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

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Project Summary

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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.

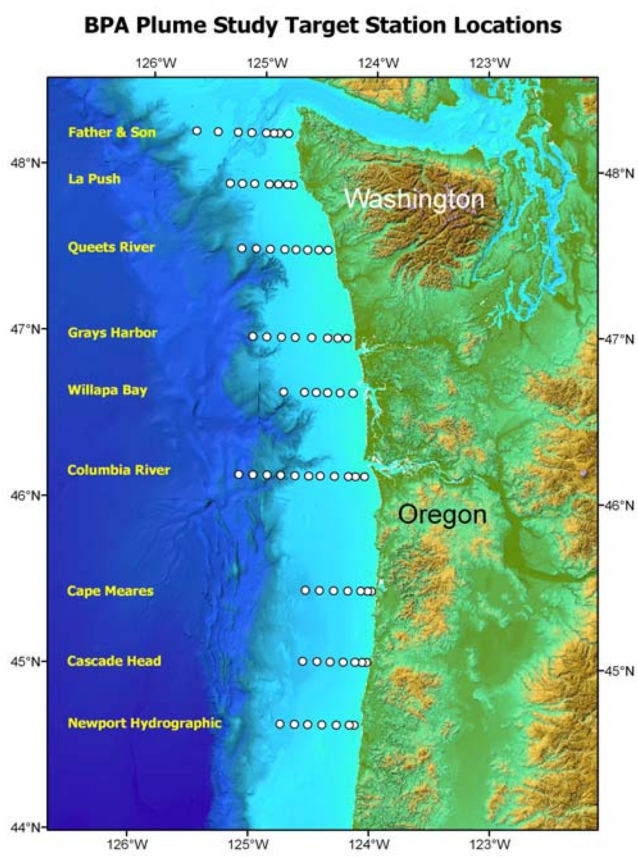


Figure 1. Transects sampled during trawling surveys off the coast of Oregon and Washington.

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 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.

2010 Ocean Ecosystem Indicators

The trend of cold ocean conditions, which started to become established in 2007, was interrupted in mid–2009 by the emergence of an El Niño event at the equator. This event continued into spring 2010 before dissipating. Because of this 2009–2010 El Niño event, the ocean began to warm and remained warm through April 2010. However, a cooling trend resumed in May, and by July 2010, the ocean was the coldest observed in recent years. These alternating conditions produced both the "best of times" and "the worst of times" in terms of ocean conditions for salmon, making it difficult to predict returns of coho in 2011 and Chinook in 2012.

Below we review the overall ranking of indicators in 2010 and briefly discuss each of our indicators for 2010 in the context of how they compare to those measured by our research team each year since 1998. Specific values for each indicator and year (1998–present) are listed in Table 3.

Overall ranking of 2010 indicators—In terms of the relative status of combined ocean ecosystem indicators, the year 2010 has an overall rank of 8 out of 13 (Table 3). This suggests below–average returns of adult coho in 2010 and Chinook in 2012. However, several 2010 indicators pointed to above–average returns of spring Chinook salmon in 2012.

Positive signs in 2010

- Negative PDO through summer
- Colder–than–normal SST anomalies during summer (–1 to –4°C)
- Coldest deep water temperatures in Jul–Aug of the past 13 years
- High biomass of northern copepods during summer (3rd of 13)
- High catches of spring Chinook in June (5th of 13)

Oddly, despite these strong indicators of apparently favorable ocean conditions for salmon in 2010, there were also several indicators pointing to poor conditions:

Negative signs in 2010

- Positive PDO signal and warm SSTs during winter (2009–2010)
- Discontinuous coastal upwelling until 9 June—short upwelling season
- High values of copepod species richness Jan–Sep
- Low catches of juvenile coho in September (11th of 13)

Because of these mixed signals, we cannot provide a definitive forecast based on ocean ecosystem indicators in 2010. Nevertheless, we are excited to see the adult run sizes from 2010 juveniles because they may help us to refine our suite of indicators. For example, we may find a set of indicators specific to coho salmon and a different set specific to spring Chinook. Moreover, a third set of indicators may be found that is specific to fall Chinook salmon, etc. In 2011, we will explore sets of indicators that might be useful in forecasting returns of sockeye and chum salmon, as well as steelhead.

Pacific Decadal Oscillation—During 2009, the PDO was strongly negative through April (Figure 5) but turned positive in August and remained so through winter 2009–2010. As shown by Logerwell et al. (2003), one prerequisite for good coho salmon survival is a cold ocean during the winter before juvenile spring migrants arrive. We assume that the same is true for yearling Chinook salmon. Because of this relationship, the value of the PDO during winter is thought to be an important leading indicator of ocean conditions.

During winter 2009–2010, PDO values were positive, indicating poor ocean conditions during this critical period for 2010 juvenile salmon migrants. However, negative PDO values returned in May 2010, marking the start of productive ocean conditions and the end of El Niño. Average PDO values during May–September 2010 were the 3rd most negative of our time series (Figure 2), and a negative PDO throughout summer 2010 indicates good ocean conditions.

Multivariate ENSO Index—In May 2009, the MEI switched from a negative to a positive signal, indicating the start of a small, but perhaps significant, El Niño event. The MEI remained positive through May 2010 (Figure 4), indicating poor ocean conditions in late summer 2009 and winter 2009–2010. In June 2010, the MEI signal abruptly turned negative, and extreme negative values were seen from August through November 2010. Values this low have not been seen since the mid–1950s and mid–1970s. The persistence of El Niño through winter–spring 2010 suggested poor ocean conditions during that period; however, strongly negative MEI values in late summer–fall (aka La Niña) point to the likelihood of especially productive ocean conditions in winter 2011.

Sea Surface Temperature (SST)—During 2010, the ocean was warm, with anomalies up to +1°C, but certainly not as warm as during past El Niño events. For example, SST data at NOAA Buoy 46050 showed anomalies of +2 and +3°C during 1997–1998 and +2°C during 2002–2003 (Figure 5). During 2010, SST anomalies were consistently +1°C from January through most of April, but in mid–May, the first major cooling event began (Figure 6). With the onset of a La Niña pattern, near–record cooling was observed in July and August, with anomalies of –3 to –4°C. However, significant warming resumed in September–November 2010. Summer SST values at station NH 05 were near the long–term average of 11.55°C (Figure 7).

Coastal Upwelling and Length of the Upwelling Season— Upwelling was initiated fairly early in 2010, on 6 April (day 96), but was not established for any lengthy period until 9 June. Upwelling was interrupted by several relaxation events, which caused downwelling at the coast. The first major downwelling event in early April (horizontal bar in Figure 10) did not result in anomalously warm water.

However, two subsequent downwelling events in early July and mid–August resulted in onshore transport of very warm water, and this was clearly reflected in SSTs (Figure 6). Upwelling in 2010 ended early, on 13 September (day 256), resulting in an upwelling season of only 161 days, 20% shorter than the climatological average. Despite the short season, some of the coldest water temperatures of the decade were observed in summer 2010.

Physical Spring Transition—The spring transition date in 2010 came on 6 April (day 95); however, northerly winds were weak and inconsistent until 9 June (day 160). Thus, even though strong winter storms ended on 6 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—Temperature and salinity profiles are recorded every 2 weeks during our sampling cruises off Newport, Oregon. Data from 2010 clearly show the differences observed in ocean conditions during spring (end of El Niño) as compared to summer 2010 (start of La Niña).

During spring 2010, deep water was slightly warmer and fresher than "normal," whereas during summer, deep water was the coldest of our 14–year time series (1997–present), but was not quite as salty as in other cold years (Figures 16 and 17). The presence of warm, lower–salinity water indicates relatively "poor" ocean conditions; however, the sudden change to cold, salty water in

July 2010 indicates that the latter half of the upwelling season could be characterized as having "good" ocean conditions.

Copepod Species Biodiversity (species richness)—Species richness is simply the relative number of species observed in a given area. We measure copepod biodiversity in terms of species richness in our monthly plankton samples. Monthly average values for copepod species richness continue to track quite closely with the PDO and SSTs (Figure 21). That is, 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 species. Conversely, when the PDO is positive, SSTs are warm, and the copepod community is dominated by a greater number of warm–water, subtropical species. Throughout 2010, we found very high values of species richness, rivaling those found during the 1998 El Niño event. Thus, given that the 2009–2010 El Niño was judged as a relatively weak event (i.e., positive SST anomalies were not particularly high), we are uncertain how to interpret these very high values of copepod biodiversity. Species richness during the year coho enter the ocean is weakly correlated with adult returns 1 year later (Figure 22); thus the average species–richness value of 13.2 in 2010 suggests low returns of coho salmon in 2011.

Northern Copepod Anomalies—Copepods transported to the Oregon coast from the north are cold–water species referred to as "northern copepods." Because these copepods originate in the coastal Gulf of Alaska, their presence indicates that waters from the coastal Gulf of Alaska are being fed into the coastal California Current. We developed the northern copepod biomass index as the log biomass anomaly of three species of cold–water copepods: *Calanus marshallae*, *Pseudocalanus mimus*, and *Acartia longiremis*. This index is calculated monthly, with anomalies measured against the averaging period for which we have collected samples (1996–2009).

Figure 24 compares time series between the PDO and northern copepod biomass anomalies. Data from 1996 to the present track closely with the PDO. This was especially significant in summer 2010, when the PDO had negative values for all months from May to September (the 3rd most negative values since 1998). The northern copepod index in 2010 was also quite high (4th highest since 1998). These were both indications of "good" ocean conditions and stand in stark contrast to values for copepod biodiversity, which point to "poor" ocean conditions in 2010." The northern copepod biomass index suggests coho returns of 3.7% in 2011, as well as above–average returns of both spring and fall Chinook salmon in 2012.

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. In most years, there is a time–lag between the date when coastal currents begin to reverse (the physical spring transition) and the date when animals from distant sources arrive in waters off the Oregon coast (distant sources being the coastal Gulf of Alaska in spring and coastal central California in autumn).

During 2010, the biological transition came late, on 15 May (day 135), as shown in Table 3. This is a somewhat negative indicator for salmonid fisheries in 2011 and 2012 because it means that ocean productivity was probably low in April–May 2010, when juvenile salmon first entered the sea. Several methods are used to calculate dates of the spring and fall transition, and a compilation of these methods (including our biological transition, is available from Columbia River DART (Data Access in Real Time), a project of the University of University of Washington School of Aquatic and Fishery Sciences.

Catches of Spring Chinook in June—Pelagic trawl surveys have been carried out for 13 years, since 1998. Catches of spring Chinook salmon have been high for the past 3 years, with the highest catches in 2008, and the 4th and 5th highest catches in 2009 and 2010, respectively (Figure 34). Results from the June 2010 surveys suggest above–average returns of spring Chinook salmon to the Columbia River in 2012.

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 34). Catches over the past 2 years have been among our lowest since 1998: the survey of September 2010 produced the 3rd lowest catch numbers of coho (11th of 13 surveys) since 1998. This suggests very low returns of adult coho salmon in both 2010 and 2011.

Forecast of Adult Returns for Coho in 2010 and Chinook Salmon in 2012

A trend toward cold ocean conditions that started in 2007 was interrupted by the emergence of an El Niño event in autumn 2009. This event caused warm ocean conditions, which continued through April 2010. In May, the El Niño receded and cooling resumed, and by July, the ocean was the coldest observed in recent years. In terms of ocean conditions for salmon, 2010 could be summarized in the words of Charles Dickens: "It was the best of times, it was the worst of times…" Our annual update of ecosystem indicators during 2010 is here, and our "stoplight" rankings and predictions are shown below in Table 1, Table 2, and Figure A.

Extremely mixed signals from ocean ecosystem indicators in 2010 made it difficult to forecast returns of coho salmon in 2011 and Chinook salmon in 2012. Our best guess is to expect near–average returns of coho in 2011 and Chinook in 2012. We do not think that the 2009–2010 El Niño had a devastating effect on juvenile salmon because by the time they entered the ocean in April–May, conditions were about average. Perhaps the most positive sign was that the ocean became very cold (and the PDO signal strongly negative) in summer 2010 and has remained so to date. These developments suggest that ocean conditions in 2011 may be among the best of the past 15 years.

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 2009.

	Juvenile migration year				Forecast of adult returns	
					Coho	Chinook
	2007	2008	2009	2010	2011	2012
Large–scale ocean and atmospheric indicators						
PDO (May–Sep)	■ red	■ green	■ yellow	■ green	● green	● green
MEI (annual)	■ green	■ green	■ yellow	■ yellow	● yellow	● yellow
Local and regional physical indicators						
Sea surface temperature anomalies	■ red	■ green	■ yellow	■ yellow	● yellow	● yellow
Coastal upwelling	■ green	■ green	■ yellow	■ red	● red	● red
Physical spring transition	■ green	■ yellow	■ yellow	■ yellow	● yellow	● yellow
Deep water temperature and salinity	■ yellow	■ green	■ yellow	■ red	● red	● red
Local biological indicators						
Copepod biodiversity	■ yellow	■ green	■ yellow	■ yellow	● yellow	● yellow
Northern copepod anomalies	■ green	■ green	■ green	■ green	● green	● green
Biological spring transition	■ green	■ green	■ green	■ yellow	● yellow	● yellow
June spring Chinook	■ green	■ green	■ green	■ yellow	—	● yellow
September Coho	■ red	■ yellow	■ red	■ red	● red	—

Key
- ■ (green) good conditions for salmon
- ■ (yellow) intermediate conditions for salmon
- ■ (red) poor conditions for salmon
- ● (green) good returns expected
- — no data
- ● (red) poor returns expected

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 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, 5–9 yellow, and 10–13 red. To arrive at these rank scores, 13 years of sampling data were compared across years (within each row), and each year received a rank between 1 and 13. Note that 2010 was characterized by a mix of ocean conditions resulting from a warm winter–spring and cold summer. Our "best guess" forecast would be for average returns of coho in 2011 and Chinook in 2012.

	Year of Samples												
	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Pacific Decadal Oscillation													
Dec–Mar	12	4	2	8	5	13	7	11	9	6	3	1	10
May–Sep	7	2	4	3	8	12	11	13	9	10	1	6	5
Multivariate El Niño Southern Oscillation Index													
MEI Annual	13	1	3	6	12	11	10	7	8	5	2	9	4
MEI Jan–Jun	13	1	3	4	9	10	8	11	5	7	2	6	12
Mean sea surface temperature (°C)													
Buoy 46050 (May–Sep)	11	8	3	4	1	7	13	10	5	12	2	9	6
NH 05 (May–Sep)	8	4	1	6	2	5	13	10	7	12	3	11	9
Winter prior to ocean entry (Nov–Mar)	13	10	3	5	6	9	11	8	7	2	1	4	12
Coastal upwelling													
Physical transition (upwelling index)	3	6	12	11	4	8	10	13	8	1	5	2	7
Anomalies (April–May)	7	1	12	3	6	10	9	13	7	2	4	5	11
Season length (upwelling index)	6	2	12	9	1	10	8	13	5	3	7	3	11
Deep water at NH 05 (May–Sep)													
Temperature (°C)	13	4	6	3	1	9	10	11	12	5	2	8	7
Salinity	13	3	6	2	5	11	12	8	7	1	4	9	10
Copepod indicators													
Biodiversity (species richness)	13	2	1	5	3	9	8	12	10	6	4	7	11
Anomalies	13	10	3	7	2	11	8	12	9	6	1	5	4
Community structure	13	3	4	6	1	9	10	12	11	7	2	5	8
Biological transition	13	7	5	3	6	11	9	12	10	4	1	2	8
Trawl survey catch													
Winter ichthyoplankton	13	6	2	4	5	9	12	8	11	10	1	7	3
Spring Chinook (June)	12	2	3	10	7	9	11	13	8	6	1	4	5
Coho (Sep)	9	2	1	4	3	5	10	12	7	8	6	13	11
Overall Ranking													
Mean rank	10.8	4.1	4.5	5.4	4.6	9.4	10.0	11.0	8.2	5.9	2.7	6.1	8.1
Rank of mean ranks	12	2	3	5	4	10	11	13	9	6	1	7	8

To generalize conditions for each year, the sum of all the rank scores for that year is divided by the number of indicators observed in that year. Mean ranks are then compared among years to give a generalized concept of "good" vs. "bad" ocean conditions for salmon in a given year. Data used in the rank scores above are shown in Table 3 below.

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

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Pacific Decadal Oscillation													
Dec–Mar	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
May–Sept	−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
Multivariate El Niño Southern Oscillation Index													
Annual	0.87	−0.85	−0.51	−0.18	0.59	0.46	0.38	0.40	0.22	−0.20	−0.65	0.32	–0.31
January–June	2.22	−0.85	−0.67	−0.30	0.31	0.57	0.26	0.62	−0.27	0.25	−0.84	−0.17	0.84
Sea surface temperature (°C)													
Buoy 46050 (May-Sep)	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
NH 05 (May-Sep)	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
NH 05 (Nov-Mar pre–entry)	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
NH 05 winter post–entry	10.80	9.96	10.04	10.11	10.78	11.02	10.74	10.47	9.84	9.36	10.03	11.28	--
Coastal upwelling													
Physical transition (d)	83	88	134	120	84	109	113	142	109	70	87	82	95
Anomalies (Apr–May)	−14	19	−36	2	−12	−34	−27	−55	−14	9	0	−5	–35
Season length (d)	191	205	151	173	218	168	177	129	195	201	179	201	161
Deep water at NH 05 (50 m)													
Temperature (°C)	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
Salinity	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
Zooplankton/copepod indicator													
Species richness	5.49	−2.46	−3.03	−0.41	−0.72	1.52	0.57	5.02	3.67	−0.39	−0.53	−0.35	3.7
N biomass anomalies	−1.97	−0.08	0.72	0.49	0.83	−0.08	0.26	−1.74	0.16	0.62	0.87	0.66	0.68
Community structure	0.75	–0.84	–0.83	–0.78	–0.98	–0.18	–0.11	0.57	0.00	–0.66	–0.93	–0.81	–0.19
Biological transition (d)	365	134	97	79	108	156	146	230	150	81	64	65	135
Trawl survey catch													
Winter Ichthyoplankton	0.16	0.90	1.80	1.25	1.05	0.63	0.58	0.83	0.59	0.60	1.84	0.89	1.65
June Chinook (fish/km)	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
September coho (fish/km)	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

In Figure A, counts of adult salmon at Bonneville Dam are plotted against the "Mean rank" from Table 2. "Mean rank" is a simple integrative index that we use to express the relative quality of ocean conditions in each juvenile migration year for which we have measurement data. As can be seen in the figure below, this index correlates well with adult counts at Bonneville Dam.

Figure A shows returns of adult salmon to Bonneville Dam (black dots) plotted against the mean ranks listed in Table 2. For forecasting purposes, the mean rank of 8.1 for 2010 corresponds to predicted returns (arrows) of about 160,000 spring Chinook and 325,000 fall Chinook in 2012, and 100,000 coho salmon in 2011. Adult return years are lagged behind mean ranks by 2 years for spring and fall Chinook salmon and by 1 year for coho salmon. Given that ocean conditions in 2010 were poor during winter–spring but excellent during summer, we are uncertain about the accuracy of these forecasts.

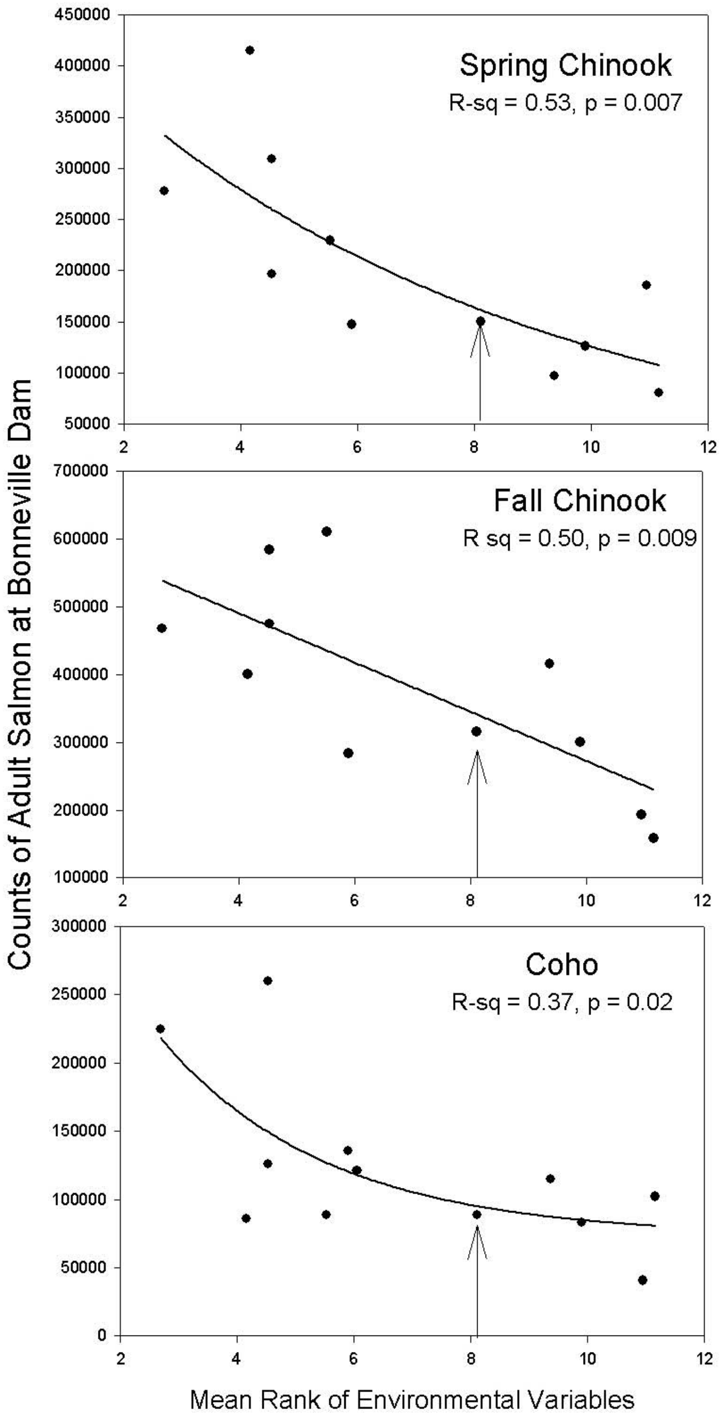


Figure A. Adult salmon returns at Bonneville Dam vs. mean rank of ocean indicators. Arrows show predicted returns. With a mean rank of 8.1 for 2010, the spring Chinook salmon forecast (top panel) is 160,000 adults in 2012, slightly more than the long–term mean. Returns could be 325,000 for fall Chinook (middle panel) and on the order of 100,000 for coho (lower panel passing Bonneville Dam in 2011.

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 is color–coded according to ranks of adult return data from each year for which we have corresponding ocean indicator data. Adult data is lagged behind ocean entry by 1 year for coho and 2-3 years for spring and fall Chinook salmon; therefore, as of 2010, we have 13 years of indicator data but only 10 years of adult return data. Our adult color–coding system ranks 1−3 green, 4−7 yellow, and 8−10 red.

Table 4. Ranks among years for adult returns by year of ocean entry, 1998–2007. With 10 years of data available, color-coded ranks are 1−3 green, 4−7 yellow, and 8−10 red.

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	10	4	6	1
1999	8	1	3	3
2000	1	2	1	4
2001	4	3	2	2
2002	2	5	5	8
2003	3	9	8	9
2004	9	8	10	10
2005	7	10	7	5
2006	6	6	9	7
2007	5[2]	7	4	6[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.

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 13 years of ocean ecosystem indicator data, we have only 10 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	390,496	218,077
1999	0.0227	391,367	463,745	187,333
2000	0.0459	268,813	600,353	160,788
2001	0.0258	192,010	574,976	191,448
2002	0.0399	168,656	410,426	78,944
2003	0.0282	74,038	298,897	65,227
2004	0.0185	96,456	151,490	61,374
2005	0.0228	66,624	307,834	132,131
2006	0.0231	124,336	275,000	92,758[2]
2007	0.0245	114,525	459,761	100,748
2008	0.0468[2]	244,418	—	—

[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.

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 (PFMC 2000–present). Counts of spring and fall Chinook at Bonneville were provided by the Columbia River DART project (1996–present). These sources are publicly available via the internet.

Note also that these estimates were not adjusted for catch in the fisheries, which can have a major impact on adult numbers. For example, in 2005, the subyearling Chinook fishery in the Klamath River was closed, and adult numbers were far higher than in either the preceding or following year. This was likely due to the fishery closure, which would have masked any change related to ocean conditions or other factors.

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.

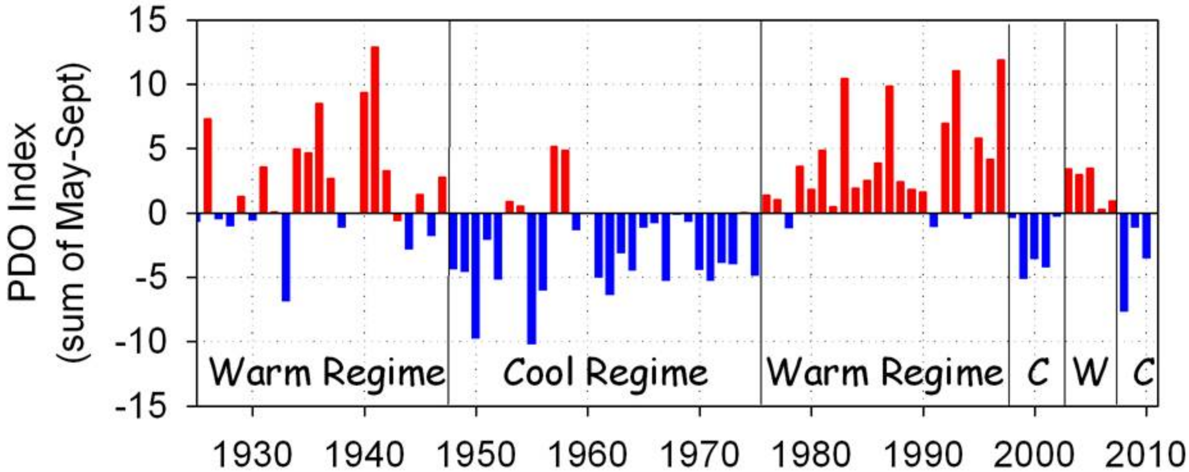


Figure 2. Time series of shifts in sign of the Pacific Decadal Oscillation (PDO), 1925 to 2010. Values are averaged over the months of May through September. Red bars indicate positive (warm) years; blue bars negative (cool) years. Note that 2008 was the most negative since 1956.

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. Recently, however, these decadal cycles have 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 became strongly negative through summer and autumn 2010.

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.

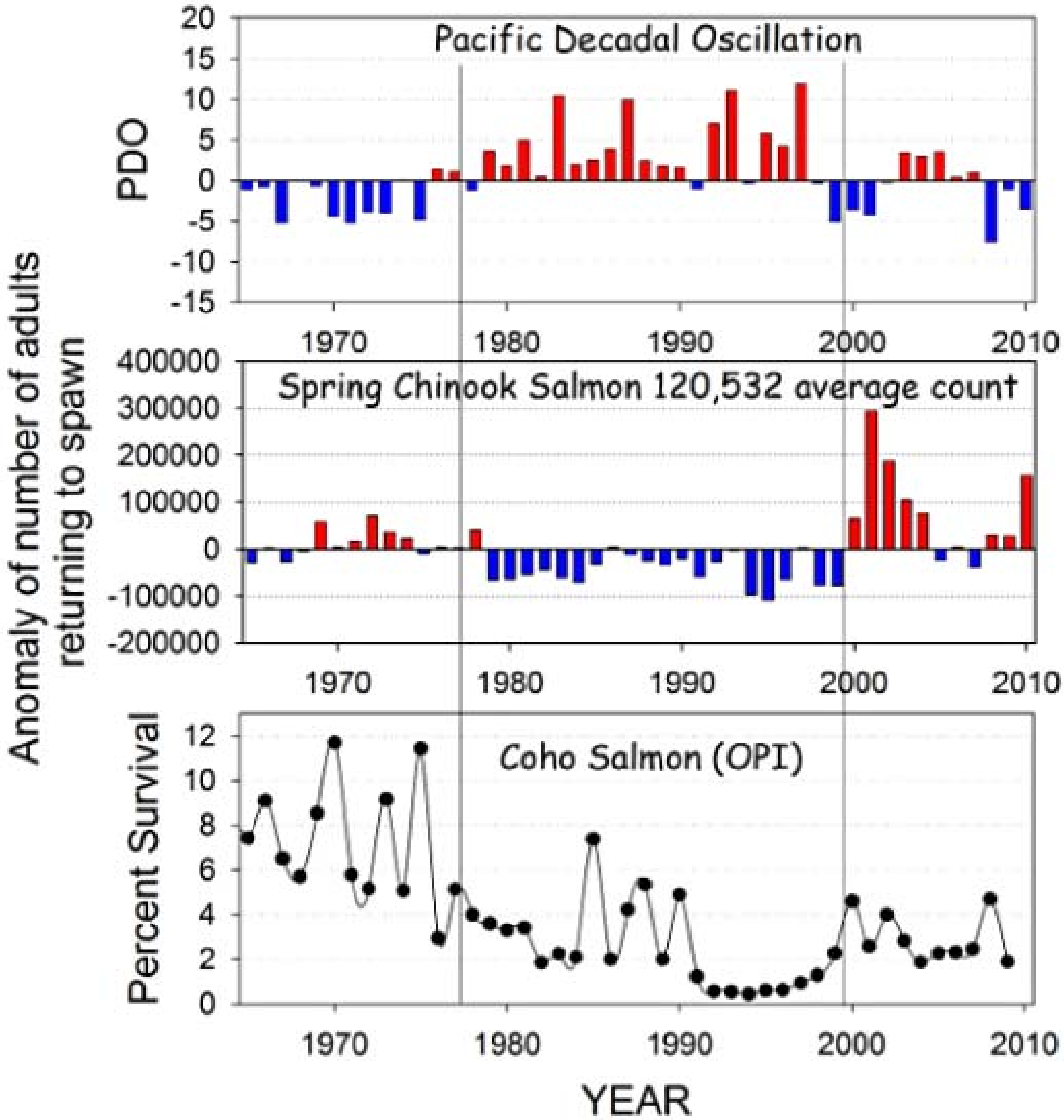


Figure 3. Upper panel shows summer average PDO, 1965–2010; middle panel shows anomalies in counts of adult spring Chinook passing Bonneville Dam for the same period; lower panel shows survival of hatchery coho salmon from 1965–2009. Vertical lines indicate climate–shift points in 1977 and 1998.

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 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.

Multivariate El Niño Southern Oscillation Index (MEI)

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.

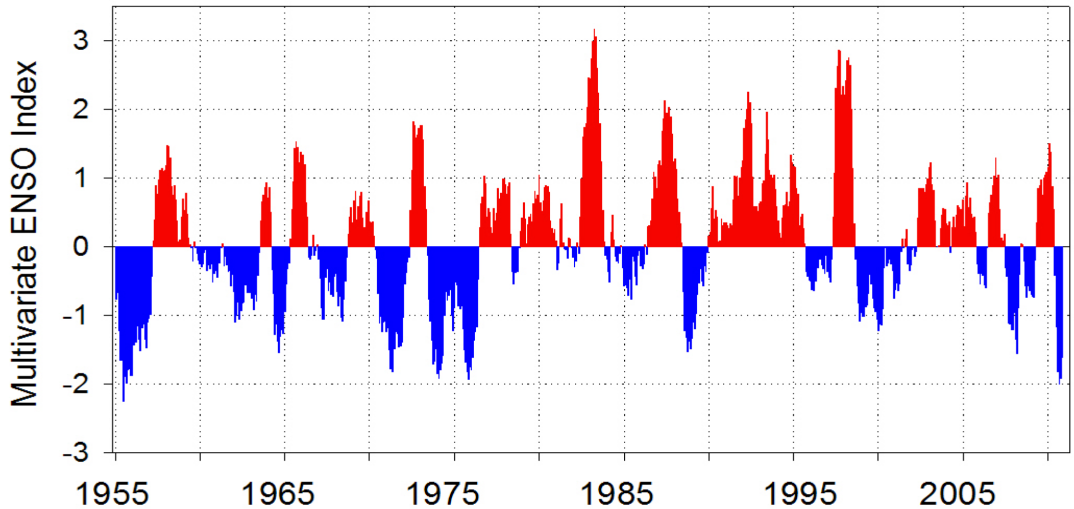


Figure 4. Values of the MEI, 1955–2010. Red bars indicate warm conditions in the equatorial Pacific, blue bars indicate cool conditions in equatorial waters. Large and prolonged El Niño events are indicated by large values of the index: note the +3 value associated with the 1983 and 1998 events and the prolonged period of warm conditions at the equator from 1977 to 1996. Note cool anomalies during 1999–2002 and 2007–spring 2009. An El Niño event developed in equatorial waters in mid–2009 and remained in effect from May 2009 through May 2010. Extreme negative values of nearly –2 were seen from August through November 2010. The last time such values were seen was the mid–1950s and mid–1970s.

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 Multivariate ENSO Index, or MEI. A time series of the MEI 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).

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, MEI values turned negative and remained so for nearly 4 years, similar to the trend observed in the PDO. The MEI 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 once again, and the largest negative values seen since the mid–1950s and mid–1970s were observed in August–November 2010.

Both the PDO and MEI 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 MEI 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.

The winter of 2009–2010 did result in El Niño conditions in the northern California Current as shown by elevated sea surface temperatures (Figure 5) and increased copepod biodiversity (Figure 21). The impact of El Niño events on survival of coho salmon is well documented (Pearcy 1992). For example, large El Niño events in both 1983 and 1998 were followed by low adult return rates of coho salmon the following year.

Likewise, the extended period of El Niño conditions in 1977–1983 was accompanied by declines in adult coho returns during the same years. A second extended El Niño period during 1990–1996 was followed by extremely low returns of adult fish that migrated to sea as juveniles from 1991 to 1998. For spring Chinook, the two large El Niño events resulted in lower–than–average smolt–to–adult return rates, but the lowest adult return rates were observed during the weaker but prolonged El Niño events of 1990–1998.

Declines in adult Chinook salmon returns from 2004 to 2007 were likely related to the period of warm ocean and weak but persistent El Niño conditions during 2003–2006. The impact of the 2009–2010 El Niño event on salmonid stocks remains uncertain, since adult returns of smolts that entered the ocean in spring 2010 are not due until 2011 for coho and 2012 or later for Chinook.

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 2010. This is the period during which we have been measuring local ocean conditions.

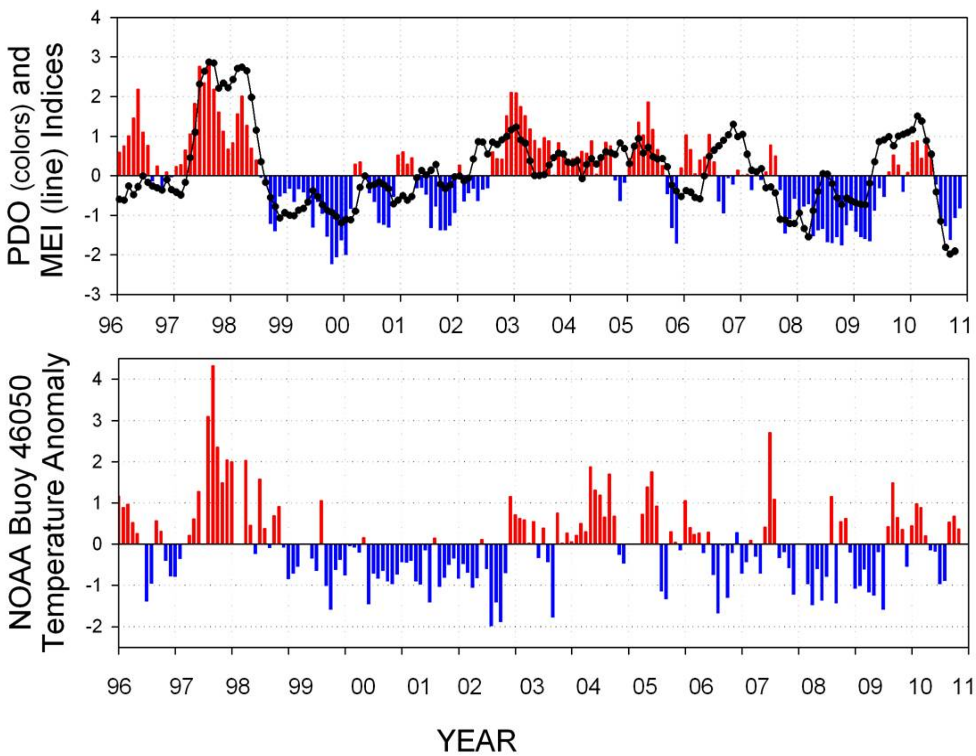


Figure 5. The PDO and monthly sea surface temperature anomalies at NOAA Buoy 46050, 22 miles west of Newport OR.

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 2010, moderately warm ocean conditions were found from January through most of May, after which upwelling was initiated. Upwelling was initially quite weak, and was interrupted by a strong downwelling event in late June. However, several lengthy and strong events occurred in July and August, after which upwelling ceased in mid–September (Figure 6).

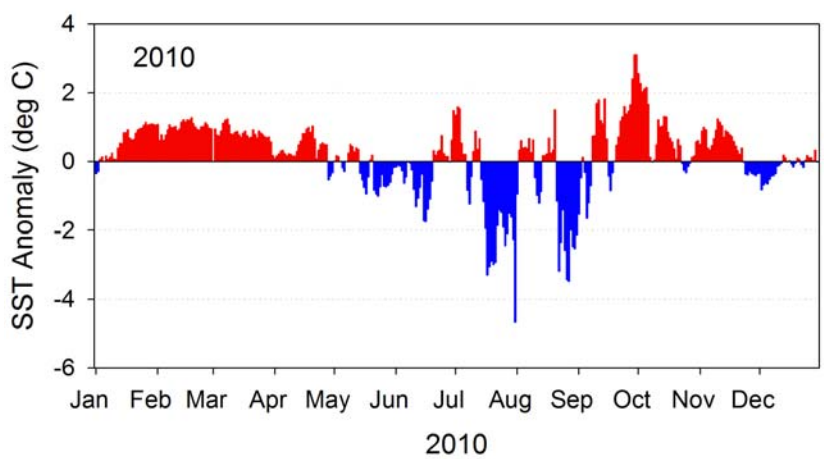


Figure 6. Daily sea surface temperature anomalies measured at NOAA Buoy 46050, located 22 miles off Newport, OR, in 2010.

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 (2009–2010) was about +0.5°C below normal, whereas SSTs during the previous three winters were colder by about −0.9°C. Summer SST in 2010 was slightly below average.

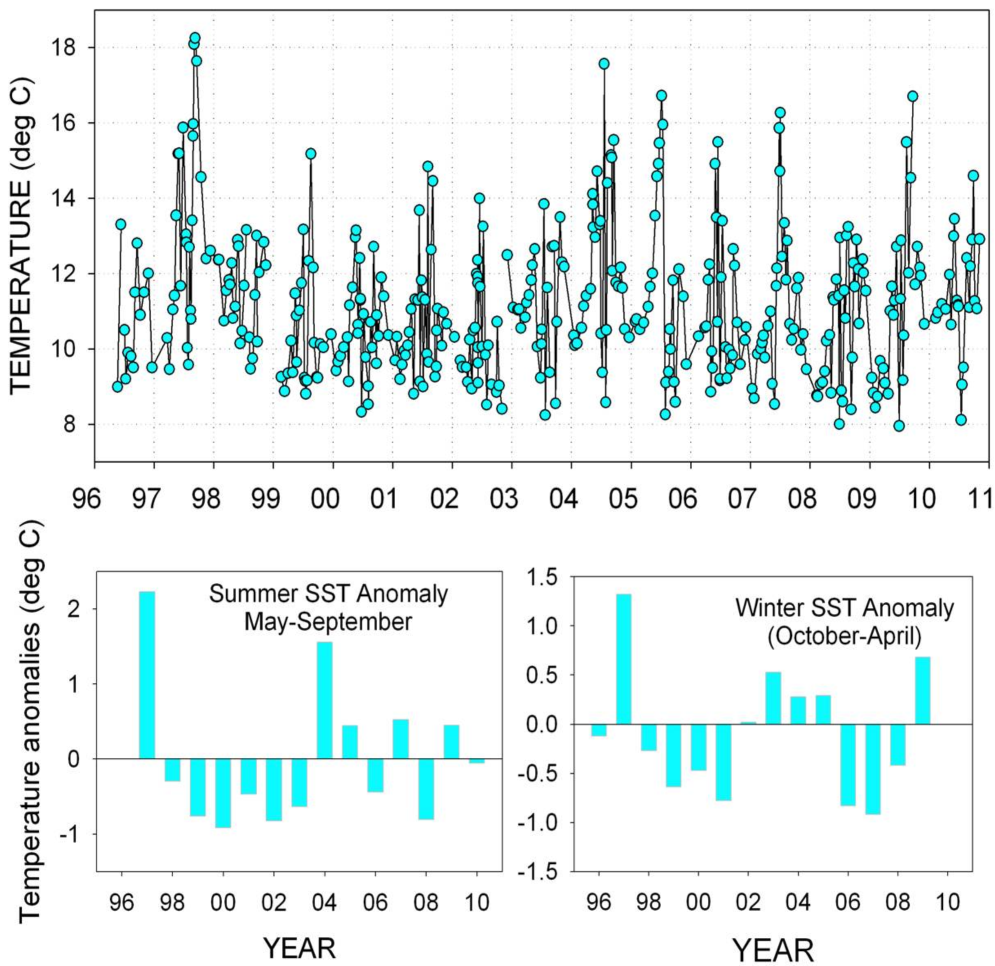


Figure 7. Upper panel shows average sea surface temperatures at Station NH 05, located 5 miles off Newport, Oregon, from 1996 through 2010. Lower panel shows temperature anomalies during the same years during summer (left) or May–September and winter (right) or October–April.

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).

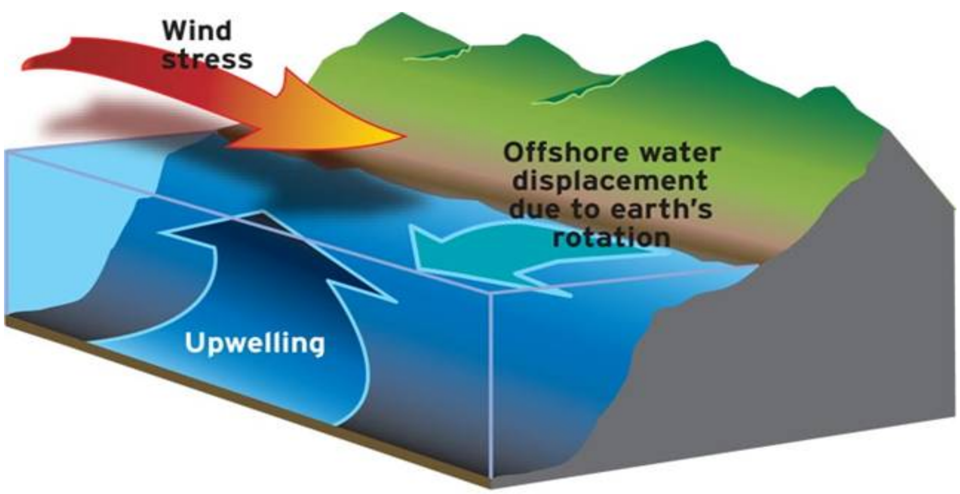


Figure 8. Forces affecting coastal upwelling.

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.

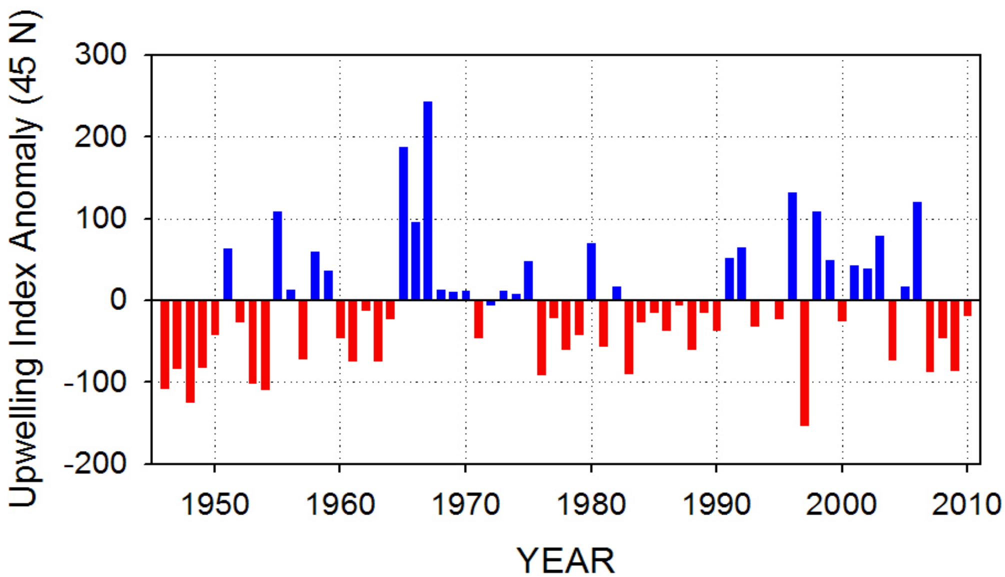


Figure 9. Anomalies of the coastal Upwelling Index during May to September each year, 1946–2010.

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.

Upwelling in 2010—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 96 (6 April) in 2010. Upwelling was interrupted by a significant 3–week downwelling event from mid–May to early June (black bar in Figure 10). Following this event, there was consistent and relatively strong upwelling throughout much of the summer, with an ultimate reversal to primarily downwelling on day 256 (13 September). The cessation of upwelling in mid-September resulted in one of the shortest annual upwelling periods since 1998. The total amount of upwelling for 2010 was 4,910 m^3/s per 100 m of coastline, which was 20% lower than the 40–year average of 6,163 m^3/s per 100 m.

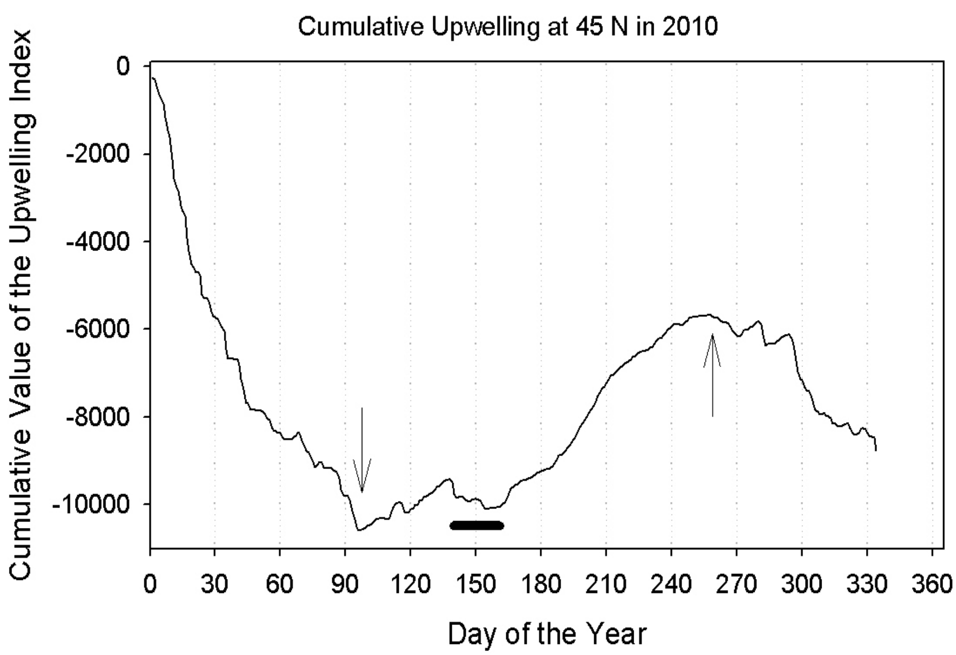


Figure 10. Cumulative upwelling index through 2010. Black horizontal bar indicates a weak downwelling event from mid–May to early June 2010.

When Figure 10 is compared to Figure 6 (which shows SST time series to 2010), one sees the result of an early end to upwelling in the warm temperature anomalies persisting from early September through the end of 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).

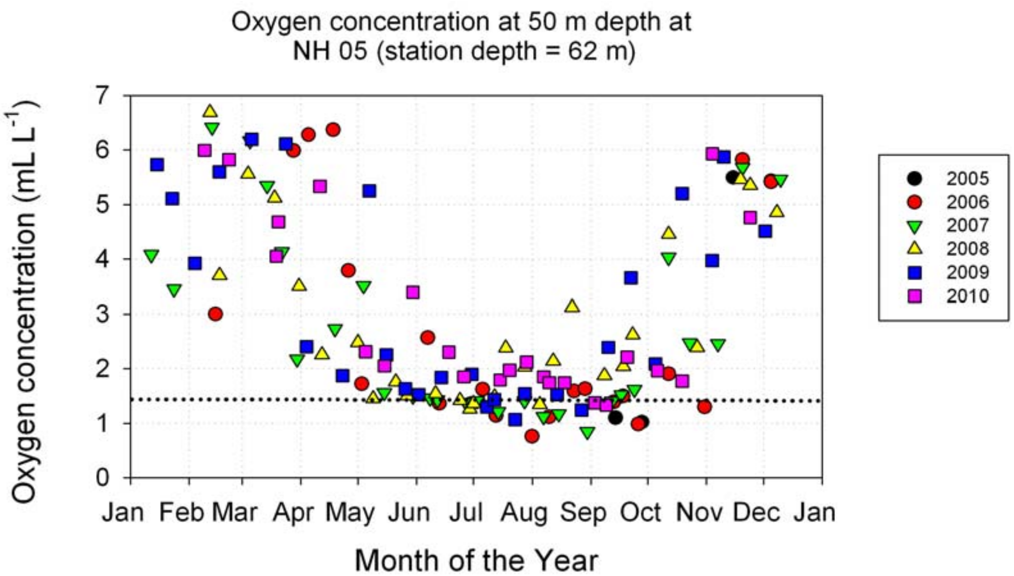


Figure 11. Oxygen concentration in bottom waters at a baseline station NH 05. Hypoxia is defined as waters with oxygen concentrations <1.4 mg/L, and is observed only during the coastal upwelling season, especially during Jun–Sep. Hypoxia was particularly severe during July 2006, but relatively weak in 2010. Values <1.4 mg/L were seen only during the month of September.

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.

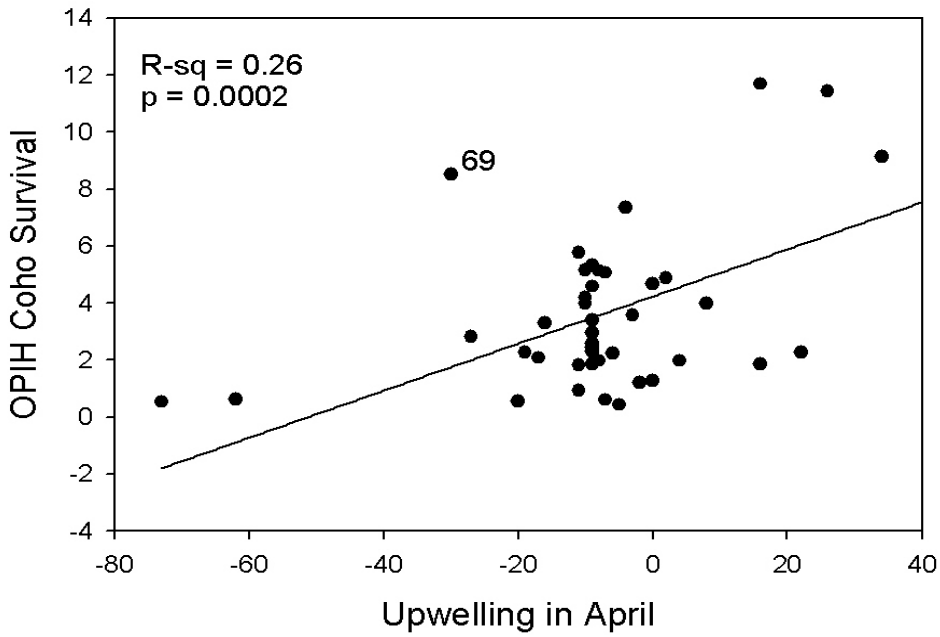


Figure 12. Scattergram of coho survival (%) vs. upwelling anomalies at 45°N during April 1969–present. No other month produced a significant correlation. When the year 1969 was excluded from the regression, R^2 improved from 0.20 to 0.26.

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.

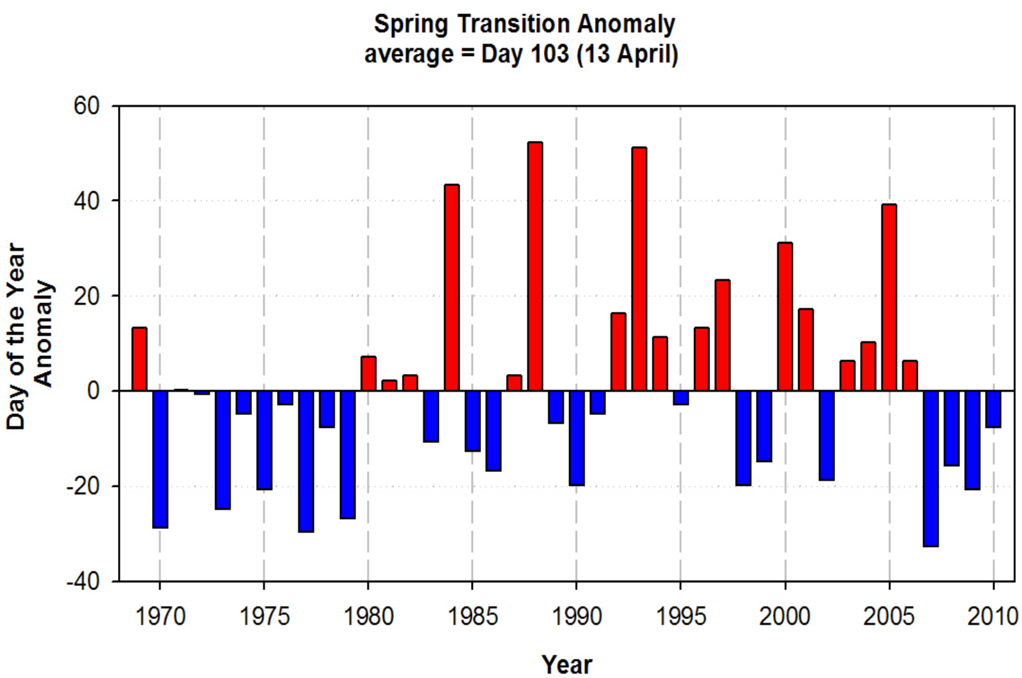


Figure 13. Anomalies in the date of the physical spring transition from 1969 to 2010. Anomaly is based on an average date of 13 April using the minimum cumulative upwelling index (CUI) value.

The date of spring transition can be indexed in several ways. 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 (Figure 13). Based on the index of Logerwell and her associates, the mean date of the transition is 6 April, but it can range from early February to early July. 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).

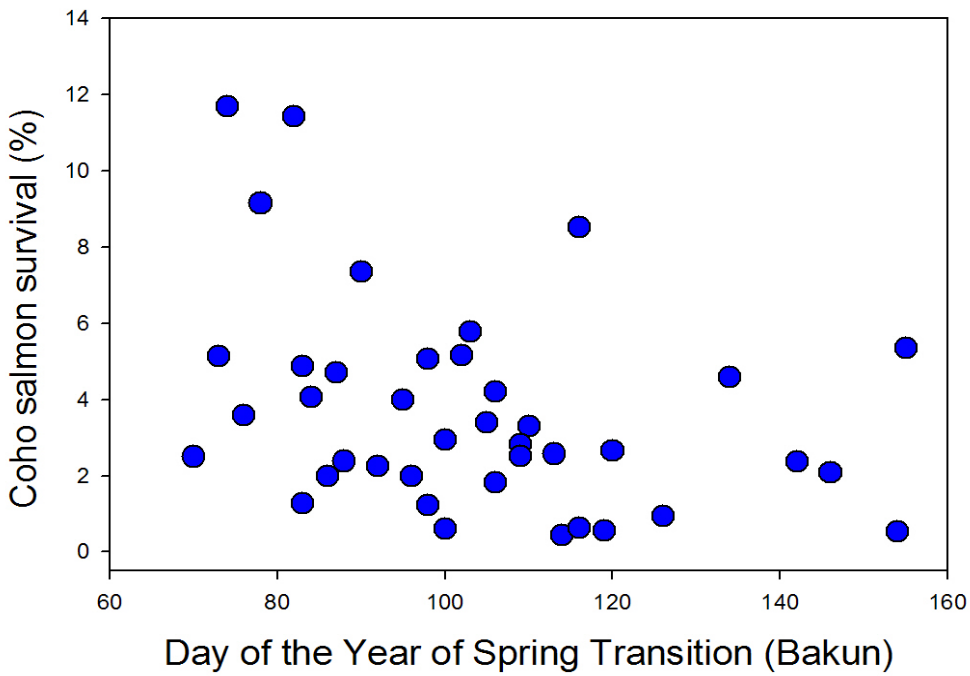


Figure 14. Coho salmon survival vs. day of spring transition. Date of spring transition is based on the lowest cumulative Upwelling Index value. Data are from 1969–2008.

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.

Another measure of the spring transition comes from monitoring of ocean currents on a daily basis. Dr. Mike Kosro, College of Oceanic and Atmospheric Sciences, Oregon State University, 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.

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.

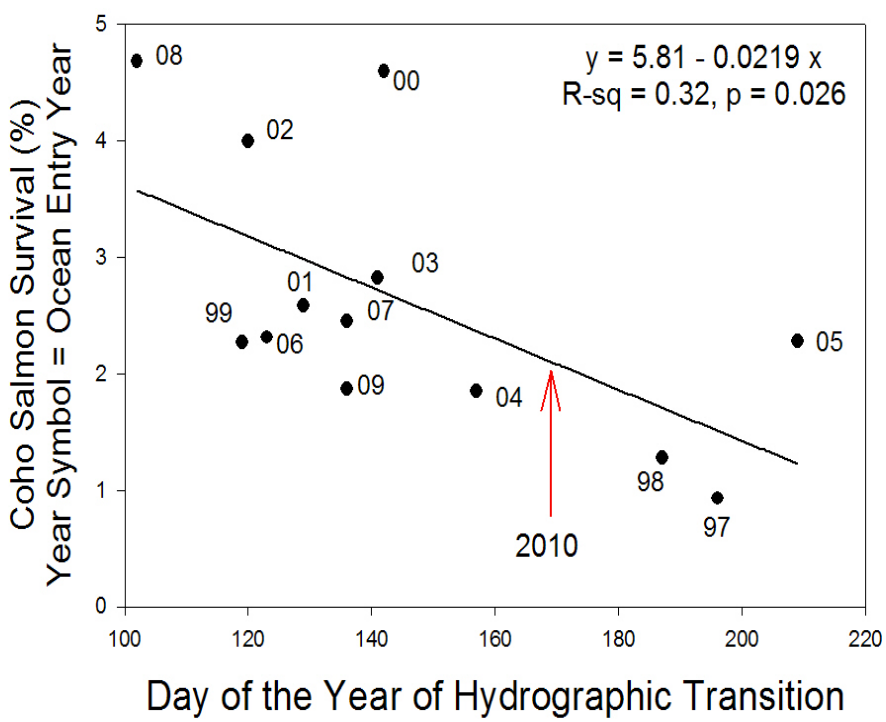


Figure 15. Coho survival vs. spring transition as indicated by the day of the year when bottom water temperature dropped below 8.0°C.

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 (CC). 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 West Wind Drift is nutrient depleted.

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 2007–2008 were colder than average and corresponded to a cool–phase PDO (and to negative SST anomalies at Buoy 46050). The years 2009 and 2010 had intermediate salinity and temperature values.

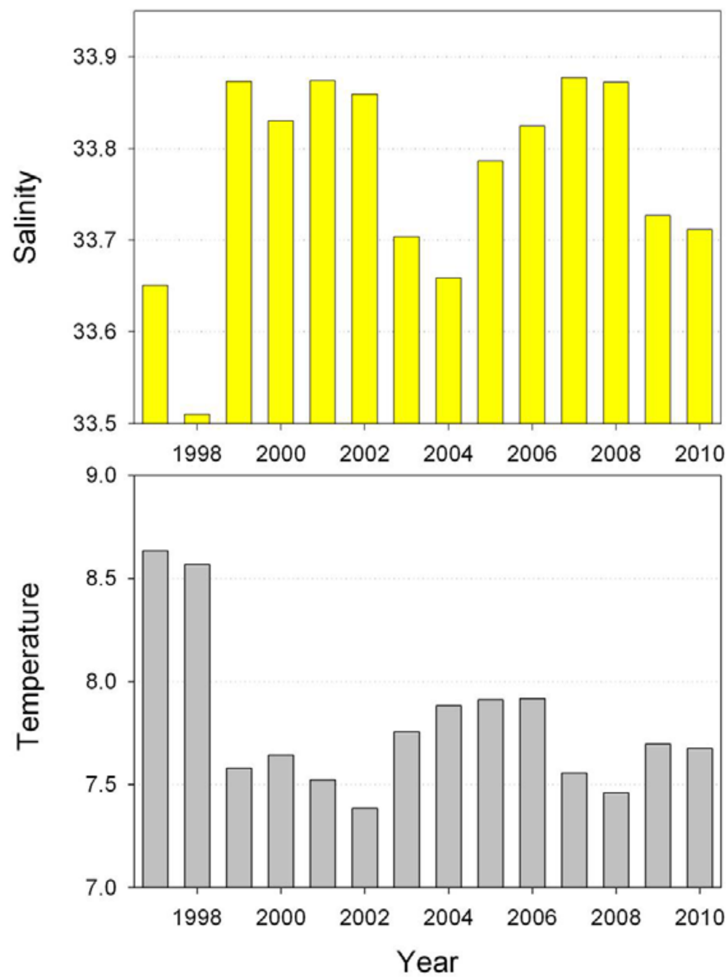


Figure 16. Mean salinity (upper panel) and temperature (lower panel) at 50–m water depth from station NH 05 (water depth 60 m) averaged over all cruises from May to September each year. Note that the deeper waters of the shelf in 2009 are slightly warmer and saltier than values observed during the previous "cold phase" of 1999–2002 and 2007–2008.

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 2009–2010.

Finally, Figure 17 illustrates the unusual nature of hydrographic conditions during 2010 (middle and lower panels): between April and June, upwelling was weak, and intermediate temperature and salinity values were found in shelf waters; however, a sudden reversal of temperatures in mid–July led to the coldest summer average temperatures (July–September) observed since our time series began. As noted in Figure 6, strong upwelling in July and August drove extremely cold waters to the surface, producing anomalies of –2 to –3°C.

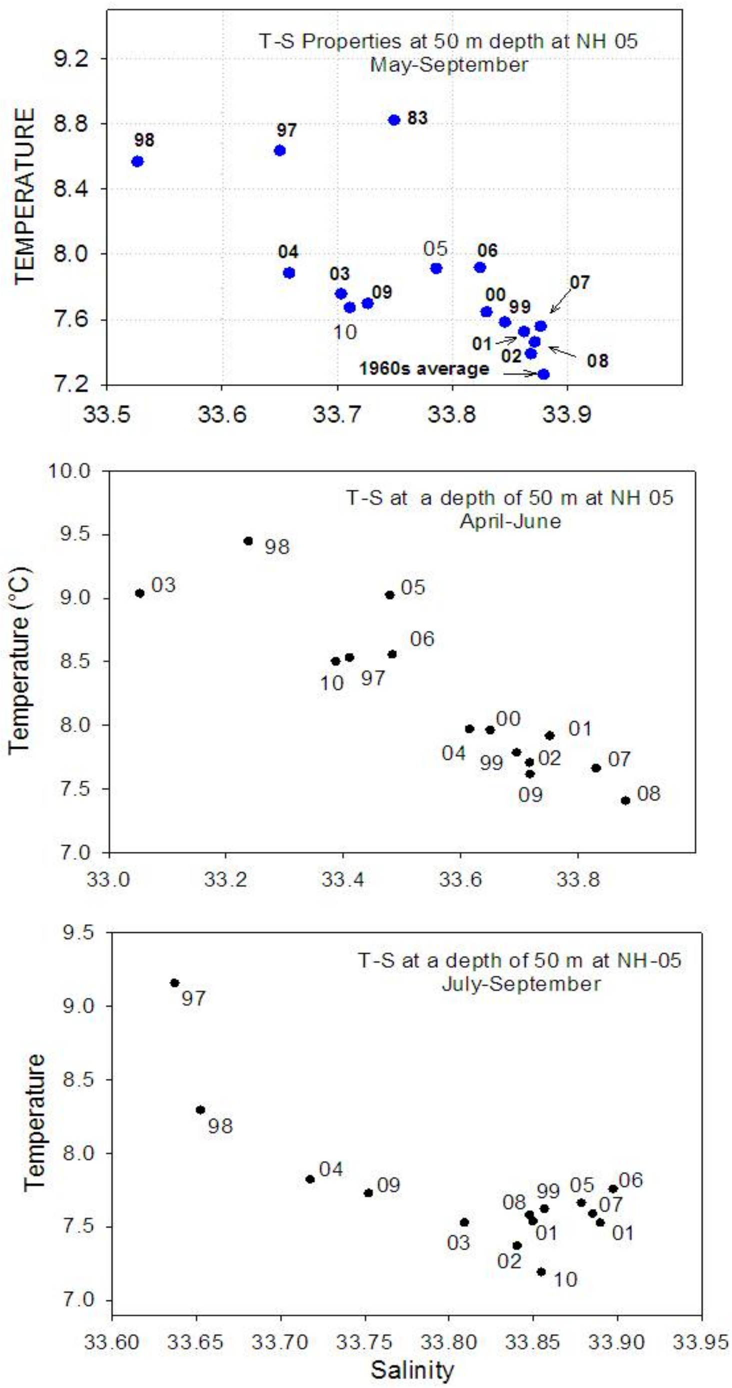


Figure 17. Average temperature and salinity during the April–June (upper panel) and May–September (middle panel) upwelling season from 1997 to 2010. Lower panel Average temperature and salinity values during July–September 1997–2010. Early in the upwelling season of 2010, upwelling was weak, with intermediate values of temperature and salinity, but later in the season (July) upwelling intensified and temperatures dropped to the lowest seen in our 14–year record.

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.

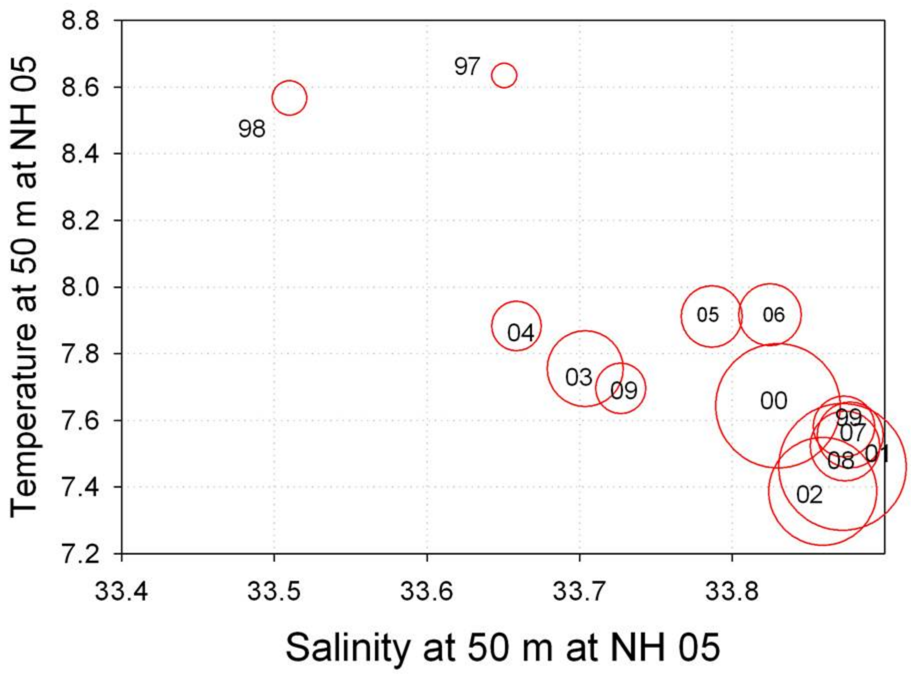


Figure 18. Coho survival shown as a bubble plot vs. temperature and salinity at the 50–m depth at hydrographic station NH 05. Bubble size is proportional to OPIH estimates of total freshwater escapement (proportion of the juvenile population returning to spawn). Coho survival is high when upwelling is strong, as indicated by the presence of "cold salty" water on the continental shelf. For example, in 2000, 2002, and 2008, the OPIH was 4.6, 4.0, and 4.7%.

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.

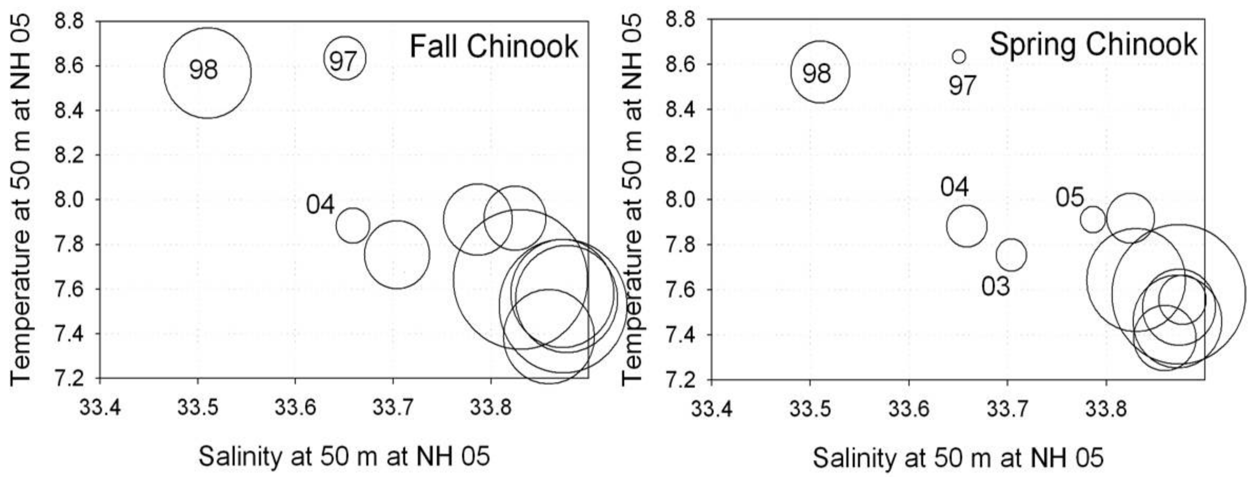


Figure 19. Bubble plot showing relationship between Chinook returns (circles) and summer average temperature and salinity measured 2 years earlier at the 50–m depth of hydrographic station NH 05.

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 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.

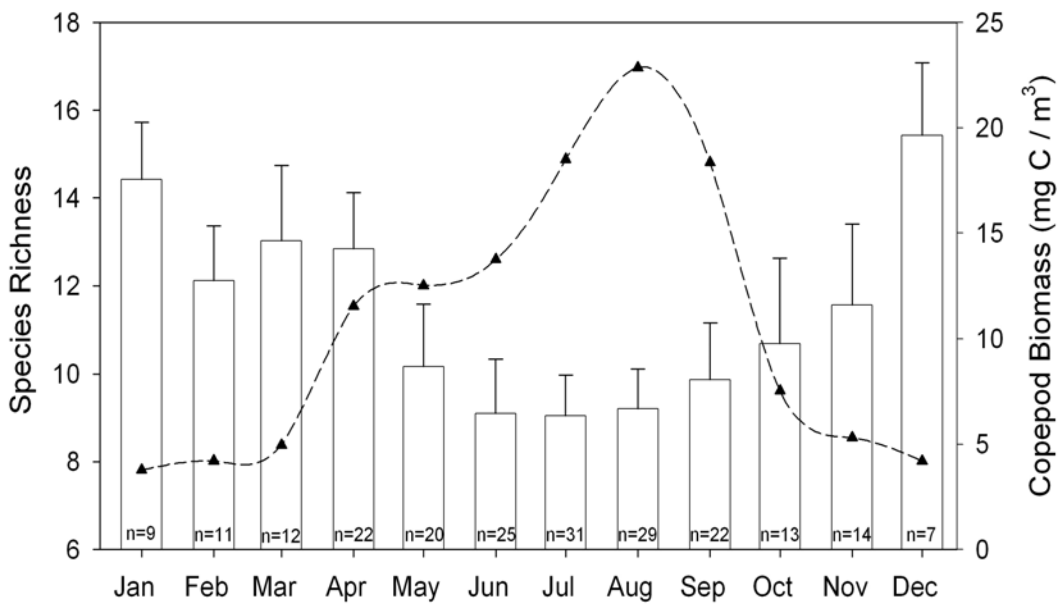


Figure 20. Vertical bars are the climatology of monthly averaged copepod species richness, a measure of biodiversity, at station NH 05 off Newport OR. Dashed line with filled triangles is the climatology of monthly averaged copepod biomass (Y–axis on right side of graph). Note the inverse relationship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

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 1996–2010. This time series is derived by taking the average number of species for each month, then subtracting the observed monthly average for that month.

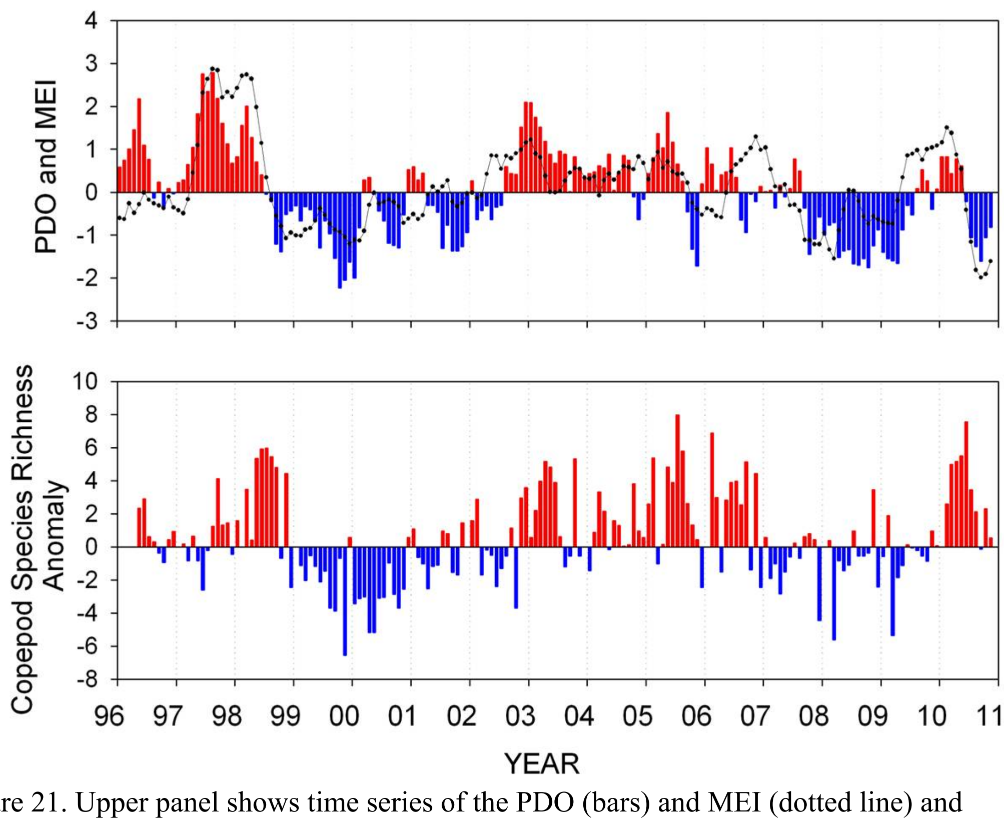


Figure 21. Upper panel shows time series of the PDO (bars) and MEI (dotted line) and lower panel shows anomalies in copepod species richness during 1996–present. Note the brief lag between long–term persistent shifts in the PDO and MEI and anomalies in copepod species richness, as seen in 1998, 2002,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

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

Note that three pronounced changes in copepod species richness lagged the PDO and MEI 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 in July and MEI in August. 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 MEI in August and April, respectively.

Additional signal changes occurred in summer 2007 and 2010, although species richness showed only a moderate response to the former. Note that the brief El Niño event of 2009–2010 (shown by moderately positive PDO and MEI values) resulted in high species richness during February–August 2010).

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 the OPIH survival time series (Figure 22), suggesting that copepods are reasonably good indicators of salmon survival.

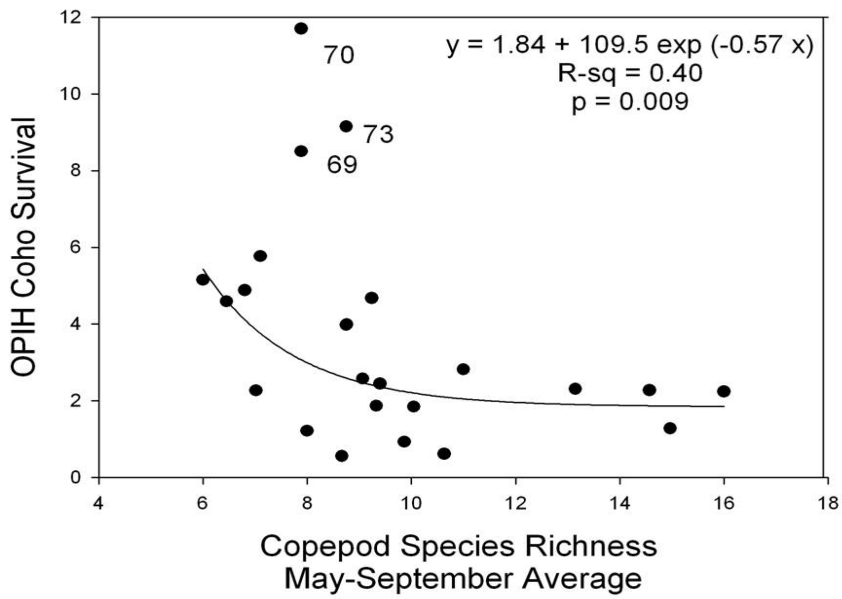


Figure 22. Scattergram showing relationship between copepod species richness and survival of OPIH coho salmon. The regression equation shown was calculated after excluding the years 1969, 1970, and 1973—years with extraordinarily high survival.

The regression of OPIH coho on 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).

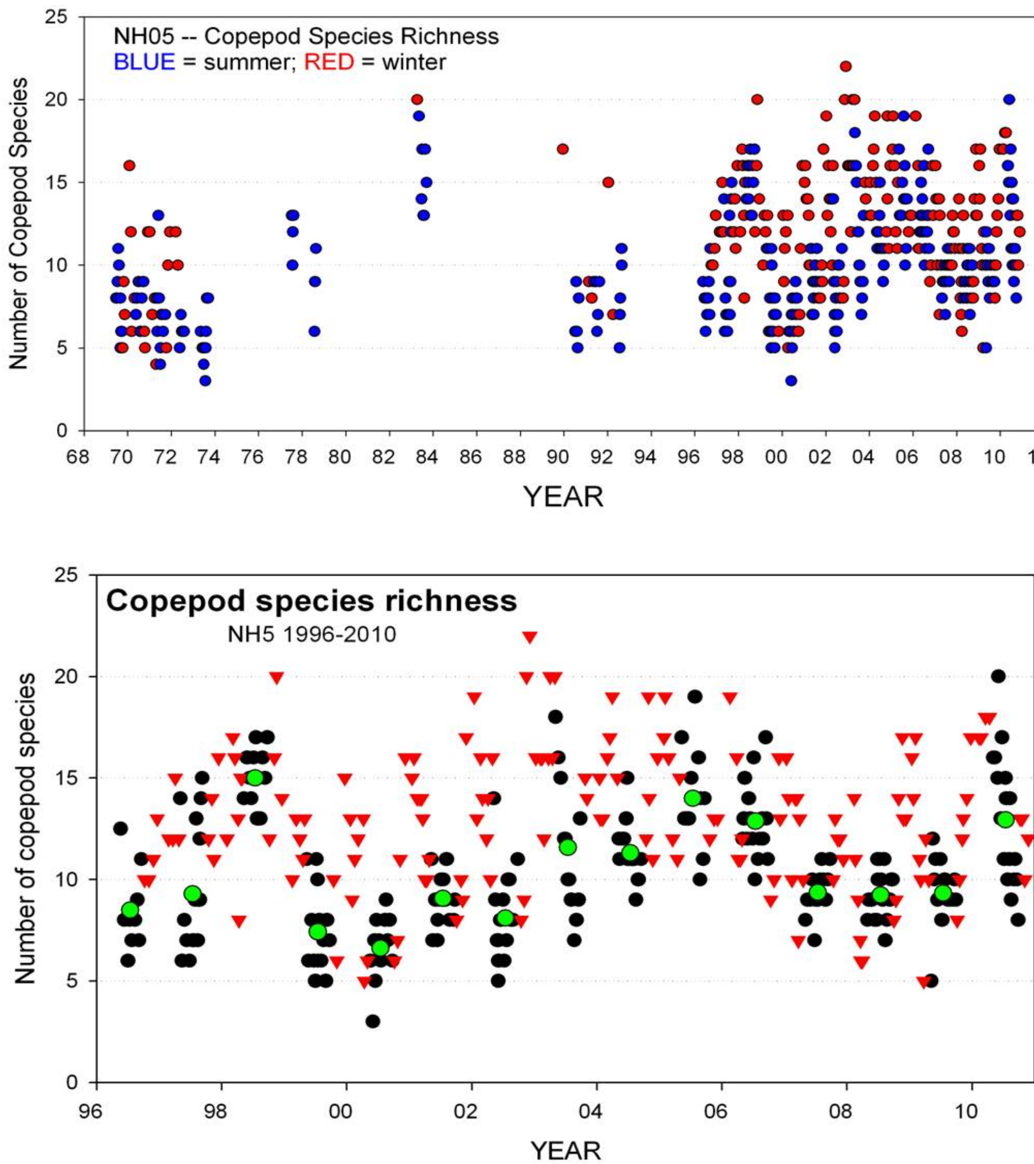


Figure 23. Copepod species richness from 1969 to present (upper panel) and from 1996 to present (lower panel) to highlight the among–year differences. Note that the number of copepod species has been increasing over the past decade compared to the 1970s. Red triangles are winter, black circles summer, 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.

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*.

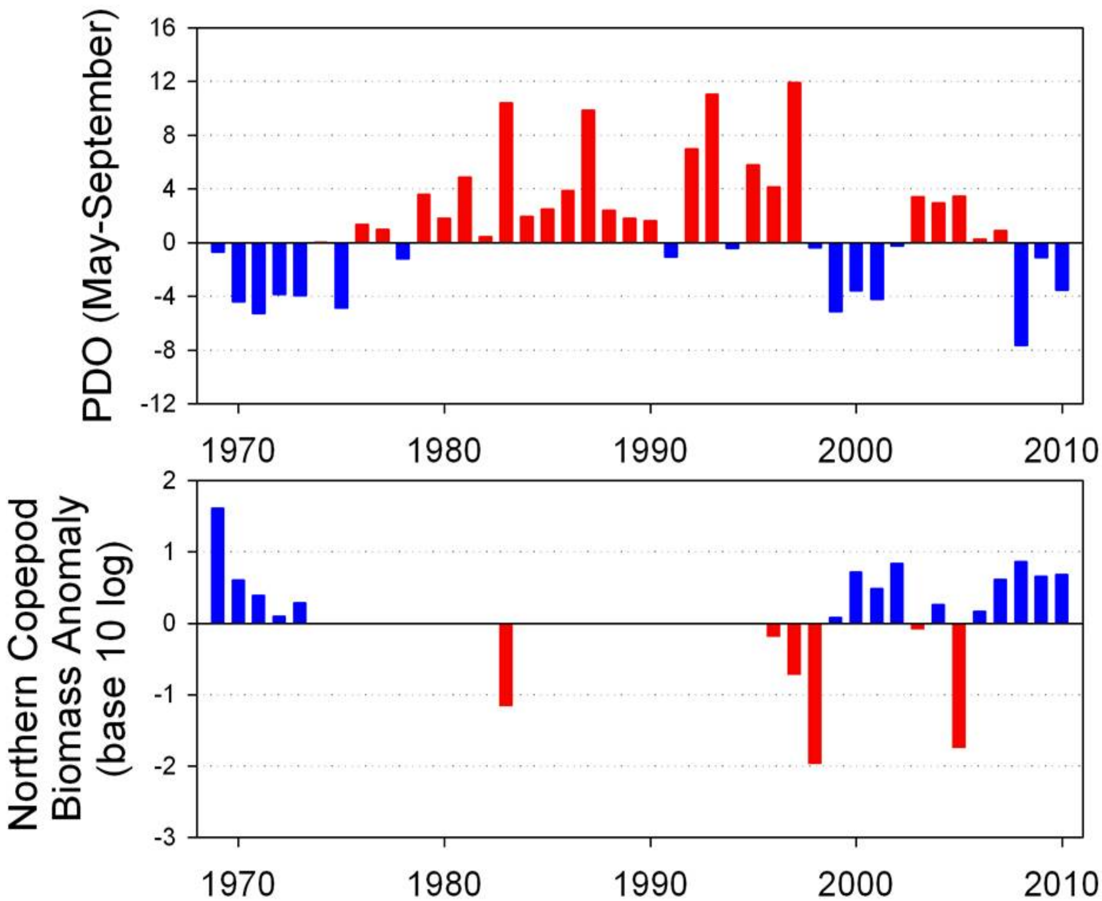


Figure 24. The Pacific Decadal Oscillation (upper), and northern copepod biomass anomalies (lower), from 1969 through 2010. Biomass values are log base–10 in units of mg carbon m^{-3}.

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 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.

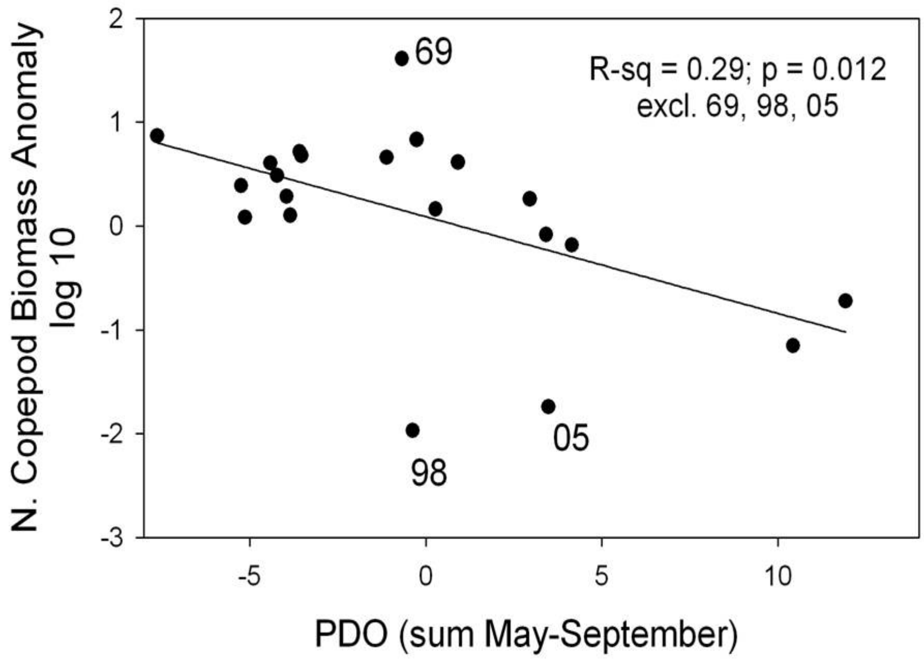


Figure 25. Regression of northern copepod anomalies vs. the PDO. Units of biomass are mg carbon m^3. Strongly negative PDO values lead to high biomass of cold–water copepods and vice versa. The regression line shown was calculated after excluding the outlying data points from 1998 (an El Niño year) and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

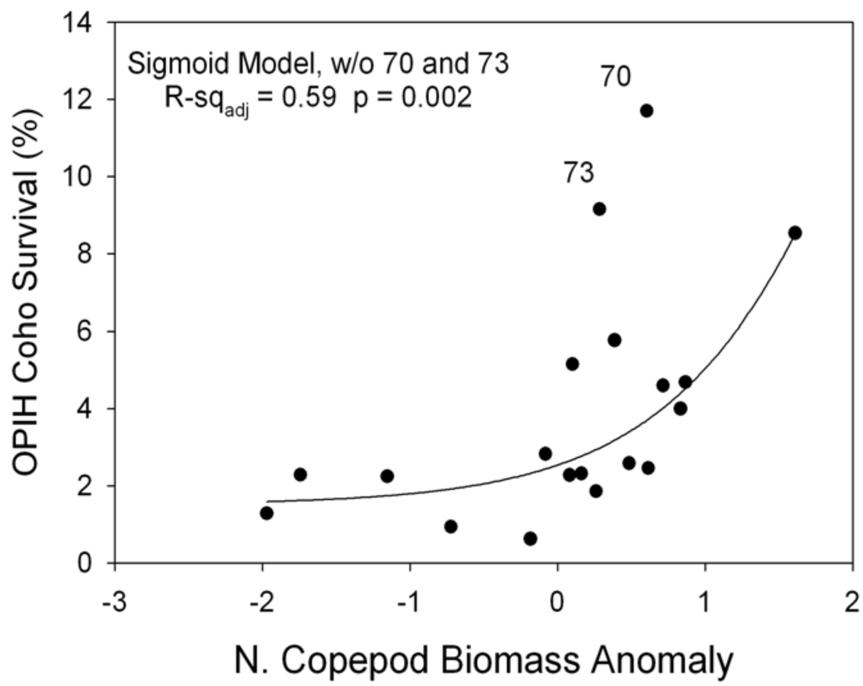


Figure 26. Regression of OPIH coho survival on the northern copepod biomass anomalies.

[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).

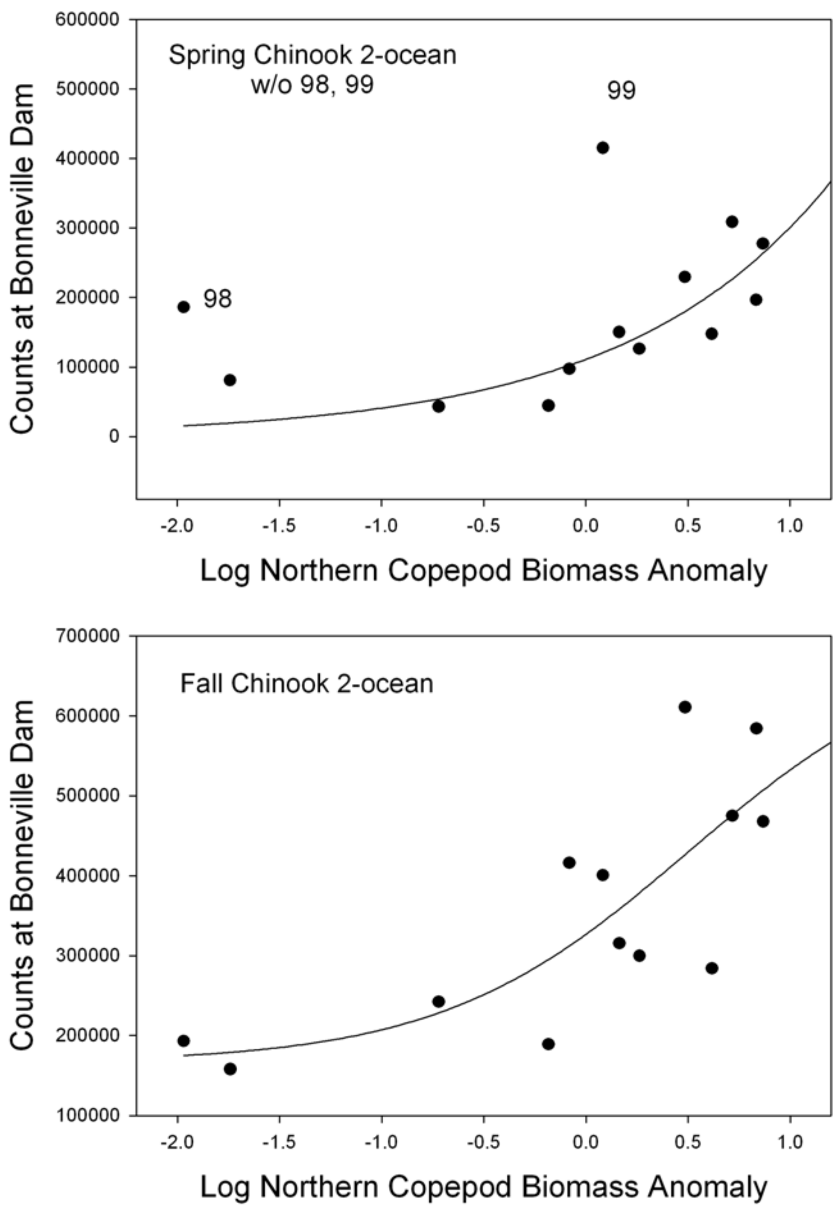


Figure 27. Relationship between counts of adult spring Chinook (upper panel) and fall Chinook (lower panel) at Bonneville Dam vs. log of the northern copepod biomass anomaly during the year of ocean entry. Counts at Bonneville are lagged by 2 years.

Northern copepod biomass predicted spring Chinook returns well if ocean entry years of 1998 and 1999 were excluded. An exponential model (y = 110,871 e0.998×) yielded the best fit, with an R^2 (adjusted) of 0.68. When 1999 was included in the same model, R^2 dropped to 0.25 and P to 0.06. For fall Chinook runs, a 3–parameter sigmoid model resulted in the best fit, with an R^2 (adjusted) = 0.47 and P = 0.03.

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 ecoystem 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 89% of the variability between copepod communities, with the X–axis accounting for 68% and the Y–axis for 15%. Figure 28 compares these summer-average scores.

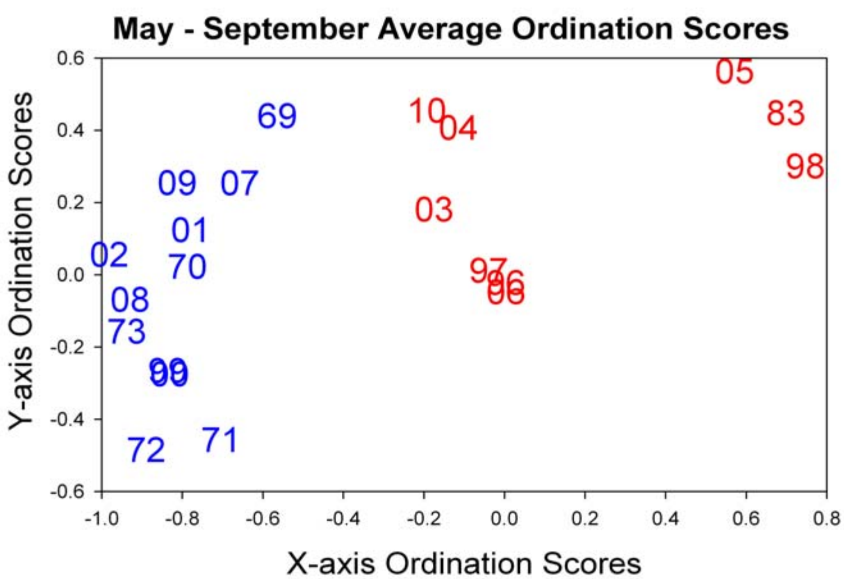


Figure 28. Ordination of copepod community structure averaged over May–September, by year. Years when summer community structure was dominated by cold, boreal species fall into the left quadrant (1970–1973, 1999–2002, 2007–2009); years with warm subtropical species fall in to the center of the graph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

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).

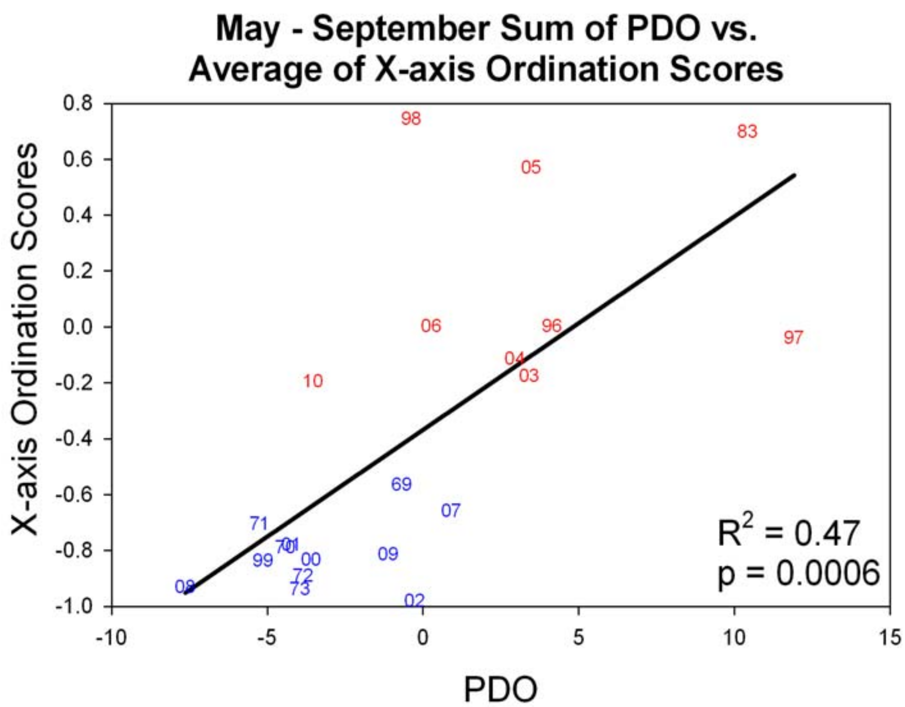


Figure 29. Relationship between the PDO and X–axis ordination scores. A "cold–water zooplankton community" is associated with the negative (cold) phase of the PDO and vice versa. Red and blue numbers indicate the year.

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.

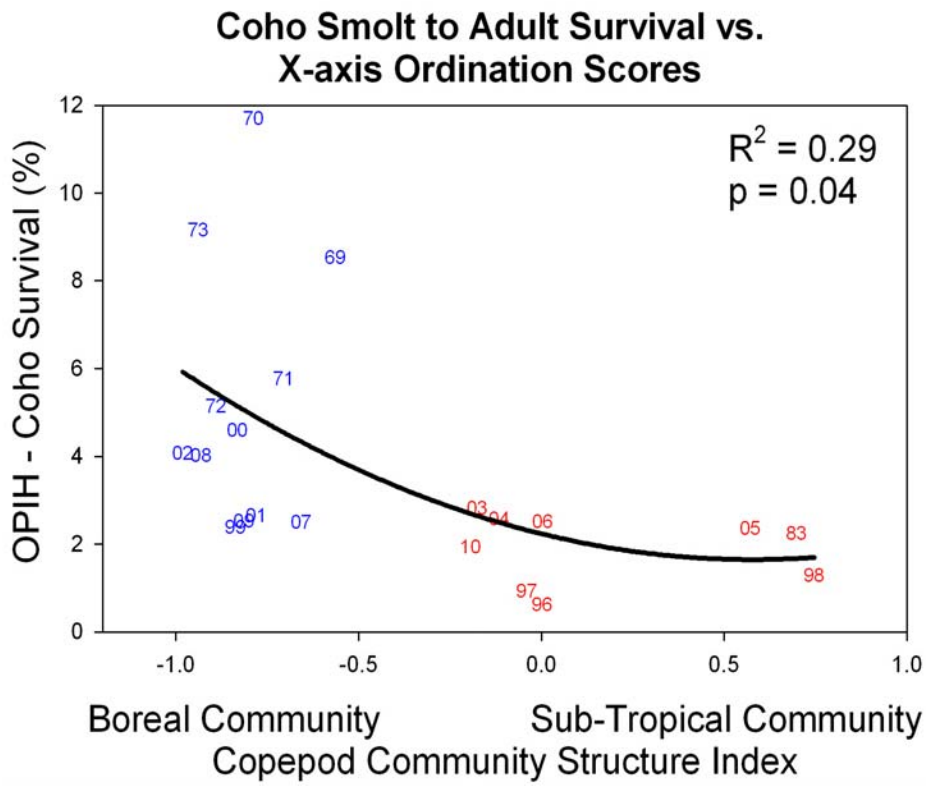
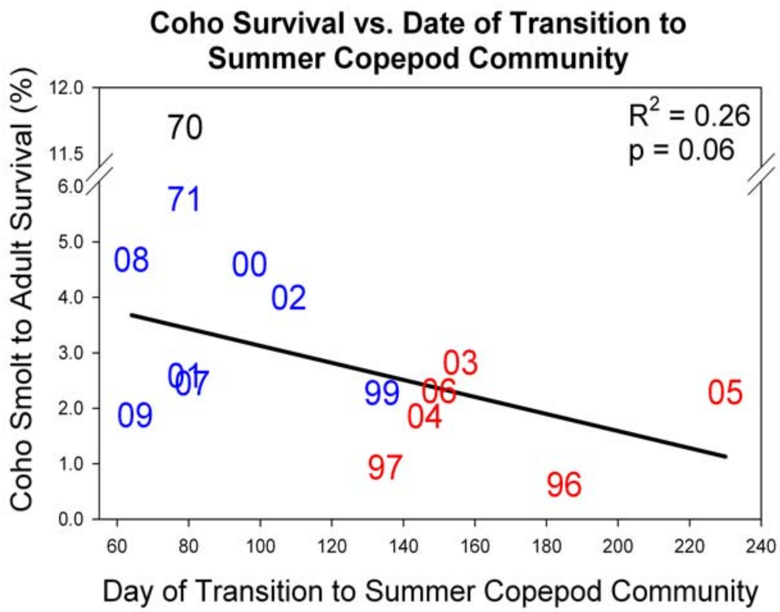


Figure 30. Plot showing the relationship between coho survival and copepod community structure. The stronger the boreal community, the greater the coho survival. Note also that when a subtropical copepod community prevails, coho survival usually averages < 2%. The X-axis ordination score for May-September 2010 was –0.19, indicating poor coho survival. Red and blue numbers indicate the year.

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.



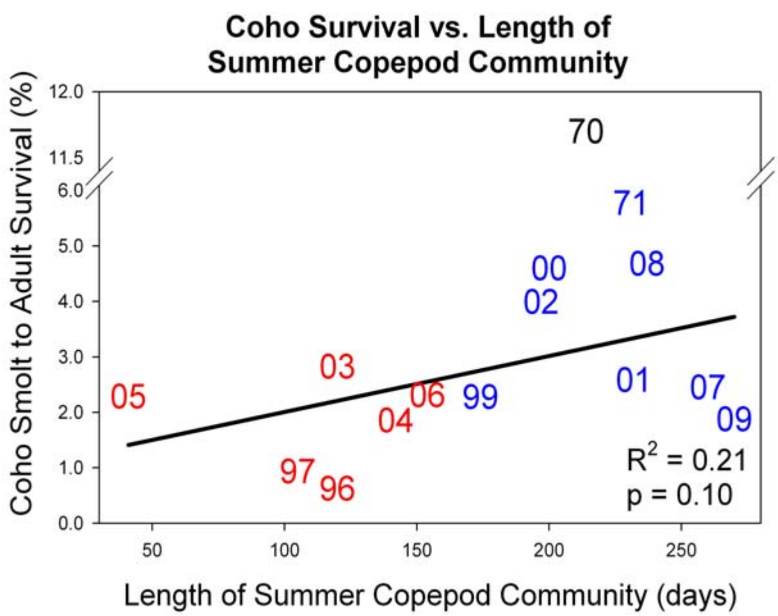


Figure 31. Upper panel: Regression of coho survival vs. day of the year when copepod community structure transitioned to a summer community. The earlier this transition takes place, the higher coho survival.
Lower panel: Regression of coho survival vs. length of the biological upwelling season, measured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

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.

Table 6. Historical dates of the biological spring transition, as measured by the timing of change in the zooplankton 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	never	never	0
1996	3 Jul	31 Oct	120
1997	15 May	28 Aug	105
1998	never	never	0
1999	14 May	4 Nov	174
2000	6 Apr	23 Oct	200
2001	20 Mar	7 Nov	232
2002	18 Apr	1 Nov	197
2003	5 June	3 Oct	120
2004	25 May	14 Oct	142
2005	18 Aug	28 Sep	41
2006	30 May	31 Oct	154
2007	22 Mar	7 Dec	260
2008	4 Mar	27 Oct	237
2009	6 Mar	1 Dec	270
2010	15 May	—	—

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.

The arrival of the "northern" species in spring signals that the ecosystem is primed to begin a productive upwelling season. Also listed is the length of the upwelling season, in days, as reckoned by the zooplankton. Note that the transition date over the three years of 2007-09 came very early, in March, whereas in 2010 it occurred in mid-May.

Both the date of "biological spring transition" and "length of the biological upwelling season" correlate well with Spring Chinook adult salmon counts at Bonneville (lag of two years; Figure 32) and with counts of adult fall Chinook salmon at Bonneville Dam (lagged two years; Figure 33). In the case of fall Chinook adults, the year 2007 was an outlier and had it not been included in the linear regression, the R-sq increases to 70% and p = 0.001 (for the transition date) and to 74% and p = 0.001 (for the length of the biological upwelling season).

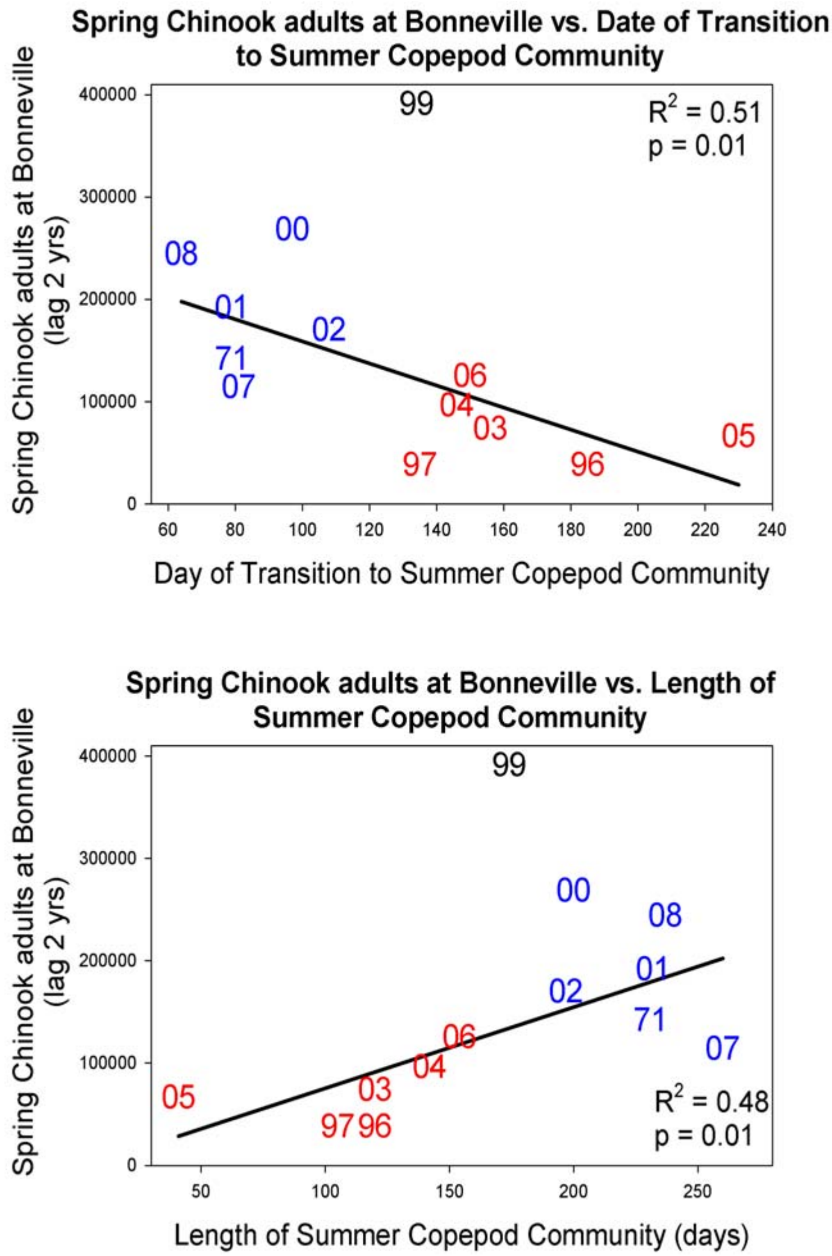


Figure 32. Spring Chinook adult counts at Bonneville (lag 2 years) vs. date of biological spring transition (upper panel) and length of the biological upwelling season (lower panel). 1999 is an outlier and not included in the regression. Red and blue numbers indicate the year.

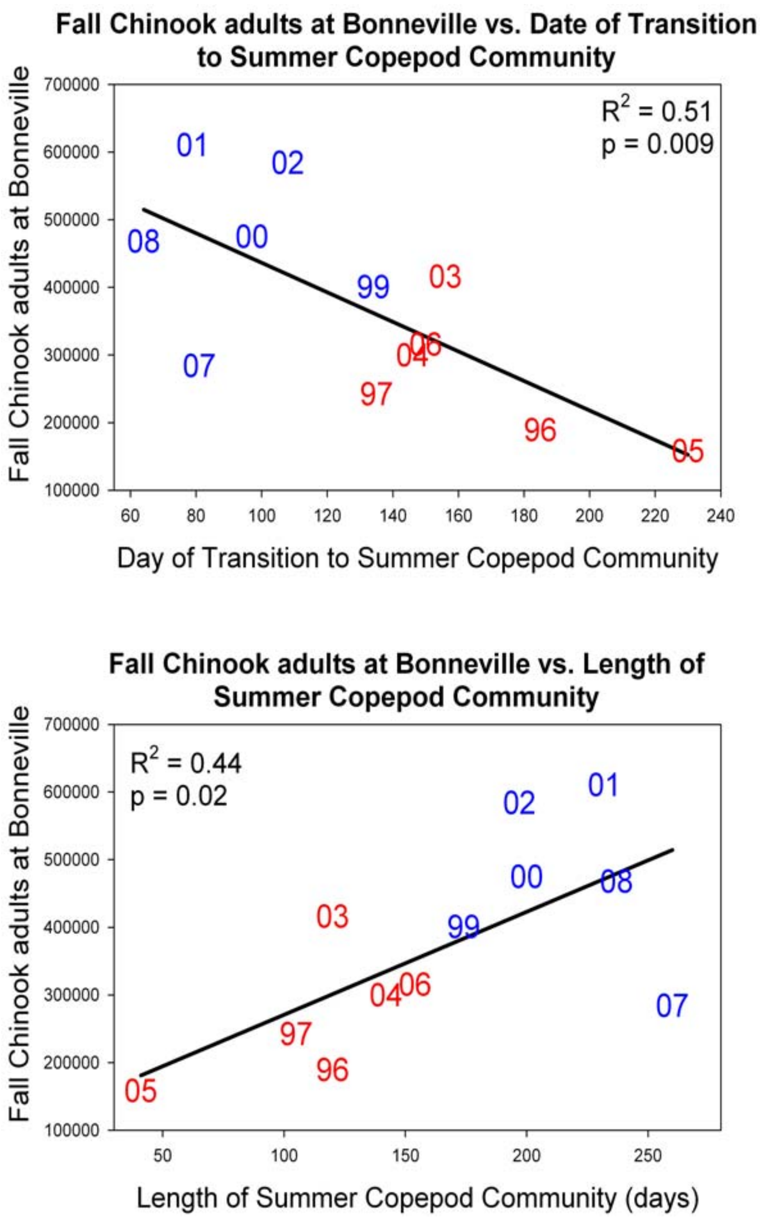


Figure 33. Fall Chinook adult counts at Bonneville (lag 2 years) vs. date of biological spring transition (upper panel) and length of biological upwelling season (lower panel). Red and blue numbers indicate the year.

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.

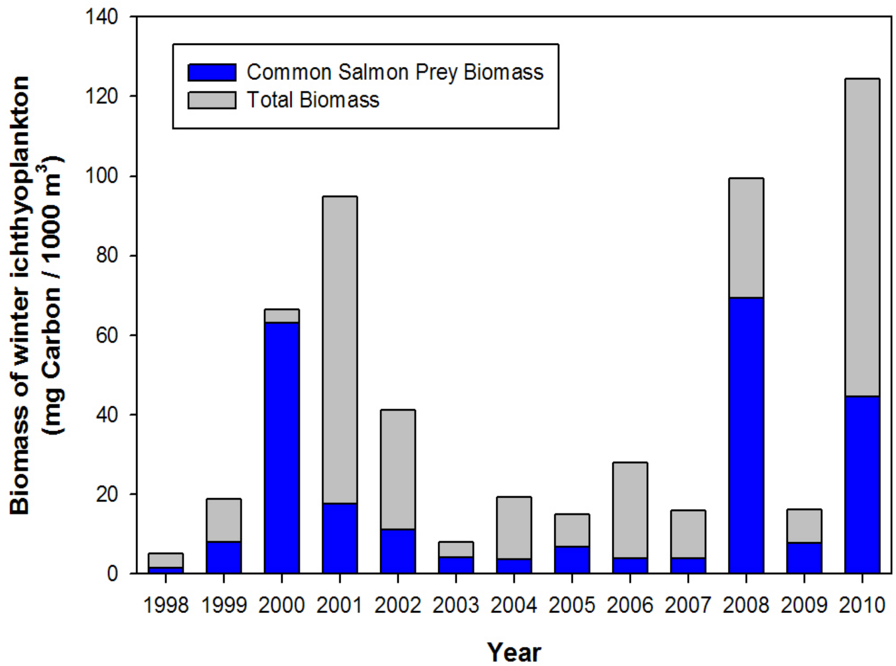


Figure 34. Estimates of total winter ichthyoplankton biomass from 1998 to present. Proportions composed of fish larvae considered prey items for juvenile salmon are represented by blue bars.

Winter ichthyoplankton biomass was highest in 2008 and 2010 and lowest in 1998, an El Niño year (Figure 34). Years with the highest biomass of 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% of the biomass was fish 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

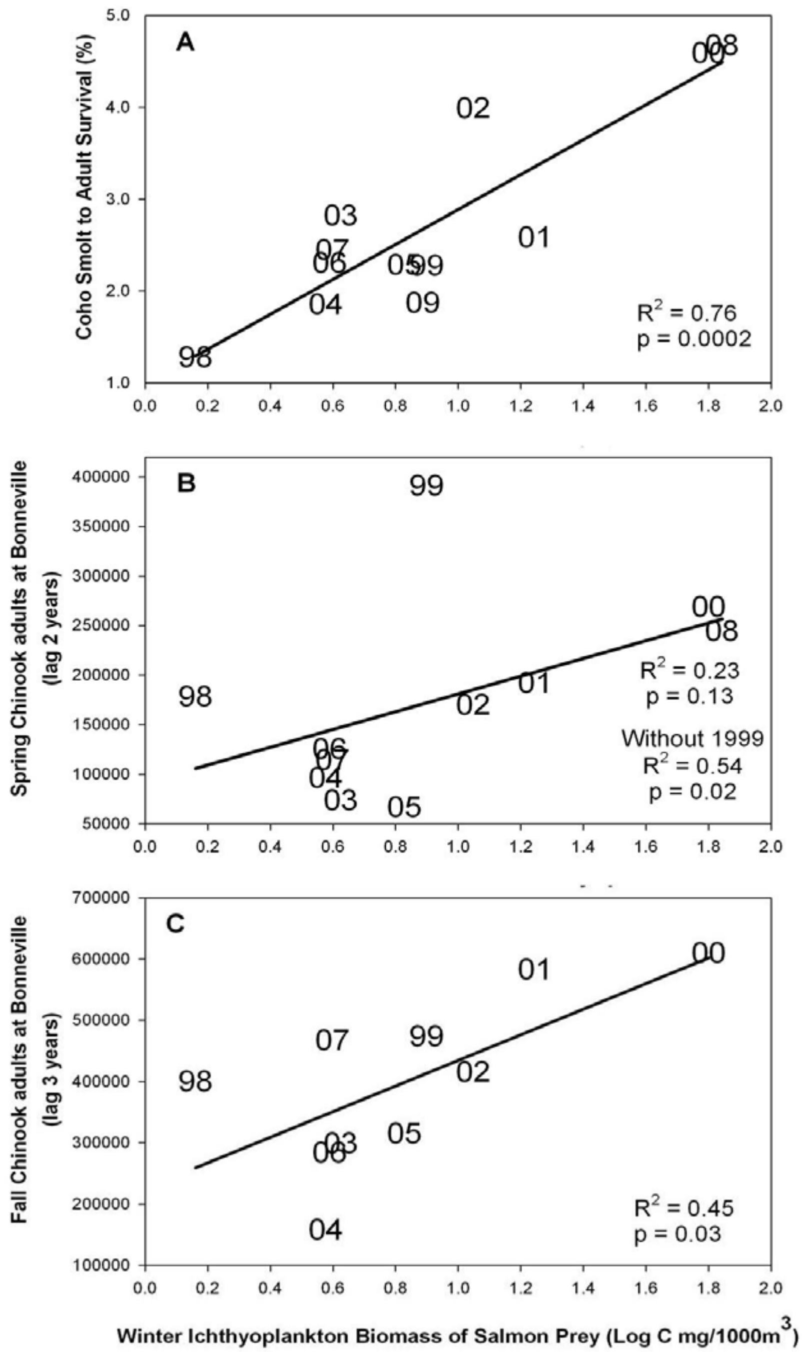


Figure 35. Respective panels show regression of biomass of salmon prey with A) coho smolt–to–adult returns, B) spring Chinook adult counts at Bonneville Dam, and C) fall Chinook adult counts at Bonneville.

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. Life history characteristics of the common prey eaten by juvenile salmon during their first marine summer.

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

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.

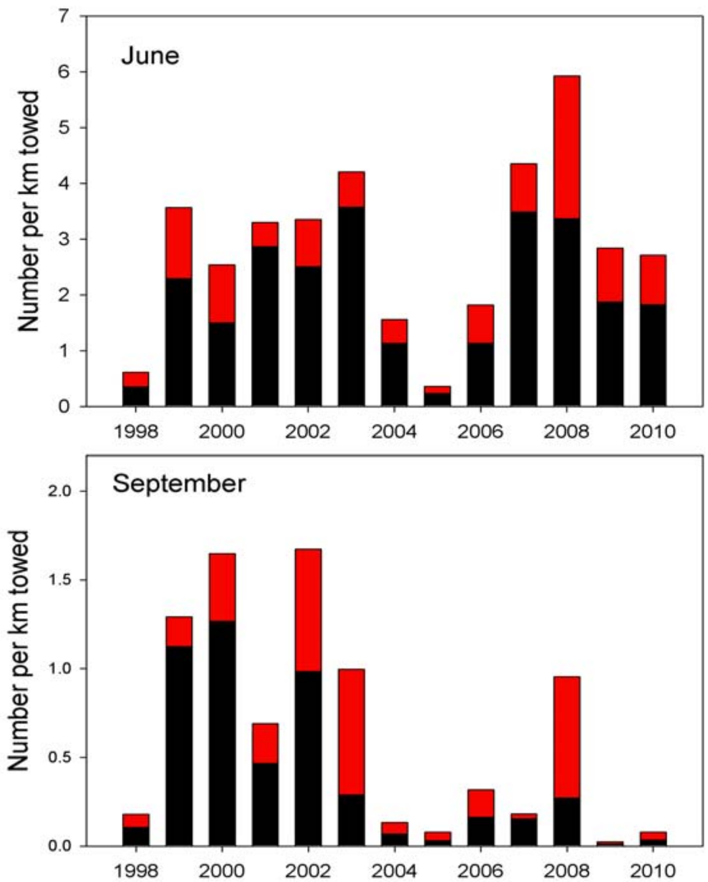


Figure 36. Average catches of juvenile coho (black bars) and yearling Chinook (red bars) during trawl surveys off the coast of Washington and Oregon. Surveys were conducted in June (upper panel) and September (lower panel) from 1998 to 2010.

Catch rates were lowest for both species during 2005, but rebounded gradually during 2006–2008, only to decline again in 2009-2010.

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.

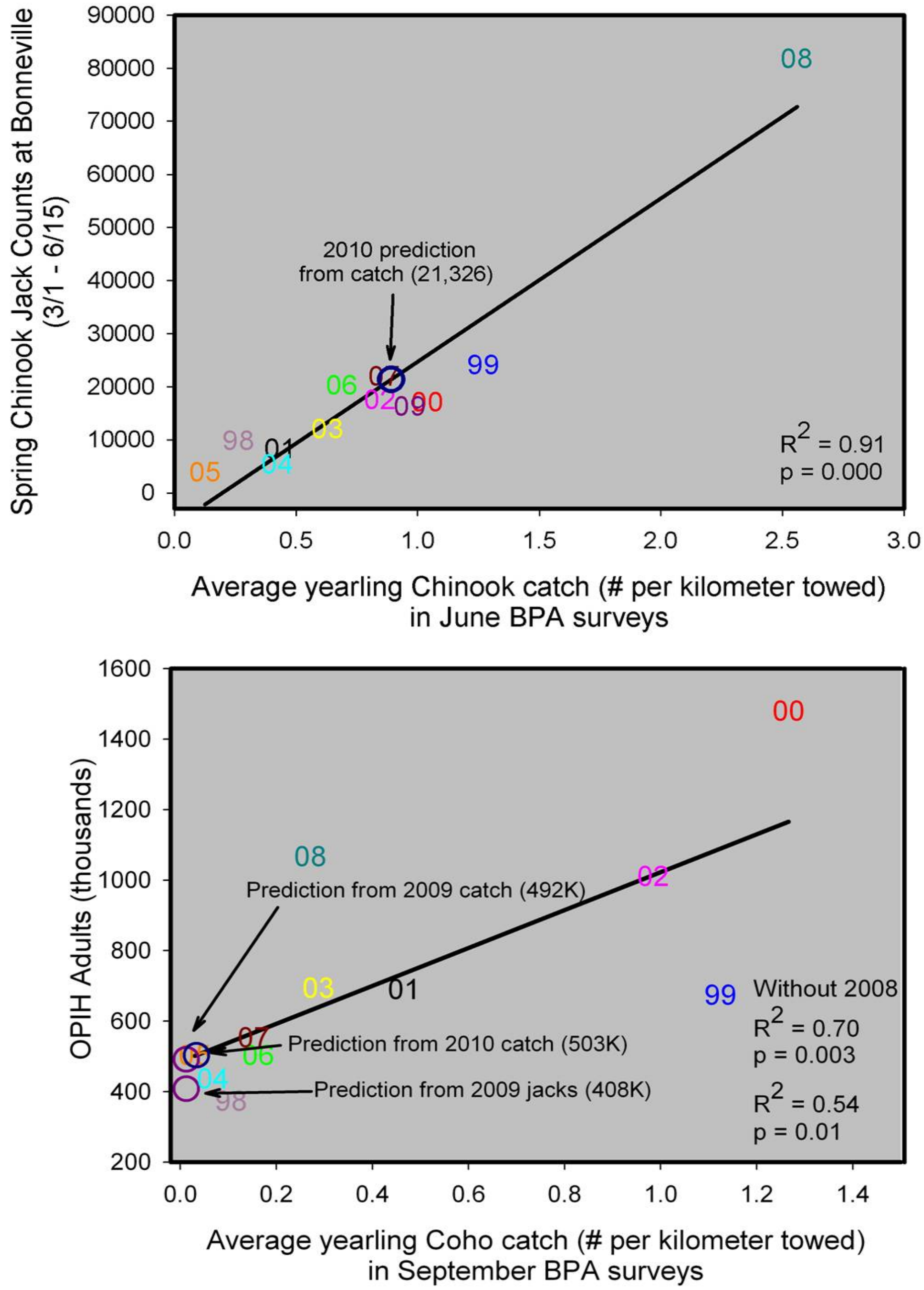


Figure 37. Regression of spring Chinook salmon jack counts at Bonneville Dam (1998–2010) vs. average CPUE of yearling Chinook salmon caught during each of June cruise (upper panel). Open point indicates observed CPUE in June 2010 (0.89) and predicted OPIH from the regression (21,326). Lower panel shows regression of OPIH adult coho salmon abundance on the average CPUE of juvenile coho salmon catches in trawl surveys the previous September. Years indicated are for catches of juvenile fish. Dark blue open circle indicates observed juvenile CPUE (0.02) in September 2010 and predicted OPIH from the regression (503 thousand).

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.

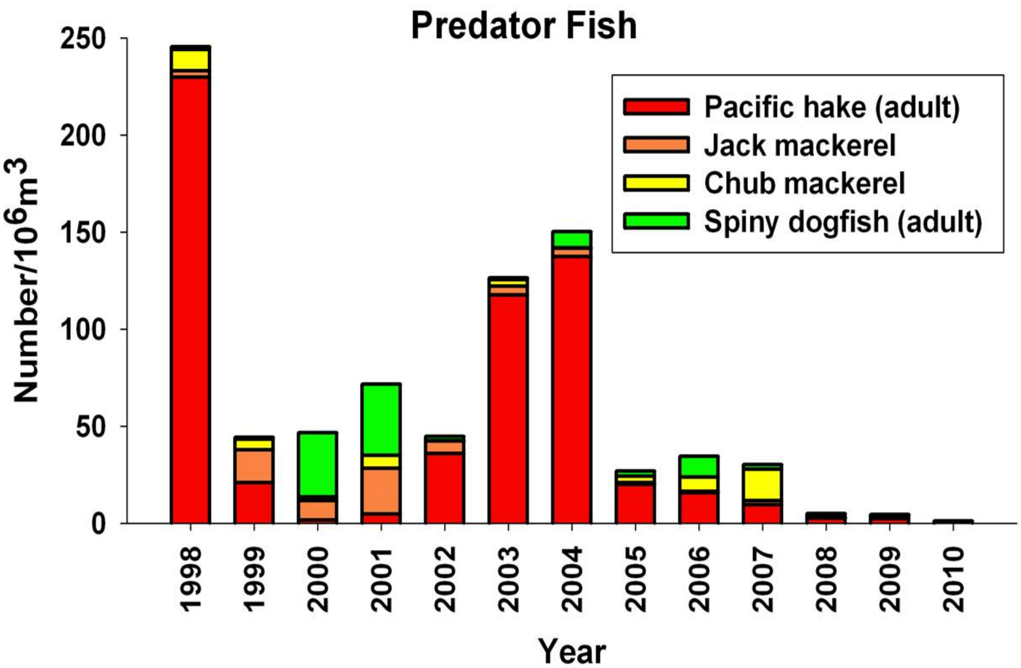


Figure 38. Catches of potential piscivores that prey on juvenile salmon. Pacific hake numbers are usually very high during "warm years" such as the 1998 El Niño event and during the first 2 years of a warm–phase PDO (2003–2004). However, numbers were surprisingly low from 2008–2010, despite the 2009 El Niño. Data shown are from the surveys of R. Emmett, conducted May–August 1998–2010.

For Pacific hake, (Figure 38) note that low abundances were observed during the cool, negative–PDO phases of 1999–2002 and 2008–2010. Conversely, high abundances occurred during the warm, positive–PDO years of 1998, 2003, and 2004. These correspond respectively to "good" and "poor" periods for coho survival. We expected high abundance levels for hake in 2005 and 2006, but this expectation was not met, due possibly to the timing of its 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 on the other hand, 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). Given 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, there were no simple linear relationships between either salmon catches or survival and forage fish or hake.

Forage fish numbers remained low in 2006 (Figure 39), probably as a result of poor recruitment in 2005. These low numbers comprise a negative indicator, since juvenile forage fish (ages

0 and 1) are among the favored prey of both coho and Chinook salmon. Thus salmon may have been food-limited in 2006. High numbers of forage fish in 2010 may be an indication of favorable ocean survival for coho and Chinook in 2011.

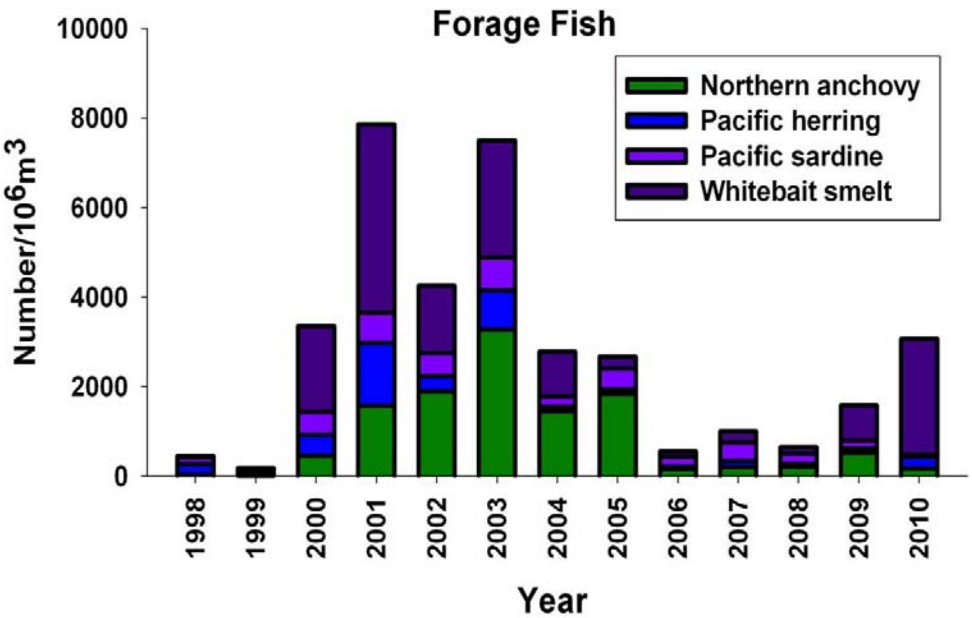


Figure 39. Catches of forage fish along the Columbia River and Willapa Bay transects, 1998-2010. Note low numbers of forage fish in 2006; note also low numbers in 1999, demonstrating that there can be time lags of at least 1 year following a crash before forage fish numbers begin to increase. Data shown are from the surveys of R. Emmett, conducted May–August 1998–2010.

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.

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.

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

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 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). Most data presented here were collected during these cruises, which initiated in May 1996.

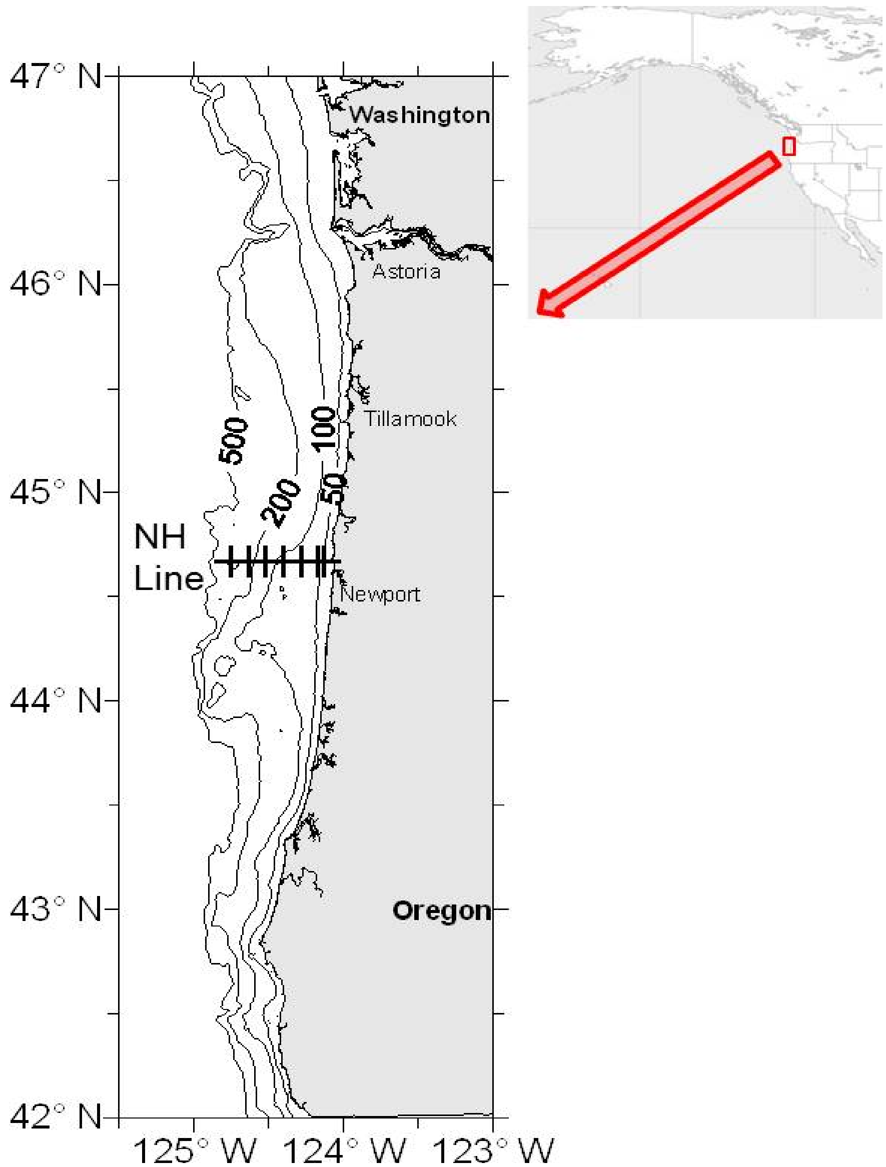


Figure 40. Transects and stations sampled during cruises by the NOAA Fisheries Service.

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, 55–ft) research vessel 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.

At each station, a CTD profile (conductivity, temperature, and depth) is taken (Seabird‡ SBE 19 CTD), 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 0.05 m in diameter with a mesh size of 202 µm. A double oblique tow is made for ichthyoplankton (1–m diameter net with 333–µm mesh) over the upper 20 m. Since 2005, CTD casts have included fluorometry (WetLabs fluorometer) and oxygen (Seabird oxygen sensor).

From 1998 to 2003, we sampled each transect line 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 each transect in May (2004–2006), along with several visits to the Newport Line, out to 85 miles from shore, in summer 2004. As a result, the Newport biweekly data are nested within larger scale quarterly surveys, an approach that is useful in helping us interpret locally derived data from the inner portions of the Newport Line.

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.

Juvenile Salmon Sampling Program

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).

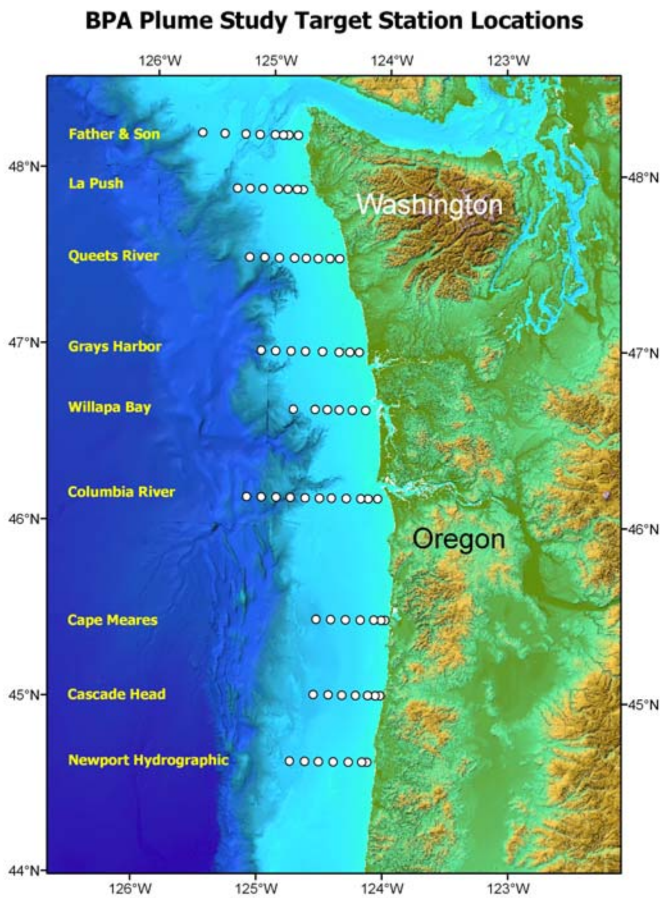


Figure 41. Transects sampled for coho and yearling and subyearling Chinook salmon, 1998–2010.

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

Oceanographic data collected at each station include continuous underway sampling of sea surface temperature and salinity, depth profiles of salinity and temperature with a CTD (Seabird SBE–19 plus) and water transparency (Secchi depth and transmissometer). A water sample is collected from a depth of 3 m for analysis of chlorophyll–a (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 (Robert Emmett) also carry out cruises every 10 days during which pelagic fish are sampled at night along transects off the Columbia River and Willapa Bay. This work provides data to index the abundance of fish predators (such as hake) and forage fish (which can serve as an alternate prey of the fish predators).

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 (June 1999, 2008, & 2010) and extremely low flows (June 2001), and during anomalously warm conditions in the coastal ocean due to lack of upwelling (June 2005). During this period, the Pacific Decadal Oscillation moved from warm phase (pre–1999), to cool phase (1999–2002), then to warm phase again (2003–2007) and then back to a cool phase (2008-2010). Thus, nature has handed us a grand experiment that allows us to determine in what ways and how quickly salmon and other ecosystem components respond to short–term climate variability.

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.

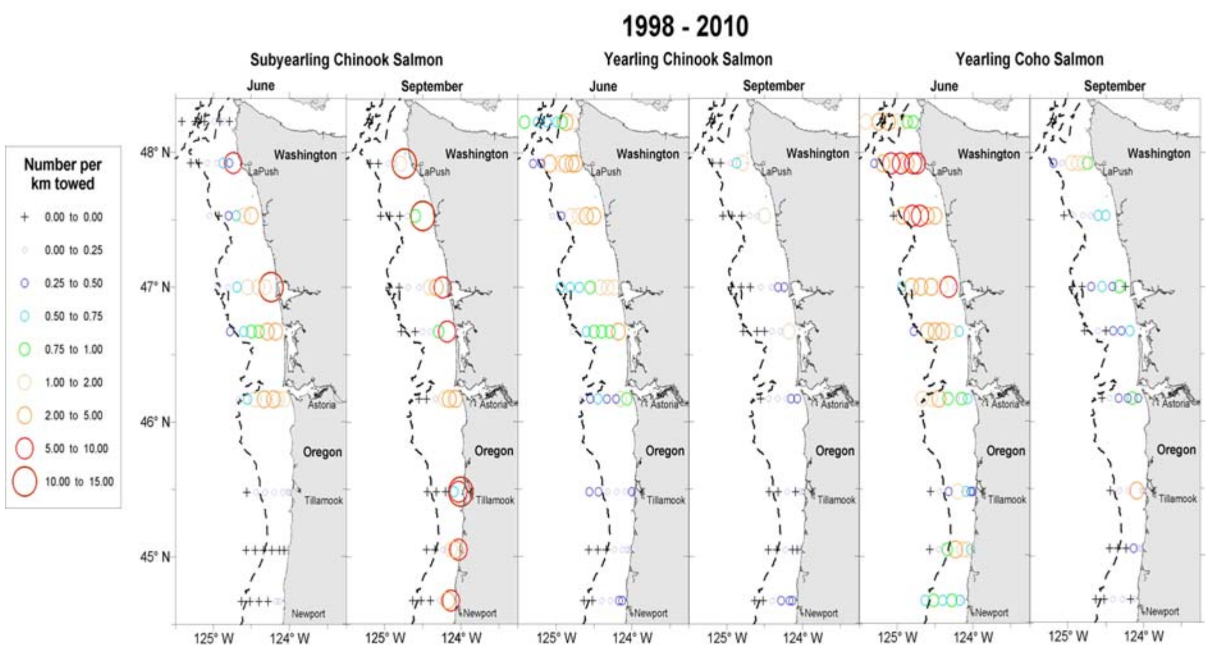


Figure 42. Average catch of salmonids per km towed at stations in June and September, for each life history type, averaged over 1998-2010.

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.

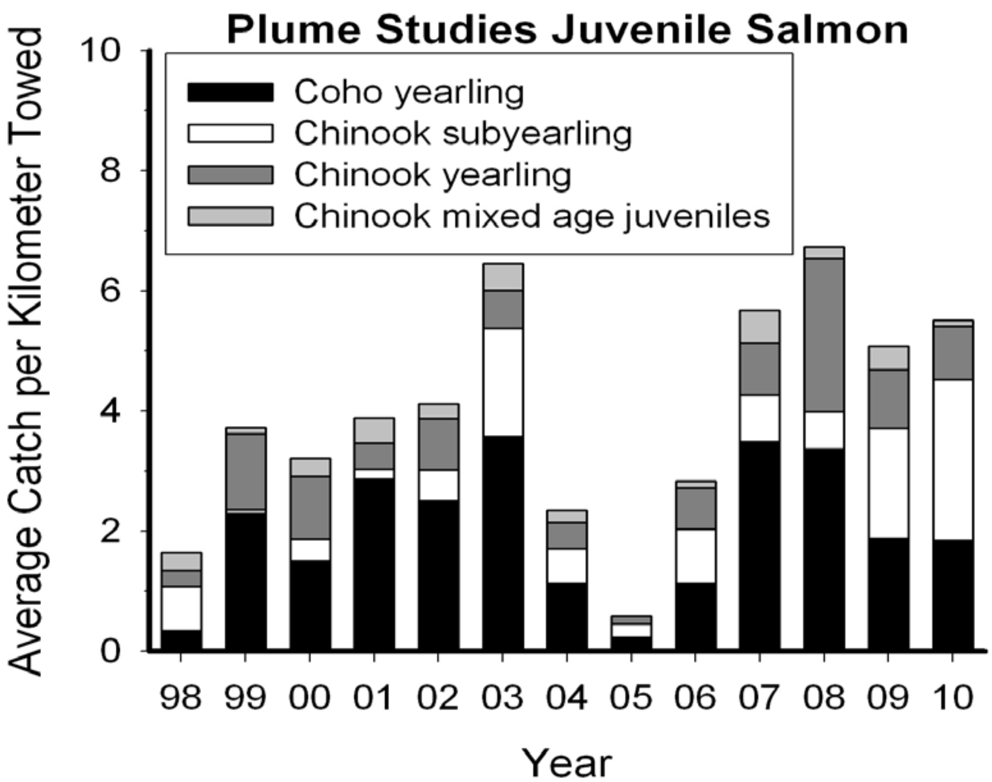


Figure 43. Annual variation in catches of juvenile coho and Chinook salmon during June trawl surveys, 1998–2010.

Year–to–year variations 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 and June 2005 (Figure 43). Highest catches were during the cold phase of the Pacific Decadal Oscillation (1999-2003, 2008-2010).

Acknowledgments

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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).

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.

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.