn 2008 and late summer 2009).

However, in autumn 2009, an El Niño event arrived (as predicted by NOAA scientists) and SSTs warmed, with anomalies of nearly +1°C. These warm temperatures persisted through the first half of 2010. In spring 2010, a La Niña (cooling) event began, and SSTs responded with negative anomalies of –1.5°C through late summer and autumn.

Note also in Figure 5 that there is a time lag between a sign change of the PDO and a change in local SSTs. In 1998, the PDO changed to negative in July, and SSTs cooled in December. In 2002, the opposite pattern was seen, with a PDO signal changing to positive in August followed by warmer SSTs in December. Thus, it takes 5–6 months for a signal in the North Pacific to propagate to coastal waters.

These measurements show that basin–scale indicators such as the PDO do manifest themselves locally: local SSTs change in response to physical shifting on a North Pacific basin scale. Other local ecosystem indicators influenced by the basin–scale indicators (and discussed here) include source waters that feed into the northern California Current, zooplankton and forage fish community types, and abundance of salmon predators such as hake and sea birds.

Thus, local variables respond to change that occurs on a broad spectrum of spatial scales. These range from basin–scale changes, which are indexed chiefly by the PDO, to local and regional changes, such as those related to shifts in the jet stream, atmospheric pressure, and surface wind patterns.

During 2011, the buoy was out of service from Jan 10 - July 5. Initial temperatures in January were cooler than average, reflecting the La Nina conditions.

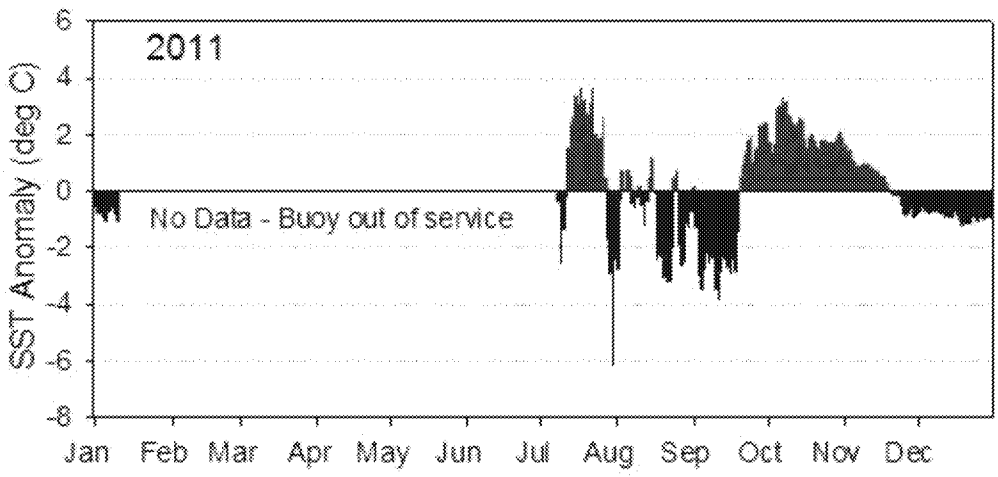

Figure 6. Daily sea surface temperature anomalies measured at NOAA Buoy 46050, located 22 miles off Newport, OR, in 2011. No data were available from Jan. 10 - July 5 due to problems with the buoy. .

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Figure 7 summarizes SST measurements made during our biweekly cruises made off Newport Oregon, at station NH 05. Seasonal averages for winter (Oct–Apr) and summer (May–Sep) show that SST during the past winter (2010–2011) was about 0.5°C below normal, reverting back to the colder–than–average trend seen during 3 of the previous 4 winters. Winter SST in 2009–2010 was warmer than average.

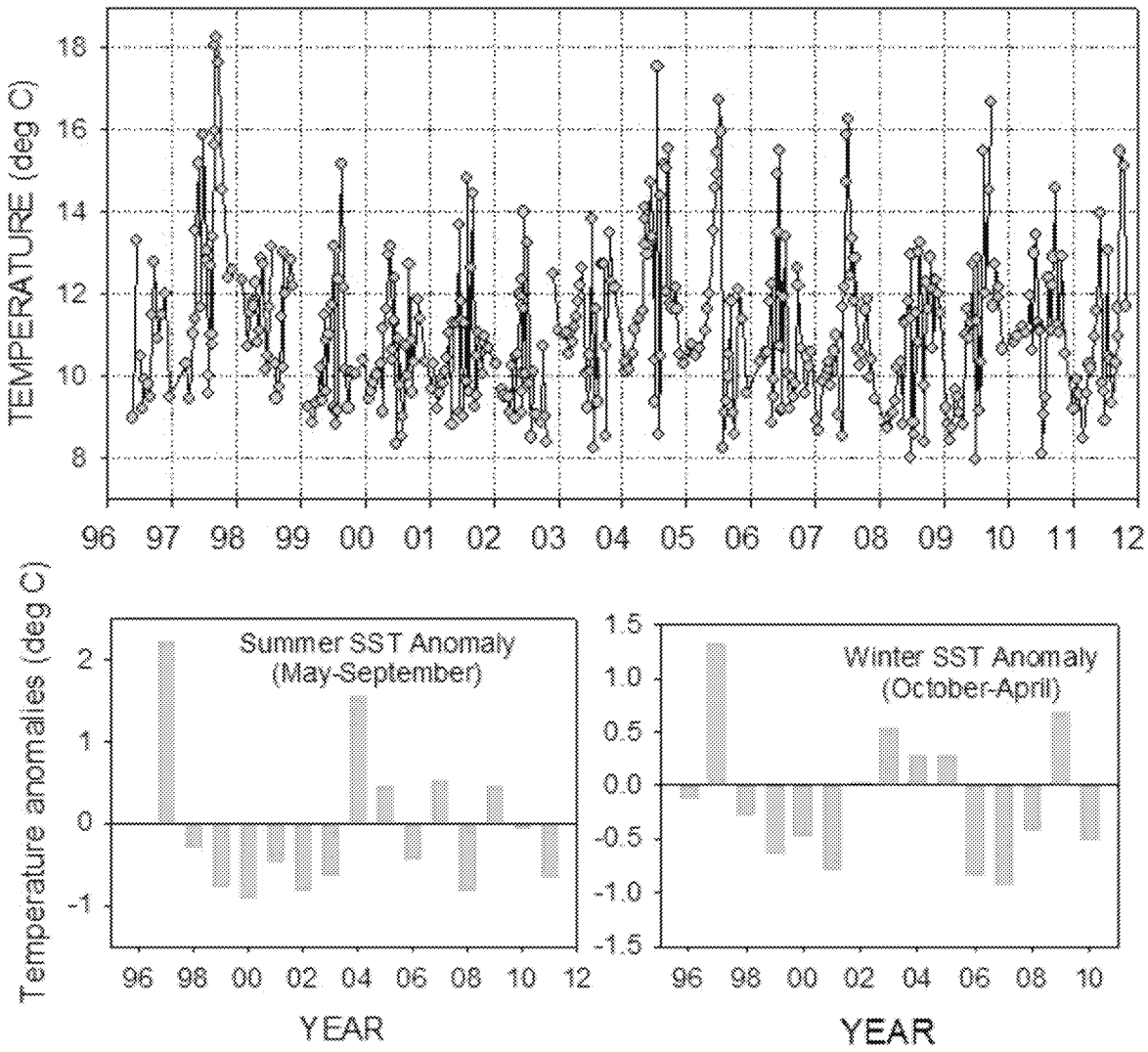

Figure 7. Figure 7. Upper panel shows average sea surface temperatures at Station NH 05 (located 5 miles off Newport, Oregon) since 1996. Lower panel shows temperature anomalies over the same years during summer (left; May-September) and winter (right; October-April).

Coastal Upwelling

Perhaps the most important process affecting plankton production off the Pacific Northwest is coastal upwelling. Upwelling is caused by northerly winds that blow along the Oregon coast from April to September. These winds transport offshore surface water southward (orange arrow in Figure 8), with a component transported away from the coastline (to the right of the wind, light green arrow). This offshore, southward transport of surface waters is balanced by onshore, northward transport of cool, high–salinity, nutrient–rich water (dark blue arrow).

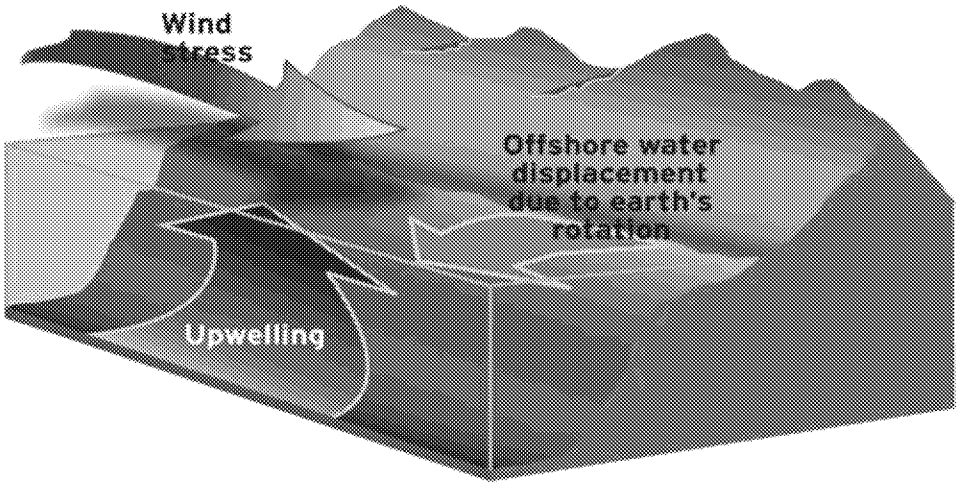

Figure 8. Forces affecting coastal upwelling.

The strength of an upwelling process can be calculated based on estimates of wind speed. Using such data, Dr. Andy Bakun (1973) developed the coastal Upwelling Index.

The Upwelling Index is, as its name implies, a measure of the volume of water that upwells along the coast; it identifies the amount of offshore transport of surface waters due to geostrophic wind fields. Geostrophic wind fields are calculated from surface atmospheric pressure fields measured and reported by the U.S. Navy Fleet Numerical Meteorological and Oceanographic Center (FNMOC) in Monterey, California.

The Upwelling Index is calculated in 3–degree intervals from 21°N to 60°N latitude, and data are available from 1947 to present. For the northern California Current, relevant values are from 42, 45, and 48°N. Year–to–year variations in upwelling off Newport (45°N) are shown as anomalies of the upwelling index Figure 9. The years of strongest upwelling were 1965–1967.

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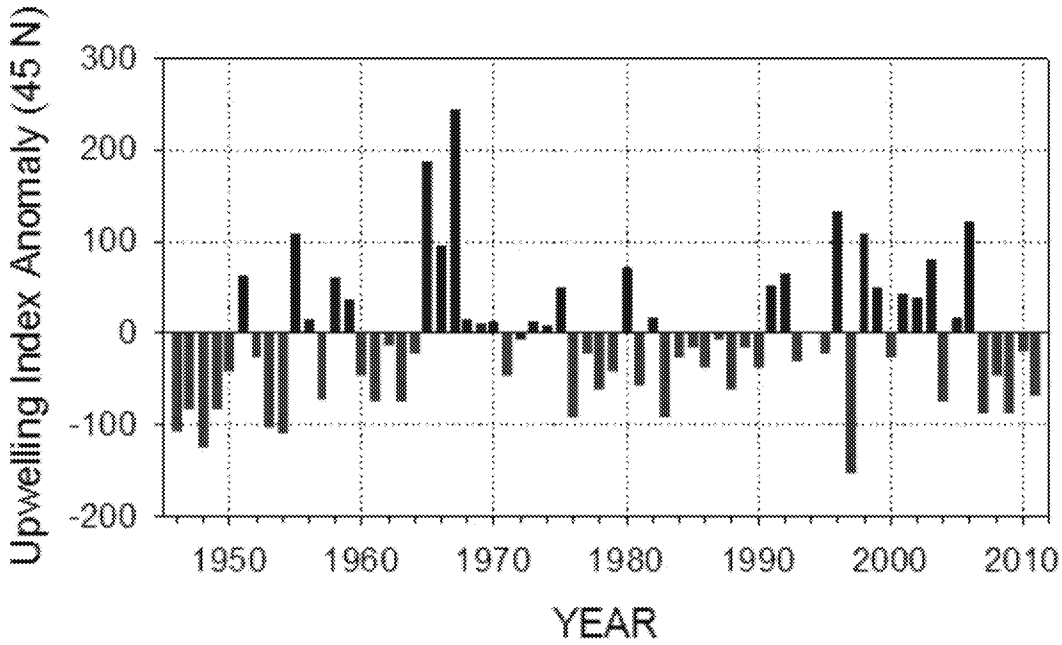

Figure 9. Anomalies of the coastal Upwelling Index during May to September each year, 1946 - present

Upwelling was anomalously weak in all but 8 of the 21 years from summer 1976 to summer 1997, and this is expected during warm PDO phases. When the PDO was in a cool phase (late 1998–2003), upwelling strengthened. With the change in PDO sign to positive in 2004–2005, upwelling again weakened.

Many studies have shown correlations between the amount of coastal upwelling and production of various fisheries. The first to show a predictable relationship between coho survival and upwelling were Gunsolus (1978) and Nickelson (1986).

Knowledge of upwelling alone does not always provide good predictions of salmon returns. For example, during the 1998 El Niño event, upwelling was relatively strong, as measured by the upwelling indices; however, plankton production was weak. This occurred because the deep source waters for upwelling were warm and nutrient–poor. Low levels of plankton production may have impacted all trophic levels up the food chain.

Upwelling was also strong during summer 2006, yet SST anomalies only averaged −0.3°C. On the other hand, upwelling was relatively weak during the summers of 2007 and 2008, yet these summers had some of the coldest temperatures in the time series, −1.0°C. These observations demonstrate that some care is required when interpreting a given upwelling index. We hypothesize that although upwelling is necessary to stimulate plankton production, its impact is greatest during negative phases of the PDO.

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Upwelling in 2011 — Figure 10 illustrates the pattern of upwelling through the use of a cumulative upwelling plot. This method simply adds the amount of upwelling on one day to that of the next day, and so on. The plot begins with day 1, on 1 January. Due to "downwelling" during winter months, upwelling values are increasingly negative for several weeks after day 1. But with the onset of the spring transition and upwelling, the downward trend reverses, and the cumulative line trends upwards.

One can see in Figure 10 that upwelling was initiated on day 105 (15 April) in 2011. The winds were relatively weak in the beginning of the season, so significant upwelling did not start until day 155 (June 4). There was a rather abrupt end to the 'season', with an ultimate reversal to primarily downwelling on day 259 (16 September). The cessation of upwelling in mid-September resulted in one of the shortest annual upwelling periods since the 1997 El Nino. The total amount of upwelling for 2011 was 4,555 m^3/s per 100 m of coastline, which is 26% lower than the 40-year average of 6,163 m^3/s per 100 m.

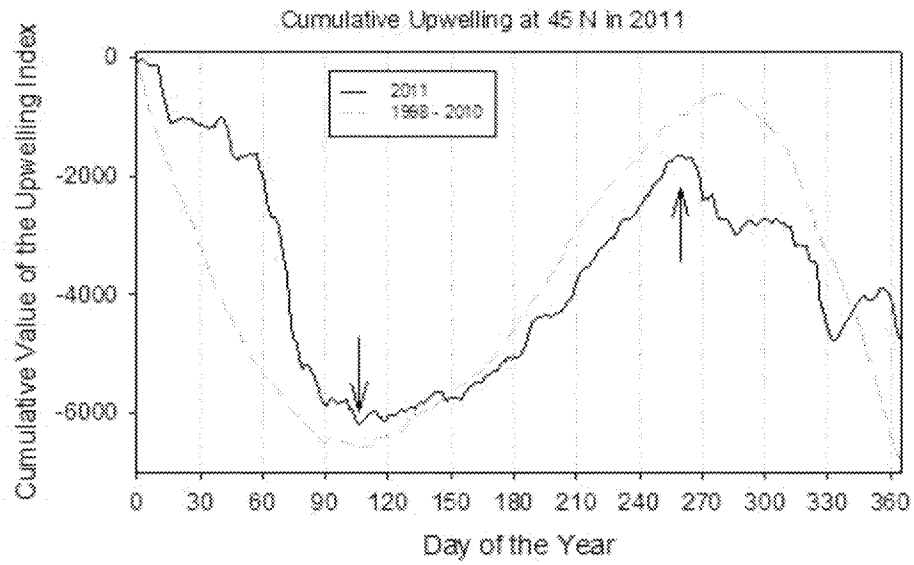

Figure 10. Cumulative upwelling index for 2011. Vertical arrows indicate the date of physical Spring transition (Day 105) and Fall transition (Day 246). 2011 had a shorter than average upwelling ◆season◆ and below average total upwelling.

When Figure 10 is compared to Figure 6 (which shows the SST time series), one can see the result of an early end to upwelling in the warm temperature anomalies persisting from mid-September to mid-November.

An additional focus of concern is the low levels of oxygen present in upwelled source water. Hypoxia continues to be a potential problem for benthic invertebrates living in continental shelf waters. Although we have no reason to believe that hypoxia is a problem for juvenile salmon, we include information on this phenomenon here due to a general interest in this topic (Figure 11).

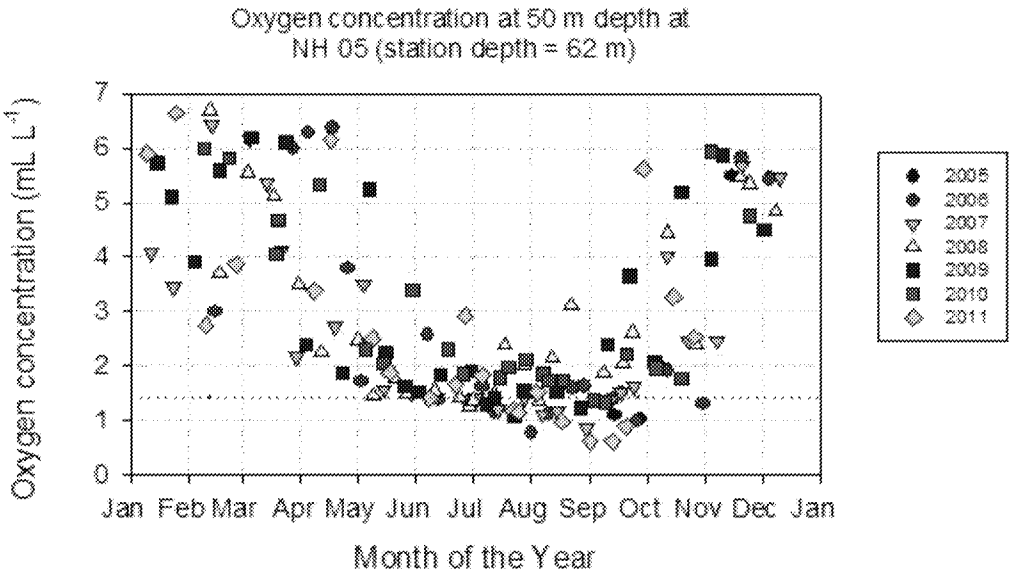

Figure 11. Oxygen concentration in bottom waters at a baseline station NH 05. Hypoxia is defined as waters with oxygen concentrations <1.4 mg/L, and is observed only during the coastal upwelling season, especially during Jun–Sep.

The relationship between coho salmon survival and upwelling is shown in Figure 12. The strongest correlations with survival were found with upwelling in April and upwelling in April and May combined. A significant, but weaker correlation was also found between upwelling and survival during the months of April, May, and June combined.

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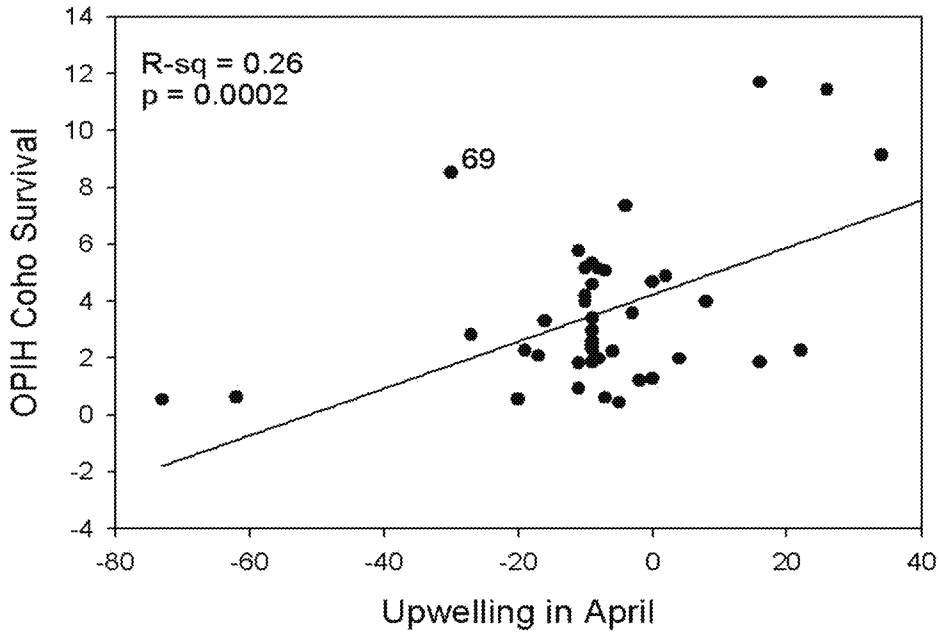

Figure 12. Scattergram of coho survival (%) vs. upwelling anomalies at 45°N during April 1969–present. No other month produced a significant correlation. When the year 1969 was excluded from the regression, R^2 improved from 0.20 to 0.26.

Scheuerell and Williams (2005) showed that the upwelling index in April, September, and October is also related to returns of Snake River spring Chinook salmon. Moreover, they developed a 1–year forecast of spring Chinook returns based on this composite upwelling index.

Physical Spring Transition

Winter in the Pacific Northwest is characterized by frequent rainfall and southwesterly winds. Southwest winds push water onshore and cause downwelling (the opposite of upwelling). Downwelling in turn brings warm, nutrient–depleted, surface water onshore from offshore sources and results in very low levels of primary production. The most critical time of the seasonal plankton–production cycle is when the ocean transitions from a winter downwelling state to a summer upwelling state. This time is known as the spring transition.

The spring transition marks the beginning of the upwelling season and can occur at any time between March and June. Generally, the earlier in the year that upwelling is initiated, the greater ecosystem productivity will be in that year. In some years the transition is sharp, and the actual day of transition can be identified easily, but in many years transition timing is more obscure. It is not uncommon for northerly winds (favorable to upwelling) to blow for a few days, only to be

followed by southwesterly winds and storms. Intense, late–season storms can erase any upwelling signature that may have been initiated, thus re–setting the "seasonal clock" to a winter state. This is what occurred during summer 2005.

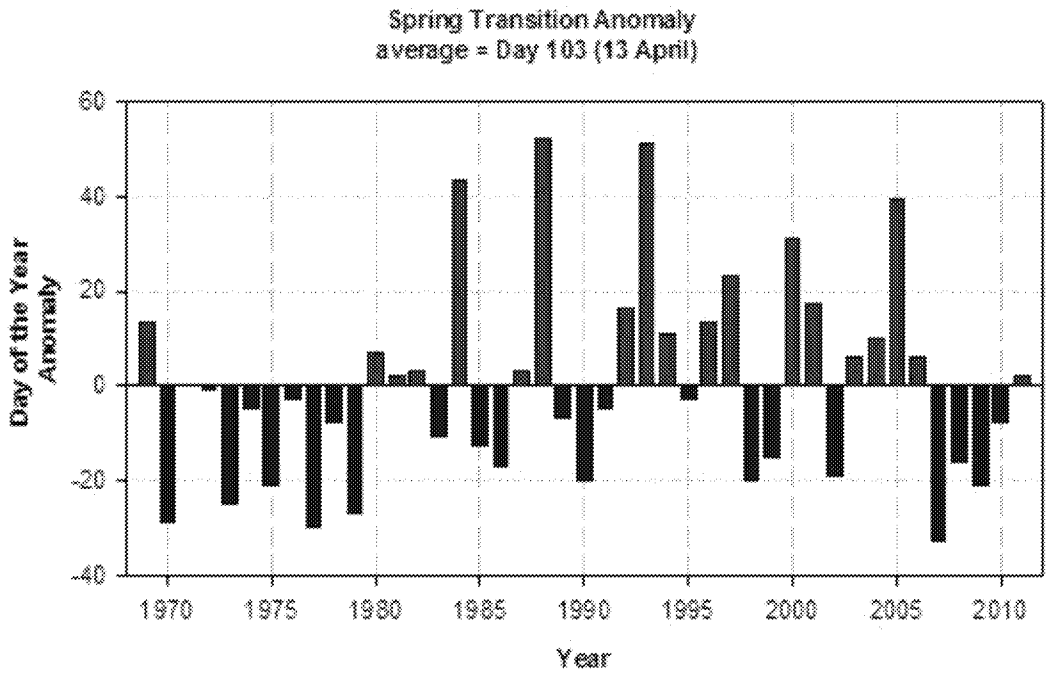

Figure 13. Anomalies in the date of the physical spring transition from 1969 to 2011. Anomaly is based on an average date of 13 April using the minimum cumulative upwelling index (CUI) value.

The date of spring transition can be indexed in several ways. Here, we use the date of the minimum value of the Cumulative Upwelling Index (CUI). Further details can be found in Bakun (1973) and Bograd et al. (2009). The average date of upwelling is 13 April (Day 103), but can range from early March to early June. Note from Figure 13 the following points:

- Most spring transition dates during the pre–1977 cool–phase PDO were earlier than average.
- Spring transition dates from the 1980s and 1990s did not reflect changes in either the PDO (Figure 2) or the Multivariate ENSO index (Figure 4).
- Transition dates have been early for the past 4 years.
- The period of early transition dates from 1985 to 1990 correlates well with the high salmon survival in the late 1980s (see Figure 3).

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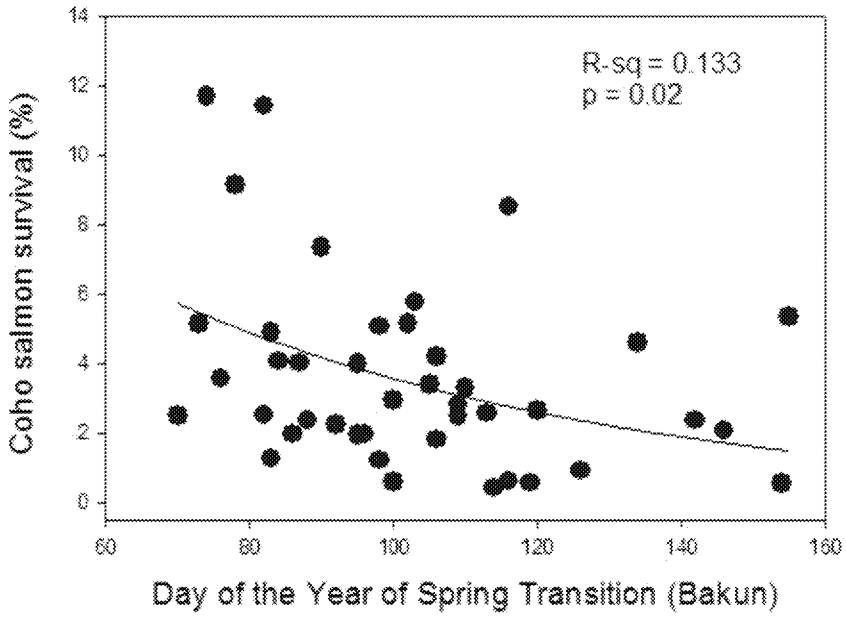

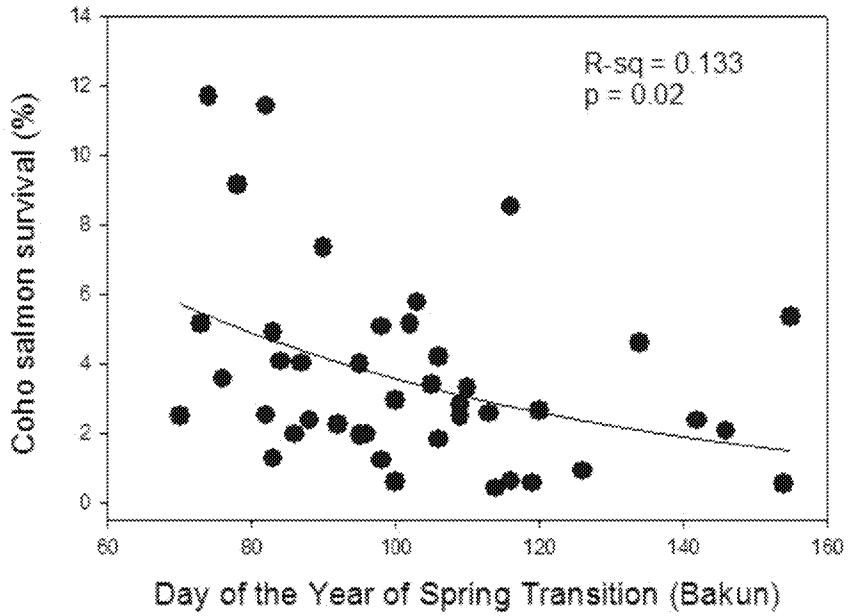

Figure 14. Coho survival vs. day of spring transition. Date of spring transition is based on the lowest cumulative Upwelling Index value. Data are from 1969 to present.

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Figure 14 shows that hatchery adult coho salmon returns are correlated with the spring transition, similar to results found by Logerwell (Logerwell et al. 2003). An analysis using smolt–to–adult return rates of Snake River spring/summer Chinook (from Scheuerell and Williams 2005), or using counts of either spring or fall Chinook at Bonneville Dam (from the DART website), did not reveal any significant correlations.

Other measures of the spring transition include ones from:

- Dr. Mike Kosro, College of Earth, Ocean and Atmospheric Sciences (CEOAS), Oregon State University, who operates an array of coastal radars that are designed to track the speed and direction of currents at the sea surface. He produces daily charts showing ocean surface current vectors, and from those one can clearly see when surface waters are moving south (due to upwelling) or north (due to downwelling). By scanning progressive images, the date of transition can be visualized.
- Dr. Steve Pierce and Dr. Jack Barth, CEOAS, Oregon State University, use local wind data from Newport, Oregon and produce annual plots of the start and end to the upwelling season based on the change in alongshore windstress.
- Logerwell et al. (2003) indexed the spring transition date based on the first day when the value of the 10-day running average for upwelling was positive and the value of the 10-day running average for sea level was negative. This index is no longer regularly updated and made available on-line.

We have developed a new measure of the spring transition based on measurements of temperature taken during our biweekly sampling cruises off Newport, Oregon. We define the spring transition as the date on which deep water colder than 8°C was observed at the mid shelf (station NH 05). This indicates the presence of cold, nutrient–rich water that will upwell at the coast with the onset of strong northerly winds, signaling the potential for high plankton production rates.

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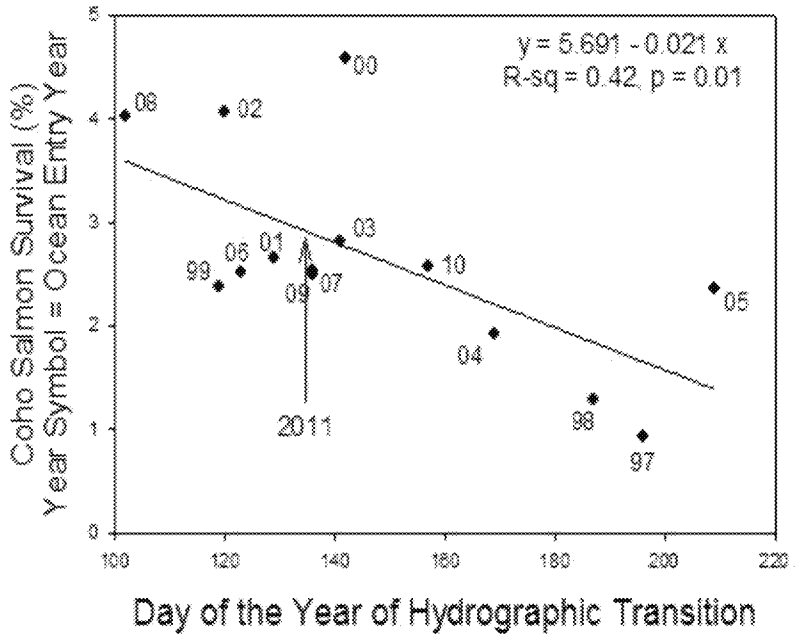

Figure 15. Coho survival vs. spring transition as indicated by the day of the year when bottom water temperature dropped below 8.0°C. Arrows indicate day of transition in years for which coho survival data are not yet available.

Figure 15 shows relationships between this index and coho salmon. Survival is higher in years with an early transition date and vice versa.

Deep–Water Temperature and Salinity

Phase changes of the Pacific Decadal Oscillation are associated with alternating changes in wind speed and direction over the North Pacific. Northerly winds result in upwelling (and a negative PDO) and southerly winds, downwelling (and a positive PDO) throughout the Gulf of Alaska and California Current. These winds in turn affect transport of water into the Northern California Current (NCC). Northerly winds transport water from the north whereas southwesterly winds transport water from the west (offshore) and south.

Thus, the phase of the PDO can both express itself and be identified by the presence of different water types in the northern CC. This led us to develop a "water type indicator," the value of which points to the type of water that will upwell at the coast. Again, cold, salty water of subarctic origin is nutrient–rich, whereas the relatively warm and fresh water of the offshore North Pacific Current is nutrient depleted.

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Figure 16 shows average salinity and temperature measured at the 50–m depth from station NH 05 (shown in Figure 1). These measurements were taken during biweekly sampling cruises that began in 1997 and continue to the present.

From these data, two patterns have become clear: first, the years 1997-1998 (and to a lesser extent 2003 and 2006) were warmer than average, and corresponded to a warm-phase PDO. Second, the years 1999-2002 and 2007-2011 were colder than average and corresponded to a cool-phase PDO (and to negative SST anomalies at Buoy 46050).

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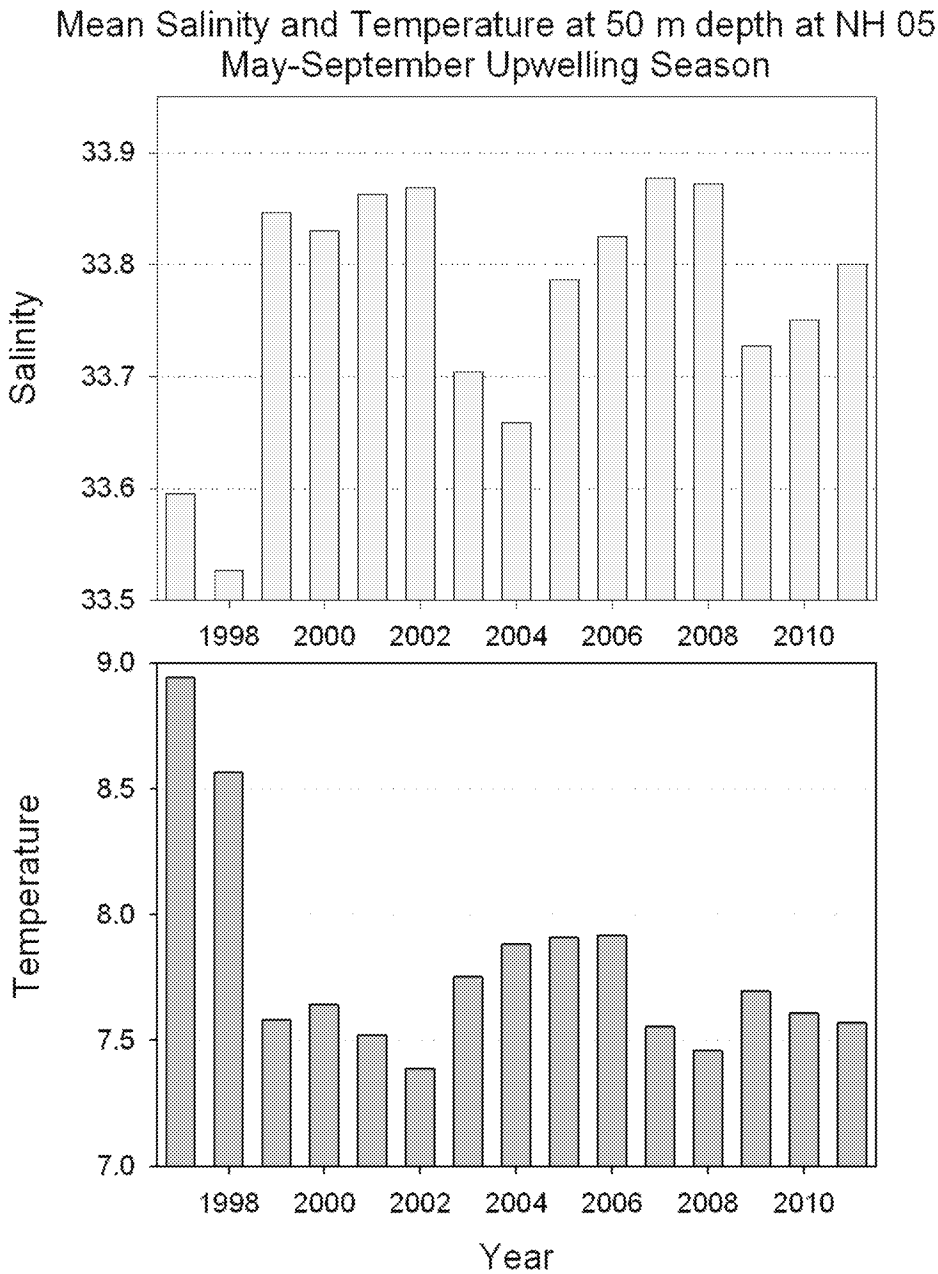

Figure 16. Mean salinity (upper panel) and temperature (lower panel) at the 50–m depth at station NH 05 (average water depth 60 m) averaged over all cruises from May to September each year.

Figure 17 shows the same data, but as a scatter diagram, illustrating several noteworthy points. First, during the El Niño event of 1997-1998, deep waters on the continental shelf off Newport were warm and relatively fresh. Second, during the contrasting negative-phase PDO years of 1999-2002 and 2007-2008, these waters were cold and relatively salty or intermediate, as in 2009-2011.

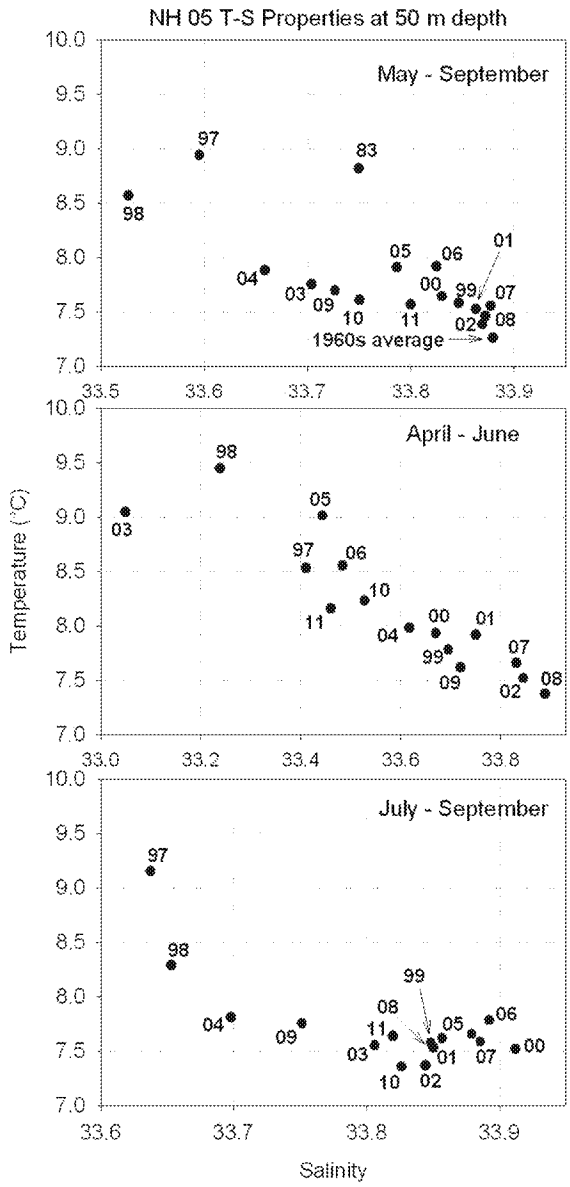

Figure 17. Upper panel Scattergram shows average temperature and salinity values during the April–June upwelling season from 1997–present.
Middle panel Scattergram of the same average values during May–September 1997–present.
Lower panel Average temperature and salinity values during July–September 1997–present.

Coho salmon survival is high when cold, salty water is present in continental shelf waters, and vice versa (Figure 18). That is, during the summer when coho first enter the ocean, if deep waters are relatively cold and salty, we can expect good coho salmon survival. Conversely, if deep water is relatively warm and fresh, coho salmon survival is poor, as in 1997 and 1998. Thus, we can use presence of different water types as a leading indicator of coho survival.

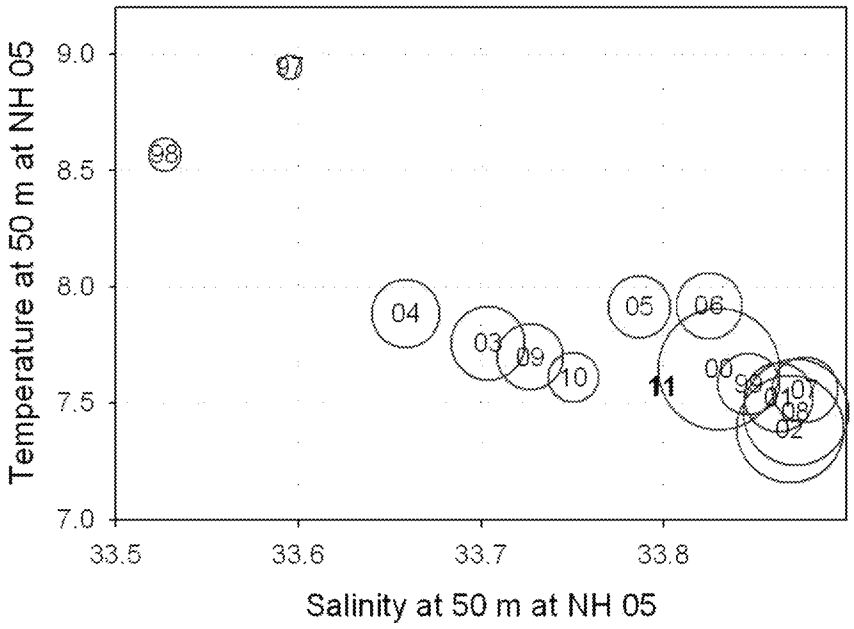

Figure 18. Coho survival (circles) in relation to summer averaged temperature and salinity measured 1 year earlier (numbers) at the 50-m depth of hydrographic station NH 05. Circle size is proportional to OPIH estimates of total freshwater escapement (proportion of the juvenile population returning to spawn) since 1997. Coho survival is generally higher when upwelling is strong, as indicated by the presence of "cold salty" water on the continental shelf.

A similar, if less pronounced relationship can be seen based on adult counts of spring and fall Chinook salmon at Bonneville Dam 2 years after ocean entry (Figure 19). This relationship is less distinct in Chinook salmon, largely because its period of ocean residency varies 1–5 years, with 2–year and 3–year ocean adults often returning from the same year class.

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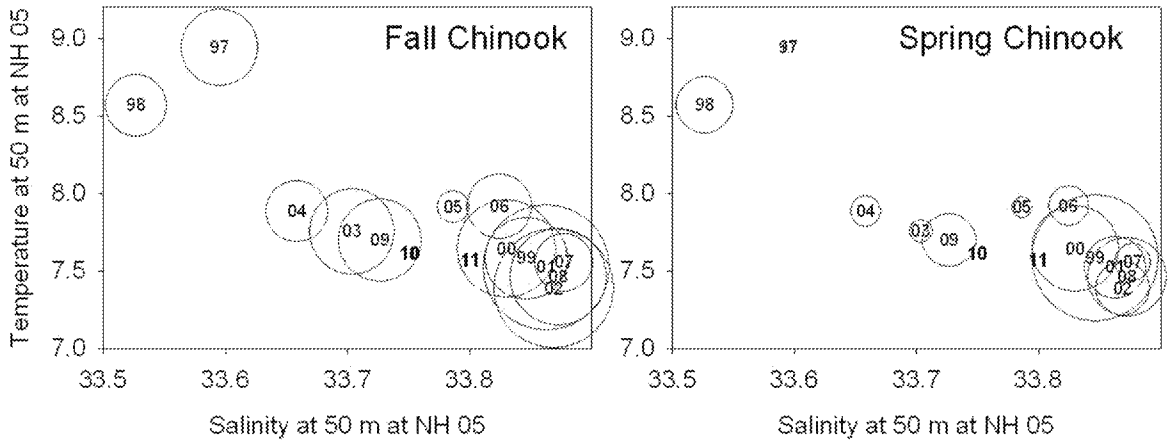

Figure 19. Percent returns of Chinook salmon to the Bonneville Dam (circles) in relation to summer averaged temperature and salinity measured 2 years earlier (numbers) at the 50-m depth of hydrographic station NH 05. The size of each bubble is proportional to the highest returns since 1997.

Moreover, the Columbia River fall Chinook salmon exhibits two distinct life–history types: the lower–river tule, which returns most frequently as a 2–ocean adult; and the upriver bright, which more often returns as a 3–ocean adult. Coho on the other hand, spends 18 months in the ocean, entering in the spring of one year and returning in the fall of the next.

Despite the variability in age class among Chinook stocks, it is clear that the 1997 El Niño can probably be blamed for low counts of adult Chinook at Bonneville in 1999. High counts of adult Chinook at Bonneville from 2001 to 2003 were accompanied by a 4–year period of very cold and salty ocean conditions. Likewise, the declining returns of 2005–2007 were from fish that entered the ocean in 2003–2005, a period when the PDO was positive, and deep waters were relatively warm and fresh. Finally, the high adult returns in 2010 reflect the highly favorable ocean conditions encountered by juvenile Chinook migrants in 2008.

Local Biological Indicators

Copepod Biodiversity

Being planktonic, copepods drift with the ocean currents; therefore, they are good indicators of the type of water being transported into the Northern California Current. Copepod biodiversity (or species richness) is a simple measure of the number of copepod species in a plankton sample

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and can be used to index the types of water masses present in the coastal zone off Oregon and Washington.

For example, the presence of subtropical species off Oregon indicates transport of subtropical water into the northern California Current from the south. Likewise, the presence of coastal, subarctic species indicates transport of coastal, subarctic waters from the north.

Thus the presence of certain copepod species offers corroborative evidence that the changes in water temperature and salinity observed during our monitoring cruises were in fact measuring different water types. Figure 20 shows average copepod species richness (i.e., the average number of species from all plankton samples) for each month from 1996 to 2004 at station NH 05.

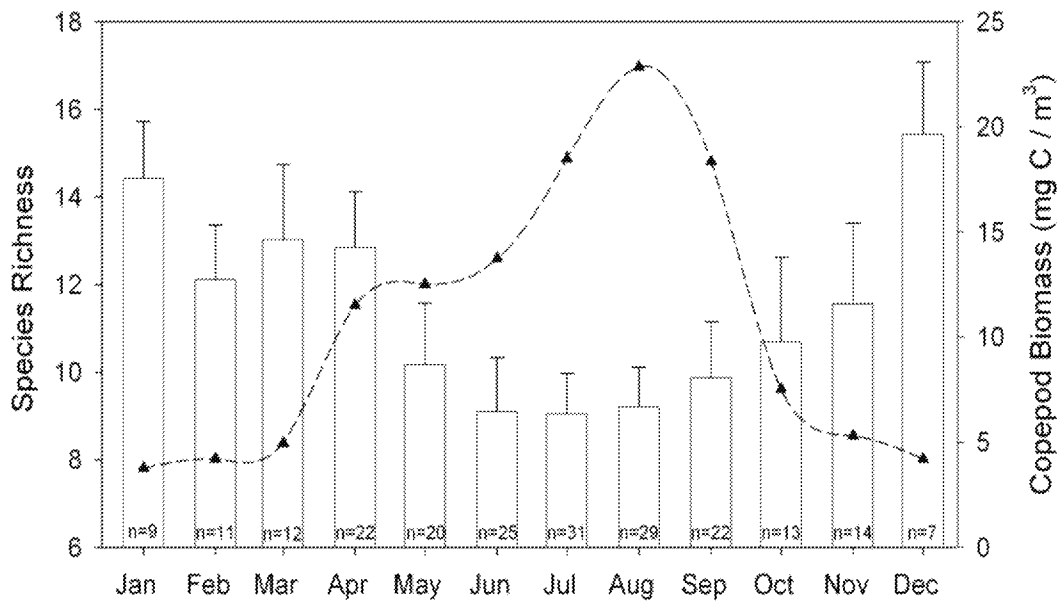

Figure 20. Vertical bars are the climatology of monthly averaged copepod species richness, a measure of biodiversity, at station NH 05 off Newport OR. Dashed line with filled triangles is the climatology of monthly averaged copepod biomass (Y–axis on right side of graph). Note the inverse relationship between copepod biodiversity and copepod biomass.

Generally, species diversity is lower during the summer months and higher during winter months. This pattern is the result of seasonally varying circulation patterns of coastal currents. During summer, source waters to the Oregon coast flow from the north, out of the coastal subarctic Pacific. This is a region of low species diversity.

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Conversely, during winter, the source waters originate offshore and from the south, bringing warm, low–salinity water into the coastal waters of the northern California Current. With it comes a more species–rich planktonic fauna with subtropical neritic and warm–water offshore affinities. Variations in species richness from the average values shown in Figure 20 index the relative contribution of subarctic vs. subtropical water to the northern California Current.

The annual cycle of copepod biodiversity and copepod biomass are related in an inverse manner (Figure 20). During the winter months, when biodiversity is high, the biomass of copepods is low; during summer, when biodiversity is low, biomass of copepods is high. We also find that during summers when biodiversity is high that copepod biomass is low (not shown).

Figure 21 shows monthly anomalies of copepod species richness during 1996-present. This time series is derived by taking the average number of species for each month, then subtracting the observed monthly average for that month.

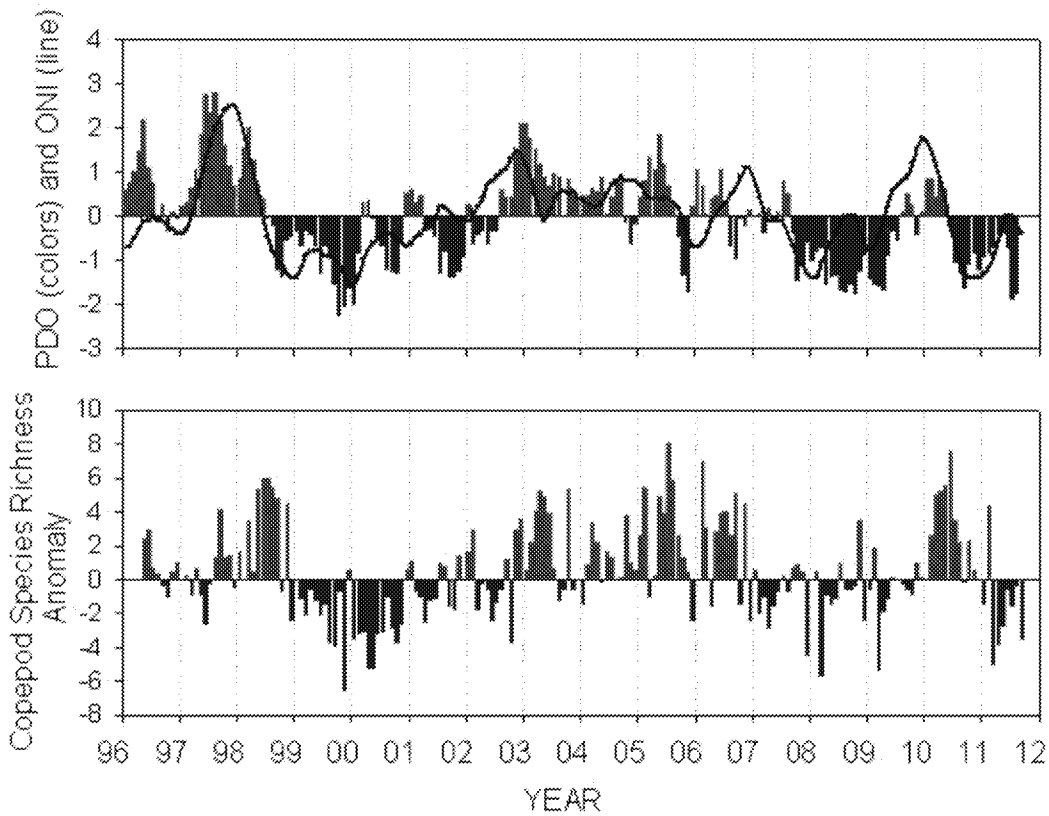

Figure 21. Upper panel shows time series of the PDO (bars) and ONI (line) during 1996-present. Lower panel shows anomalies in copepod species richness during the same period. Note the brief lag between long-term persistent shifts in the PDO and ONI and anomalies in copepod species richness, as seen in 1998, 2002, 2007, and 2010.

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Also shown in Figure 21 are time series of the Pacific Decadal Oscillation and Oceanic Niño Index (ONI). Comparisons among these time series show clear relationships between interannual variability in basin-scale physical climate indicators (PDO and ONI) and copepod species richness anomalies at Newport Oregon.

Note that three pronounced changes in copepod species richness lagged the PDO and ONI by about 6 months. The first of these was in 1998, when a change to a negative anomaly of species richness in December was preceded by sign changes of the PDO and ONI in July. The second pronounced change was seen in 2002, with the shift to a positive anomaly of copepod species richness in November, which followed changes in the PDO and ONI in August and April, respectively.

Additional persistent signal changes occurred in summer 2007 and 2010, although species richness showed only a moderate response to the former. Note that the El Niño event of 2009-2010 (shown by moderately positive PDO and ONI values) resulted in high species richness during February-August 2010 and a switch back to low species richness in early 2011.

We saw earlier that local sea surface temperatures off Newport showed strong correspondence with the PDO (Figure 5). The interpretation of simultaneous change in sea surface temperature and copepod species richness is that when the PDO is in a cool phase, cold water from the subarctic Pacific dominates the northern California Current. Moreover, there can be a time lag of about 6 months between a changes in the PDO sign and changes in water temperature and copepod species composition. For further detail on the relationships between copepod species richness and oceanographic conditions, see Hooff and Peterson (2006).

We have found that this simple measure of species richness is correlated with salmon survival (Figure 22). This suggests that the copepod community, when these salmon first enter the ocean two and one years prior for Chinook and Coho respectively, is a reasonably good indicator of adult salmon survival.

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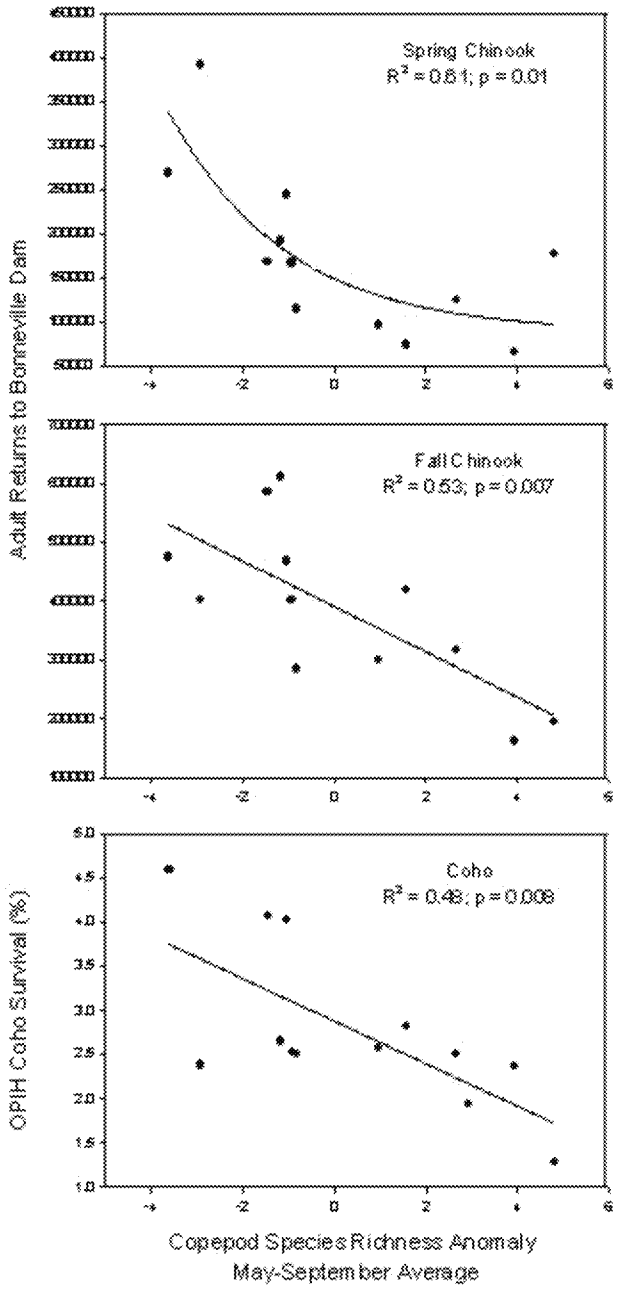

Figure 22. Relationship of Spring and Fall Chinook adult returns to the Bonneville Dam, and Coho salmon survival (OPIH) to the copepod species richness anomaly when these fish first enter the ocean 2 and 1 years prior (Chinook and Coho respectively) from 1996 - present.

The relationship with salmon survival and copepod species richness is somewhat biased and complicated by the trend towards increasing species richness with time. Figure 23 shows that species richness has increased at a rate of 4.4 species over the past 40 years. Although this increase in biodiversity may be due to climate change, it is probably too soon to draw this conclusion (see Peterson 2009).

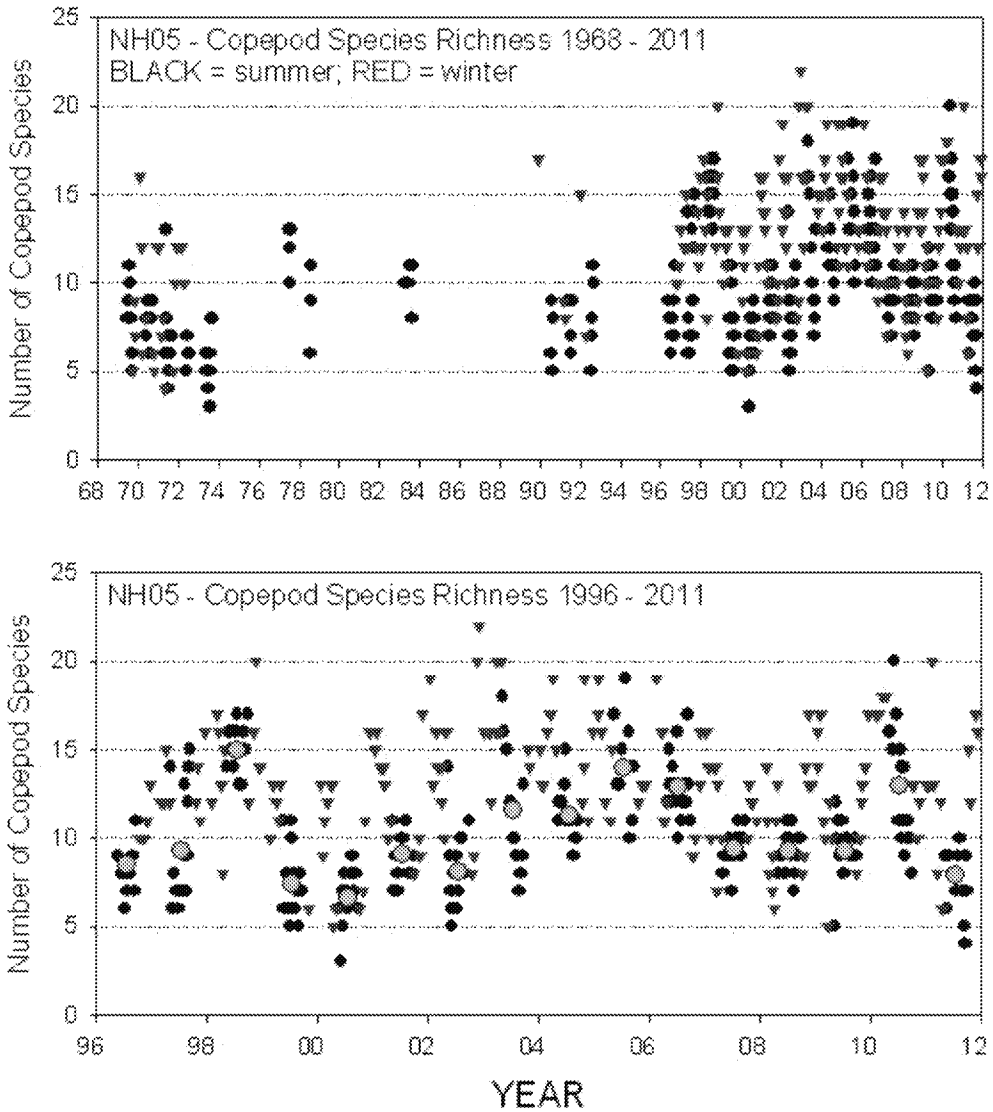

Figure 23. Upper panel shows time series of copepod species richness from 1969 to present. Note that the number of copepod species has been increasing over the past decade compared to the 1970s. Red triangles represent winter (Oct - April) and black circles represent summer (May - Sept).
Lower panelshows the same time series from 1996 to present to highlight the among-year differences. Red triangles represent winter, black circles summer, and green circles indicate summer-averaged values. This figure illustrates the trend towards increasing copepod biodiversity, especially apparent when comparing the cool years of 1999-2002 to the recent cool years of 2007-2009.

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Northern and Southern Copepod Anomalies

To explore the relationship between water type, copepod species richness, and the PDO, we developed two indices based on the affinities of copepods for different water types. The dominant copepod species occurring off Oregon at NH 05 were classed into two groups: those with cold–water and those with warm–water affinities. The cold–water (boreal or northern) group included the copepods Pseudocalanus mimus, Acartia longiremis, and Calanus marshallae. The warm–water group included the subtropical or southern species Mesocalanus tenuicornis, Paracalanus parvus, Ctenocalanus vanus, Clausocalanus pergens, Clausocalanus arcuicornis and Clausocalanus parapergens, Calocalanus styliremis, and Corycaeus anglicus.

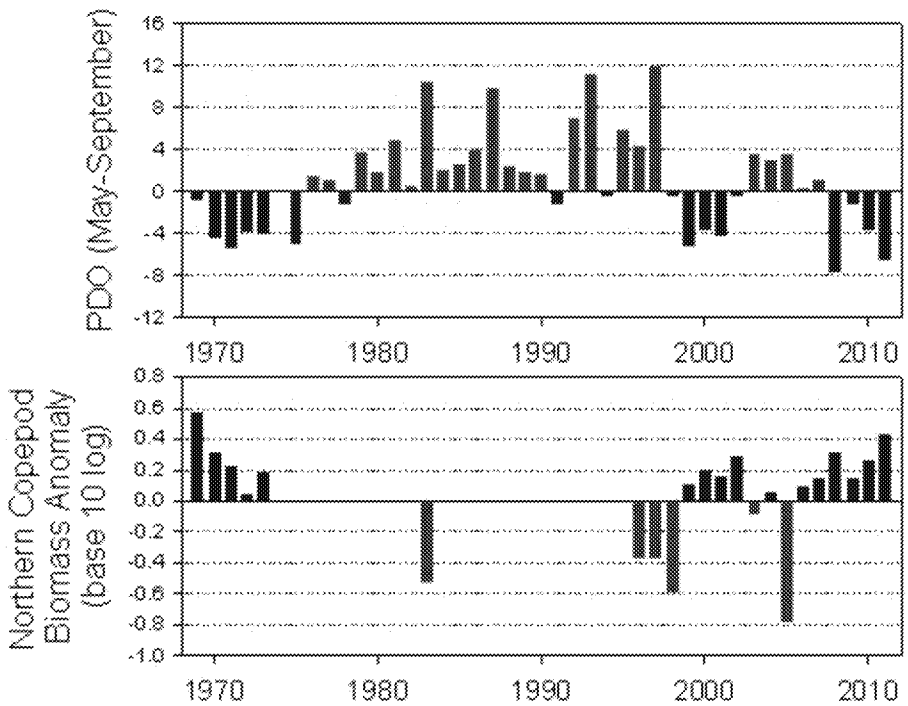

Figure 24. The Pacific Decadal Oscillation (upper), and northern copepod biomass anomalies (lower), from 1969 to present. Biomass values are log base-10 in units of mg carbon m^{-3}.

The cold–water group usually dominates the Washington/Oregon coastal zooplankton community in summer, whereas the warm–water group usually dominates during winter (Peterson and Miller 1977; Peterson and Keister 2003). This pattern is altered during summers with El Niño events and/or when the PDO is in a positive (warm) phase. At such times the cold–water group has negative biomass anomalies and the warm group positive anomalies. Figure 24 shows a time series of the PDO, along with biomass anomalies of northern and southern copepod

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species averaged over the months of May–September. Changes in biomass among years can range over more than one order of magnitude. When the PDO is negative, the biomass of northern copepods is high (positive) and biomass of southern copepods is low (negative), and vice versa.

Figure 25 shows the same data, but as a scatter plot, with copepod anomalies plotted against the PDO. We hypothesize that the correspondence between the PDO and northern copepod anomalies is due to physical coupling between the sign of the PDO, coastal wind, water temperature, and the type of source water (and zooplankton it contains) that enters the northern California Current and coastal waters off Oregon.

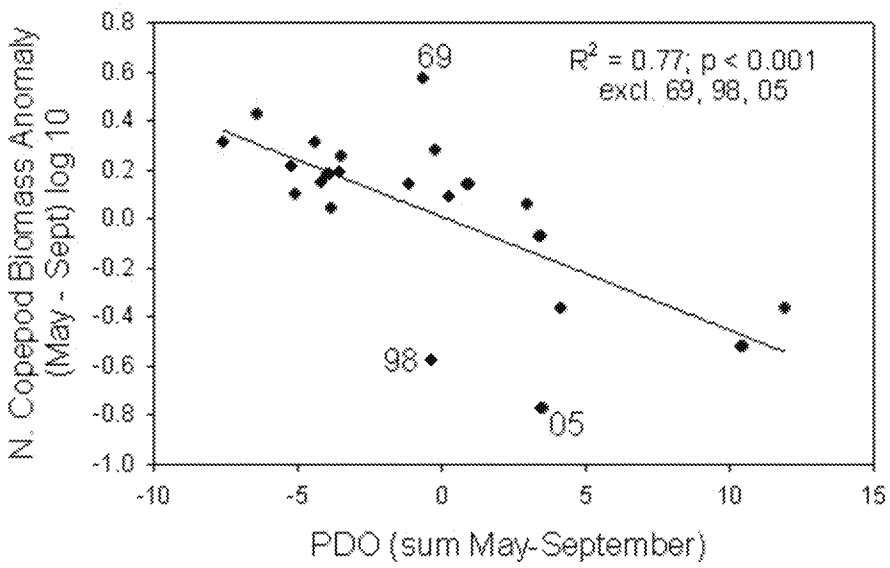

Figure 25. Regression of northern copepod anomalies vs. the PDO. Units of biomass are mg carbon m^3. Strongly negative PDO values lead to high biomass of cold–water copepods and vice versa. The regression line shown was calculated after excluding the outlying data points from 1998 (an El Niño year) and 2005 (an anomalously warm ocean year).

When winds are strong from the north (leading to cool water conditions and a PDO with a negative sign), cold–water copepod species dominate the ecosystem. During summers characterized by weak northerly or easterly winds, (e.g., 1997–1998 and 2004–2005), the PDO is positive, warm–water conditions dominate, and offshore animals move onshore into the coastal zone.

Perhaps the most significant aspect of the northern copepod index is that two of the cold–water species, Calanus marshallae and Pseudocalanus mimus, are lipid–rich. Therefore, an index of northern copepod biomass may also index the amount of lipid (wax–esters and fatty acids) transferred up the food chain. These fatty compounds appear to be essential for many pelagic

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fishes if they are to grow and survive through the winter successfully. Beamish and Mahnken (2001) provide an example of this for coho salmon.

Conversely, the years dominated by warm water, or southern copepod species, can be significant because these species are smaller and have low lipid reserves. This could result in lower fat content in the bodies of small pelagic fish that feed on "fat–free" warm–water copepod species as opposed to cold–water species. Therefore, salmon feeding on pelagic fish, which in turn have fed on warm–water copepod species, may experience a relatively lower probability of surviving the winter.

The "northern copepod index" appears to be a good predictor of the survival of hatchery coho salmon. Figure 26 shows the correlation between adult returns of coho salmon and northern copepod biomass anomalies during the year when these coho entered the ocean (i.e., OPIH coho values in year y + 1 × copepod biomass in year y).

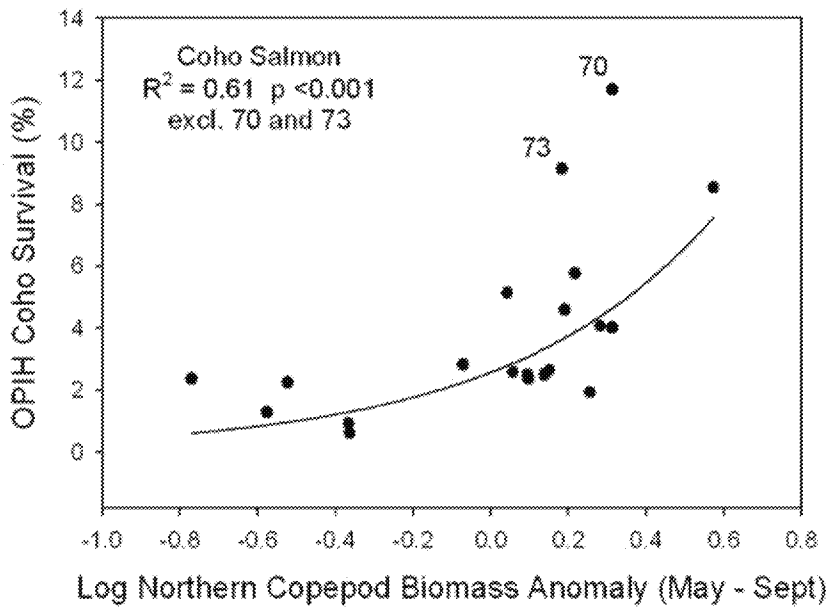

Figure 26. Regression of OPIH coho survival on the northern copepod biomass anomalies.

Figure 27 shows similar relationships for Columbia River spring and fall Chinook salmon counts at Bonneville Dam. Only more recent data (1996-present) are shown for spring Chinook. For both data sets, we assumed the fish spent 2 years at sea before returning to spawn, and that fall Chinook counts included both lower-river tules (believed to be mostly 2–ocean fish) and upriver brights (believed to be mostly 3–ocean fish).

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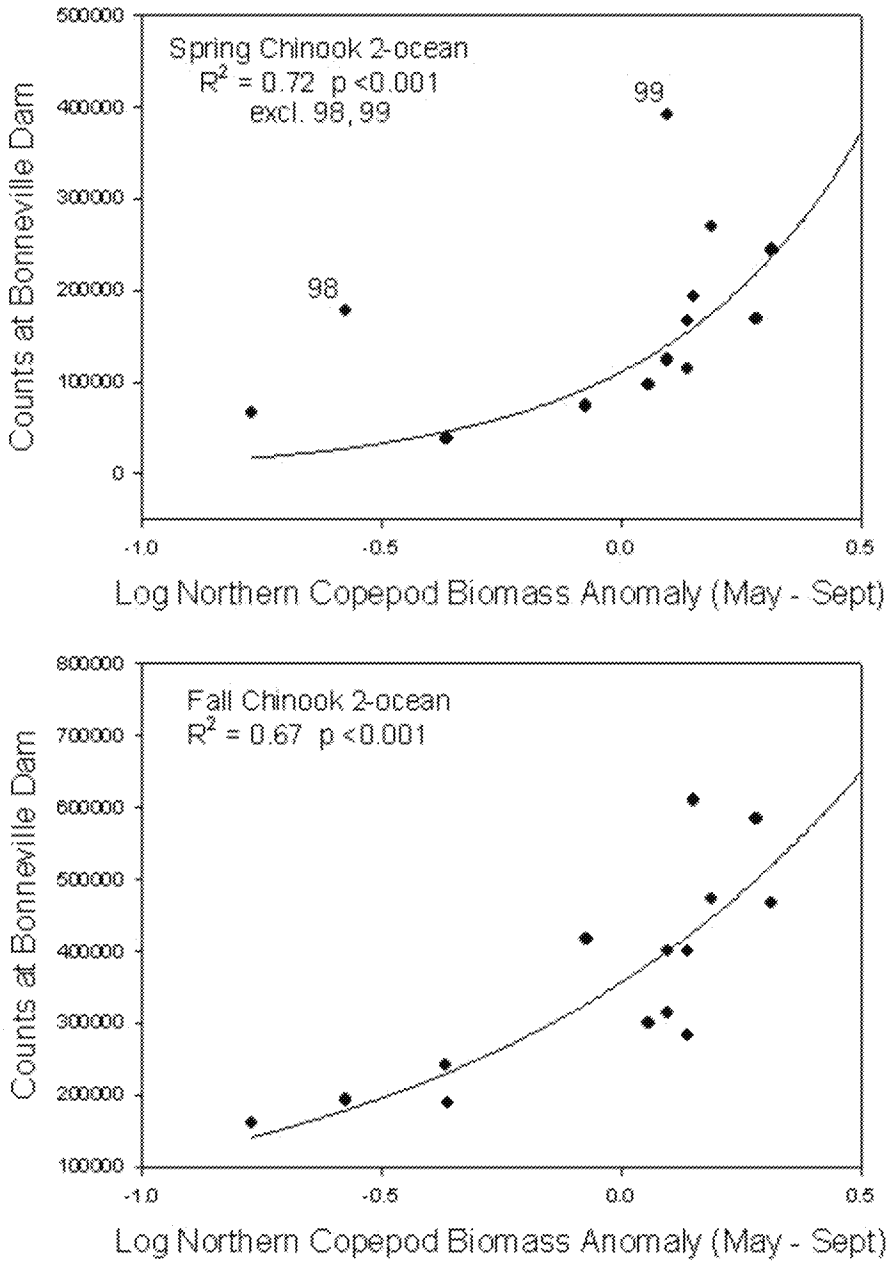

Figure 27. Relationship between counts of adult spring Chinook (upper panel) and fall Chinook (lower panel) at Bonneville Dam vs. log of the northern copepod biomass anomaly during the year of ocean entry. Counts at Bonneville are lagged by 2 years.

Copepod Community Structure

A more recently developed index of our forecasting suite is based on the presence/absence of two alternate copepod community types. Data sets upon which this index is based are from our zooplankton samples off Newport, OR, taken biweekly since 1996, and from zooplankton samples taken since 1998 during June and September surveys of juvenile salmonid.

As an ocean ecosystem indicator, copepod community structure is based on multidimensional scaling (MDS), an ordination technique that helps visually represent non-numerical data (Figure 28). The full ordination is not shown, but rather the averaged X- and Y-axis scores: these two alone accounted for about 82% of the variability between copepod communities, with the X-axis accounting for 69% and the Y-axis for 13%. Figure 28 compares these summer-average scores.

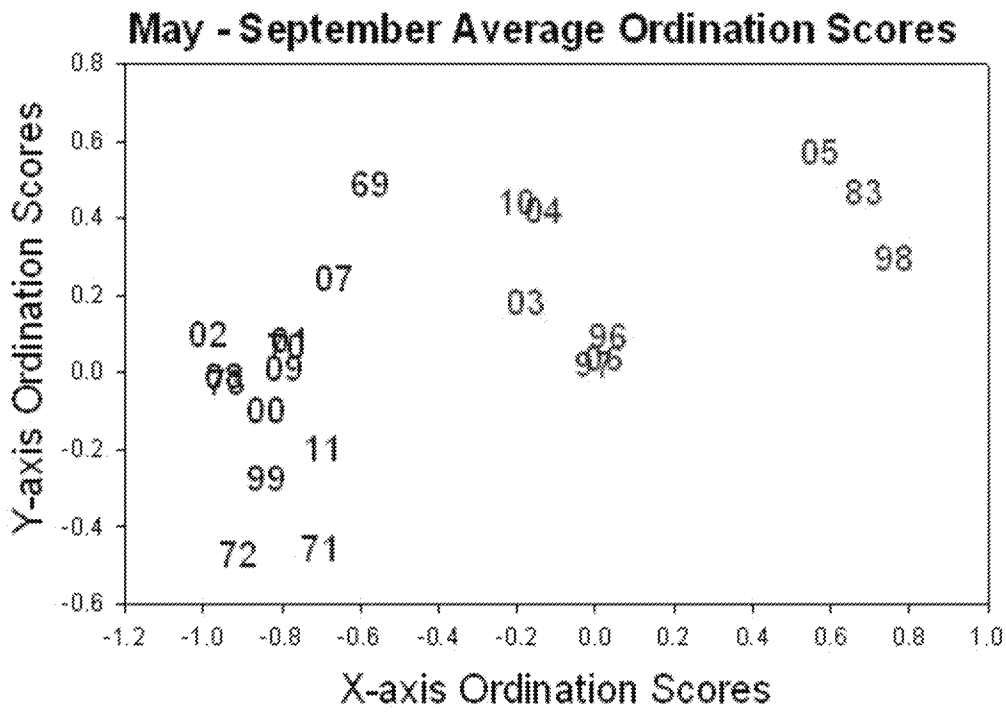

Figure 28. Ordination of copepod community structure averaged over May-September, by year. Years when summer community structure was dominated by cold, boreal species fall to the left (1970-1973, 1999-2002, 2007-2009, 2011); years with warm subtropical species fall in to the center of the graph (1996, 1997,2003, 2004, 2006, 2010); years characterized by El Niño conditions (1983, 1998) or El Niño-like conditions (2005) fall to the right. Numbers indicate the warm (red) and cold (blue) years.

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The different community types are clearly a function of the state and phase of the Pacific Decadal Oscillation (Figure 29). Negative X–axis scores are associated with negative PDO and vice versa. This relationship seems to be related to advection. That is, a negative–phase PDO results in more boreal water coming into the northern California Current from the north; whereas a positive–phase PDO results in more subtropical water coming in either from the south (as during the large El Niño events of 1983 and 1998) or from offshore (as during the El Niño–like event of 2005).

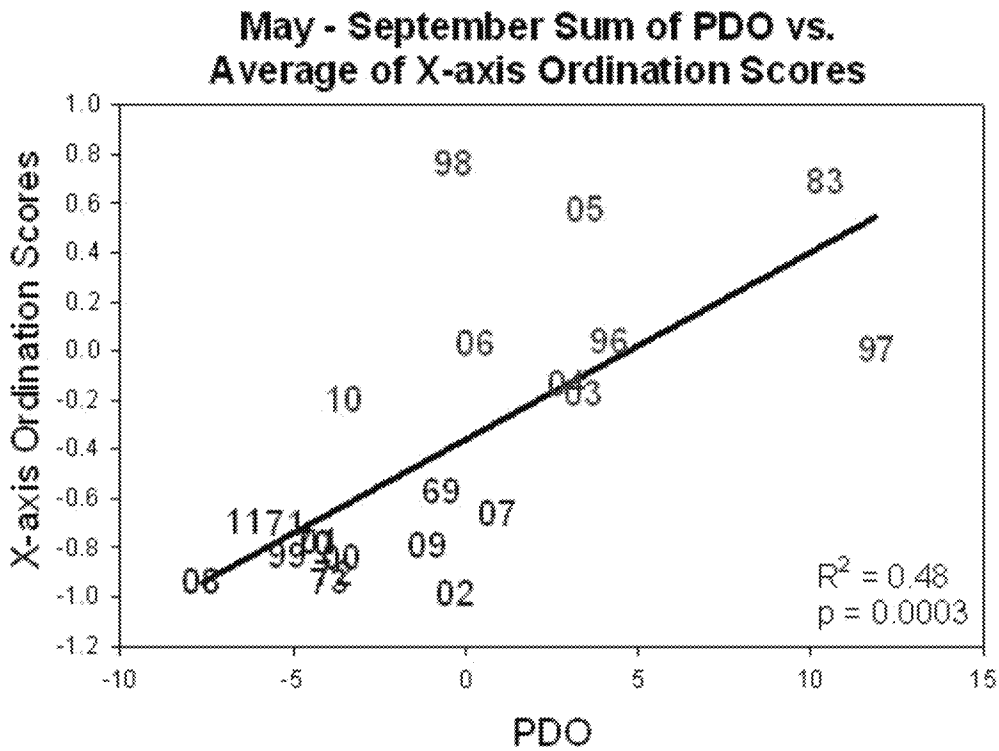

Figure 29. Relationship between the PDO and X-axis ordination scores. A "cold-water zooplankton community" is associated with the negative (cold) phase of the PDO and vice versa. Numbers indicate the warm (red) and cold (blue) years.

Coho survival is related to the copepod community structure in that when a cold–water community dominates, coho survival is often high, and vice versa (Figure 30). The link between copepods and salmon is almost certainly through the food web, since when a cold–water copepod community prevails, a cold–water fish community probably prevails. Since juvenile coho and Chinook salmon feed primarily on fishes, we hypothesize that copepods index the abundance of cold–water coastal fishes such as herring, smelt, and sand lance.

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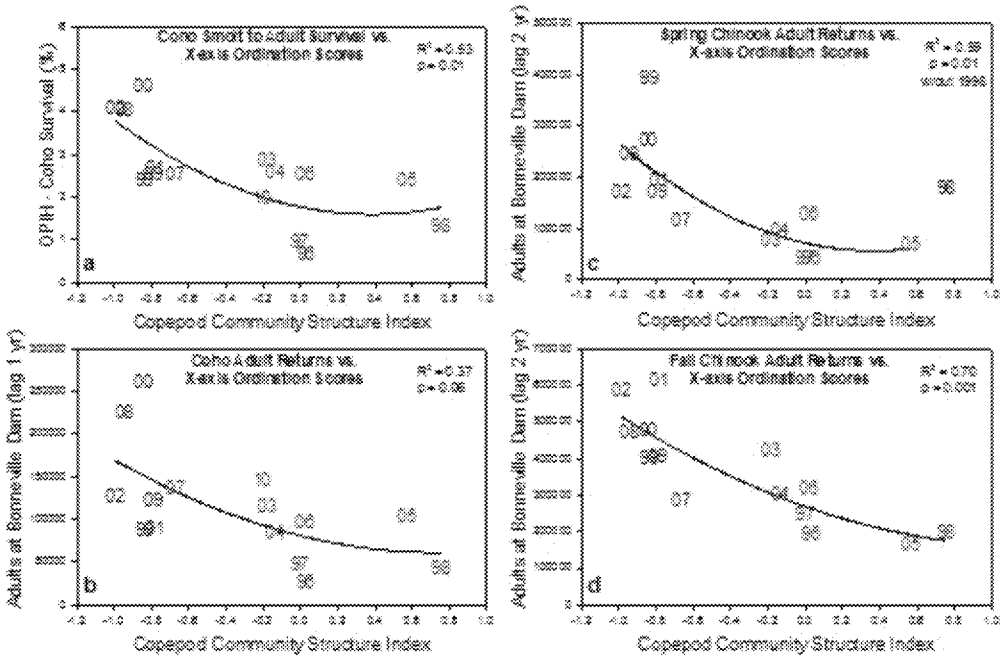

Figure 30. Plot showing the relationship between a) coho smolt-to-adult survival (SAR) (lag 1 year), b) coho adult returns at Bonneville dam (lag 1 year), c) spring Chinook adult returns at Bonneville dam (lag 2 years), and fall Chinook adult returns at Bonneville dam (lag 2 years) versus the copepod community structure index (X-axis ordination score). The stronger the boreal copepod community (negative side of plot), the greater the returns. The X-axis ordination score for May-September 2011 was -0.70, indicating good subsequent salmon survival. Numbers indicate the warm (red) and cold (blue) years.

Biological Spring Transition

We suggested earlier that the spring transition could be defined in several ways, one of which was the date that cold water first appeared in mid–shelf waters. In Figure 15, we saw coho survival correlated with the date when cold water first appeared at our baseline station, NH 05. Figure 31 shows a similar relationship, but using the date when a northern (cold–water) copepod community first appeared at station NH 05. We define this as the date of the biological spring transition.

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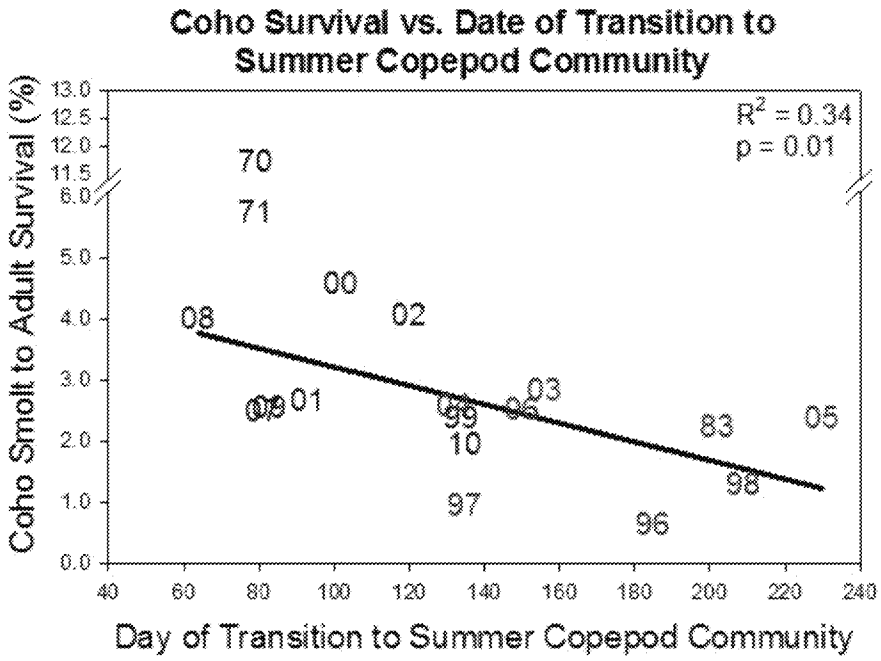

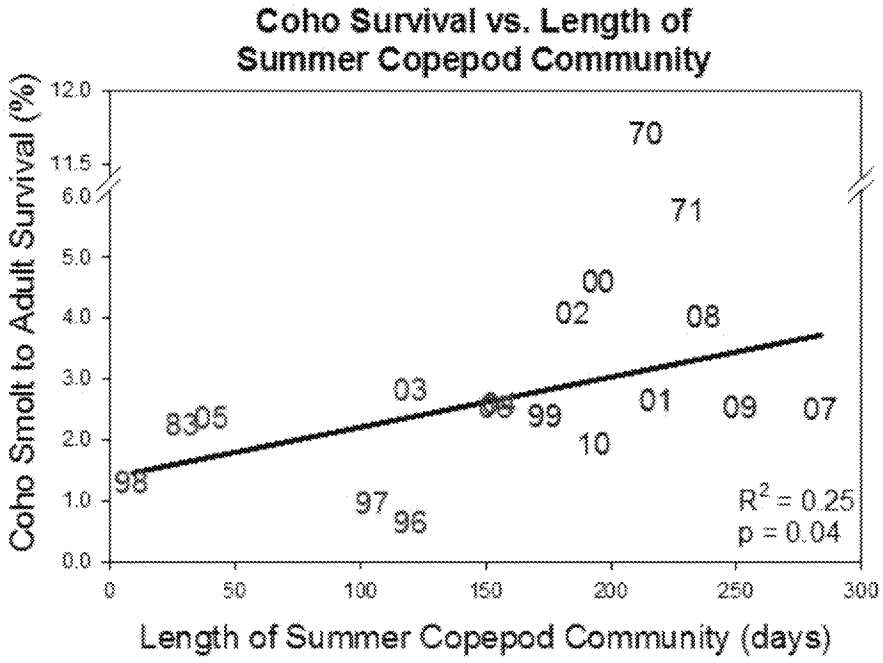

Figure 31. Upper panel: Regression of coho survival vs. day of the year when copepod community structure transitioned to a summer community. The earlier this transition takes place, the higher the coho survival.
Lower panel: Regression of coho survival vs. length of the biological upwelling season, measured as the number of days that the summer community structure persisted. Data from the year 1970 were excluded from the regression. Numbers indicate the warm (red) and cold (blue) years.

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We believe this date may be a more useful indicator of the transition in ocean conditions because it also indicates the first appearance of the kind of food chain that seems most favorable for coho and Chinook salmon; that is, one dominated by large, lipid–rich copepods, euphausiids, and juvenile forage fish.

Thus we suggest that potential feeding conditions for juvenile salmon are more accurately indexed using both northern copepod biomass and the biological spring transition date (as compared to an upwelling index, which is presumed to serve as an index of feeding conditions). We say this in light of the following two instances wherein the upwelling index alone failed to correctly indicate feeding conditions.

First, during El Niño years, or years with extended periods of weak El Niño–like conditions, upwelling can still be strong (as in 1998), but can produce a warm, low–salinity, low–nutrient water type (rather than the expected cold, salty, and nutrient–rich water). Upwelling of this water type results in poor plankton production.

A second example of upwelling as a misleading indicator occurred during 2005, when mean total upwelling levels from May to September were "average." However, the zooplankton community did not transition to a cold–water community until August (Table 6). Therefore, in spite of early upwelling, conditions for salmon feeding, growth, and survival were unfavorable throughout spring and most of summer 2005.

The end of the upwelling season marks the return of a winter community for zooplankton, the timing by which the fall transition is measured.

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Table 6. Dates of the biological spring transition, measured by the change in the zooplankton timing from a winter to a summer community.

	Arrival of cold–water copepod community		Length of cold–water copepod presence
Year	Start date	End date	(in days)
1970	~20 Mar	20 Oct	214
1971	20 Mar	6 Nov	231
1983	21 Jul	19 Aug	29
1996	3 Jul	31 Oct	120
1997	15 May	28 Aug	105
1998	28 Jul	6 Aug	9
1999	14 May	4 Nov	174
2000	11 Apr	23 Oct	195
2001	3 Apr	7 Nov	218
2002	30 Apr	1 Nov	185
2003	5 June	3 Oct	120
2004	11 May	14 Oct	156
2005	18 Aug	28 Sep	41
2006	30 May	31 Oct	154
2007	22 Mar	31 Dec	284
2008	4 Mar	27 Oct	237
2009	24 Mar	1 Dec	252
2010	15 May	24 Nov	193
2011	23 Mar	—	—

These changes in community type occur because of coastal currents, which reverse in spring to flow from the north with the onset of upwelling. Another reversal occurs in the fall, when the northward–flowing Davidson Current appears on the shelf due to winter downwelling.

Arrival of the "northern" species in spring signals that the ecosystem is primed to begin a productive upwelling season. Also listed is length of the upwelling season in days, as reckoned by the zooplankton. Note that over the 3 years of 2007–2009, the transition date came very early, in March, whereas in 2010 it came in mid–May.

Both the date of "biological spring transition" and "length of the biological upwelling season" correlate well with counts of adult spring Chinook (Figure 32) and adult fall Chinook (Figure 33) at Bonneville Dam 2 years later. In the case of fall Chinook adults, the year 2007 was an outlier; had it not been included in the linear regression, R^2 would have increased to 70% for the transition date ($p = 0.001$) and to 74% for length of the biological upwelling season ($p = 0.001$).

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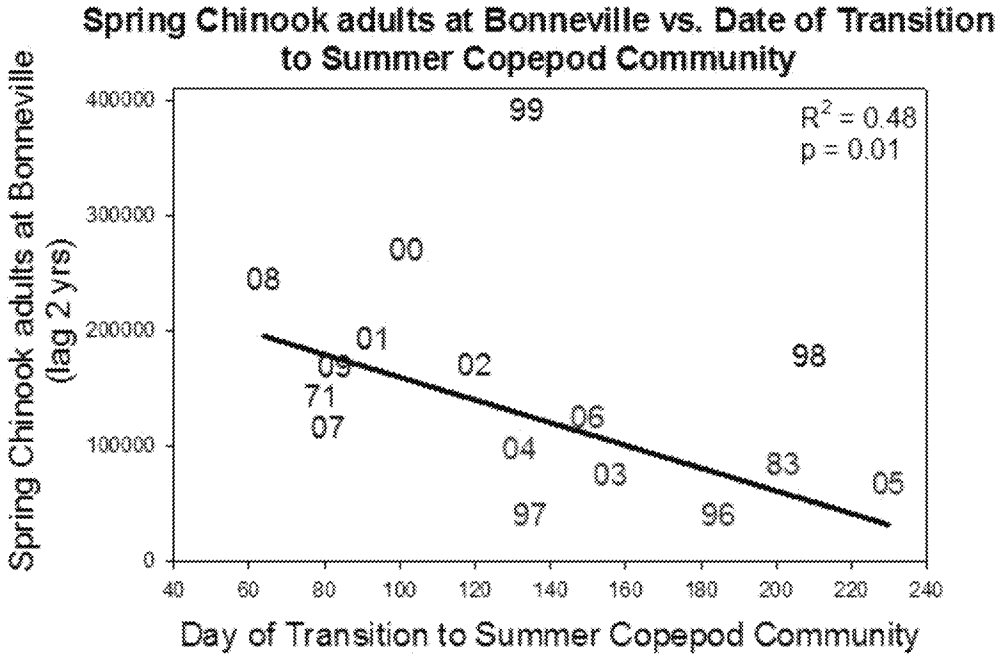

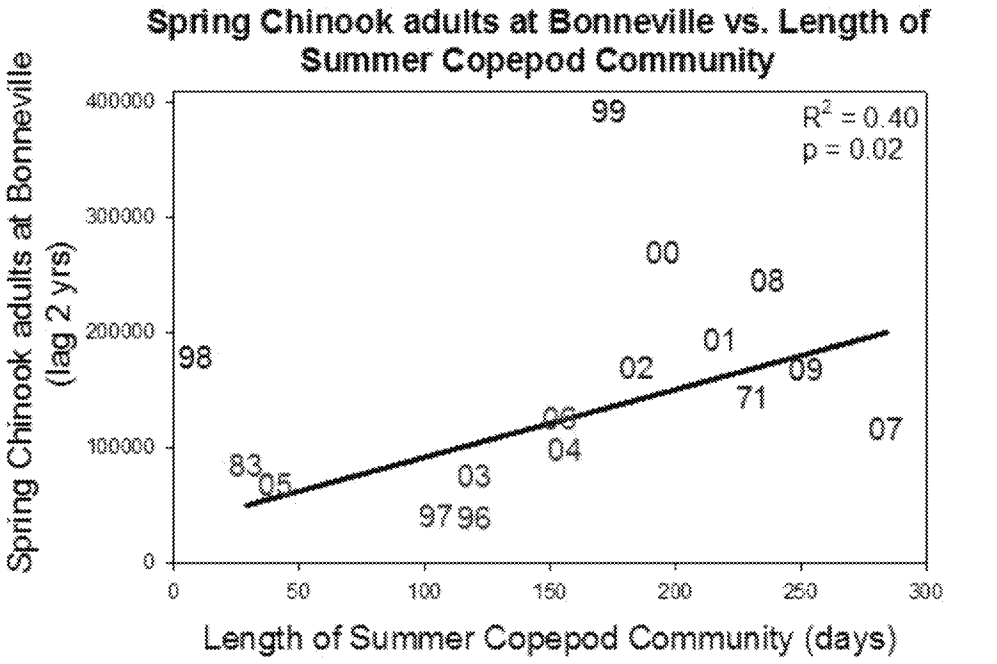

Figure 32. Spring Chinook adult counts at Bonneville (lagged by 2 years) vs. date of biological spring transition (upper panel) and length of the biological upwelling season (lower panel). The years of 1998 1999 were outliers and were not included in the regression. Numbers indicate the warm (red) and cold (blue) years.

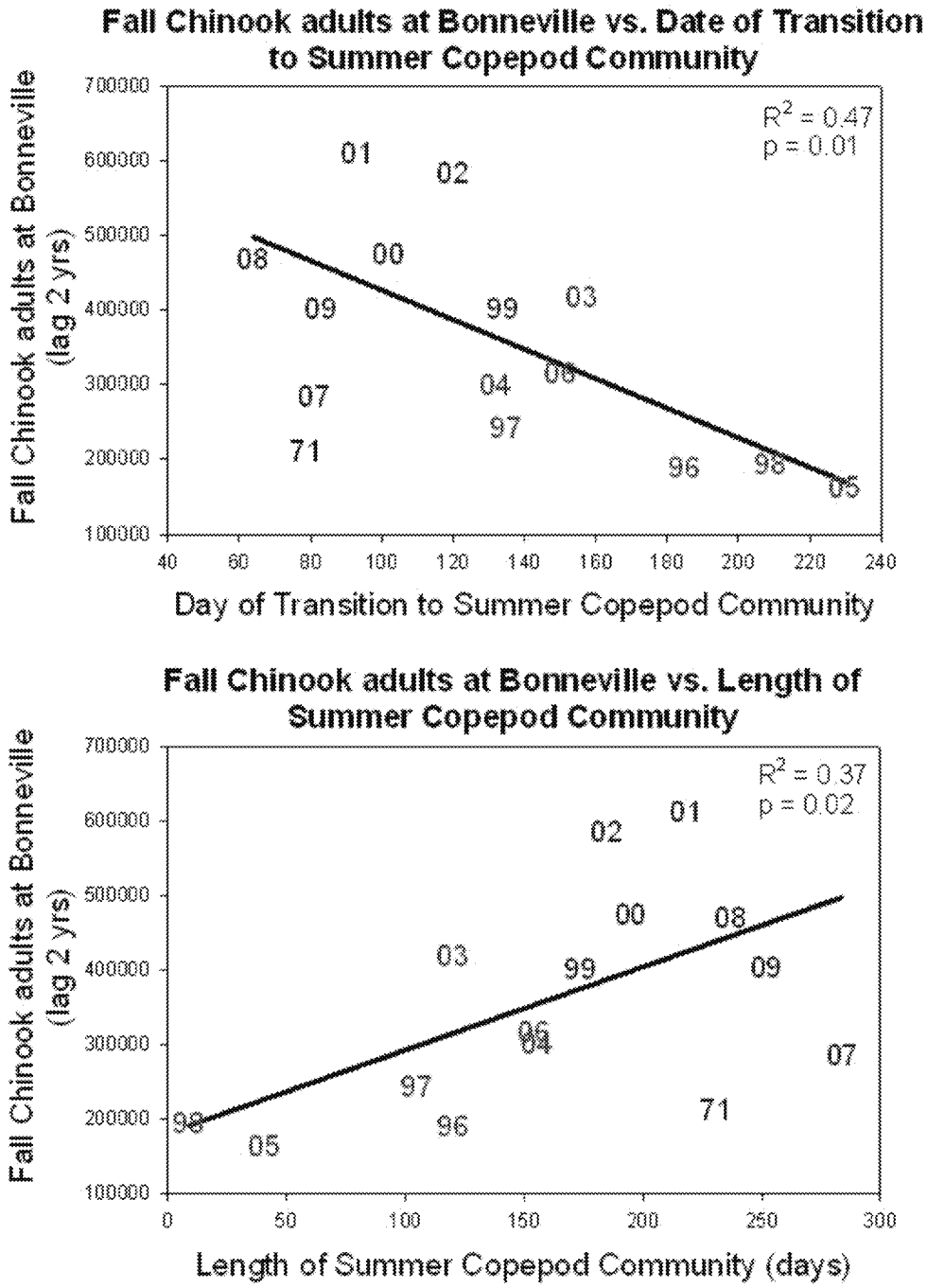

Figure 33. Fall Chinook adult counts at Bonneville (lagged by 2 years) vs. date of biological spring transition (upper panel) and length of biological upwelling season (lower panel). The year 1971 was an outlier and was not included in the regression. Numbers indicate the warm (red) and cold (blue) years.

Winter Ichthyoplankton

Marine diets of juvenile coho and Chinook salmon are primarily made up of zero–age winter–spawning juvenile fish such as rockfish, Pacific sand lance, cottids, and smelts (Brodeur et al. 2007; Daly et al. 2009; Table 7). Measures of winter ichthyoplankton biomass are a recent addition to our toolbox. Annual abundance estimates of key salmon prey in winter and early spring provide an indicator of survival in the months before juvenile salmon enter the sea because these estimates reflect the feeding conditions they will potentially encounter. Figure 34 shows the proportions of winter ichthyoplankton biomass composed of food items for juvenile salmon.

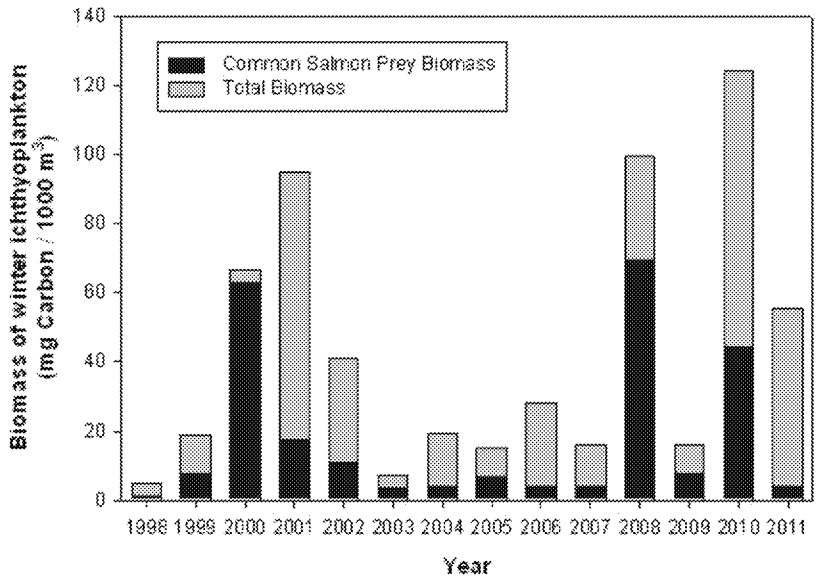

Figure 34. Estimates of total winter ichthyoplankton biomass from 1998 to present. Proportions composed of fish larvae considered prey items for juvenile salmon are represented by blue bars.

Winter ichthyoplankton biomass was highest in 2000, 2001, 2008 and 2010 and lowest in 1998, an El Niño year (Figure 34). Years with the highest biomass of the ichthyoplankton typically eaten by juvenile salmon were 2008 and 2000; those with low biomass were 1998 and 2003–2007. The proportion of total ichthyoplankton biomass considered common salmon prey fluctuated from a low of 13.9% in 2006 to a high of 95.0% in 2000. Even though the total biomass of ichthyoplankton was high in 2001, only 18.6% was prey commonly seen in salmon diets.

We compared these annual values (log of mean of Jan–March samples) to juvenile coho salmon smolt–to–adult return ratios (SARs), and to counts of adult spring, summer, and fall Chinook salmon at Bonneville Dam to determine whether our index of prey availability is a good predictor of salmon returns. Results of this comparison are shown in Figure 35. Data from winter 2011 suggest low–to–average returns of adult coho in 2012, spring Chinook in 2013, and fall Chinook in 2014.

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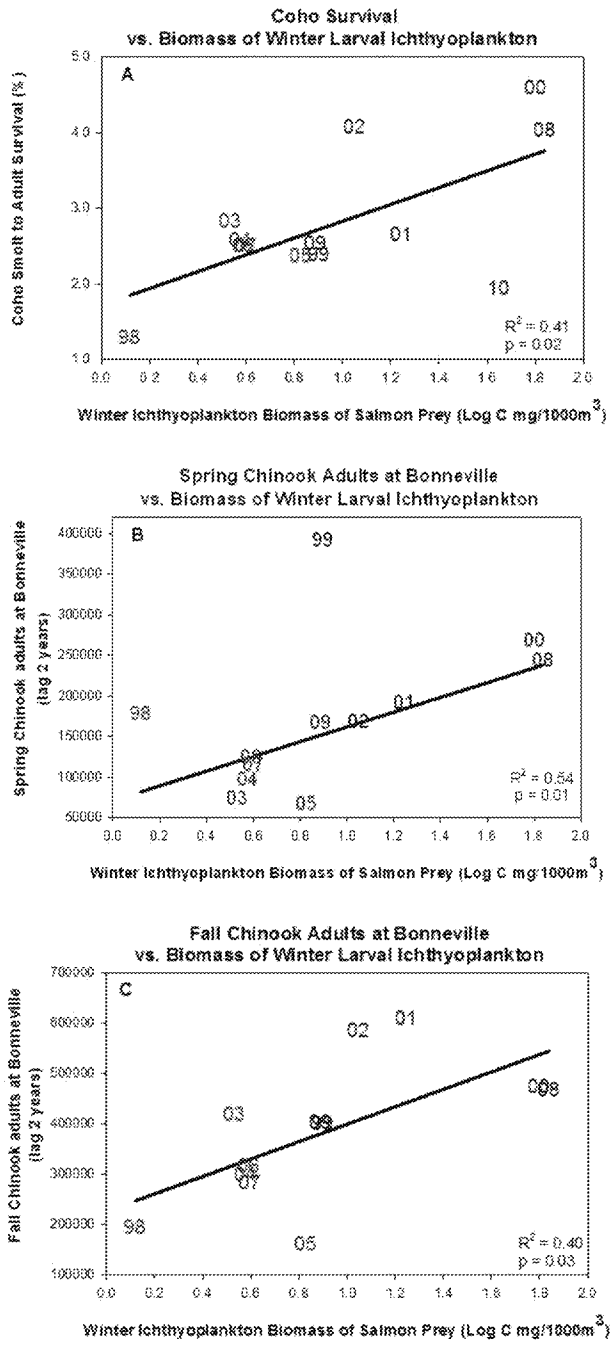

Figure 35. Coho salmon smolt-to-adult survival was positively related to winter ichthyoplankton salmon prey biomass (Figure 35A). The relationship between spring Chinook adult salmon returns (lagged by 2 years) at Bonneville Dam and log of the winter ichthyoplankton salmon prey biomass also exhibited a positive relationship (1999 excluded; Figure 35B). Counts of fall Chinook salmon adult returns (lagged by 2 years) at Bonneville Dam vs. log of the biomass for winter ichthyoplankton salmon prey exhibited a significant positive relationship (Figure 35C).

Coho salmon smolt–to–adult survival was positively related to winter ichthyoplankton salmon prey biomass (Figure 35A). The relationship between counts of spring Chinook adult salmon (lagged by 2 years) at Bonneville Dam and log of the winter ichthyoplankton salmon prey biomass exhibited a weak, yet positive relationship (Figure 35B). If the year 1999 is excluded, the relationship is stronger. Counts of fall Chinook salmon adult returns (lagged by 3 years) at Bonneville Dam vs. log of the biomass for winter ichthyoplankton salmon prey exhibited a significant positive relationship (Figure 35C).

Data for these analyses were collected during our sampling cruises along the Newport hydrographic line. Winter ichthyoplankton data shown here were from samples taken 1 January to 31 March. All fish larvae were identified and lengths were measured on a subset of each species per sampling station. Length–to–biomass conversions were made using published values, and total biomass in mg carbon per 1000 m^3 at each station was calculated for all sampled larval fish and a subset of fish biomass that included only fish prey typically eaten by juvenile salmon. Table 7 lists common prey eaten by juvenile salmon in their first marine summer and provides data on the size and availability of each.

Table 7. Common prey eaten by juvenile salmon during their first marine summer. Shown are the peak spawning season, hatch time and size, estimated days to reach the juvenile stage and average size of prey when eaten by juvenile salmon.

Common prey of juvenile salmonids						
Scientific name						
	Ammodytes hexapterus	Clupeidae	Cottidae	*Engraulis mordax*	Osmeridae	Sebastes
Common name						
	Pacific sand lance	Pacific herring	Sculpin	Northern anchovy	Smelt	Rockfish
Spawning season						
	Nov–Mar	Feb–Apr	Jan–Feb	Feb–Jun	Year–round[1]	Jan–May
Time to hatching (d)						
	21	14	9–14	2–4	10–40	N/A
Size at hatching (mm)						
	5	7.5	4–5	2–3	3–6	3–6
Time to juvenile stage (d)						
	90–120 d	60 d	60 d	70 d	90 d	120–150 d
Juvenile size (mm)						
	30	25–40	15–20	25	20	25–30
Mean size when eaten by salmonids (mm)						
	42	34	22	60	39	34
Source						
	Emmett et al. 1991	Hart 1973	Emmett et al. 1991	Emmett et al. 1991	Hart 1973; CDFG 2009	Love et al. 2002; Matarese et al. 1989

[1] winter peak

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Catches of Yearling Chinook in June and Coho in September

Numbers of juvenile salmon caught during our June and September trawl surveys can serve as an index or surrogate measure of ocean survival for spring Chinook and coho salmon. Figure 36 shows catch per unit effort (CPUE) during our trawl surveys from 1998 to 2010.

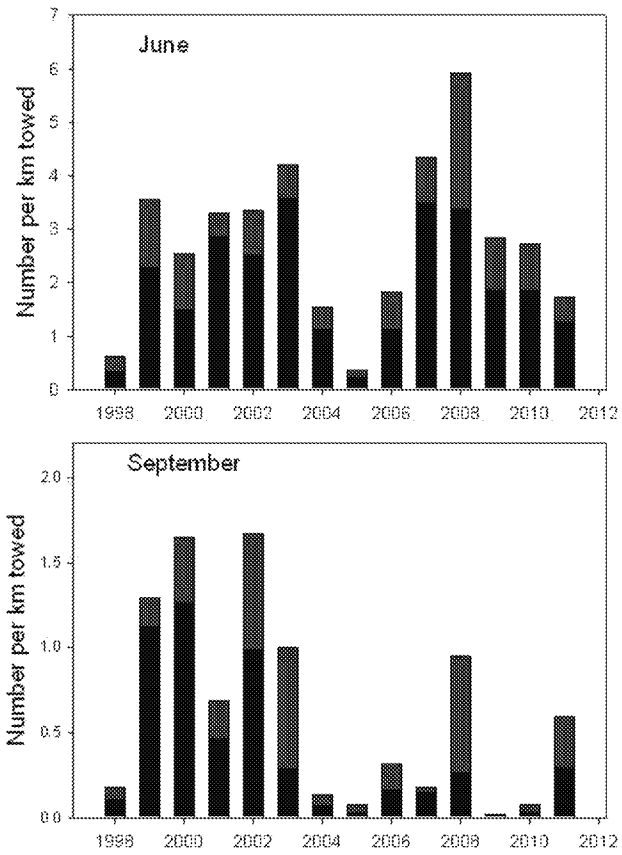

Figure 36. Average catches of juvenile coho (black bars) and yearling Chinook (red bars) during trawl surveys off the coast of Washington and Oregon. Surveys were conducted in June (upper panel) and September (lower panel) from 1998 to present. Note the difference in the scale of the y-axis between plots.

Catch rates were lowest for both species during 2005, but rebounded gradually from 2006-2008, only to decline again from 2009-present (June).

Figure 37 shows the relationship between catches of juvenile Chinook and coho and returns the following year of coho adults and Chinook jacks. In the upper panel, trawl catches of coho in September of year i are correlated with adult counts from the Oregon Production Index of hatchery coho adult returns (OPIH in year i + 1). Similarly, catches of yearling Chinook in June of year i are correlated with counts of spring Chinook jacks at Bonneville Dam in year i + 1.

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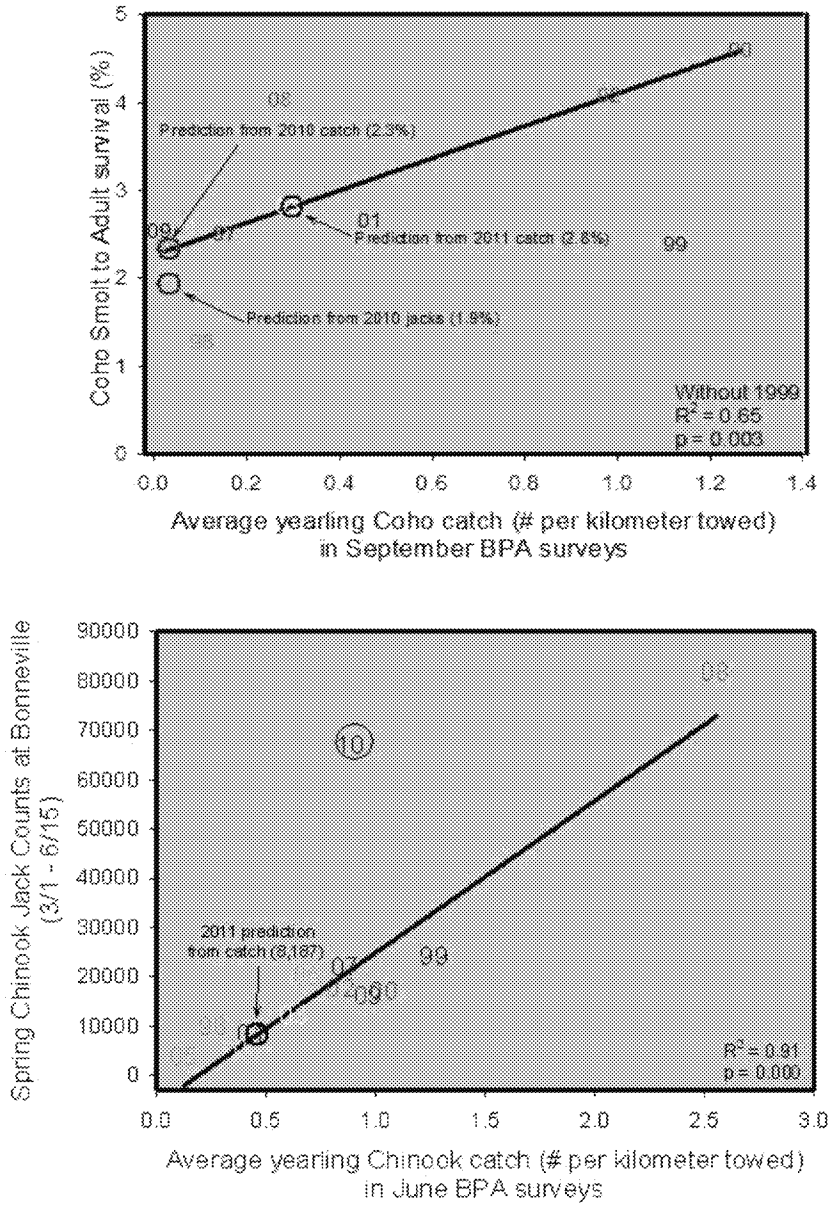

Figure 37. Upper panel shows regression of the OPIH smolt-to-adult survival (SAR) of coho salmon on the average CPUE of juvenile coho salmon catches in trawl surveys the previous September. Years indicated are for catches of juvenile fish. The purple open circles indicate observed juvenile CPUE in September 2010 (0.03) and predicted SAR from jack returns (1.9%) and from our September 2010 catch (2.3%). Black open circle indicates observed juvenile CPUE (0.30) in September 2011 and predicted SAR (2.8%)

Lower panel shows regression of spring Chinook salmon jack counts at Bonneville Dam (1998-2011) vs. average CPUE of yearling Chinook salmon caught during each June cruise. Open black circle indicates observed CPUE in June 2011 (0.46) and predicted jacks from the regression (8,187). The year 2010 (circled) was excluded from the regression.

Indicators Under Development

Forage Fish and Pacific Hake Abundance

We are developing an index that describes food–web interactions between juvenile salmon and their fish predators, chiefly Pacific whiting, aka Pacific hake. The index is based on interactions between forage fish (e.g., anchovies, smelt and herrings), juvenile salmon, and hake.

This interaction is somewhat complex and probably non–linear: we hypothesize that during warm–ocean years, hake move to continental shelf waters, where salmon are more susceptible to predation. During cold–ocean years, hake feed in deeper waters offshore, near the shelf break, and are not actively feeding in the shallow continental–shelf waters inhabited by juvenile salmon.

During cold ocean conditions, when zooplankton production is high, small forage–fish biomass increases. This increase in forage–fish abundance allows predators to "see" and prey upon forage fish more often than salmon. Most forage fish populations (smelt, herring, and anchovy) do well during cold conditions but tend to crash during warm conditions, but there is a lag of at least 1 year between boom and bust periods. Thus, the interaction among zooplankton production, forage fish abundance, juvenile salmon survival, and hake predation is likely to be non–linear.

We have not analyzed or modeled these interactions. Nevertheless, Figures 38 and 39 demonstrate the pronounced interannual differences in abundance of forage fishes; these are in part related to the cycles gauged by the current ocean ecosystem indicators.

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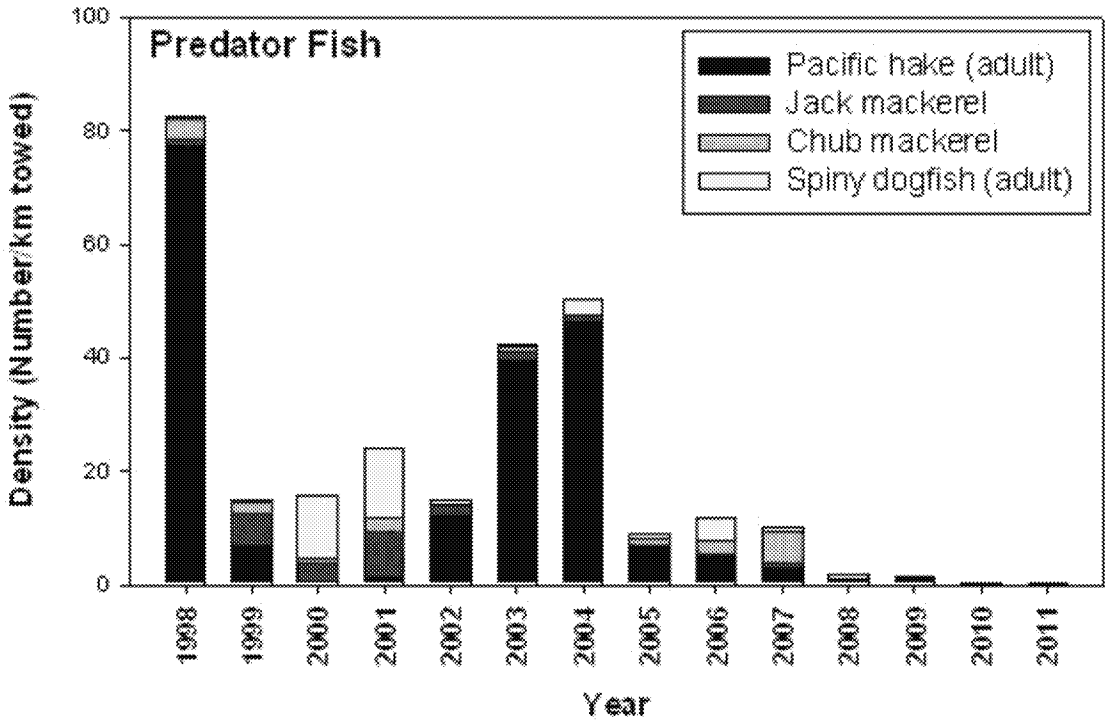

Figure 38. Catches of potential piscivores that prey on juvenile salmon. Pacific hake numbers are usually very high during "warm years" such as the 1998 El Niño event and during the first 2 years of a warm-phase PDO (2003-2004). However, numbers were surprisingly low from 2008-present, despite the 2009 El Niño. Data shown are from the surveys of R. Emmett, conducted May-August 1998-present.

In 2011, Pacific hake, (Figure 38) continued to be found in very low abundances compared to 1998, 2003, and 2004. Low densities were observed during the cool, negative-PDO phases of 1999-2002 and 2008-2011. Conversely, high abundances occurred during the warm, positive-PDO years of 1998, 2003, and 2004. Probably not coincidentally, these years correspond respectively to "good" and "poor" periods for coho survival. We expected high abundance levels for hake in 2005 and 2006 (warm years), but this expectation was not met, due possibly to the timing of their northward migration. That is, hake may have moved further north (off Canada) during the warm years of 2004 and 2005, and thus would have been preying on salmon earlier (May) rather than later (Jun-Jul) in the season.

Forage fish clearly show a 1-year lag between change in ocean phases and population response: anomalously low abundances were observed during the first year of a "cool phase" (1999), and anomalously high abundances were observed during the first year of "warm phase" (2003). This lag time reflects the time it takes for 0-age fish to grow large enough (i.e., 1-year-old) to be captured by the surface trawl. The failure of hake to maintain high abundances in 2005 and 2006, and the 1-year lag in response of forage fish to changes in ocean conditions, contributes to the lack of a linear relationship between salmon catches or survival and forage fish or hake densities.

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The relationship between salmon marine survival and other fishes appears to be very complicated and probably influenced by additional factors.

Forage fish numbers continued to be relatively high in 2011 (Figure 39), probably as a result of relatively good recruitment in 2010. These high densities comprise a positive indicator, since juvenile forage fish (ages 0 and 1) are among the favored prey of both coho and Chinook salmon. Thus salmon were probably not food limited in either 2010 or 2011. High numbers of forage fish in 2011 and a probable cold ocean in spring 2012 (which is good for forage fish recruitment) indicates favorable ocean survival for coho and Chinook salmon in 2012.

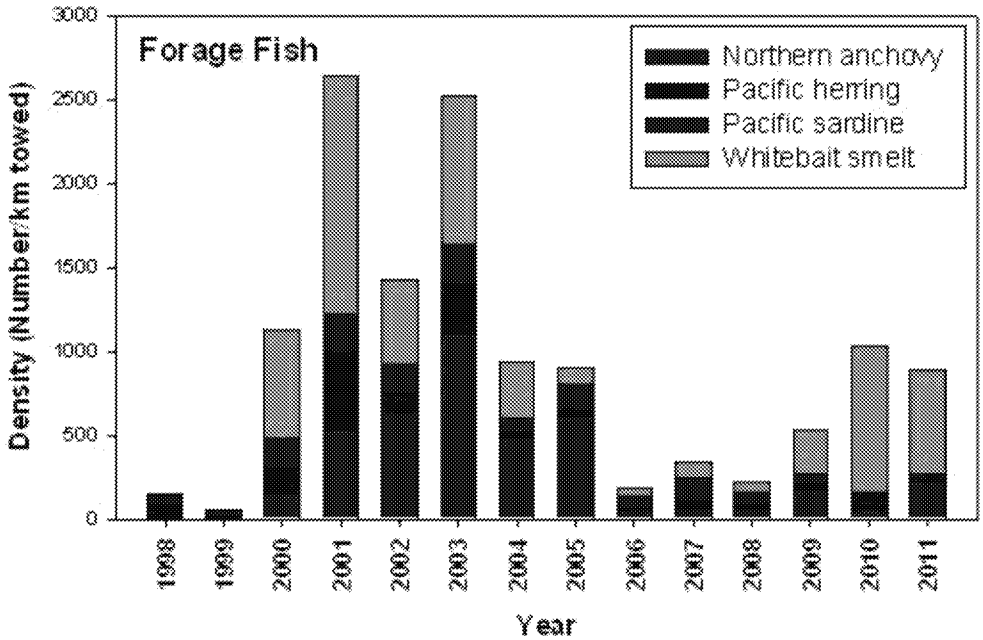

Figure 39. Catches of forage fish along the Columbia River and Willapa Bay transects, 1998-present. Note low numbers of forage fish in 2006; note also low numbers in 1999, demonstrating that there can be time lags of at least 1 year following a crash before forage fish numbers begin to increase. Data shown are from the surveys of R. Emmett, conducted May-August 1998-present.

A Second Mode of North Pacific Sea Surface Temperature Variation

Changes in sign of the PDO tend to follow an east/west dipole; that is, when the North Pacific is cold in the west, it is warm in the east, and vice versa. Bond et al. (2003) showed that variability of sea surface temperature has a second mode, which reflects north/south variations. This pattern first appeared in 1989 and continues to the present.

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We have not yet investigated this pattern fully because the negative phase of the first mode (the PDO) indicates favorable conditions in the northern California Current, as does the negative phase of the second mode (called the "Victoria" mode). However, oscillation in the second mode would index good vs. poor ecological conditions between the Gulf of Alaska and northern California. Therefore, it is possible that this second mode may serve as a better index of conditions for spring Chinook salmon: conventional wisdom is that spring Chinook resides in the Gulf of Alaska during most of its years at sea.

Phytoplankton Biomass

Based on samples collected along the Newport Hydrographic Line, we developed time series of both total chlorophyll and the fraction of chlorophyll smaller than 10 µm. These data serve as estimates of phytoplankton biomass, and both data types will be used to describe interannual variation in timing of the spring bloom (which can occur between February and April), as well as blooms in summer during July–August upwelling. These measures should provide an index of potential conditions (good vs. poor) for spawning of copepods and euphausiids.

Euphausiid Egg Concentration and Adult Biomass

Euphausiids are a key prey item for juvenile coho and Chinook salmon. Sampling along the Newport Hydrographic Line has also yielded a time series of euphausiid egg abundance. These data may serve as an adult euphausiid biomass index, which should prove useful in comparisons of interannual variation in abundance, survival, and growth for these salmon species.

Since 2000, we have also been sampling at night along the Newport Line in order to capture adult euphausiids. The long–term goal of this sampling is to produce an index of euphausiid biomass in the northern California Current. We are also measuring rates of molting and egg production in living animals in anticipation that these data can be used to calculate euphausiid production.

Interannual Variations in Habitat Area

From the salmon trawl surveys conducted in June and September, we are developing "Habitat Suitability Indices." We hope these will prove useful in providing more precise predictors of the potential success or failure for a given year–class of juvenile salmonids. For example, we have determined that chlorophyll and copepod biomass levels are the best predictors of habitat size for juvenile Chinook salmon. Interannual variation in potential habitat area may also serve as a correlate for salmon survival during the first summer at sea.

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Salmon Predation Index

A salmon predation index will integrate four variables found to influence predation rates of Columbia River salmon in the ocean (Emmett 2006). These variables are based on the following spring (May/June) measurements:

1. Abundance of Pacific whiting (hake) off the Columbia River
2. Abundance of forage fish off the Columbia River
3. Turbidity of the Columbia River
4. Columbia River flows

Predator and forage–fish abundances are estimated annually from the Predator/Forage Fish Survey, and turbidity will be estimated using satellite imagery, Secchi disc readings, and transmissometer measurements, each of which has been collected since 1998. Initial analyses indicates that during years when hake abundance is low and forage fish abundance, turbidity, and Columbia River flows are high, salmon marine survival is high. However, if even one variable has an opposite value, salmon marine survival declines.

Potential Indices for Future Development

Remaining indices are in very early stages of development or have not yet begun to be developed. These include:

1. An index of Columbia River flow
2. Predictors of coho and spring Chinook jack returns
3. Indices based on salmon feeding and growth
4. Indices based on salmon health (diseases and parasites)
5. Indices that estimate zooplankton production rates, such as

    - Euphausiid growth rates from direct measurement of molting rates
    - Euphausiid growth rates from cohort developmental rates
    - Copepod growth rates from direct measurement of Calanus egg production rates
    - Copepod growth rates from empirical growth equations

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Ocean Sampling Methods

Hydrography, Zooplankton, and Ichthyoplankton

Much of the oceanographic data shown in this report came from sampling along the Newport Hydrographic Line (Figure 40). We sample the coastal waters off Newport at biweekly intervals during the upwelling season in spring, summer, and fall. Sampling cruises are conducted monthly during stormy winter months. This program began in May 1996, but we also have data from these same stations from sampling conducted in 1973 (Peterson and Miller 1975), 1983 (Miller et al. 1985), and summer 1990-1992 (Fessenden 1995).

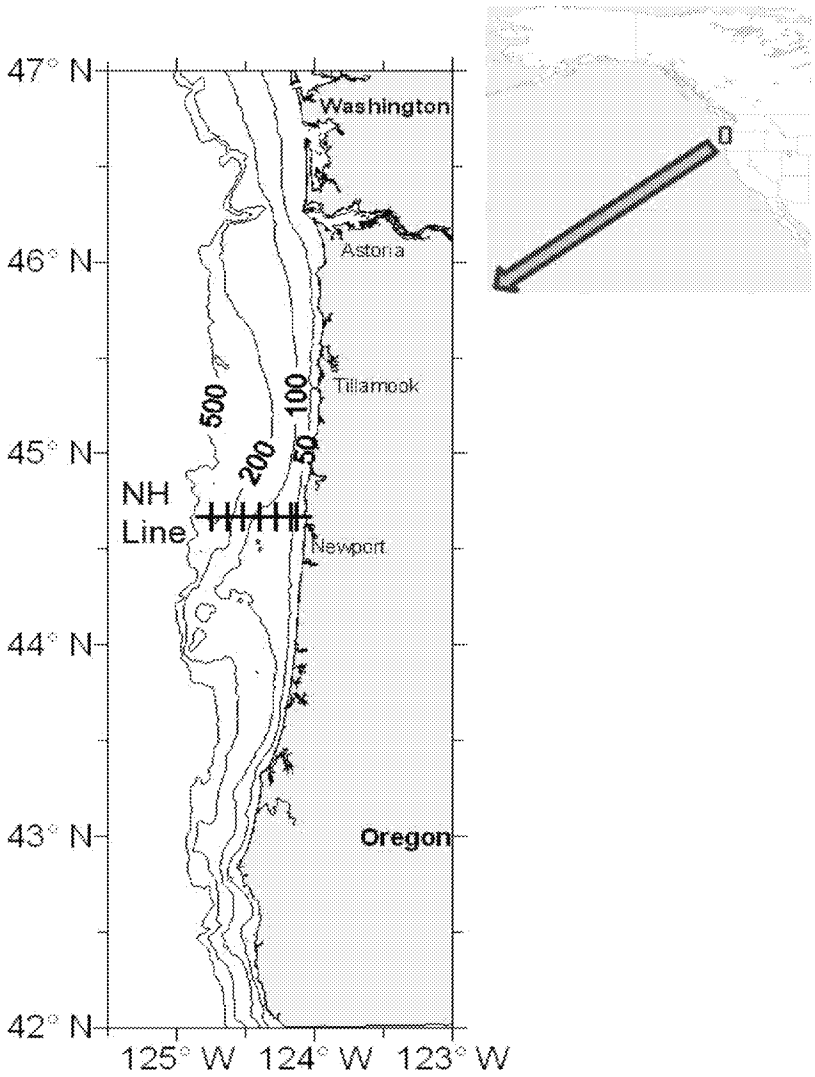

Figure 40. Transects and stations sampled during cruises by the NOAA Fisheries Service.

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Cruises during May 1996-September 2001 were made only during daylight hours because our research vessel, the RV Sacajawea was only 37 ft in length, rendering it unsafe to work at night. With the acquisition of a new and larger research vessel (RV Elakha; 54-ft.) in September 2000, we were able to sample at night. Thus in fall 2000, we began collecting data for an adult euphausiid time series.

This work included measurements of copepod and euphausiid egg production and molting rates. We are also developing a long time–series of copepod and euphausiid production, which should prove useful in evaluating if in fact there are measurable differences in zooplankton production in association with changes in sign of the Pacific Decadal Oscillation.

From 1998 to 2003, we sampled a group of transects from Newport, Oregon down to Crescent City, California five times per year as part of the U.S. Global Ocean Ecosystem Dynamics (GLOBEC) program. Since the GLOBEC project ended, we have continued to sample these same transect lines as frequently as possible. Thus far, we have been able to sample this region in 2004, 2006 and 2008-present, and have extended the Newport Line out to 200 miles from shore. Additionally, we also sample north of the Newport Line at least 3 times per year as part of the Juvenile Salmon sampling program. As a result, the Newport biweekly data are nested within larger scale semi-annual to quarterly surveys, an approach that is useful in helping us interpret locally derived data from the inner portions of the Newport Line.;

At each station, a CTD profile (Conductivity, Temperature, and Depth; Seabird‡ SBE 19 CTD) is taken, and transparency of surface waters is measured (Secchi disc). A bucket of seawater is collected from the surface for analysis of chlorophyll-a and nutrients. A vertical plankton net fitted with a flowmeter is towed from near the sea floor to the surface (or from 100 m to the surface in deeper waters). The plankton net is 0.5 m in diameter with a mesh size of 202 µm. A double oblique tow is made for ichthyoplankton (0.6-m diameter bongo net with 333-µm mesh) over the upper 20 m. Since 2005, CTD casts have included fluorometry (WetLabs fluorometer) and oxygen (Seabird oxygen sensor).

Nutrients are analyzed using a Technicon Autoanalyzer. Chlorophyll–a is extracted from glass–fiber filters in 90% acetone then analyzed using a Turner Designs Fluorometer. Zooplankton samples are processed in the laboratory by subsampling with a Stempel pipette. Species and developmental stage of copepods are enumerated with the aid of a dissecting microscope. Counts are converted to number of individuals per m^3 of water using appropriate conversion factors. Biomass is estimated by multiplying the number of individuals per m^3 by the dry weight of the taxa (using values from either literature or our own measurements). Carbon content is calculated assuming carbon is 40% of dry weight.

‡ Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

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Juvenile Salmon Sampling Program

Methods

We have sampled juvenile salmon each June and September since 1998 at offshore stations ranging from Newport, Oregon, to La Push, Washington (Figure 41). Pelagic fish are collected from the upper 20 m of the water column using a 264–rope trawl (NET Systems, Inc.; 30 × 20 × 100 m).

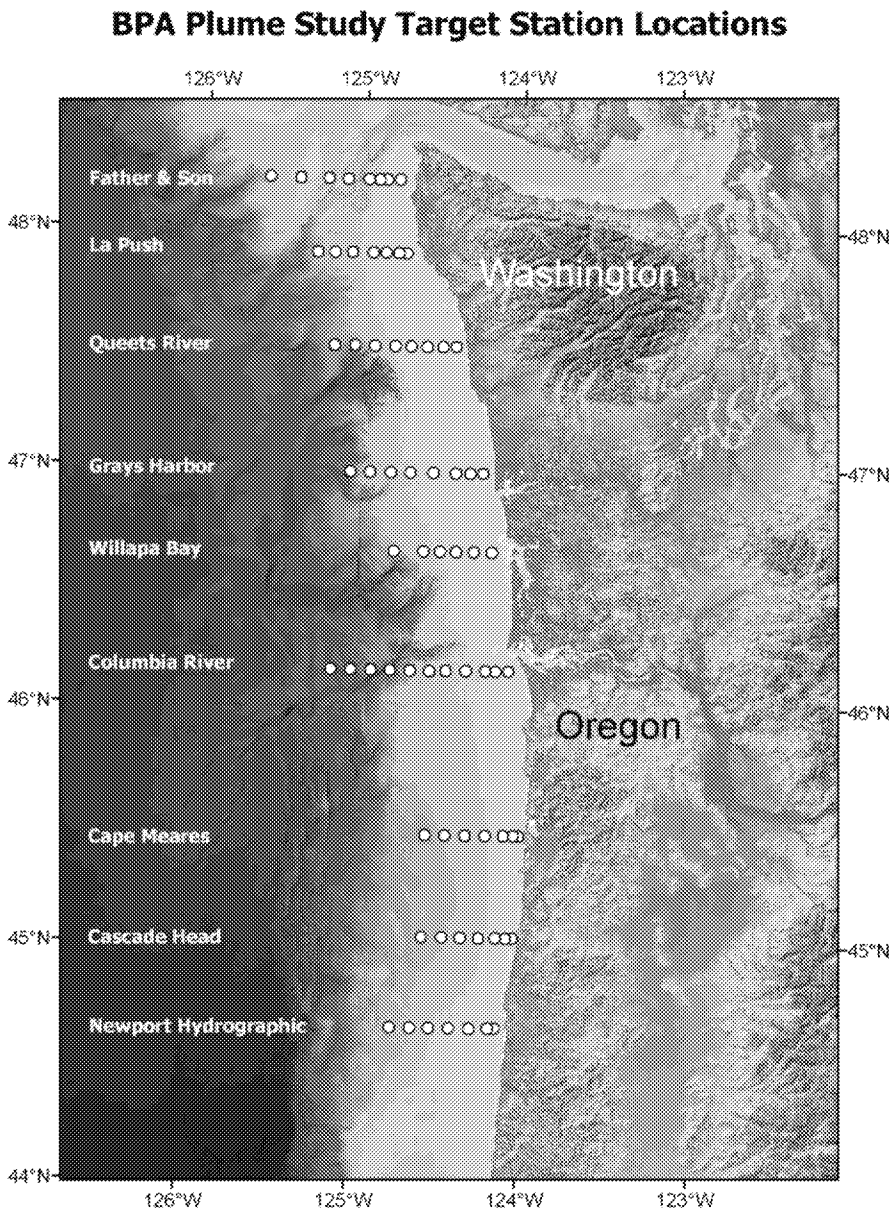

Figure 41. Transects sampled for coho and yearling and subyearling Chinook salmon, 1998 –present.

For each trawl sample, all fish and invertebrates are identified and enumerated, and the lengths of 50 randomly selected individuals are measured. For juvenile salmon, up to 60 individuals of each species and size class (i.e., subyearling or yearling Chinook, based on size) are measured and individually frozen. Remaining samples are frozen in bulk for further examination in the lab.

Oceanographic data collected at each station include sea surface temperature and salinity, depth profiles of salinity and temperature (collected with a Seabird SBE–19 plus CTD), and water transparency (measured with a Secchi disk and/or a transmissometer). A water sample is collected from a depth of 3 m for analysis of chlorophyll–a and filtered through glass fiber filters. The filtrate is frozen for later analysis of nutrient concentrations (nitrate, silicate, phosphate). Zooplankton is collected by vertical plankton tow (0.5–m diameter, 200–µm mesh) and an oblique bongo tow (60–cm diameter, 333–µm mesh bongo) from 20 m to the surface.

We also carry out surface-trawl/oceanographic cruises once every month from May-September. These cruises sample along transects located off the Columbia River and Willapa Bay. Pelagic fish are sampled at night and salmon prey are collected during day. This work provides an abundance index of fish predators (e.g., hake), forage fish (e.g., anchovy; which serve as an alternate prey for predators), and juvenile salmon prey (invertebrates and very small fishes).

During each year since 1998, we have collected samples over a wide range of ocean conditions. These data have provided many insights into the role of ocean conditions in controlling survival and growth of coho and Chinook salmon. For example, we sampled during a very strong El Niño (June 1998) and a strong La Niña (cold water) (1999 & 2008), under very high Columbia River flows of June 1999, 2008, 2010, and 2011 during extremely low flows of June 2001, and during anomalously warm conditions in the coastal ocean due to lack of upwelling in June 2005. During this period, the Pacific Decadal Oscillation moved from a warm phase (pre-1999) to a cool phase (1999-2002), then to warm phase again (2003-2007) and then back to a cool phase (2008-2011). Thus, nature has handed us a grand experiment that allows us to observe how salmon and other ecosystem components respond to short-term climate variability and on what temporal scales these responses occur.

Results

Salmon Distribution—Average juvenile salmon abundance over all June cruises has been highest in the vicinity of the Columbia River and off the Washington coast (Figure 42). Distributions of coho salmon have been more widespread, whereas both yearling (spring) and subyearling (fall) Chinook salmon were far less common off Oregon than Washington.

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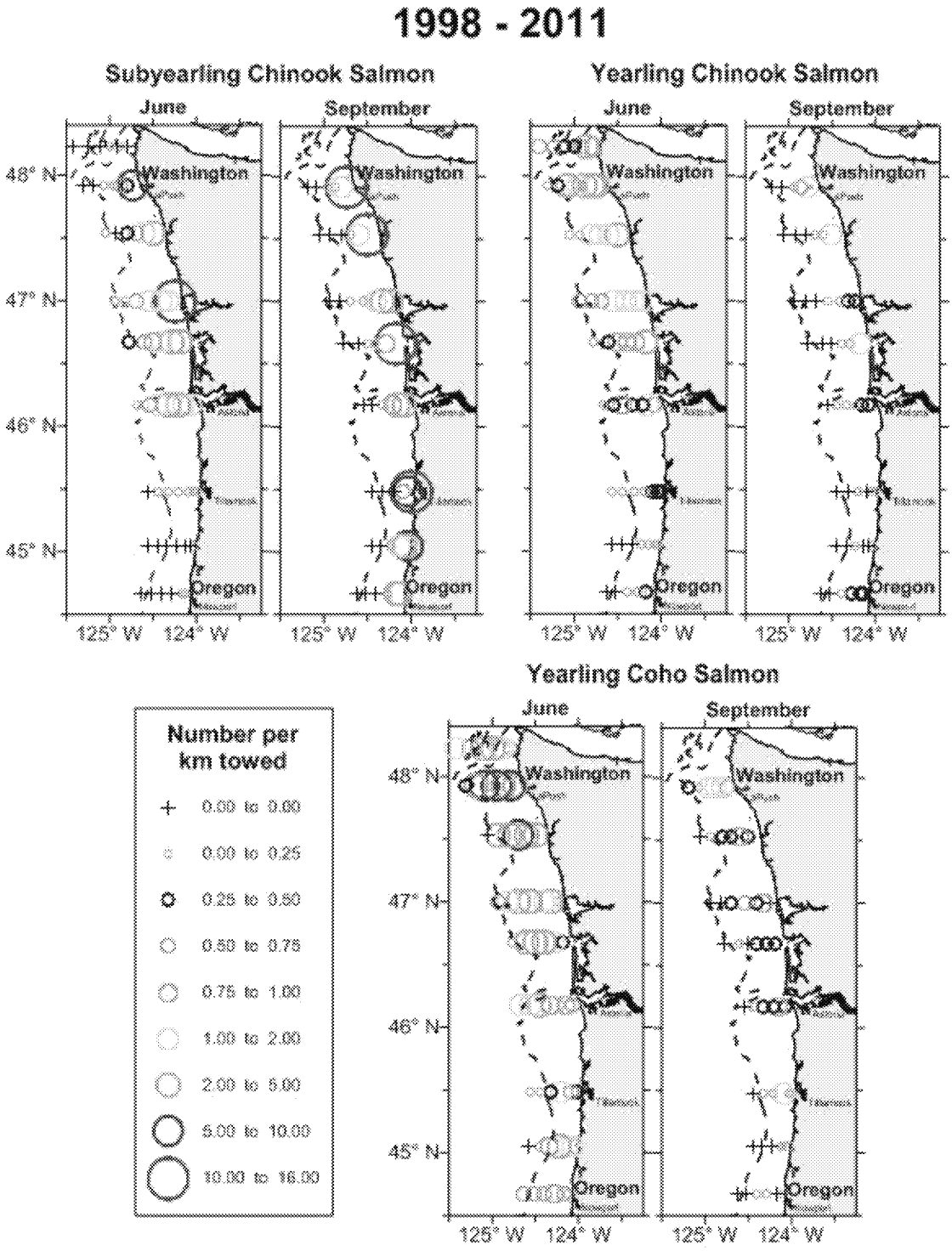

Figure 42. Average catch of salmonids per km towed at stations in June and September for each life history type during 1998-present.

In September, salmon catches were lower overall, and their distributions shifted to the north with the exception of fall Chinook, which was found mainly inshore throughout the study area. Large

catches were consistently made at several stations along the La Push (48°N), Queets River (47.5°N) and Grays Harbor (47°N) transects, as well as at two stations associated with the plume: one 5 miles off Willapa Bay (46.6°N), and the other 7 miles off the mouth of the Columbia River (46.2°N).

Catches in both June and September were also very patchy in that we generally caught half of the fish in ~5% of the trawls per cruise and did not catch any fish in 40% of the trawls (Peterson et al. 2010). Patches most generally occurred for both yearling Chinook and coho off the Washington coast in June (Figure 42) and very near shore for yearling and subyearling Chinook in September.

Annual variation in salmon abundance—The lowest June catches of Chinook and coho salmon were associated with an El Niño event in 1998 and an anomalously low upwelling period during May-June 2005 (Figure 43). Conversely, the highest June catches occurred during years with a negative signal (cold phase) of the Pacific Decadal Oscillation (1999-2003 and 2008-2010). 2011 had intermediate catches.

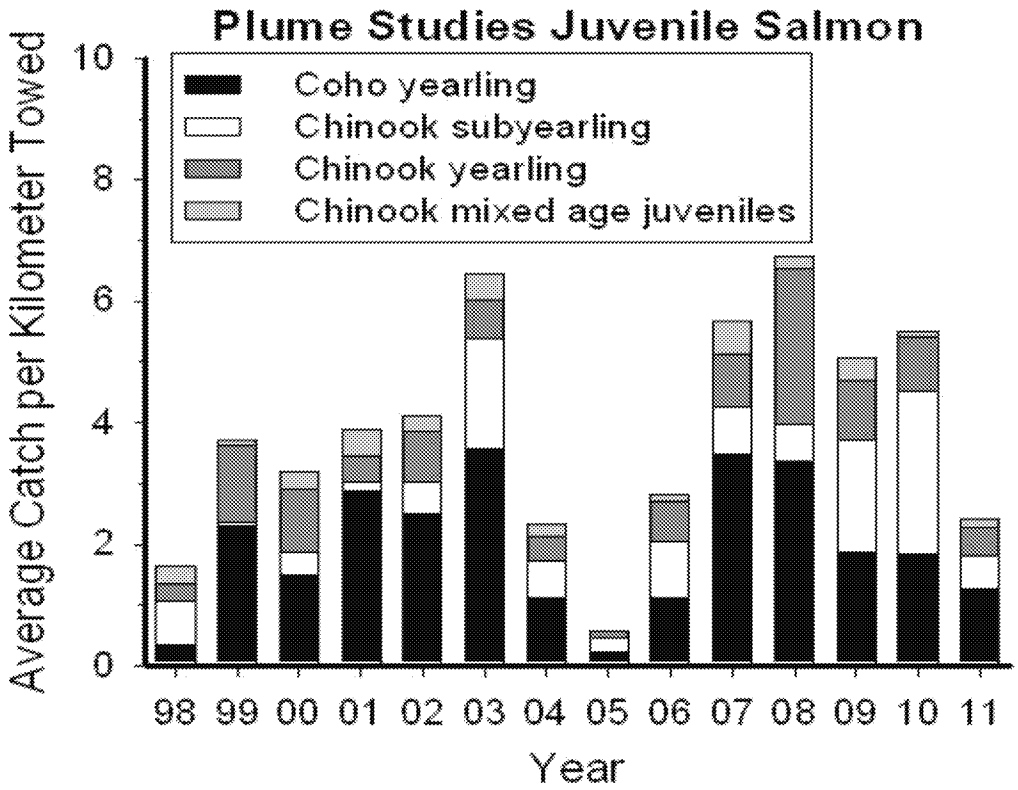

Figure 43. Annual variation in catches of juvenile coho and Chinook salmon during June trawl surveys, 1998–present.

Acknowledgments

Funding for data collection and data analysis came from the U.S. GLOBEC program NOAA–Center for Sponsored Coastal Ocean Research; grants NA 67RJ0151 and NA 86OP0589 and from the NOAA Fisheries and the Environment (FATE) Program.

Data collection was also supported by grants from the National Ocean Partnership Program (NA97FE0193), the National Science Foundation (9907854–OCE), and the Bonneville Power Administration.

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Glossary

Age Class
Age at maturity, which may differ among fish of the same year class. For example, among wild Snake River spring Chinook born in 2003, 8% may mature as jacks, 73% after 2 years in the ocean, and 19% after 3 years.

Aleutian Low
A semi–permanent, subpolar area of low pressure located in the Gulf of Alaska near the Aleutian Islands. It is a generating area for storms, and migratory lows often reach maximum intensity in this area. It is most active from late fall to late spring. During summer, it is weaker, retreating toward the North Pole and becoming almost nonexistent. During this time, the North Pacific High pressure system dominates (NOAA National Weather Service). Courtesy of NOAA National Weather Service.

California Current
The California Current System (CCS) is a southward–flowing ocean current found along the west coast of North America, beginning at the northern tip of Vancouver Island, Canada, and ending near the southern tip of Baja California/Mexico. It is one of four elements of the anticyclonic North Pacific Gyre. The North Pacific Gyre includes the southward–flowing California Current, the westward–flowing North Pacific Equatorial Current (which flows toward Japan), the Kuroshio Current (which flows north along Japan) and the North Pacific Current (which flows eastwards towards North America).

CPUE
We define catch per unit effort (CPUE) as the number of a particular species caught per kilometer traveled with the trawl under tow. However, CPUE is a relative and indirect measure of fishing effectiveness or species abundance. "Catch" can mean weight or numbers of total catch or of a particular species. "Units of effort" can be measured as individual cruises, the number of sets of a fishing net (or casts of a line), or as units of time or distance.

Geostrophic Wind
A wind that is affected by Coriolis force, blows parallel to isobars and whose strength is related to the pressure gradient (i.e., spacing of the isobars). Courtesy of NOAA National Weather Service.

Escapement
For salmon, the proportion of a population that returns as an adult to spawn in the natal stream (having "escaped" the catch in ocean fisheries).

Ichthyoplankton
Ichthyoplankton are the eggs and larvae of fish. They are usually found in the sunlit zone of the water column, less than 200 meters deep, which is sometimes called the epipelagic or photic zone. Ichthyoplankton are planktonic, meaning they cannot swim effectively under their own power, but must drift with the ocean currents.

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Jack
A "Jack" is a male Chinook or coho salmon that returns to spawn prematurely, before growing to the size of a normal adult. Jacks stay in the ocean from a few months to a year, returning to the natal stream 1–2 years before normal adults of their age class. Thus numbers of returning jacks are sometimes used as a basis to predict run size the following year.

NH 05
A sampling station located 5 miles offshore along the Newport Hydrographic Line, a transect of established stations used in oceanographic sampling by NWFSC research teams since the mid-1970s (Figure 1). Findings at this station are often used as a reference point for ocean ecosystem indicator data.

Northern California Current
The Northern California Current (NCC) is generally taken to be that part of the California Current that lies between the northern tip of Vancouver Island and the Oregon–California border, between Cape Blanco OR/Cape Mendocino CA. This portion of the CC shows a generally weak meandering flow year–round, which more–or–less flows parallel to the coast. It is characterized by strong seasonality in winds, upwelling, and biological productivity. Winter winds in the NCC are usually from the south or west, whereas summer winds are from the north and cause coastal upwelling.

North Pacific High
The North Pacific High pressure system is the region of high sea-level pressure that occurs over the eastern North Pacific Ocean in the climatological mean as shown in Figure 1 (Mass and Bond 1996).icon

Oblique Tow
A tow made by pulling the net at a slow tow speed from the sea floor to the surface. Under this configuration, the angle between the net and sea floor is maintained at 45 degrees.

OPIH (Oregon Production Index, Hatchery)
For coho, an estimate of total freshwater escapement, adjusted for ocean and freshwater catch, for public hatchery fish throughout the Oregon Production Index Area. Private hatchery production is removed from this estimate, so it reflects only public hatchery fish. Used as the numerator in calculating SARs for the OPIH.

Recruitment
Number or proportion of biomass added to a fish population as a result of growth or reproduction, especially for a given year class.

Secchi Disk
A device to measure the turbidity (transparency) of the upper water column. A 30–cm diameter white disc is lowered slowly through the upper water column to the point at which the pattern is no longer visible. The depth of the disk is then taken as a measure of transparency or turbidity.

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SAR (smolt–to–adult ratio)
For a population of salmon, the number from a given year class that survived to the smolt stage (i.e., migrated as juveniles) divided by the total number of returning adults from that year class (all age classes combined).

Teleconnection
The term "teleconnection pattern" refers to a recurring and persistent, large–scale pattern of pressure and circulation anomalies that spans vast geographical areas. Teleconnection patterns are also referred to as preferred modes of low–frequency (or long time–scale) variability. Courtesy of the NOAA National Weather Service Climate Prediction Center.

Transmissometer
A device for measuring beam attenuation, which can be used as a measure of turbidity in water. A beam of light is cast through the water and the transmissometer records the measure of light at a given point past the source of the beam.

Year Class
Fish of the same species and stock that are born in the same year.

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