

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 (*Oncorhynchus tshawytscha*) and coho (*O. kisutch*) salmon, whereas warm conditions are not.

These pages are based on our annual [report](#) 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 SF-01](#). This information is presented for the non-specialist; additional detail is provided via links when possible.

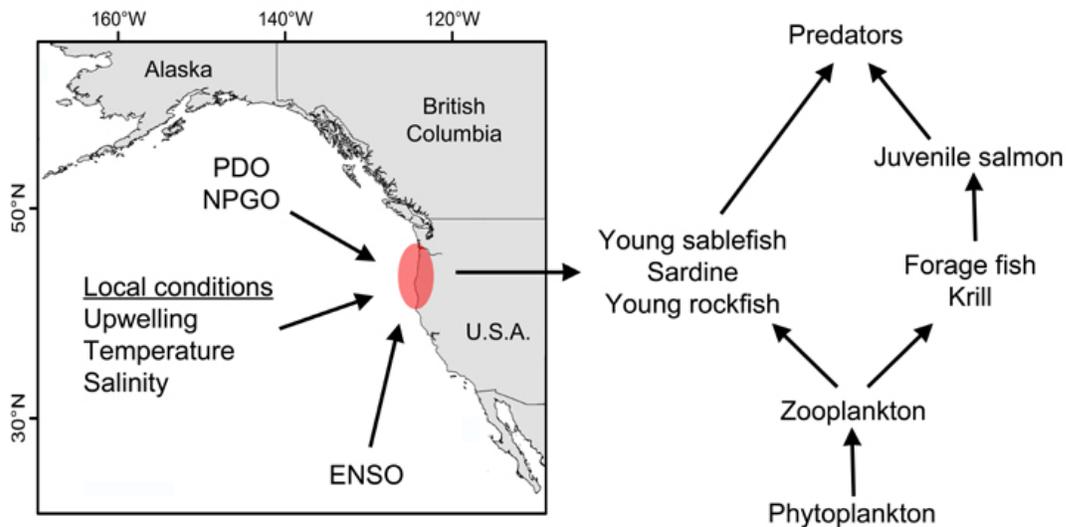


Figure HP-01. Illustration of how basin-scale and local-scale physical forces influence the northern California Current and resultant food web structure. PDO = Pacific Decadal Oscillation. NPGO = North Pacific Gyre Oscillation. ENSO = El Niño–Southern Oscillation. Figure from Peterson et al. [2014 Oceanography 27\(4\):80-89](#).

Material presented on this website has two sources. One is the World Wide Web, from which we have drawn values for the [Pacific Decadal Oscillation](#), [ENSO/ONI \(Oceanic Niño Index\)](#), [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, sampling and survey methods are presented under "Ocean Sampling Methods" (see left-side menu).

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 SF-01](#)).

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.

Annual summary of ocean ecosystem indicators for 2015 and pre-season outlook for 2016

Many of the ocean ecosystem indicators in 2015 suggest this being a relatively poor year for juvenile salmon survival. The PDO was strongly positive (warm) throughout 2015, coinciding with anomalously warm ocean conditions in the NE Pacific called "The Blob" that began in the fall of 2013 and have persisted through 2015. El Niño conditions also turned positive in April 2015 and have remained strongly positive, signaling a strong El Niño at the equator. Despite the strongest upwelling observed since 1998, sea surface and deep water temperatures off Newport Oregon remained warmer than usual (+2°C) throughout most of 2015. During the strongest

upwelling period in June, shelf waters did cool and were salty, but returned to positive temperature anomalies quickly from July onward. The zooplankton community remained in a lipid-deplete state throughout 2015, and was dominated by small tropical and sub-tropical copepods and gelatinous zooplankton that generally indicate poor feeding conditions for small fishes upon which juvenile salmon feed. Krill biomass was also among the lowest in 20 years. On the other hand, the biomass of larval fish species that are common in salmon diets in spring was above average this year, however, there were also high concentrations of larval rockfish and anchovy which are generally indicators of poor feeding conditions for salmon. We also observed many new copepod species that have never been seen off Newport since sampling began in 1969. Copepods are drifters, they go where the water goes, and therefore they are good indicators of water transport. The new species were warm water species, known to occur offshore and southwest of Oregon suggesting a tropical/subtropical origin. However, exactly where these species came from is a topic for further study.

The Blob. An anomalously warm water mass began to form in the Gulf of Alaska during autumn 2013 and was named “The Blob” by Nick Bond (Bond et al. 2015). This warm water mass spread across the entire North Pacific by summer 2014. However, in the eastern North Pacific and on the Oregon shelf, offshore Ekman transport associated with coastal upwelling kept “The Blob” offshore during summer 2014. In mid-September of 2014, northerly winds ceased and “The Blob” moved shoreward into shelf waters off southern British Columbia, Washington and Oregon, raising coastal SSTs by 6°C over a 6 hour period off Newport Oregon ([Figure TA-02](#))! By early November 2014, “The Blob” was firmly entrenched in coastal waters off Oregon, with an 80 m thick mixed layer with 2-3°C anomalies. With the exception of the strong upwelling period in June 2015, warm anomalies remained off Newport throughout most of 2015.

SST anomalies in the northeast Pacific for the period from July through December 2015 are shown in Figure IS-01. The decrease in the SST anomalies in the southern Gulf of Alaska and offshore of the Pacific Northwest from November through December 2015 can be attributed to a regional atmospheric circulation pattern that produced surface wind anomalies from the northwest (not shown). These atmospheric patterns were not indicative of El Niño, however, the recent bout of torrential rains off California, which began on 4 January 2016, are. Thus, while “The Blob” appears to be diminishing, it does not appear that the Northeast Pacific is necessarily returning to a near-normal state.

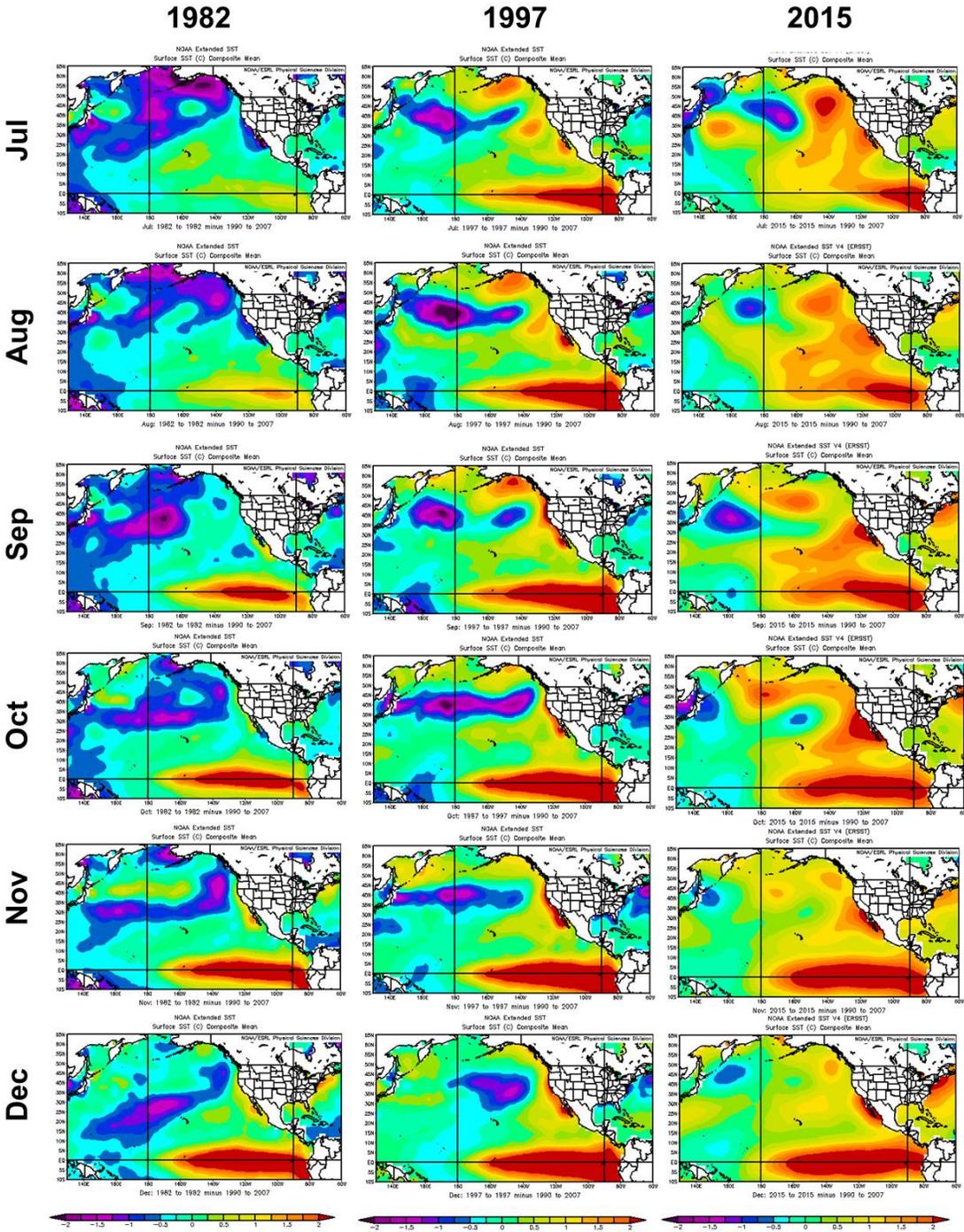


Figure IS-01. Sea-surface temperature (SST) anomalies in the Pacific from July to December during the initial phases of El Niño events of 1982, 1997, 2015. The strongest El Niño events in recent history occurred during 1982-83 and 1997-98. The 2015-16 event is expected to be the strongest on record. What sets this year, 2015, apart from the other strong El Niño events is that the northeast Pacific was already anomalously warm prior to the arrival of the El Niño, due to “The Blob”.

The ecosystem impacts of “The Blob” have not yet been fully documented, however to date, three types of responses are clear: many unusual species were found: media reports documented northward displacement of tropical and subtropical reptile and fish species on the order of several 1000 km into the northeast Pacific: moonfish (opah) and swordfish were caught off central Oregon (45°N), green and Olive Ridley turtles were found off Washington and Oregon, and 2 yellow-bellied sea snakes (*Pelamis pelamis*) have washed up on a beaches in southern California. In addition, sunfish, pomfret and pompano were caught commonly in the Gulf of Alaska. A total of 18 species of warm-water copepods occurred in 2015, 11 of which were new records for the NCC shelf/slope; an additional seven species have occurred only in waters far offshore of Oregon or during strong El Niño events (1983, 1998). Many of these copepod species had North Pacific Gyre and/or North Pacific Transition Zone affinities indicating that the source of “The Blob” was from far offshore and from the south. Copepod species richness anomalies reached a peak in August 2015, but after that, anomalies have declined and by early November 2015, turned negative ([Figure NSC-01](#)). The copepod species we are observing now are the same as those seen during any normal winter, with a dominance of subtropical neritic species that are transported to Oregon from coastal waters of central/southern California waters by the Davidson Current which runs northward from October-March in most years.

In addition to unusual species, there were impacts on commercial fisheries. Sockeye and summer-run Chinook salmon migrating back to the Columbia River in summer of 2015 experienced high mortality because river waters were anomalously warm as a result of a Blob-related drought and subsequent low flows; coho salmon returns to the Columbia River in autumn 2015 were the lowest in at least 25 years. Impacts on juvenile salmon that migrated to the sea in spring/summer 2015 will not be known for several years.

The year 2015 also witnessed perhaps the largest and most wide-spread harmful algal bloom in recorded history: a bloom of the diatom *Pseudonitzschia*, began in April 2015, and extended from southern California to the coastal Gulf of Alaska. The bloom became extraordinarily toxic such that in May 2015, the State management agencies ordered a closure of the razor clam (*Siliqua patula*) fishery off Washington and Oregon. Subsequent blooms in June and August resulted in toxicity remaining high throughout the remainder of the year leading to a ban on the harvest of Dungeness Crabs off California, Oregon and Washington in November 2015.

“The Blob” has resulted in ocean conditions that might be a precursor of future climate scenarios and provides a natural experiment to monitor it’s effects on the pelagic ecosystem and associated fisheries of the California Current (and perhaps across the entire North Pacific). Given that global climate models were (and continue to be) unable to anticipate “warm events” such as “The Blob” with much lead time, it is imperative we maintain existing marine observation programs and begin others so that ecosystem impacts can be more closely tracked. Finally, given that the strong 2015 El Niño event has begun to arrive, we expect that abnormally warm conditions will continue along the west coast of North America well into 2016, and so there may well be another chapter (or more) to this story.

PDO and ONI. Following several years of being consistently negative, the PDO turned positive (warm phase) in January 2014, and has remained strongly positive throughout 2015, reaching values similar to what was observed during the 1997-1998 El Niño. In April the equatorial

temperature anomalies crossed the threshold into El Niño conditions and the Ocean Niño Index (ONI) has remained strongly positive, indicating strong El Niño conditions at the equator.

Upwelling Index at 45°N. The upwelling season began (spring transition) on 13 April and ended on 5 Oct which are both right in line with the 40-year climatology. Despite the on-time beginning and end to the upwelling season, the total amount of upwelling ([Figure CU-04](#)) in 2015 was the highest we've observed since 1998. Upwelling began strong in mid-April, was moderate in May but was then strong and sustained throughout June. From July onward, upwelling was generally weak with a few moderate pulses.

Sea Surface Temperatures (SST) at NOAA Buoy 46050. The anomalous warm ocean conditions in the NE Pacific called "The Blob" arrived on the Oregon shelf Sept 2014, with temperature anomalies of +4°C, and dominated the surface ocean temperatures for much of 2015. Sea surface temperatures off Newport remained warmer than usual (+2°C) throughout most of 2015 apart from the month June, the strongest upwelling period, during which shelf waters cooled and were salty. However with weakening of upwelling in July, positive temperature anomalies returned from July onward ([Figure TA-02](#)).

Temperature and salinity properties on the continental shelf/slope. The upper 40 to 60 m of the water column on the shelf was dominated by "The Blob" water and was anomalously warm and fresh throughout the winter prior to the onset of upwelling. In slope and oceanic waters, the warm and fresh Blob water occupied the upper 80-100 m. Since water that upwells onto the shelf usually originates from deep waters just offshore of the shelf from a depth of ~150 m, the deep temperature and salinity during the upwelling season (May – Sept) were quite average ([Figure DTS-02](#)), being cold and salty. After the strong upwelling in June subsided, the deep water became warm and fresh, resembling the water characteristics that occurred during the strong El Niño in 1997 ([Figure DTS-02](#)).

Zooplankton. In 2015, this shift from a warm copepod community to a cold summer community did not happen, which is the first time in our 18 year time series that this biological spring transition did not occur. The zooplankton community remained in a lipid-deplete state throughout 2015, and was dominated by small tropical and sub-tropical copepods and gelatinous zooplankton that generally indicate poor feeding conditions for juvenile salmon. The biomass of southern ("warm water") copepods remained higher than average, and with the exception of June when upwelling was the strongest, the biomass of northern ("cold water") copepods remained lower than average throughout 2015 ([Figure NSC-01](#)). We also observed many new copepod species that have never been observed off Newport since sampling began in 1969 and the species richness was the highest we have observed since 1998 ([Figure CB-02](#)). Copepods are drifters, they go where the water goes, and therefore they are good indicators of water transport. We know that these new species did not arrive from coastal and southern origins, as occurs during El Niño events, rather they are likely coming from an offshore source. Exactly where the source is though, is a topic of further study. Finally, although not a topic of this web-page, it is noteworthy that krill biomass was among the lowest in our 18 year time series. Large adult *Euphausia pacifica* (18-20 mm) were conspicuously absent.

Winter Ichthyoplankton. The winter-time (Jan-March) abundance of larval stages of fish species common in salmon diets was above average this year ([Figure WI-01](#)), ranking 4th highest over the 18 years of data. However, there were high concentrations of larval rockfish and Northern anchovy found, which are generally indicators of poor feeding conditions for salmon.

Forecast of Adult Returns for coho salmon and Chinook salmon

Many of the ocean ecosystem indicators in 2015 suggest this being a relatively poor year for juvenile salmon survival. The PDO was strongly positive (warm) throughout 2015, coinciding with anomalously warm ocean conditions in the NE Pacific called “The Blob” that began in the fall of 2013 and have persisted through 2015. El Niño conditions also turned positive in April 2015 and have remained strongly positive, signaling a strong El Niño at the equator. Despite the strongest upwelling observed since 1998, sea surface and deep water temperatures off Newport Oregon remained warmer than usual (+2°C) throughout most of 2015. During the strongest upwelling period in June, shelf waters did cool and were salty, but returned to positive temperature anomalies quickly from July onward. The zooplankton community remained in a lipid-deplete state throughout 2015, and was dominated by small tropical and sub-tropical copepods and gelatinous zooplankton that generally indicate poor feeding conditions for small fishes upon which juvenile salmon feed. Krill biomass was also among the lowest in 20 years. On the other hand, the biomass of larval fish species that are common in salmon diets in spring was above average this year, however, there were also high concentrations of larval rockfish and Northern anchovy which are generally indicators of poor feeding conditions for salmon. We also observed many new copepod species that have never been seen off Newport since sampling began in 1969. Our annual summary of ecosystem indicators during 2015 is [here](#), and our "stoplight" rankings and predictions are shown below in [Table SF-01](#), [Table SF-02](#), and [Figure SF-01](#).

Table SF-01 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 2015 (coho salmon) and 2014 (Chinook salmon).

	Juvenile Migration Year				Adult Return Outlook	
	2012	2013	2014	2015	coho 2016	Chinook 2016
Large– scale ocean and atmospheric indicators						
PDO (May - Sept)	■	■	■	■	●	●
ONI (Jan - Jun)	■	■	■	■	●	●
Local and regional physical indicators						
Sea surface temperature	■	■	■	■	●	●
Deep water temperature	■	■	■	■	●	●
Deep water salinity	■	■	■	■	●	●
Local biological indicators						
Copepod biodiversity	■	■	■	■	●	●
Northern copepod anomalies	■	■	■	■	●	●
Biological spring transition	■	■	■	■	●	●
Winter Ichthyoplankton	■	■	■	■	●	●
Juvenile Chinook Salmon Catch – June	■	■	■	■	●	●
Key						
■	good conditions for salmon			●	good returns expected	
■	intermediate conditions for salmon			--	no data	
■	poor conditions for salmon			●	poor returns expected	

[Table SF-02](#) shows rank scores for the color-coding in [Table SF-01](#). Scores were assigned based on their effect on juvenile salmonids. We show variables that are correlated with returns of coho salmon after 1 year and of Chinook salmon after 2 years. For example, positive PDO values (and red colors) indicate poor ocean conditions in coastal waters off the northern California Current. Similarly, higher sea surface temperatures in summer are a negative indicator for salmon, but particularly so for resident coho salmon. [Table SF-03](#) shows the values of each variable shown by rank in [Table SF-02](#).

Ecosystem Indicators	Year																	
	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
PDO (Sum Dec-March)	16	6	3	12	7	17	11	15	13	9	5	1	14	4	2	8	10	18
PDO (Sum May-Sept)	10	4	6	5	11	15	14	16	12	13	2	9	7	3	1	8	17	18
ONI (Average Jan-June)	18	1	1	6	12	14	13	15	8	11	3	10	16	4	5	7	9	17
46050 SST (°C; May-Sept)	15	8	3	4	1	7	18	14	5	16	2	9	6	10	11	12	13	17
Upper 20 m T (°C; Nov-Mar)	17	11	8	10	6	14	15	12	13	5	1	9	16	4	3	7	2	18
Upper 20 m T (°C; May-Sept)	14	11	13	4	1	3	18	16	7	8	2	5	12	10	6	15	17	9
Deep temperature (°C; May-Sept)	18	6	8	4	1	9	12	14	10	5	2	7	13	11	3	17	16	15
Deep salinity (May-Sept)	18	3	7	4	5	14	15	8	6	1	2	11	16	10	9	13	17	12
Copepod richness anom. (no. species; May-Sept)	17	3	1	7	6	13	12	16	14	11	8	10	15	4	5	2	9	18
N. copepod biomass anom. (mg C m ⁻³ ; May-Sept)	17	13	9	10	3	15	12	18	14	11	6	8	7	1	2	4	5	16
S. copepod biomass anom. (mg C m ⁻³ ; May-Sept)	18	2	5	4	3	13	14	17	12	10	1	7	15	9	8	6	11	16
Biological transition (day of year)	17	11	6	7	8	12	10	16	15	3	1	2	14	4	9	5	13	18
Ichthyoplankton biomass (mg C 1000 m ⁻³ ; Jan-Mar)	18	9	2	5	7	16	15	11	14	13	1	10	3	12	8	6	17	4
Chinook salmon juvenile catches (no. km ⁻¹ ; June)	17	4	5	15	10	12	16	18	11	8	1	6	7	14	3	2	9	13
Coho salmon juvenile catches (no. km ⁻¹ ; June)	17	7	12	5	6	2	14	18	15	3	4	9	10	13	16	1	11	8
Mean of ranks	16.5	6.6	5.9	6.8	5.8	11.7	13.9	14.9	11.3	8.5	2.7	7.5	11.4	7.5	6.1	7.5	11.7	14.5
Rank of the mean rank	18	5	3	6	2	13	15	17	11	10	1	7	12	7	4	7	13	16
<i>Ecosystem Indicators not included in the mean of ranks or statistical analyses</i>																		
Physical Spring Trans UI based (day of year)	3	6	17	14	4	11	13	18	11	1	5	2	7	10	15	8	16	9
Physical Spring Trans Hydrographic (day of year)	17	3	13	8	5	12	14	18	6	9	1	9	16	3	11	2	15	7
Upwelling Anomaly (April-May)	8	2	15	4	7	12	11	18	8	3	5	6	13	15	13	10	17	1
Length of Upwelling Season UI based (days)	6	2	16	10	1	11	8	18	5	3	7	3	13	15	13	12	17	9
SST NH-5 (°C; May-Sept)	8	6	5	4	1	3	18	15	9	16	2	17	10	7	13	12	14	11
Copepod Community Index (MDS axis 1 scores)	18	5	4	8	1	13	14	16	15	10	2	6	12	9	7	3	11	17
Coho Juv Catches (no. fish km ⁻¹ ; Sept)	11	2	1	4	3	6	12	14	8	9	7	15	13	5	10	NA	NA	NA

Table SF-03. Data for rank scores of ocean ecosystem indicators.

Ecosystem Indicators	Year																	
	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
PDO (Sum Dec-March)	5.07	-1.75	-4.17	1.86	-1.73	7.45	1.85	2.44	1.94	-0.17	-3.06	-5.41	2.17	-3.65	-5.07	-1.67	1.24	9.26
PDO (Sum 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	-6.45	-7.79	-3.47	5.07	8.08
ONI (Average Jan-June)	1.12	-1.07	-1.07	-0.40	0.18	0.27	0.20	0.47	-0.30	0.08	-0.98	-0.23	0.55	-0.72	-0.43	-0.30	-0.28	0.67
46050 SST (°C; May-Sept)	13.66	13.00	12.54	12.56	12.30	12.92	14.59	13.56	12.77	13.87	12.39	13.02	12.92	13.06	13.26	13.37	13.43	14.05
Upper 20 m T (°C; Nov-Mar)	12.27	10.31	10.12	10.22	10.08	10.70	10.85	10.60	10.61	10.04	9.33	10.19	11.01	10.02	9.62	10.09	9.47	12.75
Upper 20 m T (°C; May-Sept)	10.38	10.13	10.19	9.77	8.98	9.62	11.39	10.73	9.97	9.99	9.30	9.90	10.14	10.05	9.95	10.63	10.97	10.04
Deep temperature (°C; May-Sept)	8.61	7.63	7.74	7.56	7.45	7.81	7.89	7.97	7.83	7.58	7.48	7.73	7.89	7.86	7.56	8.30	8.25	8.08
Deep salinity (May-Sept)	33.54	33.86	33.78	33.86	33.85	33.68	33.66	33.77	33.85	33.88	33.87	33.72	33.61	33.74	33.75	33.70	33.55	33.71
Copepod richness anom. (no. species; May-Sept)	4.4	-2.8	-3.6	-1.3	-1.4	1.7	1.2	4.1	2.5	-0.9	-1.0	-0.9	2.9	-2.4	-1.5	-3.2	-0.9	7.75
N. copepod biomass anom. (mg C m ⁻³ ; May-Sept)	-0.76	0.04	0.15	0.15	0.29	-0.13	0.06	-0.84	-0.01	0.14	0.26	0.15	0.16	0.44	0.39	0.28	0.26	-0.33
S. copepod biomass anom. (mg C m ⁻³ ; May-Sept)	0.60	-0.23	-0.21	-0.21	-0.23	0.09	0.20	0.55	0.07	-0.07	-0.23	-0.19	0.21	-0.14	-0.19	-0.20	-0.02	0.43
Biological transition (day of year)	263	134	97	101	108	156	132	230	180	81	64	65	169	82	125	91	162	Never
Ichthyoplankton biomass (mg C 1000 m ⁻³ ; Jan-Mar)	0.12	0.90	1.80	1.25	1.05	0.53	0.58	0.83	0.59	0.60	1.84	0.89	1.65	0.61	0.99	1.16	0.43	1.63
Chinook salmon juvenile catches (no. km ⁻¹ ; June)	0.26	1.27	1.04	0.44	0.85	0.63	0.42	0.13	0.69	0.86	2.56	0.97	0.89	0.46	1.32	1.38	0.86	0.56
Coho salmon juvenile catches (no. km ⁻¹ ; June)	0.35	2.29	1.50	2.87	2.51	3.58	1.13	0.23	1.13	3.49	3.37	1.87	1.84	1.26	1.12	4.91	1.63	1.96
Principal Component scores (PC1)	5.79	-2.19	-2.55	-1.86	-2.15	1.28	2.46	3.82	0.51	-0.85	-4.58	-1.46	1.03	-1.69	-2.31	-1.47	1.03	5.21
Principal Component scores (PC2)	0.56	0.09	0.10	-0.97	-1.67	-1.10	2.24	-0.19	-0.66	0.09	-1.78	0.62	-0.81	1.48	0.71	1.36	2.65	-2.72
<i>Ecosystem Indicators not included in the mean of ranks or statistical analyses</i>																		
Physical Spring Trans UI based (day of year)	83	88	134	120	84	109	113	142	109	70	87	82	95	105	123	97	129	103
Physical Spring Trans Hydrographic (day of year)	187	119	142	129	120	141	157	209	123	136	102	136	169	119	140	106	162	124
Upwelling Anomaly (April-May)	-14	19	-36	2	-12	-34	-27	-55	-14	9	0	-5	-35	-36	-35	-21	-37	50
Length of Upwelling Season UI based (days)	191	205	151	173	218	168	177	129	195	201	179	201	161	153	161	163	133	175
SST NH-5 (°C; May-Sept)	11.30	11.08	11.04	10.98	10.15	10.85	12.85	11.73	11.36	11.80	10.66	11.99	11.41	11.08	11.66	11.66	11.71	11.57
Copepod Community Index (MDS axis 1 scores)	0.69	-0.86	-0.86	-0.80	-0.99	-0.23	-0.18	0.55	-0.03	-0.68	-0.96	-0.82	-0.25	-0.73	-0.80	-0.88	-0.34	0.61
Coho Juv Catches (no. fish km ⁻¹ ; Sept)	0.11	1.12	1.27	0.47	0.98	0.29	0.07	0.03	0.16	0.15	0.27	0.01	0.03	0.30	0.13	NA	NA	NA

NOTE: The SST at 46050 for 2011 is an estimated value due to a lack of buoy data from January to July.

Data for rank scores of ocean ecosystem indicators. Click [HERE](#) to download the data as a *.csv.

[Figure SF-01](#) shows correlations between adult Chinook salmon counts at the Bonneville Dam and coho salmon smolt to adult survival (%) ([PFMC 2014a](#)) versus a simple composite integrative indicator – the mean rank of all the ecosystem indicators (the second line from the bottom) in [Table SF-02](#). This index explains about 50% of the variance in adult returns. A weakness of this simple non-parametric approach is that each indicator is given equal weight, an

assumption that may not be true. Therefore, we are exploring a more quantitative analysis of the ocean indicators shown in [Table 3](#), using principal component analysis (PCA).

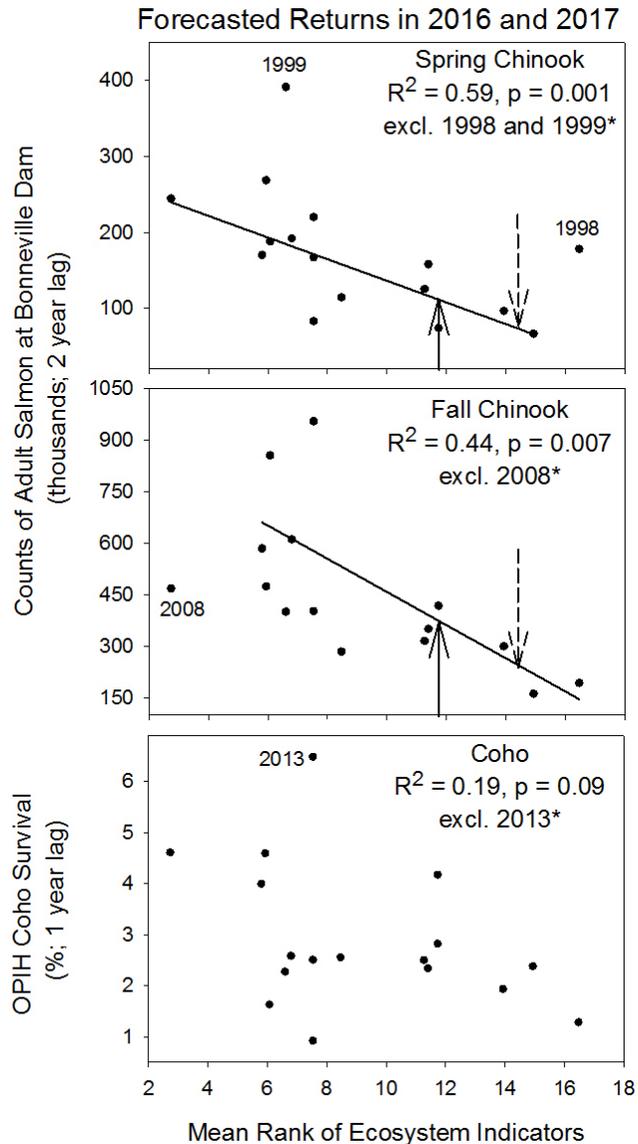


Figure SF-01. Salmon returns versus the mean rank of ecosystem indicators. Arrows show the forecasted returns of Chinook salmon in 2016 (solid line) and 2017 (dashed line). The mean rank of the ocean ecosystem indicators in 2014 was 11.7, forecasting a return of 112,094 and 375,682 adult spring and fall Chinook salmon to Bonneville Dam in 2016 respectively (top two panels). The mean rank of ocean ecosystems indicators in 2015 was less favorable (14.5) and the forecasted adult returns of spring and fall Chinook salmon in 2017 are expected to be lower; 72,220 and 240,701 respectively (dashed line). The relationship between the ocean ecosystem indicators and the smolt to adult survival of coho salmon to Oregon coastal streams was not significant (lower panel). Therefore, we cannot offer an expected percent survival for coho in 2017.

* outliers were excluded using [Cook's Distance](#)

Principal component analysis (PCA) was run on the indicator data. This procedure reduces the number of variables in the dataset as much as possible, while retaining the bulk of information contained in the data (a sort of weighted averaging of the indicators). Another important feature of PCA is that the principal components (PCs) are uncorrelated. This eliminates one of the original problems with the indicator data set (i.e., multi co-linearity). The first principal component (PC1) explains 55% of the ecosystem variability among years while the second principal component explains only 12%. Therefore, PC1 is used as a new predictor variable in a linear regression analysis of adult salmon returns (this process is termed principal component regression, or PCR) and those results are shown below in [Figure SF-02](#).

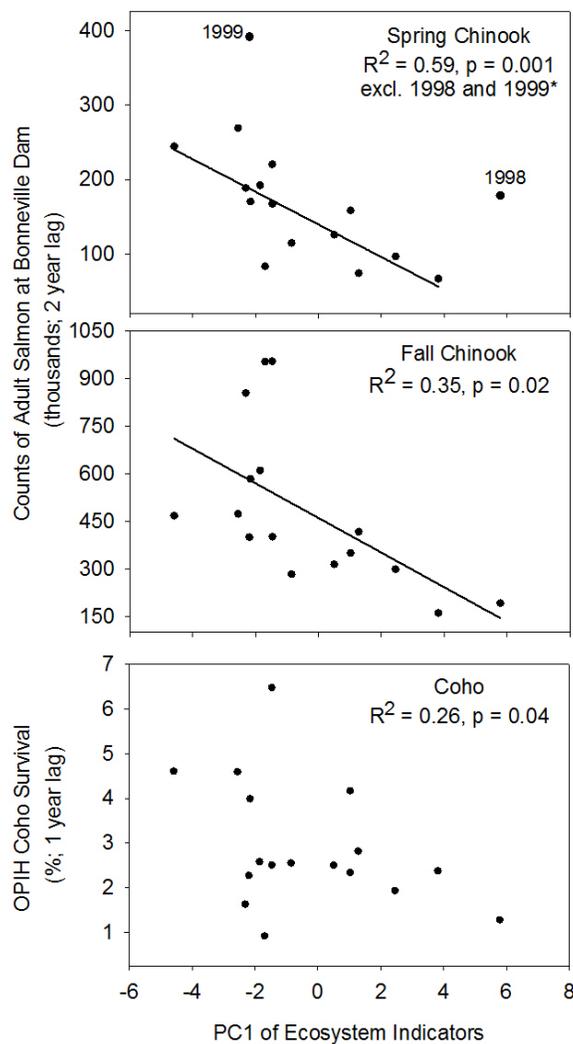


Figure SF-02. Salmon returns versus the first principal axis scores (PC1) from a Principal Component Analysis on the environmental indicators from [Table SF-02](#).

* outliers were excluded using [Cook's Distance](#)

In addition to correlating PC1 with salmon returns, we incorporated this metric into a more formal modeling structure. Specifically, we used sibling regression and dynamic linear modeling (DLM; [Scheuerell et al. 2005](#)) to relate PC1 to returns. DLMs are similar to linear regression, but allow the regression coefficient(s) to vary over time, effectively allowing for a shift in the magnitude of response to ocean conditions. We also ran models with and without siblings, as sibling data have been shown to be highly correlated with older-age adults. In all models, we allowed the intercept and the coefficients for siblings and PC1 to vary. However, the best model often showed no support for much of these dynamics and we therefore simplified the models to allow for only one parameter to vary over time. For coho salmon, there was no support for any parameter to vary, resulting in a simple linear regression model (of logit-transformed SAR). For Chinook, the models with siblings showed support for a dynamic effect of jack counts, whereas models without siblings showed support for a dynamic effect of PC1.

[Figure SF-03](#) compares the actual adult returns of adult spring and fall Chinook salmon and coho salmon to the forecasted returns derived from a maximum covariance analysis (MCA) of the ecosystem indicators. This technique is similar to the principal component regression illustrated in [Figure SF-02](#). This is work being conducted by Brian Burke (NWFSC/FE).

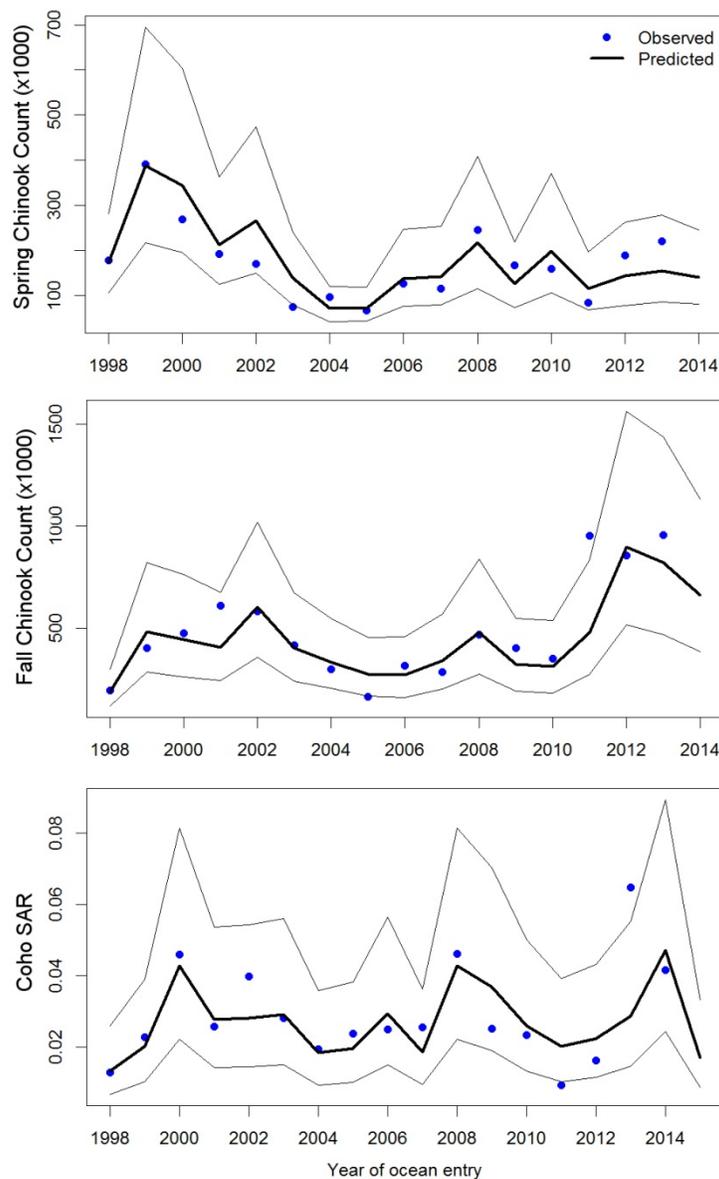


Figure SF-03. Time series of observed spring Chinook salmon adult counts (top), fall Chinook salmon adult counts (middle), and coho salmon SAR (bottom) by out-migration year. In each plot, the dark line represents a 1-year ahead forecast and lighter lines represent plus or minus 2 standard deviations from the mean. Forecasts were created from a DLM model with log (sibling count) and PC1 as predictor variables.

Although the PCA and DLM analyses represent a general description of ocean conditions, we must acknowledge that the importance of any particular indicator will vary among salmon species/runs. We are working towards stock-specific salmon forecasts by using methods that can optimally weight the indicators for each response variable in which we are interested ([Burke et al. 2013](#)).

Adult Returns of Chinook and coho Salmon

For specific stocks of Chinook and coho salmon, 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 ([Healey 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.

Adult data are lagged behind ocean entry by 1 year for coho salmon and 2 years for spring and fall Chinook salmon; therefore, as of 2015, we have up to 18 years of indicator data but only 15 - 17 years of adult return data. We have two less years of data for the Klamath adult returns because those numbers are not available from the Pacific Fishery Management Council until the following February ([PFMC 2015c](#)).

Table ARD-01. Ranks among years for adult returns by year of ocean entry, 1998 – present. Colors represent high (green), intermediate (yellow), and low (red) returns.

Adult returns by Year of Ocean Entry¹				
Year	OPIH Coho (adults:smolts)	Bonneville spring Chinook (n)	Bonneville fall Chinook (n)	Klamath River fall Chinook (n est.)
1998	16	7	15	8
1999	13	1	10	3
2000	3	2	6	5
2001	7	5	4	2
2002	5	8	5	12
2003	6	15	8	14
2004	14	13	13	15
2005	11	16	16	7
2006	10	11	12	13
2007	8	12	14	10
2008	2	3	7	11
2009	9	9	9	9
2010	12	10	11	1
2011	17	14	2	4
2012	15	6	3	6 ²
2013	1	4	1	—
2014	4 ²	—	—	—

¹ Counts of spring and fall Chinook salmon are lagged by 2 years and returns for coho salmon 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 years. For example, for fish that entered the ocean in 1998, the number listed for spring and fall Chinook salmon indicates adults that returned in 2000. Although we use a 2 year return lag for Chinook salmon, we acknowledge that there are different [age classes](#) of returning adults with lags of 2 - 5 years. For example, spring Chinook salmon that entered the ocean in 2000 may return to spawn in 2002 - 2005.

Table ARD-02. Adult return data used for ranking among years, as shown in Table ARD-01. Again, the full data set for the year of ocean entry requires a lag time of up to 2 years: thus though we have 18 years of ocean ecosystem indicator data, we have only 15 - 17 years of adult return data.

Adult returns by Year of Ocean Entry¹

Year	OPIH Coho (adults:smolts)	Bonneville spring Chinook (n)	Bonneville fall Chinook (n)	Klamath River fall Chinook (n est.)
1998	0.0128	178,302	192,793	123,856
1999	0.0227	391,367	400,205	187,333
2000	0.0459	268,813	473,786	160,788
2001	0.0258	192,010	610,075	191,948
2002	0.0399	170,152	583,754	78,943
2003	0.0282	74,038	417,057	65,227
2004	0.0193	96,456	299,161	61,374
2005	0.0238	66,624	161,415	132,131
2006	0.0250	125,543	314,995	70,554
2007	0.0255	114,525	283,691	100,644
2008	0.0461	244,384	467,524	90,860
2009	0.0251	167,097	401,576	101,977
2010	0.0234	158,075	350,083	295,322
2011	0.0092	83,299	952,944	165,025
2012	0.0163	188,078	854,503	160,444 ²
2013	0.0648	220,250	954,140	—
2014	0.0417 ²	—	—	—

¹ Counts of spring and fall Chinook salmon are lagged by 2 years. Return ratios for coho salmon are lagged by 1 year.

² Estimate based on [jack](#) returns.

Note also that these estimates were not adjusted for catch in fisheries, which can have a major impact on adult numbers. For example, ocean fisheries for Chinook salmon off California and most of the Oregon coast were closed in 2008 and 2009; these fisheries typically catch hundreds of thousands of Chinook salmon annually ([PFMC 2015b](#)). Consequently, adult returns to basins

most impacted by this closure (e.g., Klamath River) in those years reflect both substantially reduced harvest rates and the influence of ocean conditions on marine survival. Accordingly, direct comparisons of adult abundances across years should be made with considerable caution due to this high variation in harvest rates.

Time Series Plots

Low frequency (long-term) oscillations in the climate of the North Pacific basin impact regional and local physics and biology. Unfortunately, there is not a clear understanding of all the linkages associated with these impacts and the various time lags associated with biological responses to changes in climate. Plots of the long-term variability in large-scale atmospheric forcing and local physical and biological parameters can be used to visually assess relationships. Below, are plots of climate indices (i.e. the Oceanic Nino Index (ONI) and Pacific Decadal Oscillation (PDO) in relation to ocean ecosystem data collected at station NH- 05 off Newport, Oregon (Figure TSP-01).

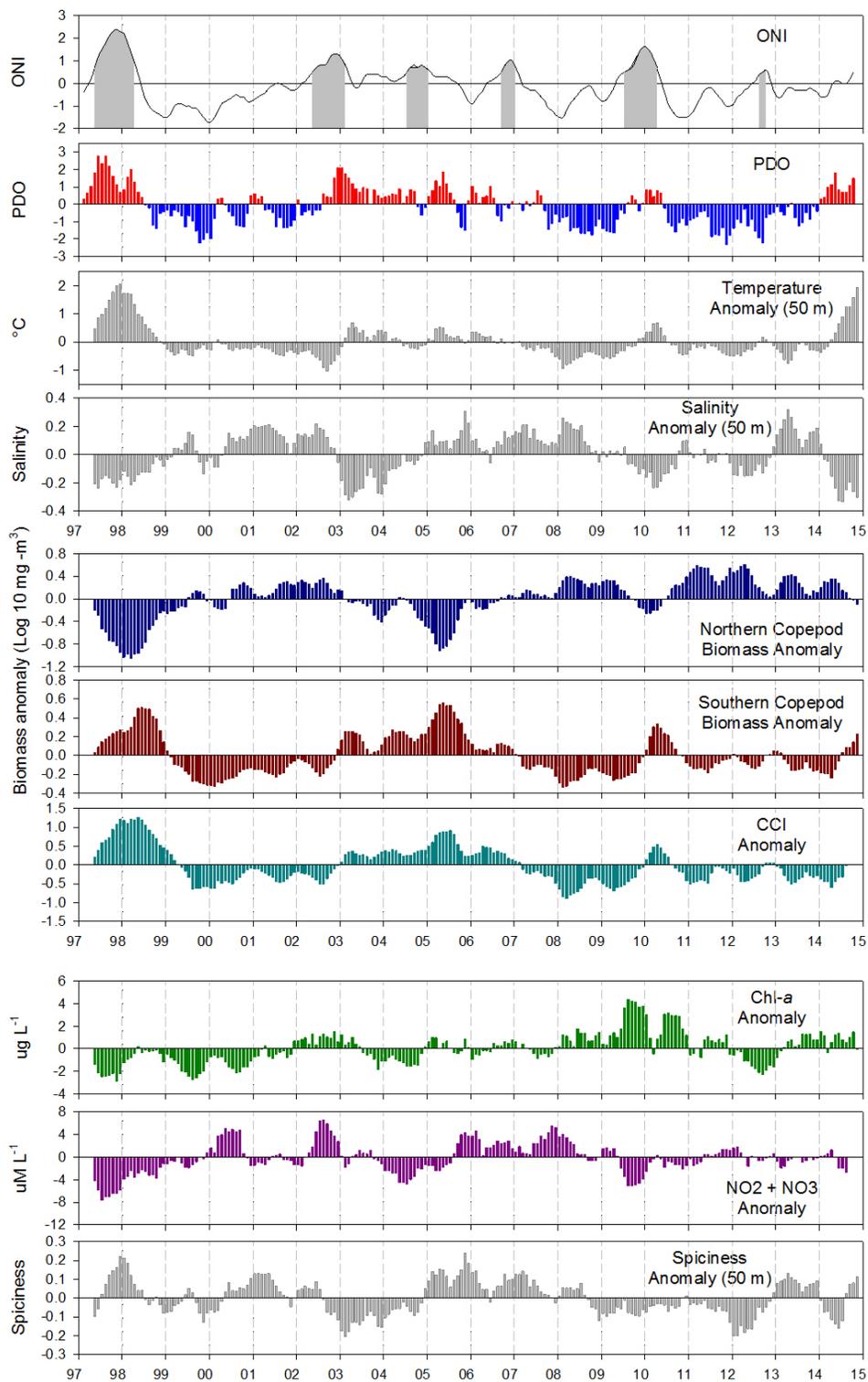


Figure TSP-01. Time series plots of large-scale atmospheric forcing and local physical and biological indicators from 1997 - present. All local indicators were smoothed with a 7-month running mean to remove high frequency variability. Shading in the top panel (ONI) indicates El Niño events.

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.

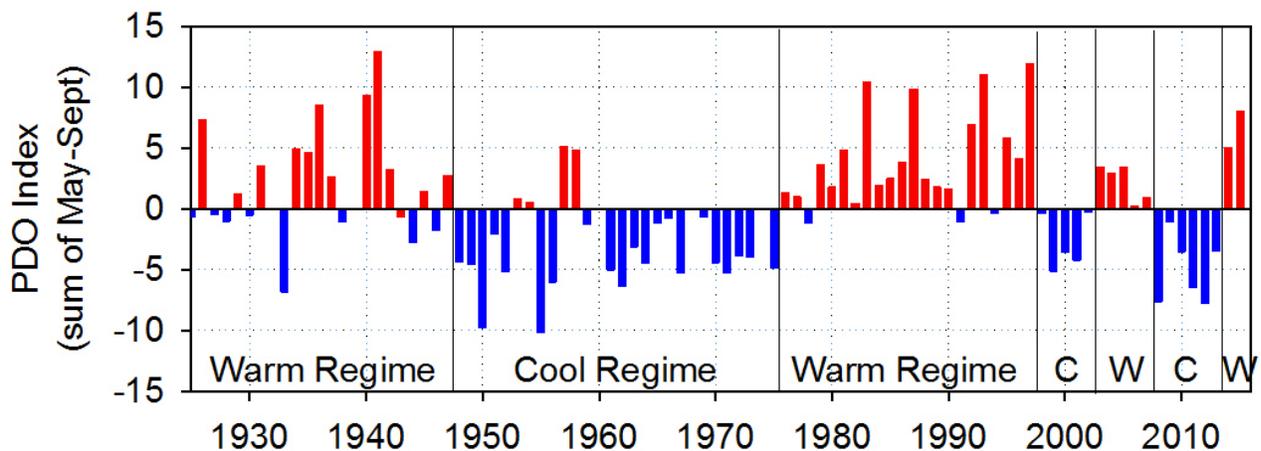


Figure PDO-01. Time series of shifts in sign of the Pacific Decadal Oscillation (PDO), 1925 to present. Values are summed over the months of May through September. Red bars indicate positive (warm) years; blue bars negative (cool) years. Note that 2008 and 2012 were the most negative values recorded since 1956.

Warm and cold phases can persist for decades. For example, a warm phase continued from 1925 to 1946 (red bars in Figure PDO-01), and a cool phase from 1947 to 1976 (blue bars). From 1977 to 1998, another 21—year warm phase occurred. However, these decadal cycles have recently broken down: in late 1998, the PDO entered a cold phase that lasted only 4 years followed by a warm phase of 3 years, from 2002 to 2005, neutral until August 2007 and abruptly changing to a negative phase that lasted through 2013, nearly 6 years, with only a short interruption during the moderate El Nino in fall/winter 2009-2010 (Figure TA-01). Since the beginning of 2014, however, the PDO has switched phase again and has been strongly positive.

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 salmon and coho salmon to Oregon rivers. Conversely, during the warm PDO cycle that followed (1977–1998), salmon numbers declined steadily.

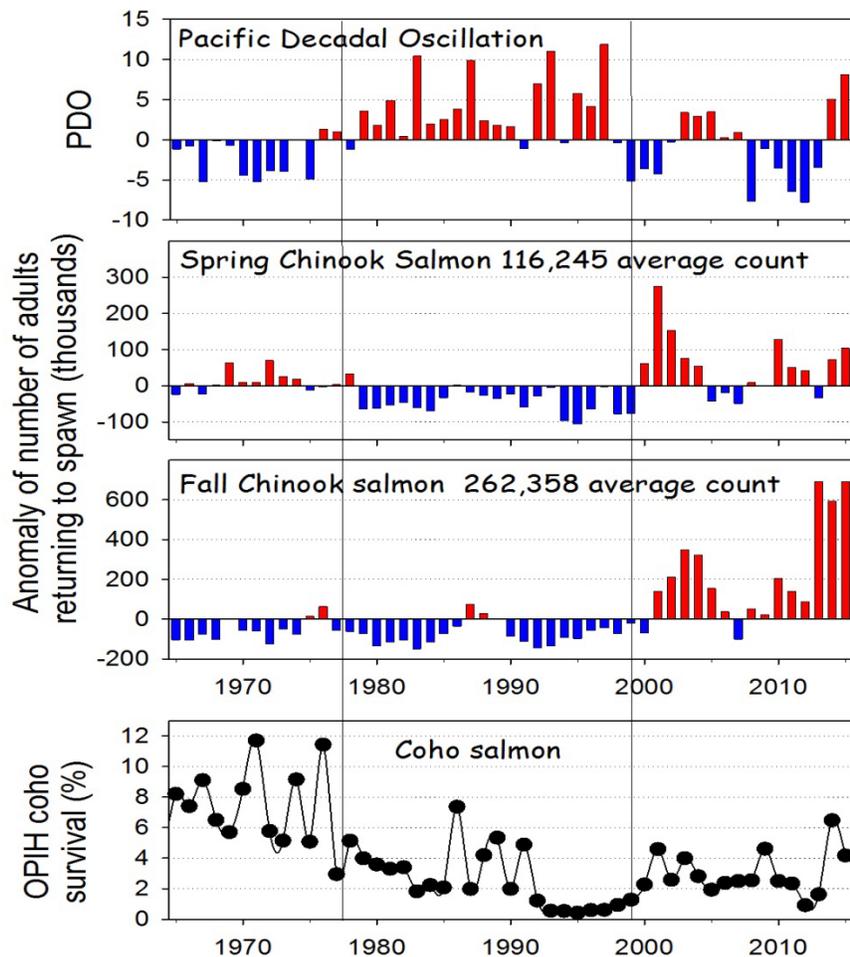


Figure PDO-02. Upper panel shows summer PDO (sum of May–Sept), 1965—present; middle panels show anomalies in counts of adult spring and fall Chinook salmon passing Bonneville Dam from 1965—present; lower panel shows survival of hatchery coho salmon from 1965—present. Vertical lines indicate climate—shift points in 1977 and 1998.

The listing of several salmon stocks as threatened or endangered under the U.S. Endangered Species Act coincides with a prolonged period of poor ocean conditions that began in the early 1990s. This is illustrated in Figure [PDO-02](#), which shows summer PDO values (sum of values from May — Sept) vs. anomalies in counts of adult spring and fall Chinook salmon 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 [PDO-02](#) shows a clear visual correlation between the PDO, adult spring and fall Chinook salmon counts and lesser so for hatchery coho salmon adult returns. Note that during the 22–year cool phase of the PDO (1955 to 1977), below–average counts of spring Chinook salmon at Bonneville Dam were seen in only 5 years (1956, 1958 60, and 1965). In contrast, below–average counts of both spring and fall Chinook salmon were common from 1977 to 1998, when the PDO was in warm phase. 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 [PDO-02](#) that a time lag of up to 2 years exists between PDO phase changes and spring and fall Chinook salmon returns: Chinook salmon runs remained above average in 1977 and 1978, 2 years after the 1976 PDO shift. Similarly, increased returns of spring and fall Chinook salmon adults in 2000 lagged 2 years behind the PDO shift of 1998.

Adult spring Chinook salmon returns declined again in 2005, likely from poor survival of juvenile fish that entered the sea in 2003 and experienced poor ocean 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. Since 2013, we’ve observed the highest adult returns of fall Chinook salmon since 1965, which is likely attributed to the strongly negative PDO phase beginning in 2011.

Oceanic Niño Index (ONI)

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

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

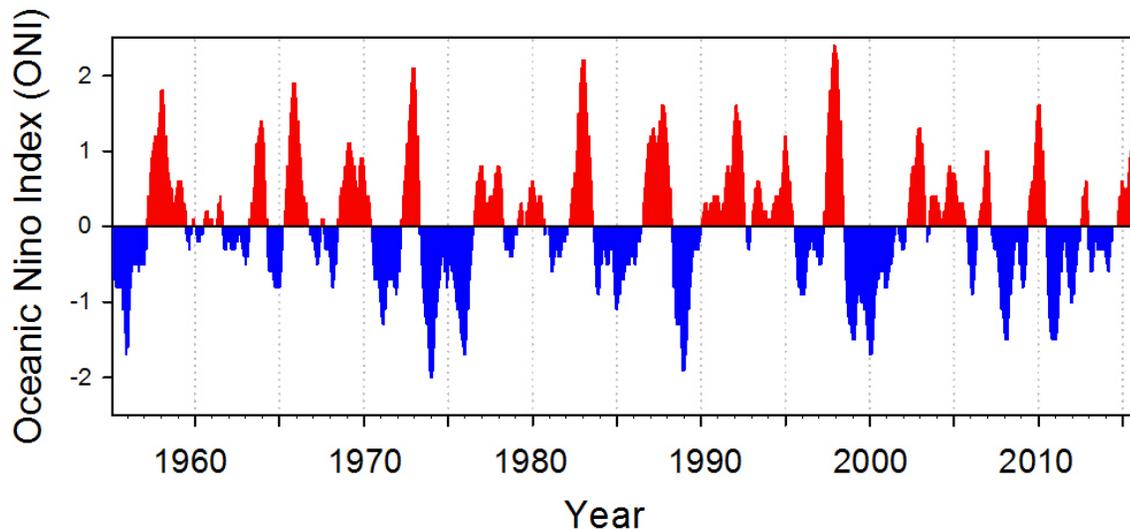


Figure ONI-01. Values of the ONI, 1955 - present. Red bars indicate warm conditions in the equatorial Pacific, blue bars indicate cool conditions in equatorial waters. Large and prolonged El Niño events are indicated by large, positive values of the index: note the $> +2$ value associated with the 1972, 1983 and 1998 events. Recent cool anomalies (La Niña) were during 1999-2002, 2007-2009 and 2010-2012.

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

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

Since 1955, the presence/absence of conditions resulting from the El Niño Southern Oscillation (ENSO) has been gauged using the Oceanic Niño Index, or ONI. A time series of the ONI is shown in Figure ONI-01. The equatorial and northern North Pacific oceans experienced several very intense El Niño events (1972-72, 1983-1984, 1997-1998, and 2015) along with prolonged events from 1990 to 1995 and 2002-2005, and a short, but relatively strong event in early 2010.

Both the PDO and ONI can be viewed as "leading indicators" of ocean conditions, since after a persistent change in sign of either index, ocean conditions in the California Current soon begin to change. The ONI is a good index of El Niño conditions, and one can find information on the status of both El Niño and La Niña at the [Climate Prediction Center](#) and other websites maintained by the [NOAA National Weather Service](#). Following the relatively strong El Niño during the winter of 2009-2010, the northern California Current experienced a rapid switch to La Niña conditions. The switch was reflected in both a drop in sea surface temperatures ([Figure TA-01](#)) and a later decrease in copepod biodiversity ([Figure CB-02](#)).

Local and Regional Physical Indicators

Temperature Anomalies

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 (*Oncorhynchus tshawytscha*) and coho (*O. kisutch*) salmon, whereas warm conditions are not.

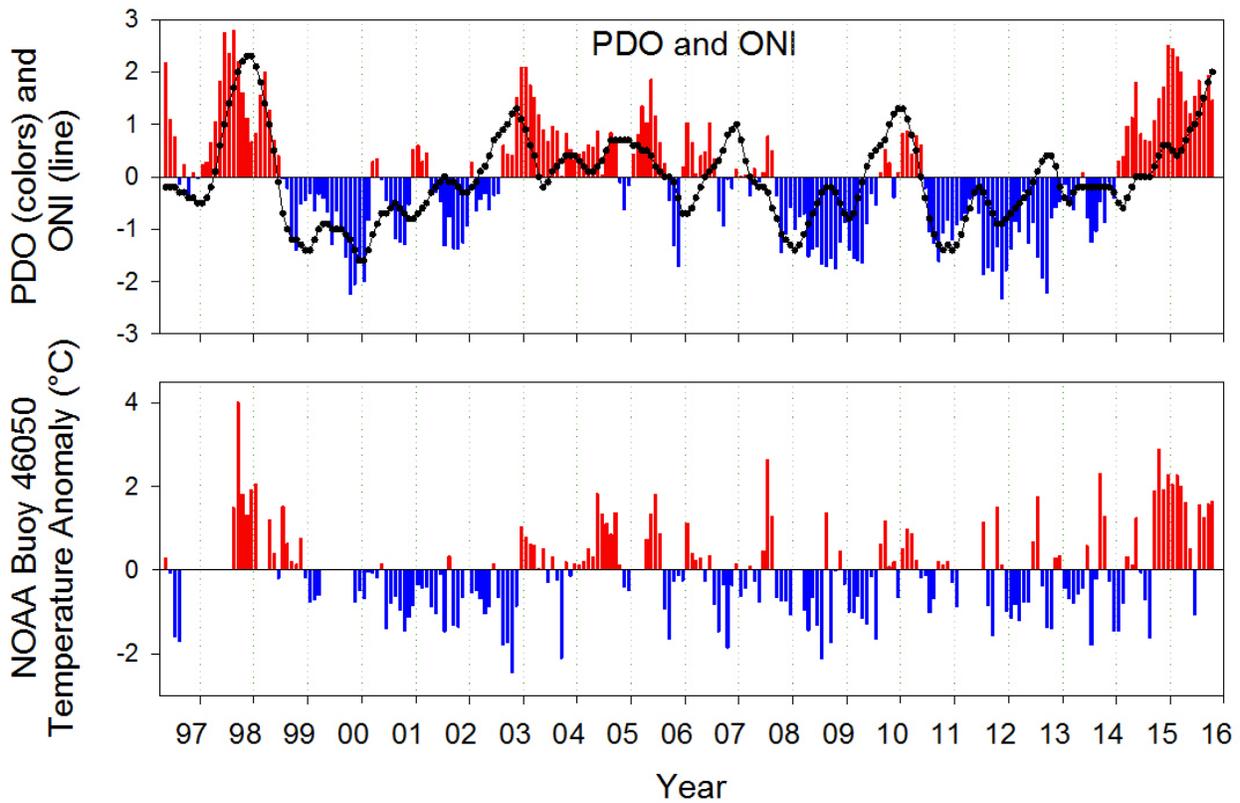


Figure TA-01. The PDO (upper panel, colored bars), ONI (upper panel, line) and monthly sea surface temperature (SST) anomalies at NOAA Buoy 46050, 20 miles west of Newport, OR (bottom panel).

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 the negative PDO period of 1999–2002, they were 2°C cooler than normal (Figure TA-01 and TA-03). The PDO switched to a positive phase from mid-2002 through 2005 when positive SST anomalies were observed up to +2°C. 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). In autumn 2009, an El Niño event arrived 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 that corresponded with a persistently negative PDO pattern, and SSTs responded with mostly negative anomalies of –1.5°C that persisted through until the autumn of 2014. Once upwelling ended in the fall of 2014, SST anomalies increased rapidly +2°C and have remained high, higher than the strong El Niño event in 1998. This most recent increase in SST anomalies is associated with the anomalously warm water, which has persisted in the NE Pacific since the end of 2013 and has been dubbed “The Blob”, coming ashore in the autumn of 2014.

Note also in [Figure TA-01](#) 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.

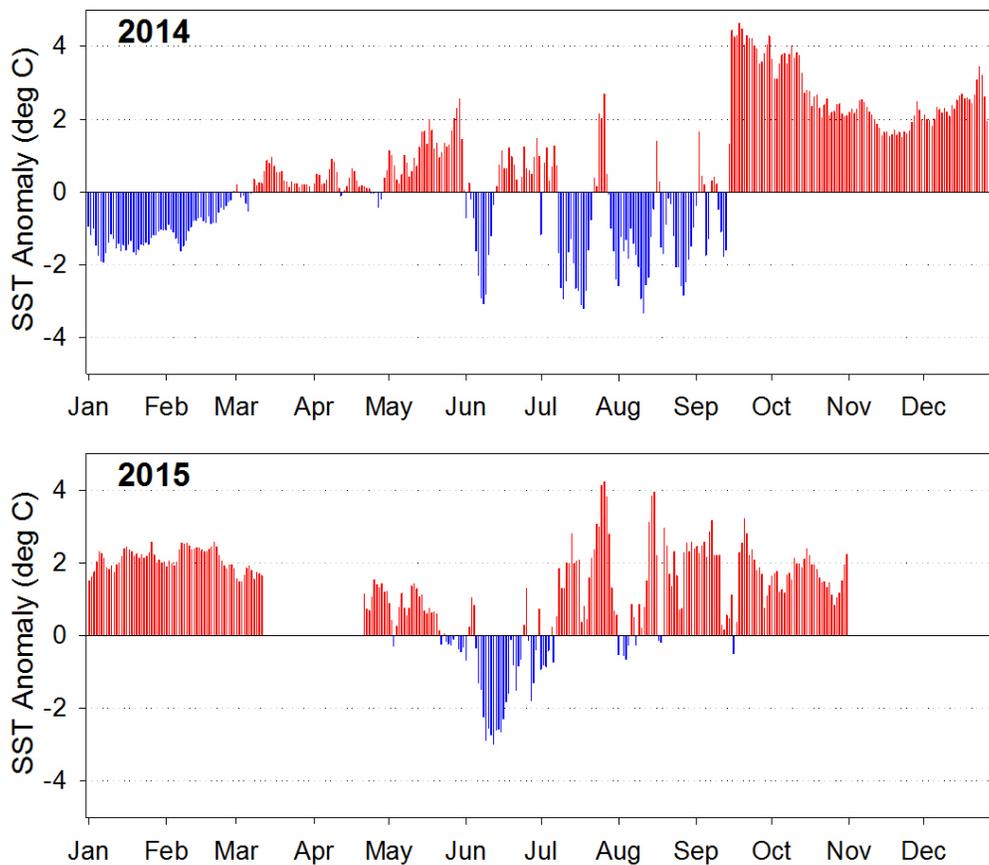


Figure TA-02. Daily sea surface temperature anomalies measured at NOAA Buoy 46050, located 22 miles off Newport, OR.

Thus, local variables respond to changes that occur on a broad spectrum of spatial scales. These range from basin-scale changes, which are indexed chiefly by the PDO and ENSO, to local and regional changes, such as those related to shifts in the jet stream, atmospheric pressure, and surface wind patterns. Within a year, there are frequent fluctuations in the SST anomaly (Figure TA-02), primarily due to the timing and intensity of the winds. We have observed rapid changes to the SST anomalies over the past two years (TA-02). In 2014, upwelling ended mid-September and the anomalously warm NE Pacific water (“The Blob”) was advected onto the continental shelf which resulted in a rapid and large increase in SST anomalies of +4°C. This warm water persisted on the shelf throughout the winter of 2014-2015 and has only been interrupted briefly during the strong upwelling that occurred in June 2015.

[Figure TA-03](#) summarizes temperature measurements made during our fortnightly cruises off Newport Oregon, at station [NH 05](#). Seasonal averages for winter (Nov-Mar) and summer (May-Sep) can increase by up to 2 °C during El Nino events (1997-98) and have a cyclic pattern reflecting influences of both the PDO and ONI. Note the signature of “The Blob” water as the highest winter temperature anomalies since 1996.

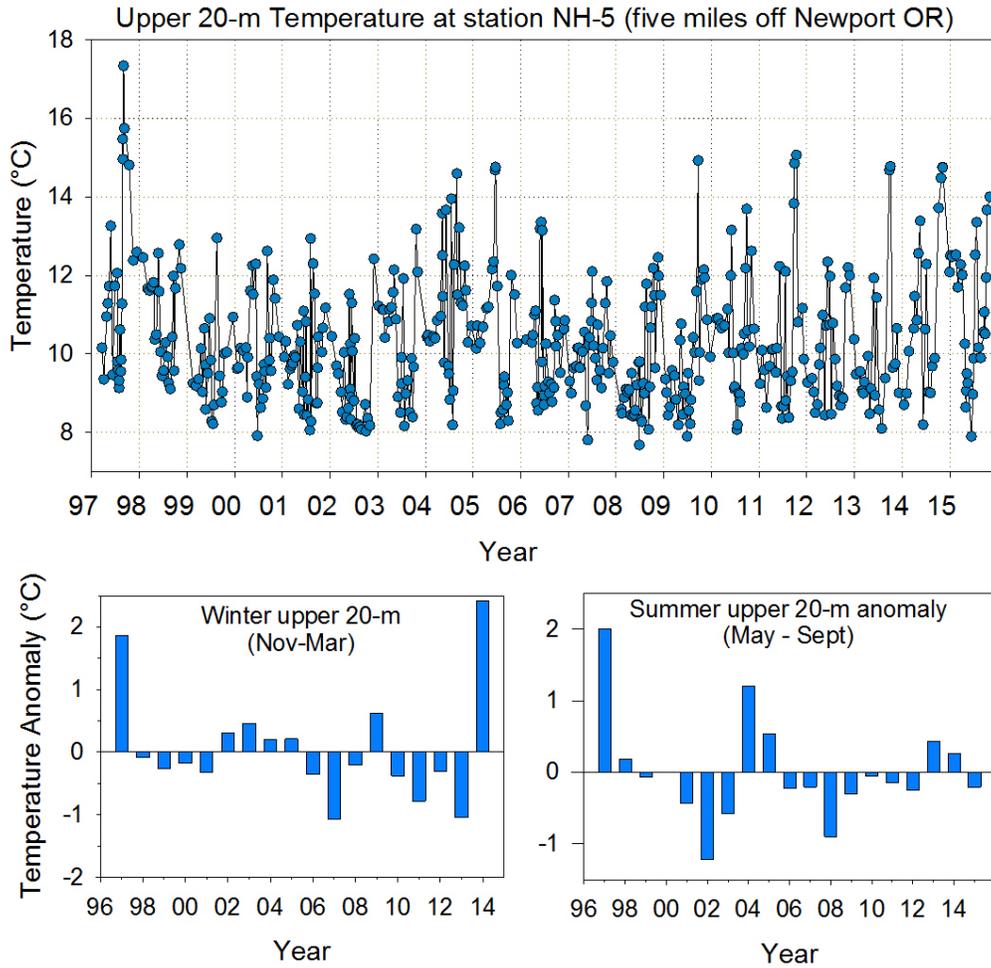


Figure TA-03. Upper panel shows the average temperature in the upper 20 m of the water column at Station NH-5 (located 5 miles off Newport, Oregon) since 1996. The lower panels depict the upper 20 m temperature anomalies over the same years during summer (left; May–Sept) and winter (right; Nov – Mar).

Coastal Upwelling

An important process affecting primary productivity during the spring and summer 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 CU-01](#)), 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).

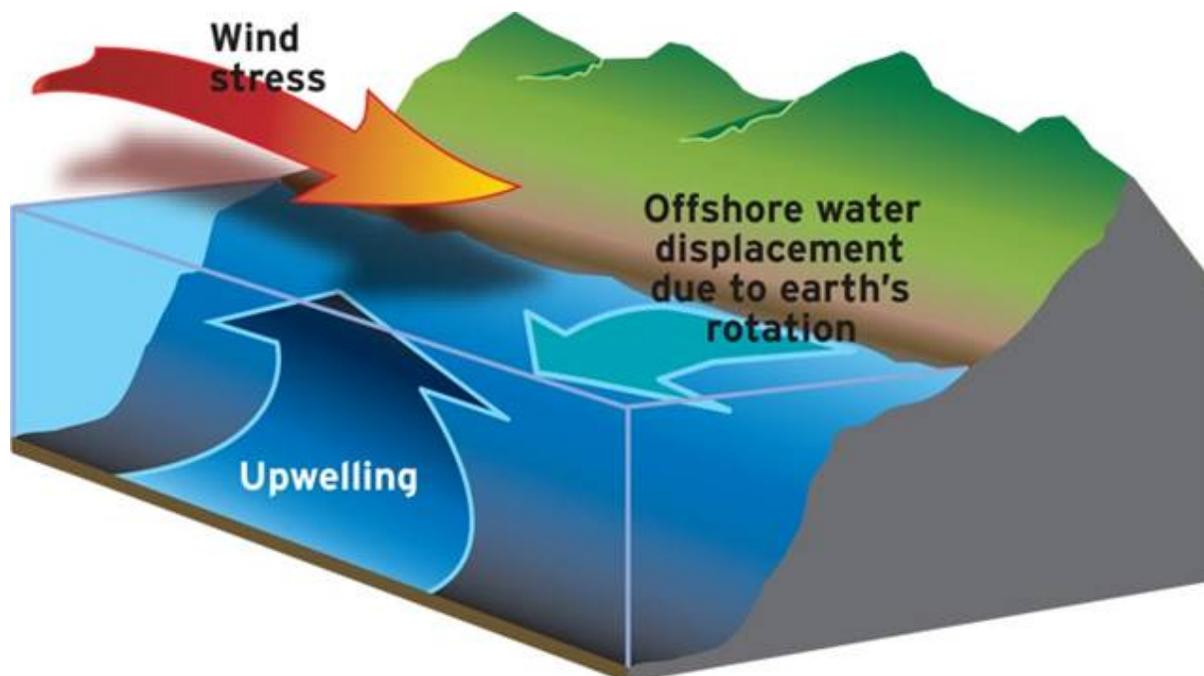


Figure CU-01. Forces affecting coastal upwelling.

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 CU-02](#). The years of strongest upwelling were 1965–1967.

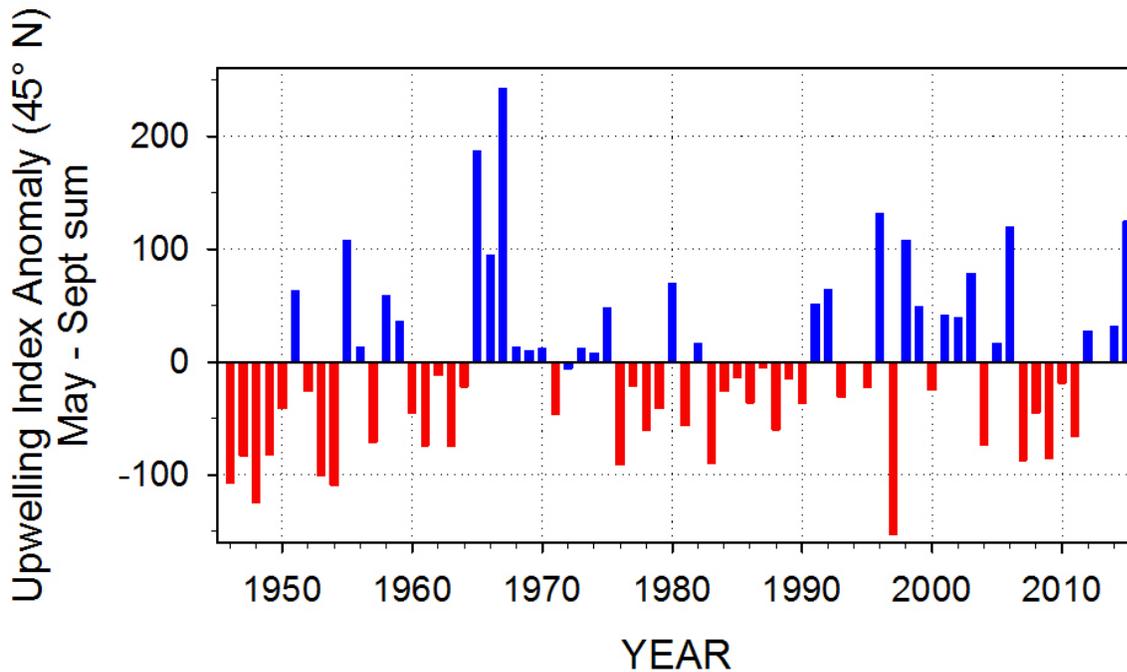


Figure CU-02. Anomalies of the coastal Upwelling Index during May to September each year, 1946 - present

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).

The relationship of spring and fall adult Chinook salmon returns to the Bonneville dam and coho salmon survival (%) with upwelling for 1996 to present is shown in Figure CU-03. The relationship is strong for spring Chinook, but there is no relationship for fall Chinook and coho salmon. Although the relationships are weak, the strongest correlations with survival were found with upwelling in April and May combined.

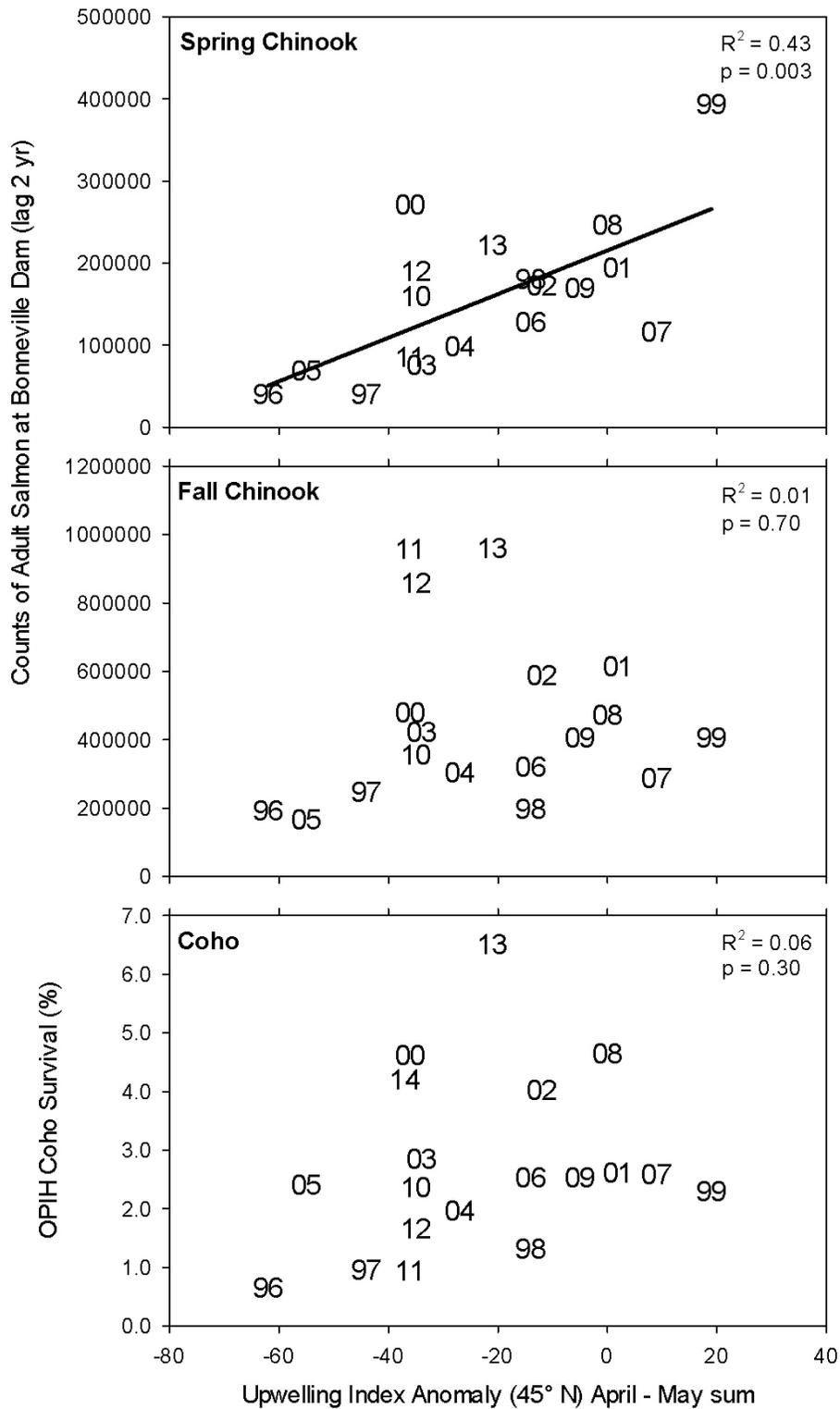


Figure CU-03. Relationship of spring and fall adult Chinook salmon returns to the Bonneville dam and coho salmon survival (%) with the April and May sum of upwelling at 45°N from 1996-present. Numbers indicate the years. The relationship with fall Chinook and coho salmon is not significant.

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 salmon returns based on this composite upwelling index.

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.

[Figure CU-04](#) 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.

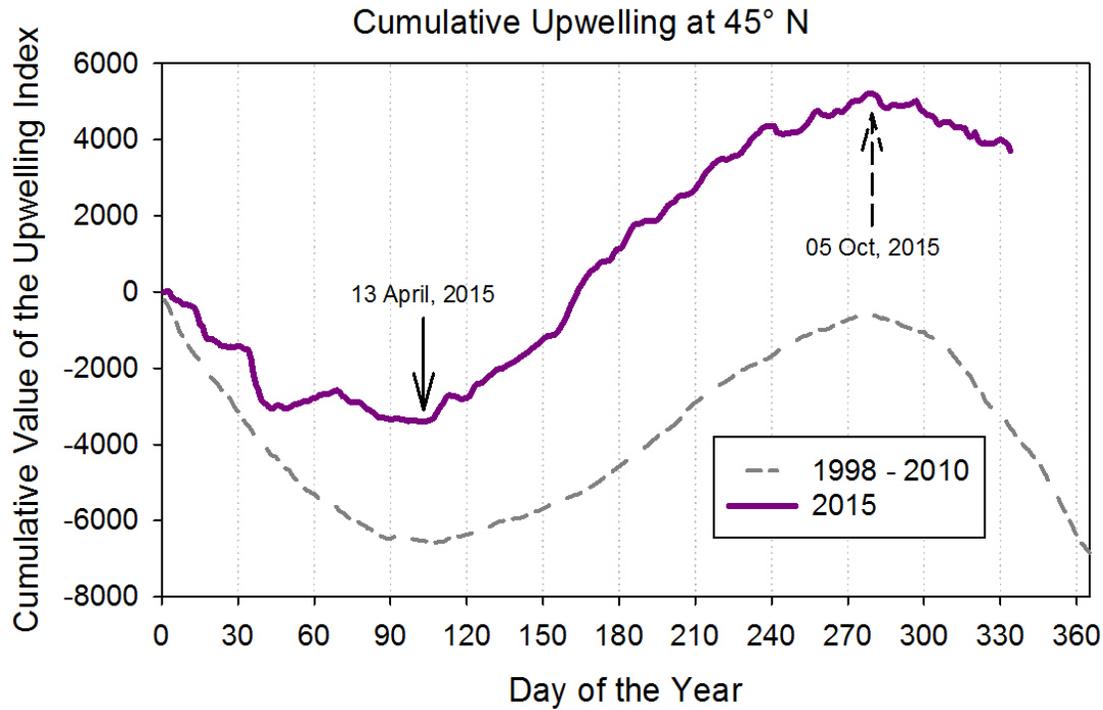


Figure CU-04. Cumulative upwelling index. Vertical arrows indicate the date of physical spring transition (solid line) and fall transition (dashed line).

One can see in [Figure CU-04](#) that upwelling began and ended as normal compared to the climatological mean. However, the total amount of upwelling for the season was much higher than the 40-year average.

Hypoxia

Hypoxia (dissolved oxygen concentrations < 1.4 ml/L) is common in bottom waters across the continental shelf off Oregon and Washington during the summer months ([Figure HYP-01](#)). The presence of hypoxic waters can be lethal to benthic invertebrates and may displace demersal fish species ([Grantham et al. 2004](#)).

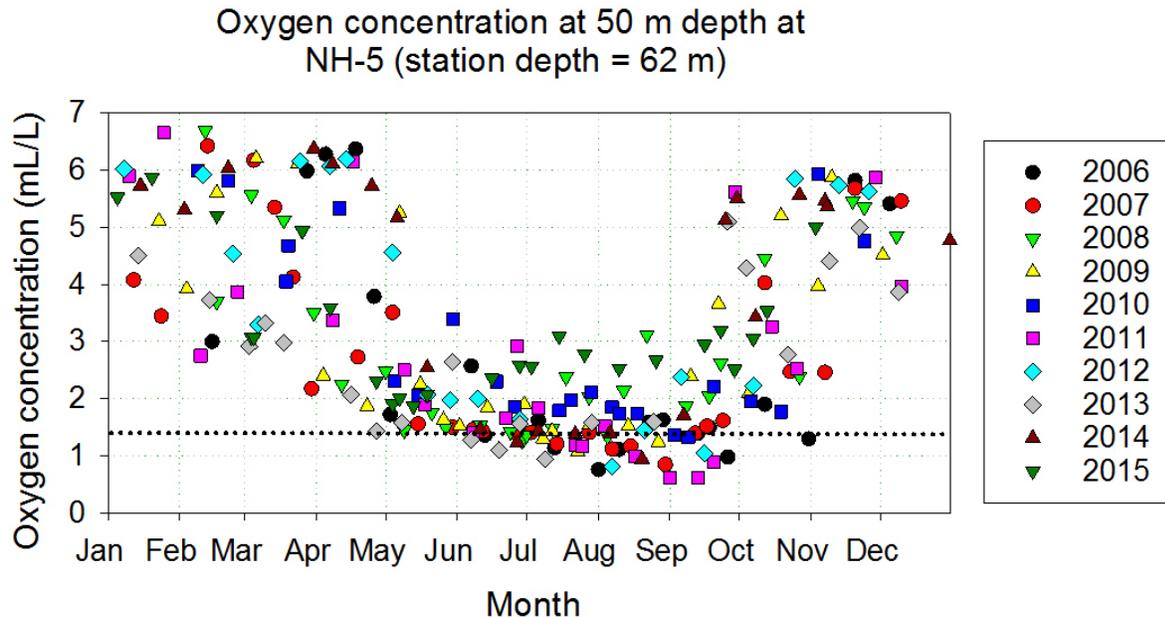


Figure HYP-01. Oxygen concentration in bottom waters at a baseline station [NH.05](#). Hypoxia is defined as waters with oxygen concentrations < 1.4 ml/L, and is observed only during the coastal upwelling season, especially during Jun-Sep.

Along the Newport Hydrographic (NH) Line, hypoxic waters tend to occupy the lower 10 - 30 m of the water column ([Figure HYP-01](#)). Spatially, hypoxic bottom waters can cover the entire width of the shelf ([Figure HYP-02](#)), but is less common in shallower areas (< 30 m depth) where wind and wave action helps to aerate the water column.

Juvenile salmon tend to reside in the upper layer of the water column and are likely not directly influenced by hypoxia.

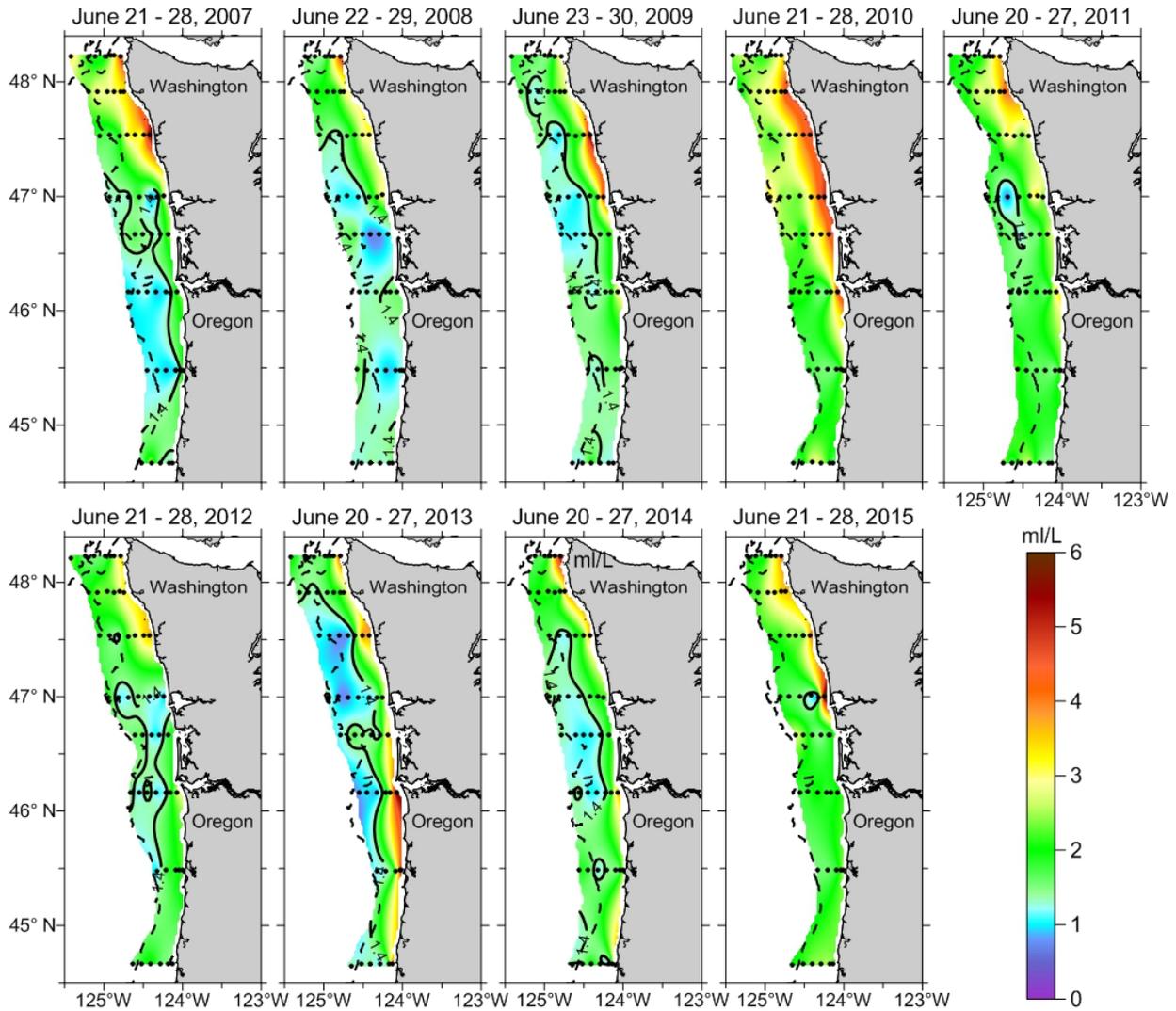


Figure HYP-02. Dissolved oxygen maps. Distribution of the minimum dissolved oxygen values (ml/L) during the June BPA surveys from 2007 - present. A level of 1.4 ml/L dissolved oxygen is used to identify hypoxic waters (outlined with bold contour line).

The greatest extent of hypoxic bottom waters typically occurs in August and September. Based on regional surveys conducted since 2006, hypoxic bottom waters can cover up to 62% of the shelf north of the Newport Hydrographic line (Figures HYP-02 and HYP-03).

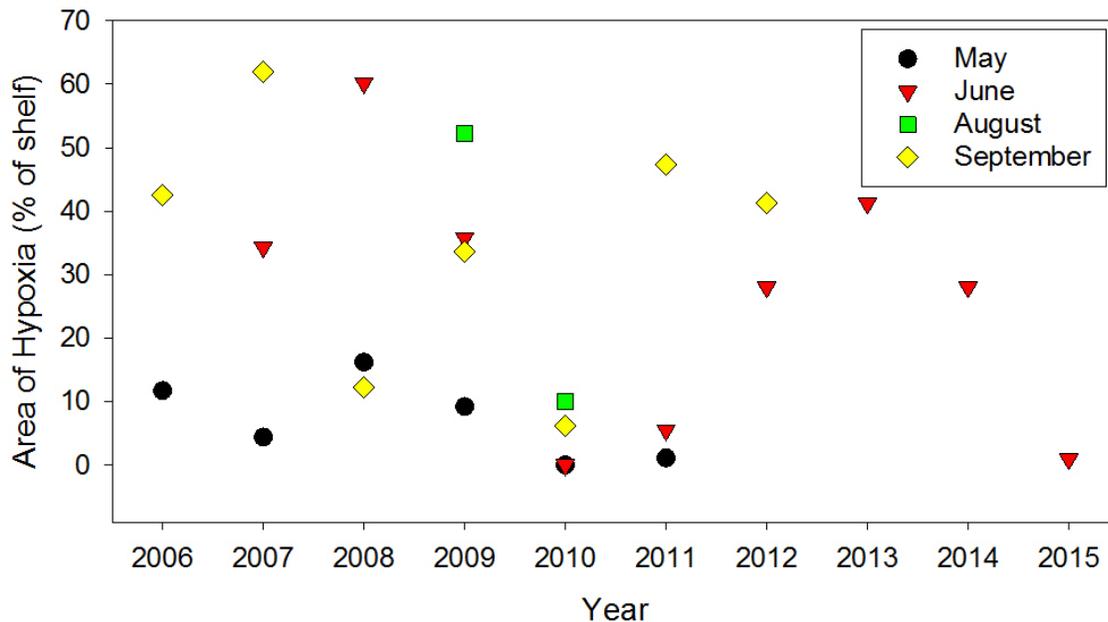


Figure HYP-03. The area of the shelf containing hypoxic bottom waters during the May, June, August and September surveys. The shelf area surveyed is 15,750 km². The shelf area and region of hypoxia were calculated from maps similar to those shown in Figure HYP-02.

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.

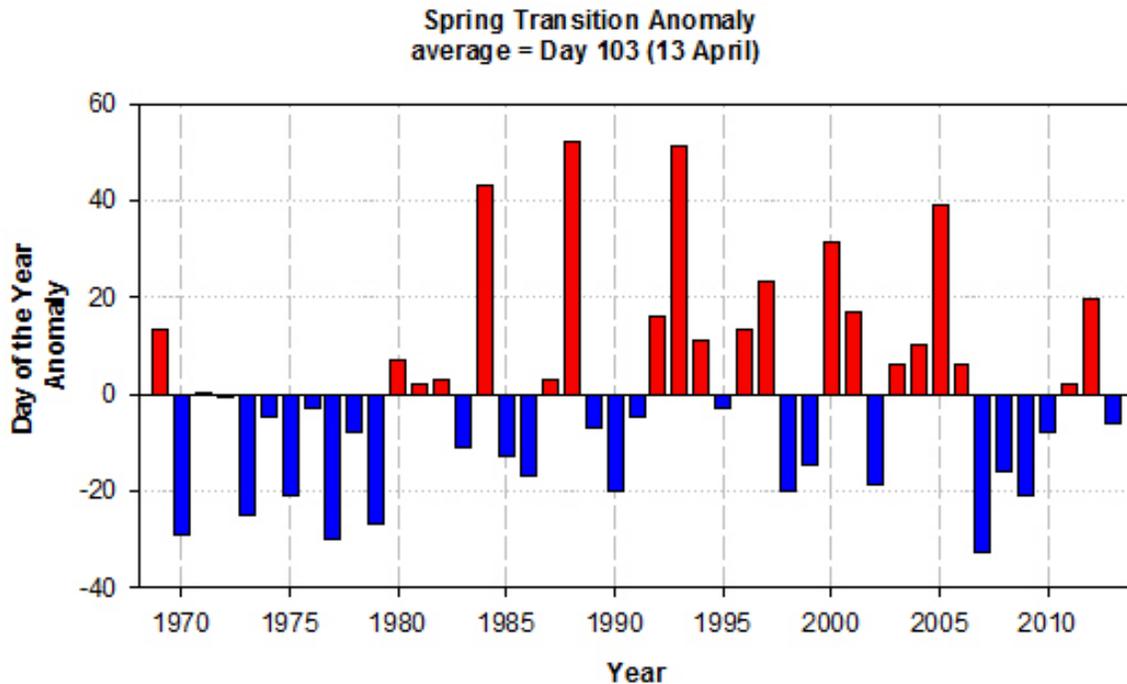


Figure PST-01. Anomalies in the date of the physical spring transition from 1969 to present. Anomaly is based on an average date of 13 April using the minimum cumulative upwelling index (CUI) value.

The date of spring transition can be indexed in several ways. Here, we use the date of the minimum value of the Cumulative Upwelling Index (CUI). Further details can be found in Bakun ([1973](#)) and Bograd et al. ([2009](#)). The average date of upwelling is 13 April (Day 103), but can range from early March to early June. Note from Figure PST-01 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 PDO-01](#)) or the Multivariate ENSO index ([Figure ONI-01](#)).
- The period of early transition dates from 1985 to 1990 correlates well with the high salmon survival in the late 1980s (see [Figure PDO-02](#)).

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 PST-02 (left) shows that adult spring and fall Chinook returns at Bonneville and coho salmon smolt-to-adult survival from 1996 to present are not well correlated with the day of spring transition using the Cumulative Upwelling (Bakun) method, though studies using an earlier and longer time series have found some correlation (Logerwell et al.

2003). An analysis using smolt-to-adult return rates of Snake River spring/summer Chinook salmon (from Scheuerell and Williams 2005) did not reveal any significant correlations with the transition date.

However, the spring transition date using our new hydrographic method does show a weak, but significant relationship with adult returns of adult spring and fall Chinook returns at Bonneville, and coho salmon smolt-to-adult-survival (Figure PST-02, right). Survival is higher in years with an earlier transition date.

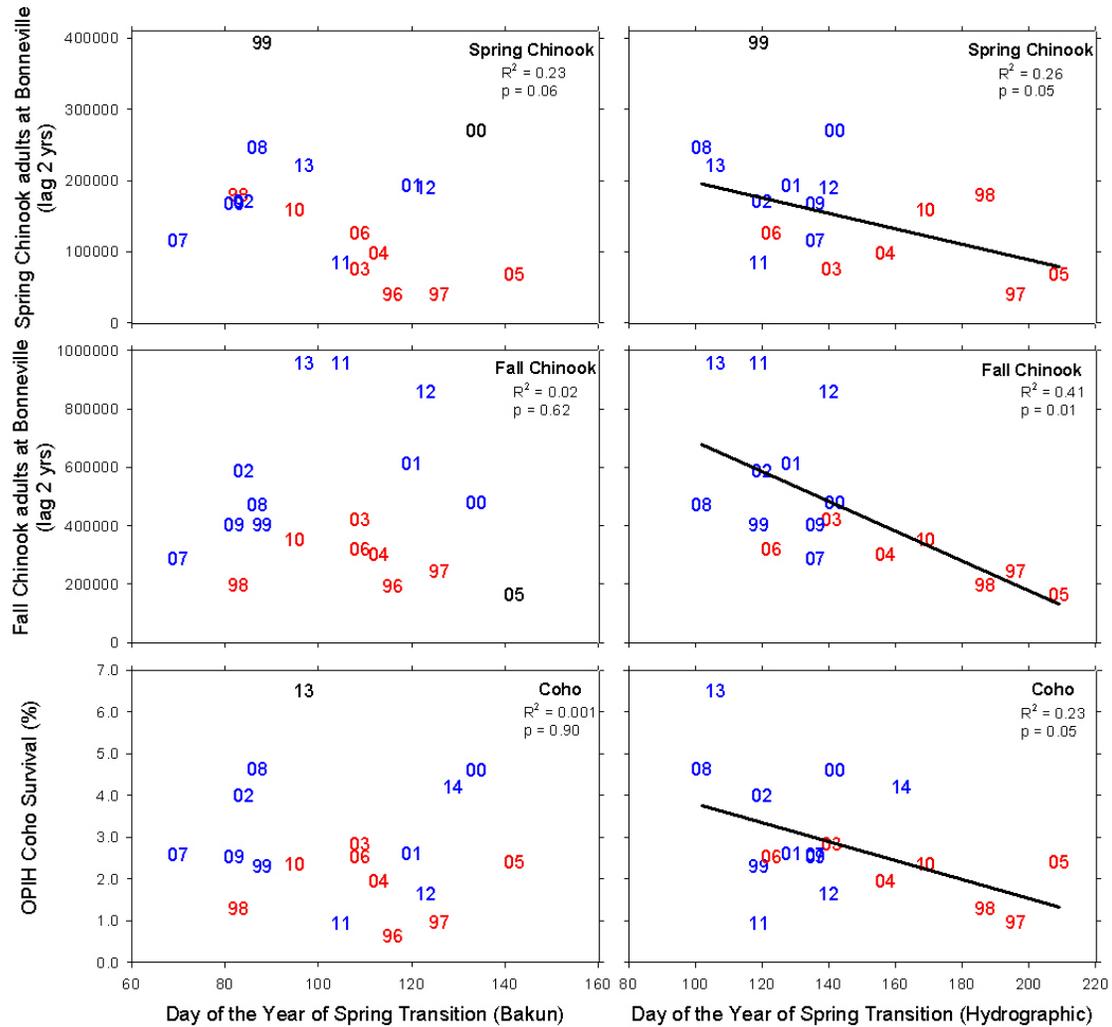


Figure PST-02. Plot showing the relationship between spring Chinook salmon adult returns at Bonneville dam (lag 2 years, top), fall Chinook salmon adult returns at Bonneville dam (lag 2 years, middle), and coho salmon smolt-to-adult survival (SAR, lag 1 year, bottom) versus the date of spring transition using the Bakun upwelling method (left) and the hydrographic method (right). Numbers indicate the warm (red) and cold (blue) years. Years in black were outliers and were excluded from the regression.

* outliers were excluded using [Cook's Distance](#)

PST-02 shows that hatchery adult coho salmon returns from 1996 to present are not well correlated with the day of spring transition, though studies using an earlier and longer time series have found some correlation ([Logerwell et al. 2003](#)). An analysis using smolt-to-adult return rates of Snake River spring/summer Chinook salmon (from [Scheuerell and Williams 2005](#)) did not reveal any significant correlations with the transition date, but when using spring Chinook salmon adult counts at Bonneville Dam (1996 – present from the [DART](#)) there is a significant linear relationship (PST-02).

Other measures of the spring transition include ones from:

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

Deep–Water Temperature and Salinity

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

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

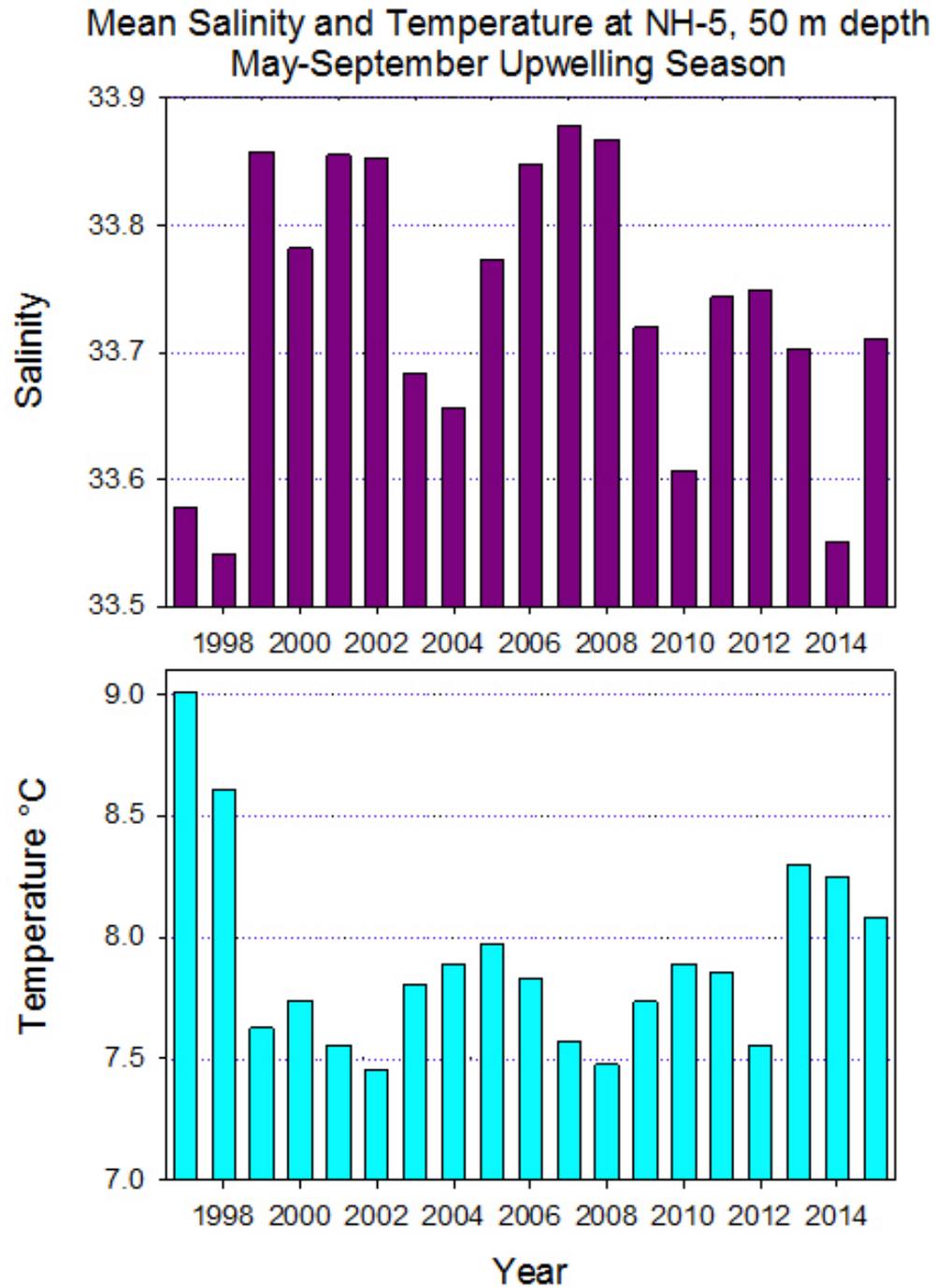


Figure DTS-01. Mean salinity (upper panel) and temperature (lower panel) at the 50-m depth at station NH-5 (average water depth 60 m) averaged over all cruises from May to September each year.

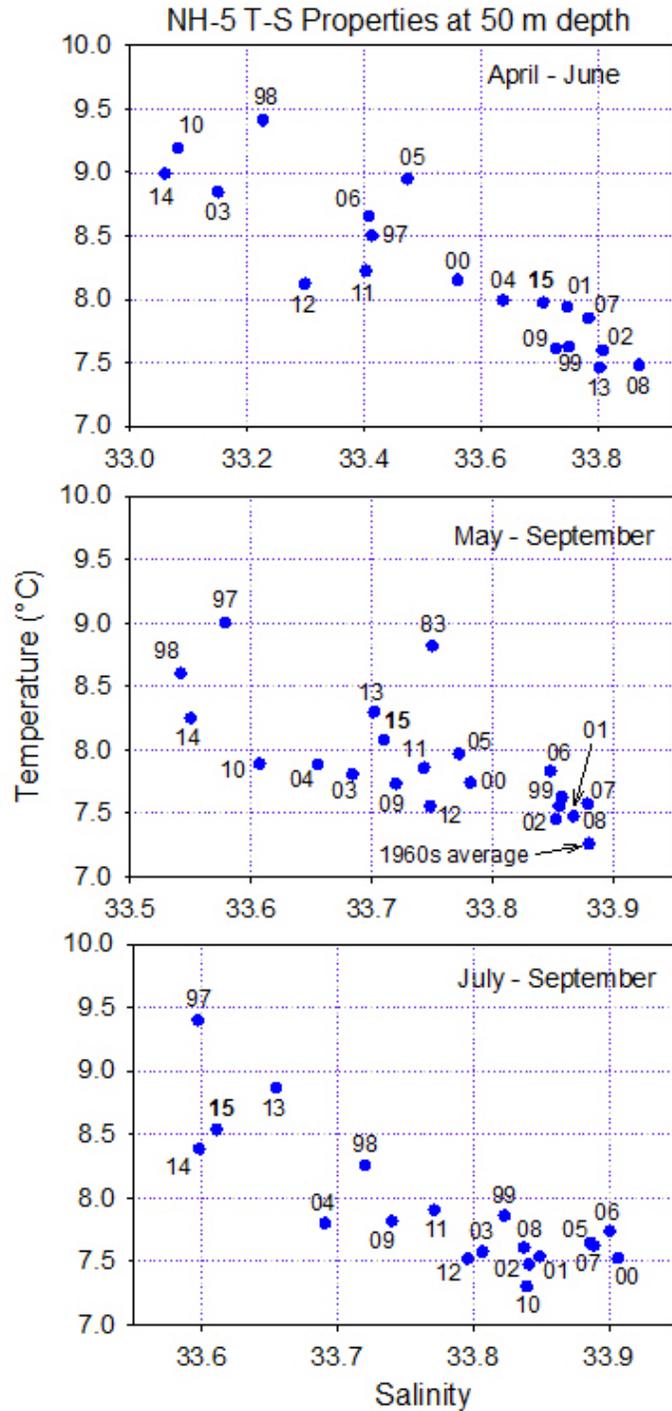


Figure DTS-02.

Upper panel Scattergram shows average temperature and salinity values during the April–June upwelling season from 1997–present.

Middle panel Scattergram of the same average values during May–September 1997–present.

Lower panel Average temperature and salinity values during July–September 1997–present.

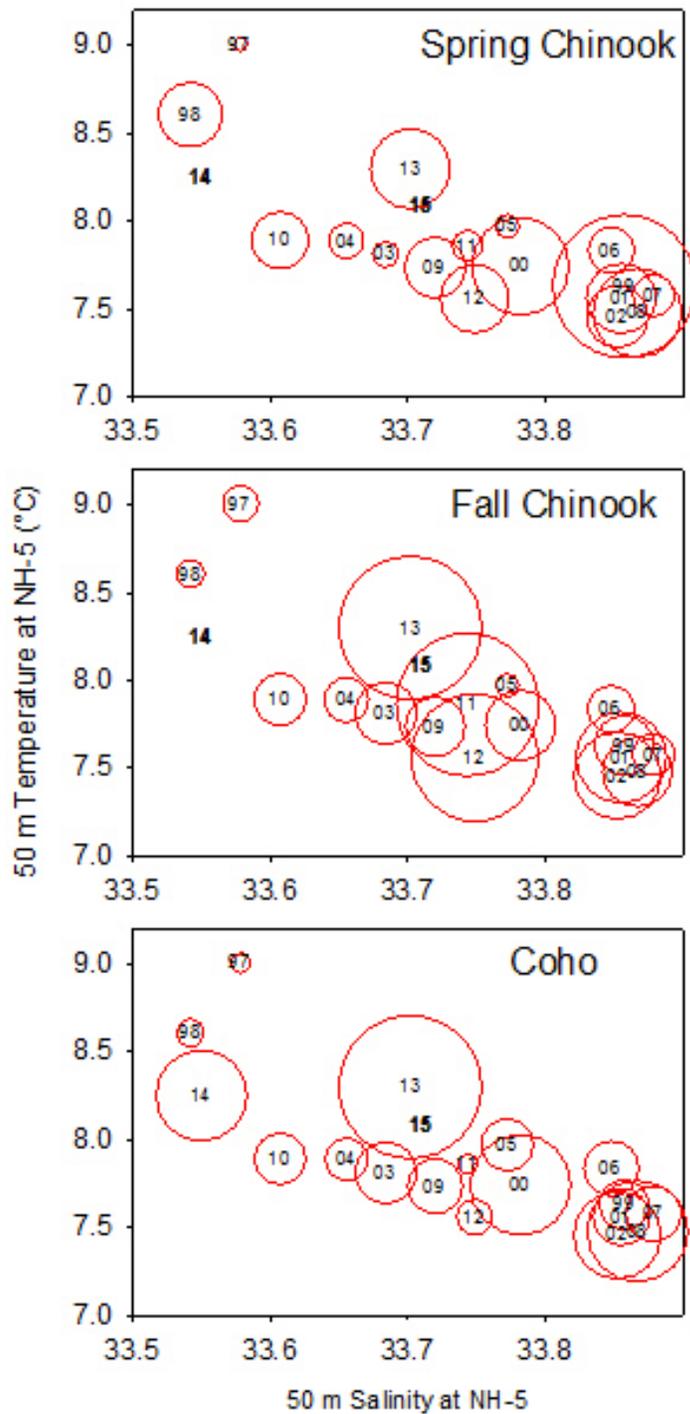


Figure DTS-03. Percent returns of Chinook salmon to the Bonneville Dam (circles) and coho salmon survival (circles) in relation to summer averaged temperature and salinity measured 2 years earlier (numbers) for Chinook salmon and 1 year earlier for coho salmon at the 50-m depth of hydrographic station NH-5. Circle size is proportional to the highest returns of Chinook salmon to Bonneville dam since 1997 and the proportion of the juvenile coho salmon population returning to spawn since 1997.

[Figure DTS-01](#) shows average salinity and temperature measured at the 50–m depth from station [NH 05](#) (shown in [Figure HP-01](#)). 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 2013-2014 were warmer than average, and corresponded to a warm-phase PDO and El Niño conditions during 1997-1998 and positive PDO during 2014. During 1997-98 and 2014, the water was also the freshest it has been during the time period.

[Figure DTS-02](#) shows the same data, but as a scatter diagram, illustrating several noteworthy points. First, during the El Niño event of 1997-1998 and during 2014, deep waters on the continental shelf off Newport were warm and relatively fresh throughout the year. 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 2009-2012.

Chinook and coho salmon survival is generally high when cold, salty water is present in continental shelf waters, and vice versa ([Figure DTS-03](#)). That is, during the summer when these fish first enter the ocean, if deep waters are relatively cold and salty, we can expect generally good salmon survival. Conversely, if deep water is relatively warm and fresh, salmon survival is poor, as was observed for fall Chinook and coho salmon in 1997 and 1998.

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](#) are in fact measuring different water types. [Figure CB-01](#) shows average copepod species richness (i.e., the average number of species from all plankton samples) for each month from 1996 to present at station NH-5.

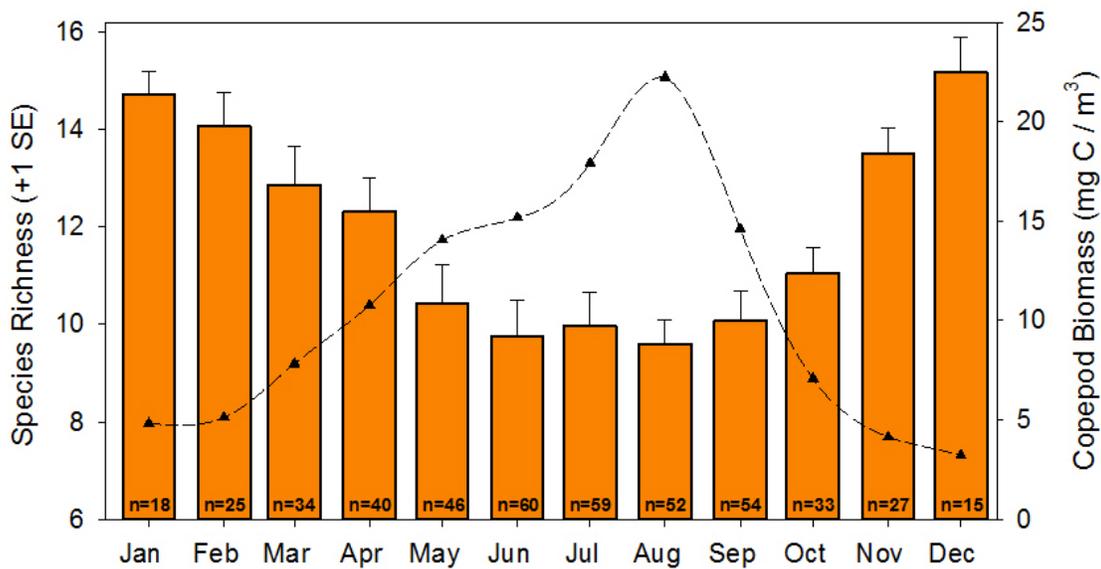


Figure CB-01. Vertical bars are the climatology of monthly averaged copepod species richness, a measure of biodiversity, at station NH-5 off Newport OR. Dashed line with filled triangles is the climatology of monthly averaged copepod biomass (Y-axis on right side of graph). Note the inverse relationship 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 CB-01](#) 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 CB-01](#)). 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 CB-02](#) shows monthly anomalies of copepod species richness during 1996-present. This time series is derived by taking the average number of species for each month, then subtracting the observed monthly average for that month.

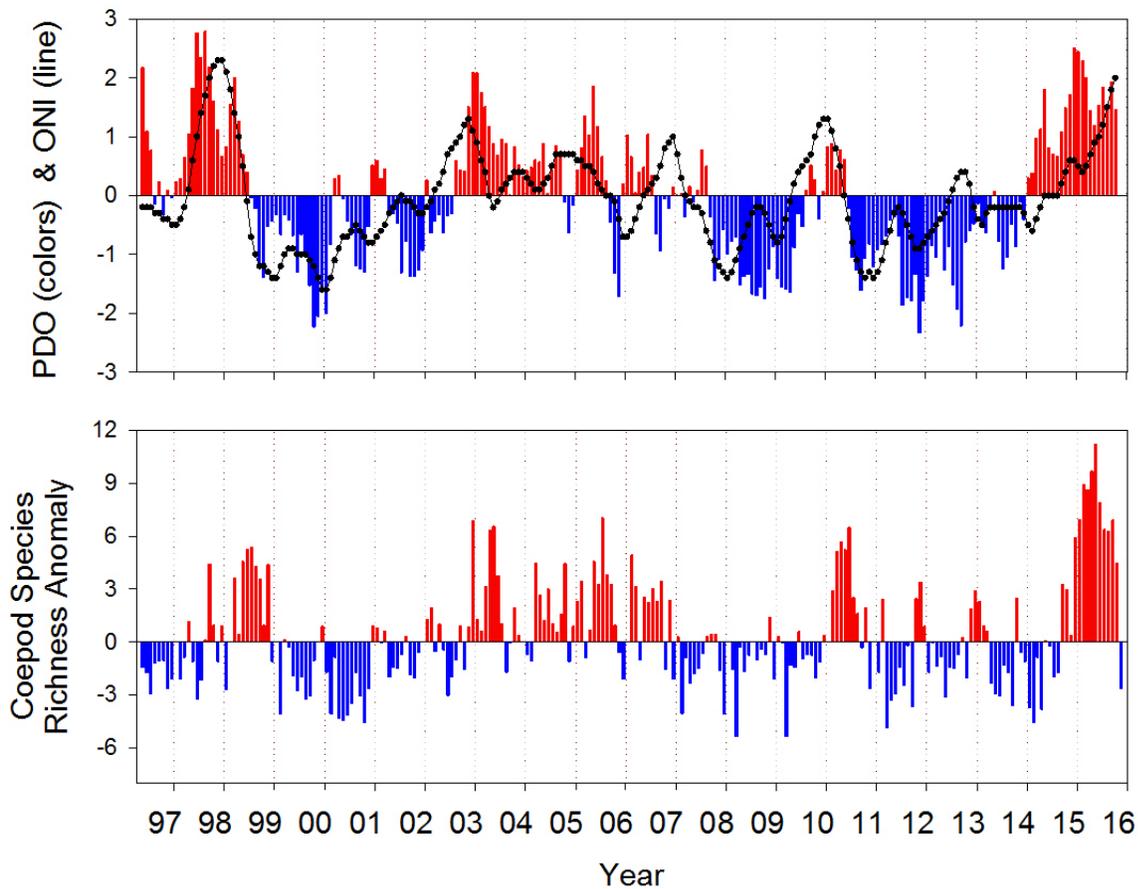


Figure CB-02. Upper panel shows time series of the PDO (bars) and ONI (line) during 1996-present. Lower panel shows anomalies in copepod species richness during the same period. Note that high species richness occurs during positive PDO years and the opposite during negative PDO years.

Also shown in [Figure CB-02](#) are time series of the Pacific Decadal Oscillation and Oceanic Niño Index (ONI). Comparisons among these time series show clear relationships between interannual variability in basin-scale physical climate indicators ([PDO](#) and [ONI](#)) and copepod species richness anomalies at Newport Oregon.

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

The third and most pronounced change occurred followed the switch to a positive PDO in the beginning of 2014. Species richness in the autumn of 2014 through 2015 has been the highest we

have observed since 1996. These species are subtropical and tropical in origin and were delivered to the continental shelf in the warm water mass called “The Blob”. The exact origin of these species is a topic of ongoing study, but we do know that these are not coastal species that are often delivered to Oregon via northward flowing coastal currents as occurs during El Niño events.

Additional persistent signal changes occurred in summer 2007, 2010 and 2014, although species richness showed only a moderate response to these events. Note that the El Niño event of 2009-2010 (shown by moderately positive PDO and ONI values) resulted in high species richness during February-August 2010 and a switch back to low species richness in early 2011.

We saw earlier that local sea surface temperatures off Newport showed strong correspondence with the PDO ([Figure TA-01](#)). The interpretation of simultaneous change in sea surface temperature and copepod species richness is that when the PDO is in a cool phase, cold water from the subarctic Pacific dominates the northern California Current. Moreover, there can be a time lag of about 6 months between a changes in the PDO sign and changes in water temperature and copepod species composition. For further detail on the relationships between copepod species richness and oceanographic conditions, see Hooff and Peterson ([2006](#)).

We have found that this simple measure of species richness is correlated with salmon survival ([Figure CB-03](#)). This suggests that the copepod community, when these salmon first enter the ocean two and one years prior for Chinook and Coho respectively, is a reasonably good indicator of adult salmon survival.

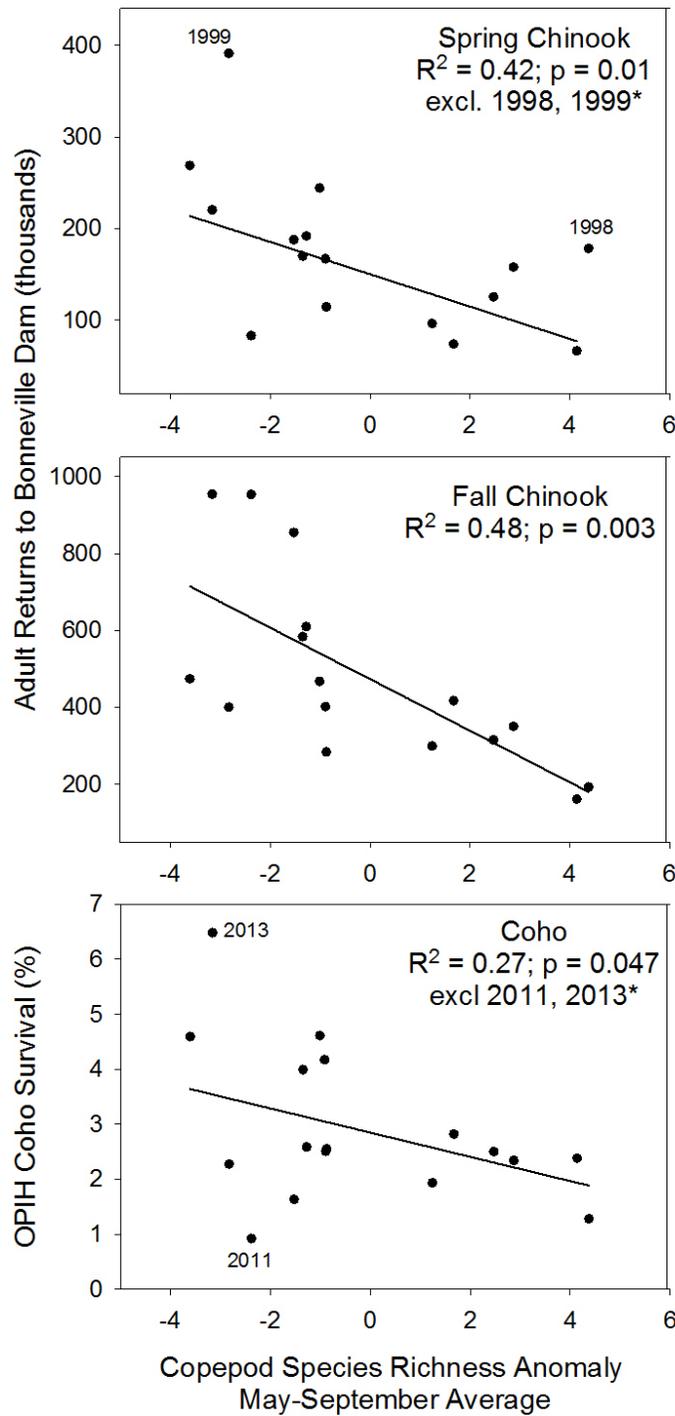


Figure CB-03. Relationship of Spring and Fall Chinook adult returns to the Bonneville Dam, and Coho salmon survival (OPIH) to the copepod species richness anomaly when these fish first enter the ocean 2 and 1 years prior (Chinook and Coho respectively) from 1996 - present.

* outliers were excluded using [Cook's Distance](#)

The relationship with salmon survival and copepod species richness is somewhat biased and complicated by the trend towards increasing species richness with time. [Figure CB-04](#) 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](#)).

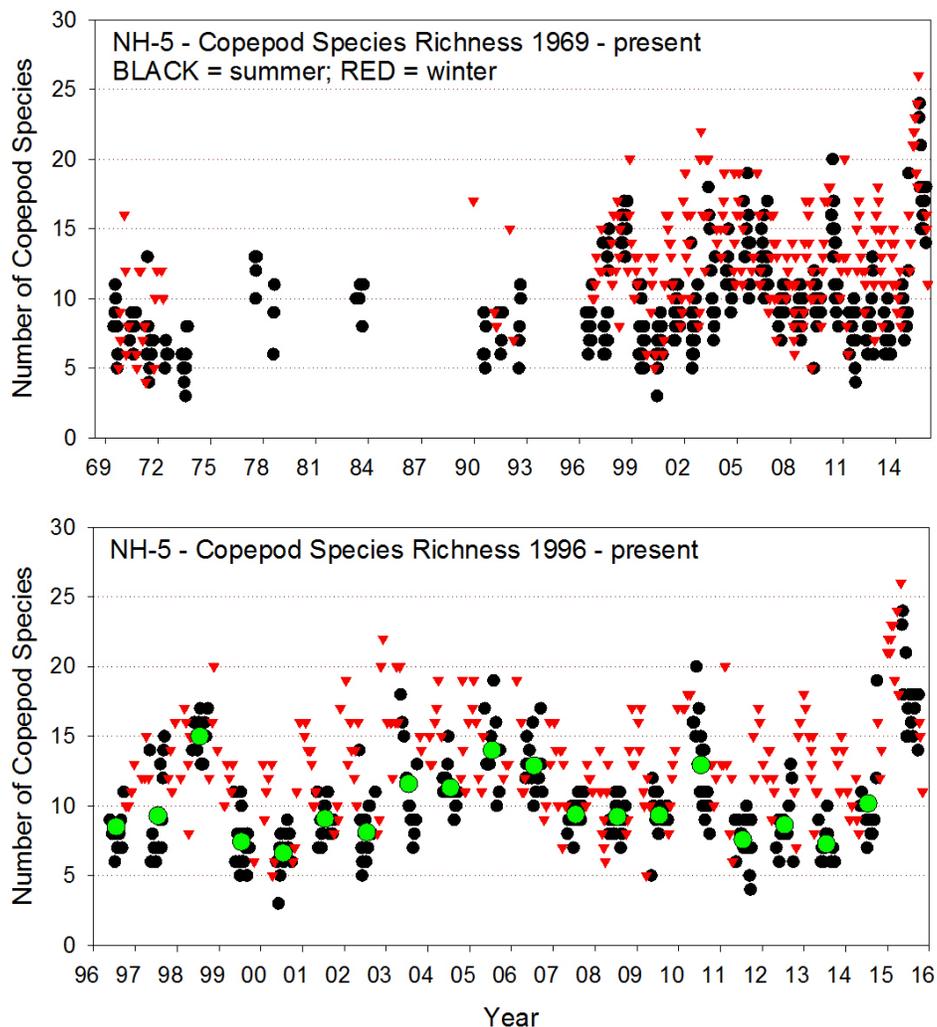


Figure CB-04. Upper panel shows time series of copepod species richness from 1969 to present. Note that the number of copepod species has been increasing over the past decade compared to the 1970s. Red triangles represent winter (Oct - April) and black circles represent summer (May - Sept).

Lower panel shows the same time series from 1996 to present to highlight the among-year differences. Red triangles represent winter, black circles summer, and green circles indicate summer-averaged values. This figure illustrates the trend towards increasing copepod biodiversity, especially apparent when comparing the cool years of 1999-2002 to the recent cool years of 2007-2009.

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*, *Clausocalanus parapergens*, *Calocalanus styliremis*, and *Corycaeus anglicus*.

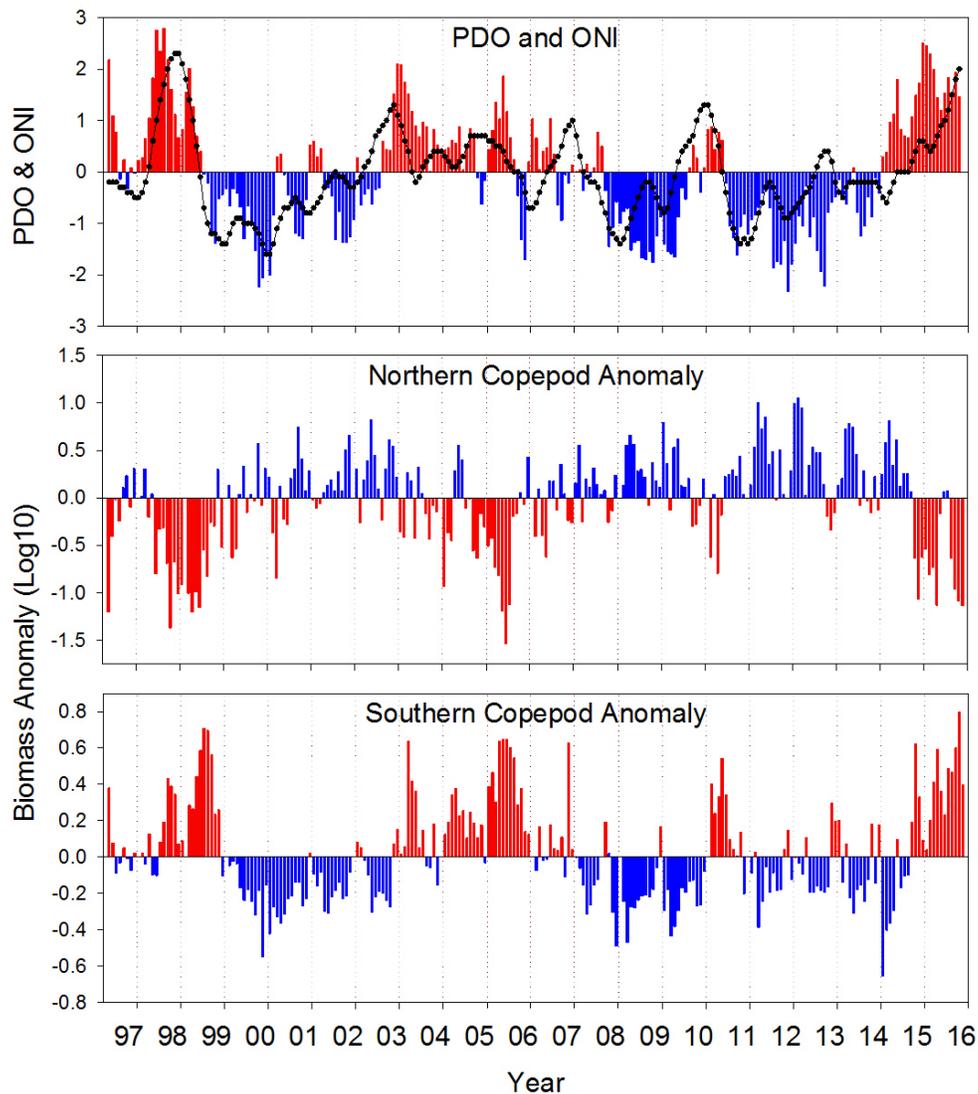


Figure NSC-01. The Pacific Decadal Oscillation (upper), and northern copepod biomass anomalies (lower), from 1969 to present. Biomass values are log base-10 in units of mg carbon m^{-3} .

The cold-water group usually dominates the Washington/Oregon coastal zooplankton community in summer, whereas the warm-water group usually dominates during winter (Peterson and Miller 1977; Peterson and Keister 2003). This pattern is altered during summers with El Niño events and/or when the PDO is in a positive (warm) phase. At such times the cold-water group has negative biomass anomalies and the warm group positive anomalies. Figure NSC-01 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 NSC-02 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.

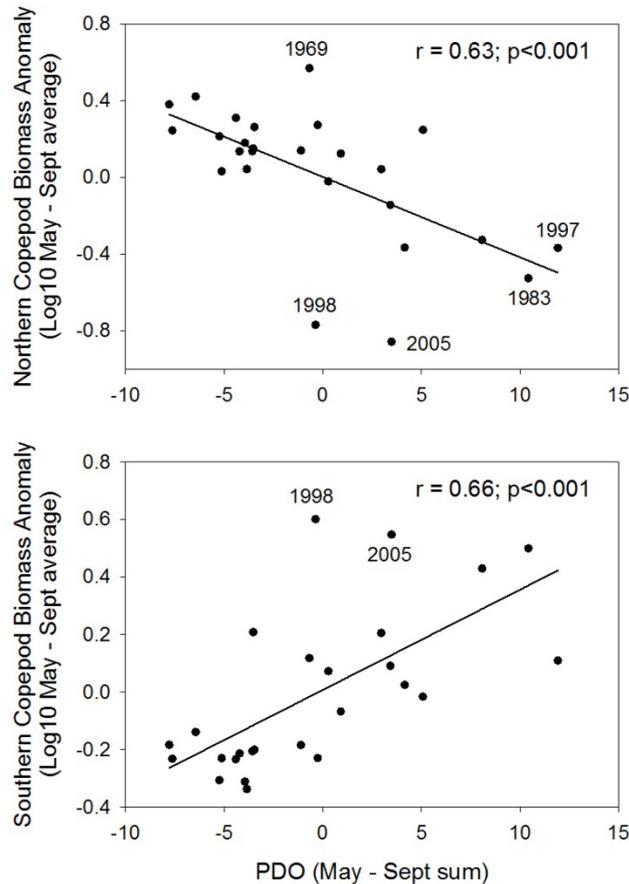


Figure NSC-02. Relationship of northern copepod anomalies and the PDO during the summer upwelling season (May - Sept). Data are from 1969 - 1973, 1983, and 1996 - present. Units of copepod biomass are $\text{Log}_{10} \text{ mg carbon m}^{-3}$. Strongly negative PDO values lead to high biomass of cold-water copepods and vice versa.

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 relatively good predictor of salmon returns. [Figure NSC-03](#) shows the relationship between the northern copepod biomass anomalies during the year the fish went to sea and the Columbia River spring and fall Chinook salmon counts at Bonneville Dam 2 years later and coho salmon survival 1 year later. For spring Chinook, 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).

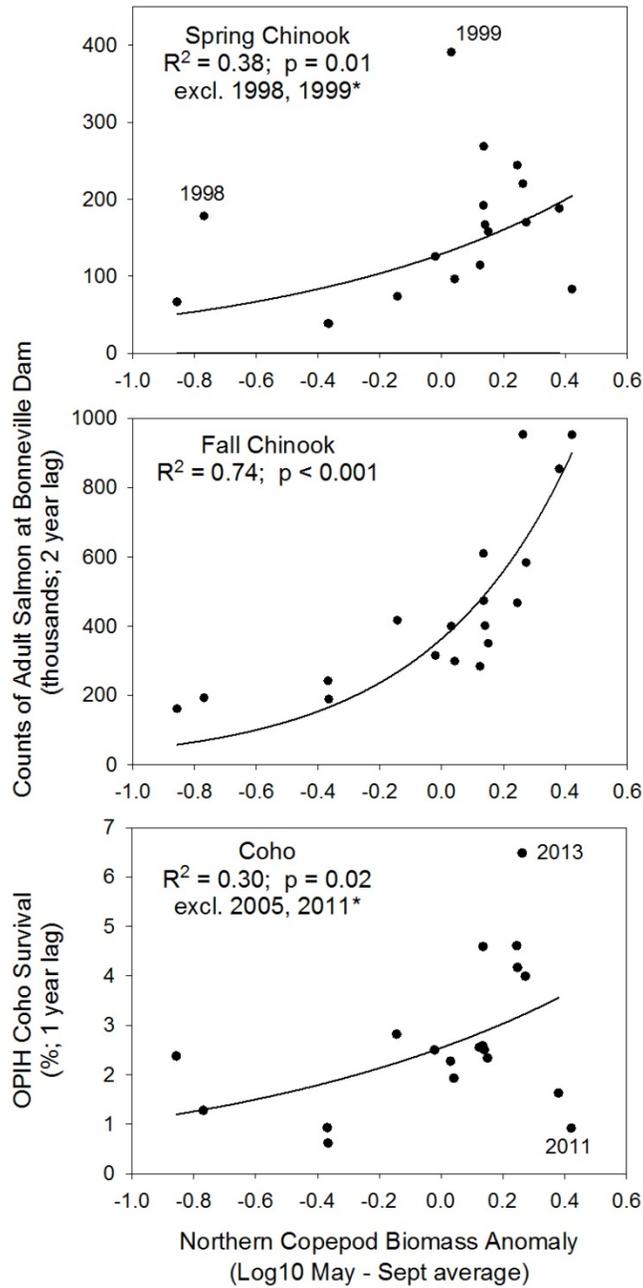


Figure NSC-03. Regression of OPIH coho survival on the northern copepod biomass anomalies. Relationship between counts of adult spring Chinook (upper panel) and fall Chinook (middle panel) at Bonneville Dam and OPIH coho survival (bottom panel) vs. log of the northern copepod biomass anomaly during the year of ocean entry. Counts at Bonneville are lagged by 2 years and OPIH coho survival is lagged by 1 year.

* outliers were excluded using [Cook's Distance](#)

Copepod Community Structure

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

As an ocean ecosystem indicator, copepod community structure is based on multidimensional scaling (MDS), an ordination technique that helps visually represent non-numerical data (Figure CCI-01). The full ordination is not shown, but rather the averaged X- and Y-axis scores: these two alone accounted for about 83% of the variability between copepod communities, with the X-axis accounting for 71% and the Y-axis for 12%. CCI-01 compares these summer-average scores.

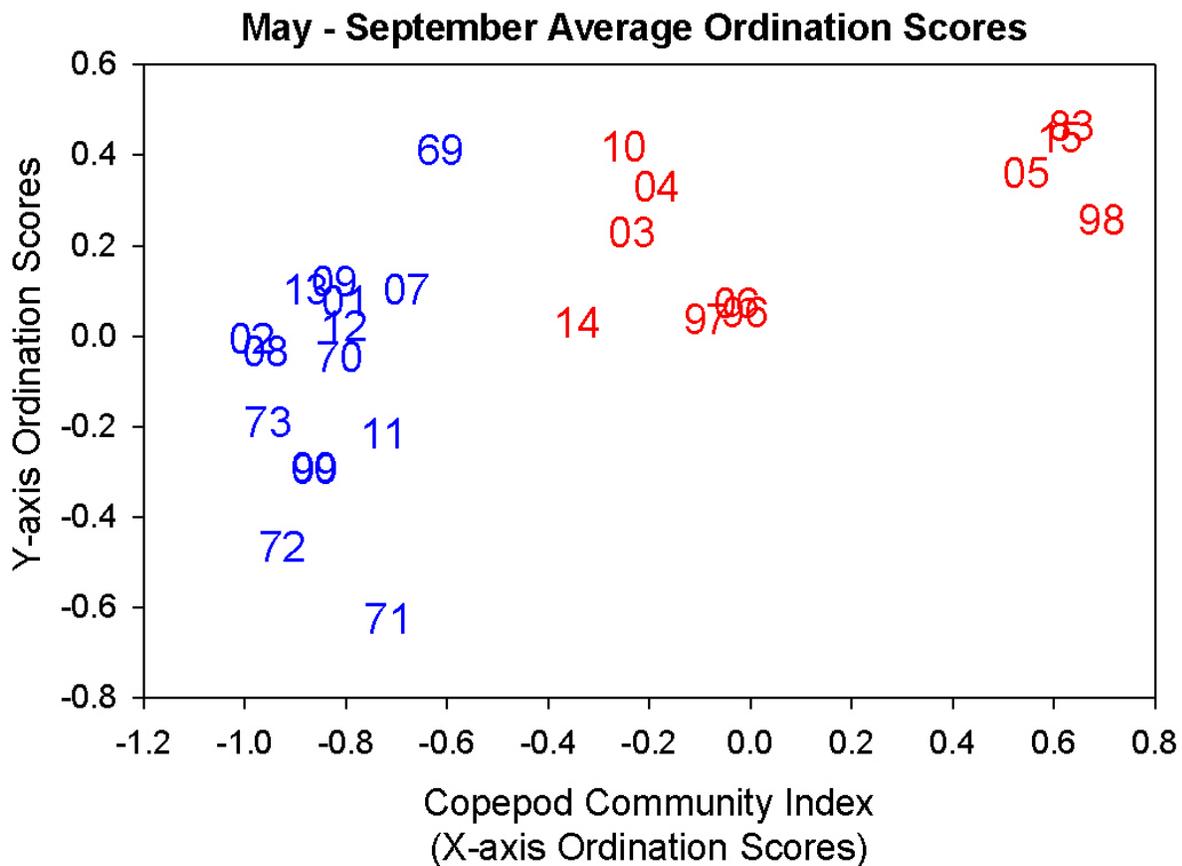


Figure CCI-01. Ordination of copepod community structure averaged over May-September, by year. Years when summer community structure was dominated by cold, boreal species fall to the left (1970-1973, 1999-2002, 2007-2009, 2011-2013); years with warm subtropical species fall in to the center of the graph (1996, 1997, 2003, 2004, 2006, 2010); years characterized by El Niño conditions (1983, 1998), El Niño-like conditions (2005), or the anomalously warm NE Pacific water in 2015 ("The Blob") fall to the right. Numbers indicate the warm (red) and cold (blue) years.

The different community types are clearly a function of the state and phase of the Pacific Decadal Oscillation ([Figure CCI-02](#)). 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).

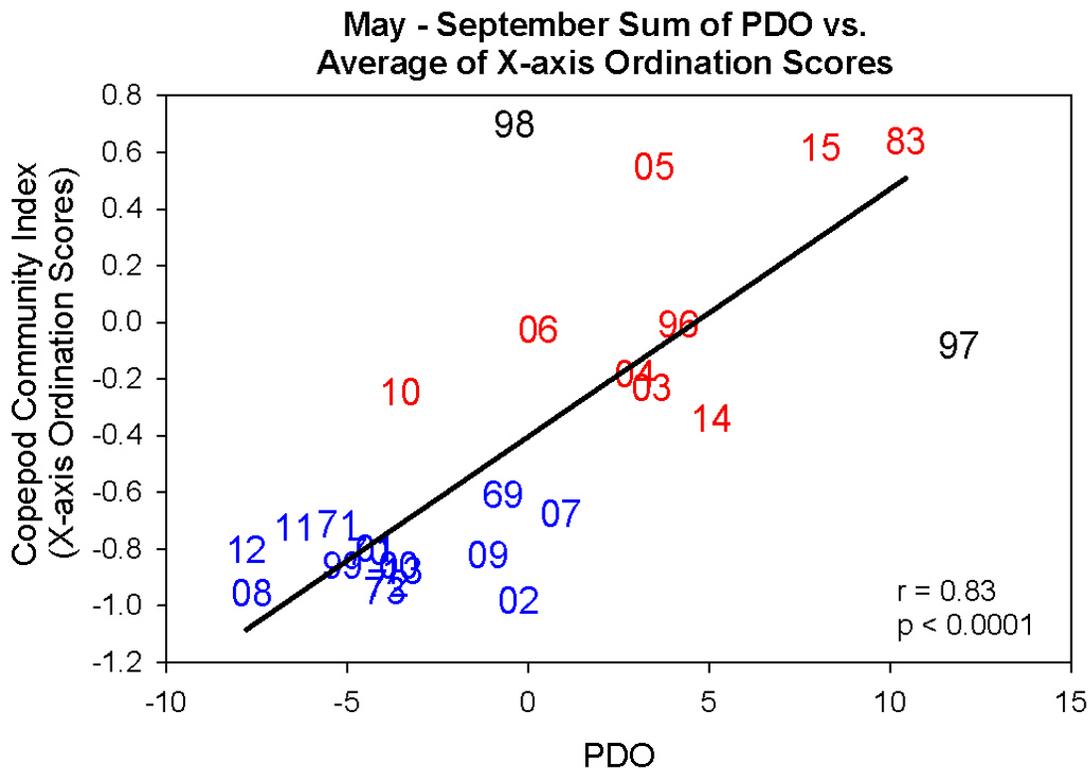


Figure CCI-02. Relationship between the PDO and X-axis ordination scores. A "cold-water zooplankton community" is associated with the negative (cold) phase of the PDO and vice versa. Numbers indicate the warm (red) and cold (blue) years. Years in black were outliers and were excluded from the regression.

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 CCI-03](#)). 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.

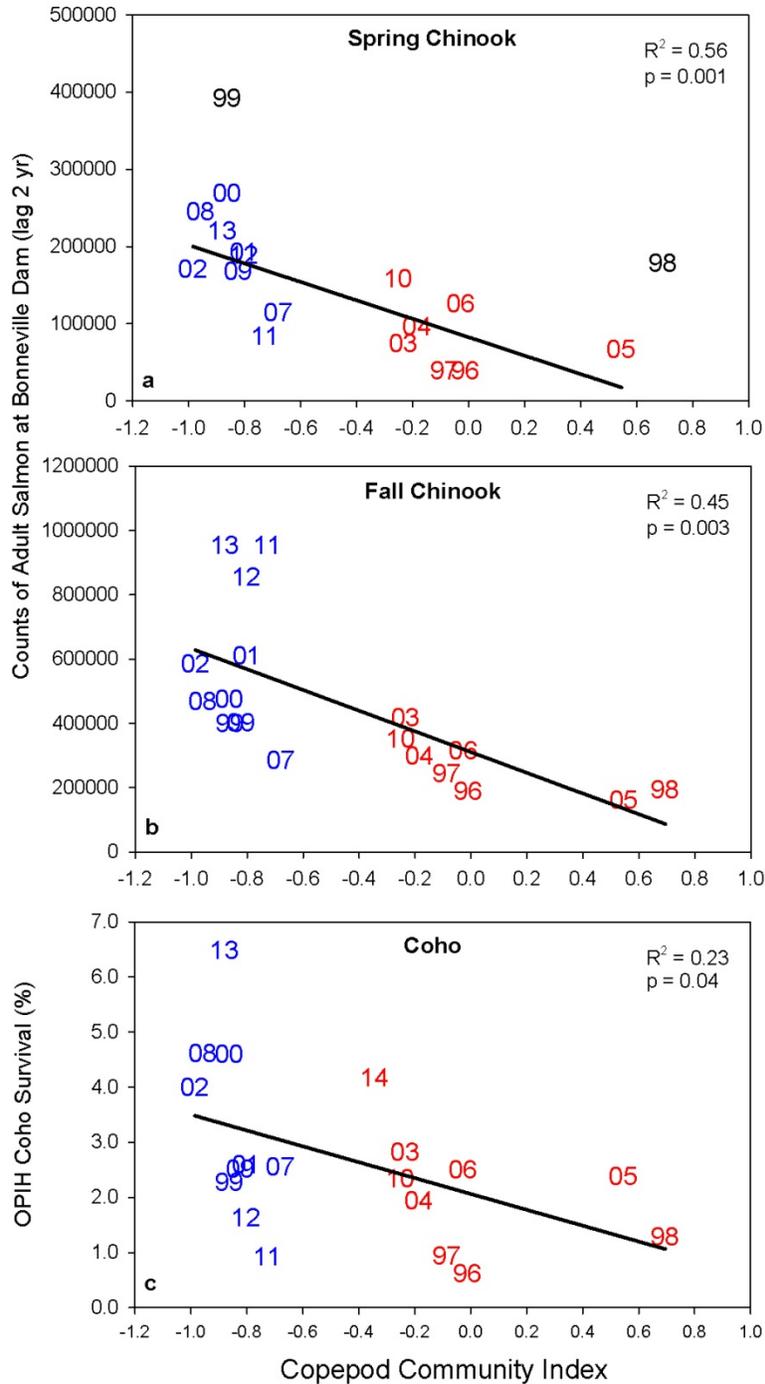


Figure CCI-03. Plot showing the relationship between a) spring Chinook salmon adult returns at Bonneville dam (lag 2 years), b) fall Chinook salmon adult returns at Bonneville dam (lag 2 years), and c) coho salmon smolt-to-adult survival (SAR, lag 1 year) versus the copepod community structure index (X-axis ordination score). The X-axis ordination score for May-September 2015 was 0.61, which indicates poor subsequent salmon survival. Numbers indicate the warm (red) and cold (blue) years. Years in black were outliers and were excluded from the regression.

* outliers were excluded using [Cook's Distance](#)

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 PST-02](#), we saw salmon survival correlated with the date when cold water first appeared at our baseline station, [NH 05](#). [Figure BST-01](#) 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.

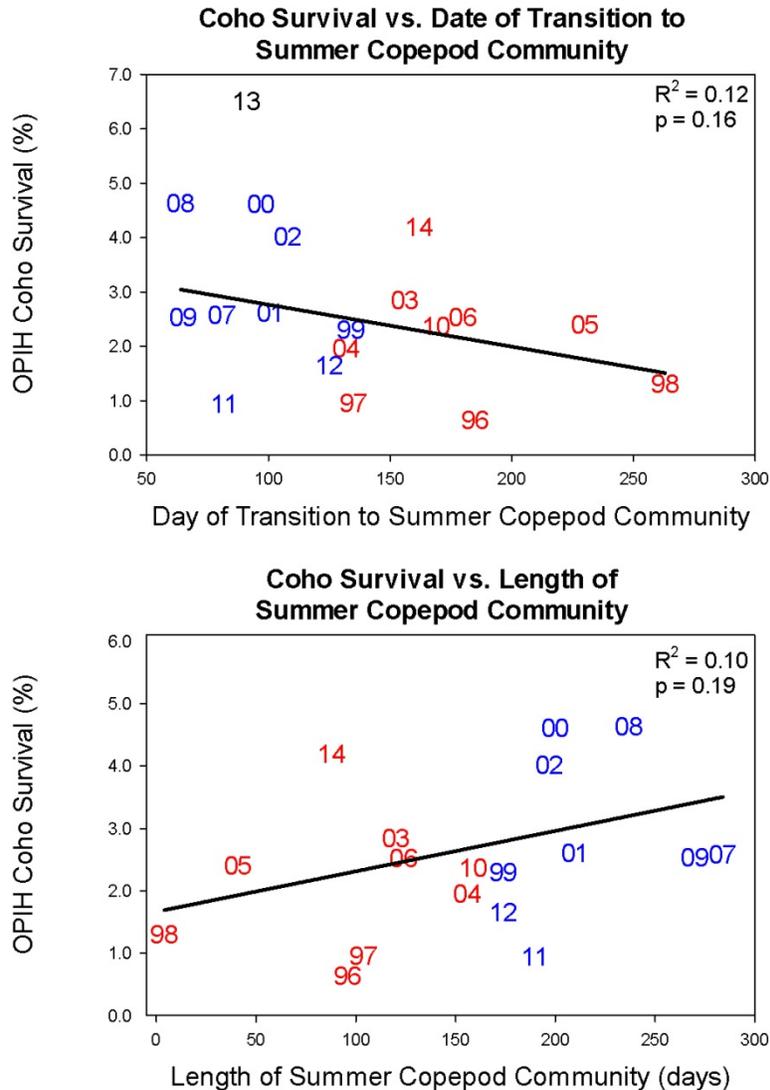


Figure BST-01.

Upper panel: Regression of coho salmon survival vs. day of the year when copepod community structure transitioned to a summer community. The earlier this transition takes place, the higher the coho salmon survival.

Lower panel: Regression of coho salmon survival vs. length of the biological upwelling season, measured as the number of days that the summer community structure persisted. Numbers indicate the warm (red) and cold (blue) years.

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 BST-01](#)). 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. These changes in community type occur because of coastal currents, which reverse in spring to flow from the north with the onset of upwelling. Another reversal occurs in the fall, when the northward-flowing Davidson Current appears on the shelf due to winter downwelling.

Arrival of the "northern" species in spring signals that the ecosystem is primed to begin a productive upwelling season. Also listed is length of the upwelling season in days, as reckoned by the zooplankton. Note that over the years of 2007-2009 and again in 2011, the transition date came very early, in March, whereas 2015, the biological spring transition never occurred.

Both the date of "biological spring transition" and "length of the biological upwelling season" also correlate well with counts of adult spring Chinook salmon ([Figure BST-02](#)) and adult fall Chinook salmon ([Figure BST-03](#)) at Bonneville Dam 2 years later.

Table BST-01. Historical dates of the biological spring transition, as measured by the timing of change in the zooplankton from a winter to a summer community.

Year	Arrival of cold-water copepod community		Length of cold-water copepod presence (in days)
	Start date	End date	
1970	~20 Mar	20 Oct	214
1971	20 Mar	6 Nov	231
1983	21 Jul	19 Aug	29
1996	3 Jul	7 Oct	96
1997	15 May	27 Aug	104
1998	20 Sep	24 Sep	4
1999	14 May	4 Nov	174
2000	6 Apr	23 Oct	200
2001	11 Apr	7 Nov	210
2002	18 Apr	1 Nov	197
2003	5 Jun	3 Oct	120
2004	11 May	14 Oct	156
2005	18 Aug	28 Sep	41
2006	29 Jun	31 Oct	124
2007	22 Mar	31 Dec	284
2008	4 Mar	27 Oct	237
2009	6 Mar	1 Dec	270
2010	18 Jun	24 Nov	159
2011	23 Mar	29 Sep	190
2012	4 May	25 Oct	174
2013	1 April	26 Sep	178
2014	11 Jun	7 Sep	88
2015	Never	—	0

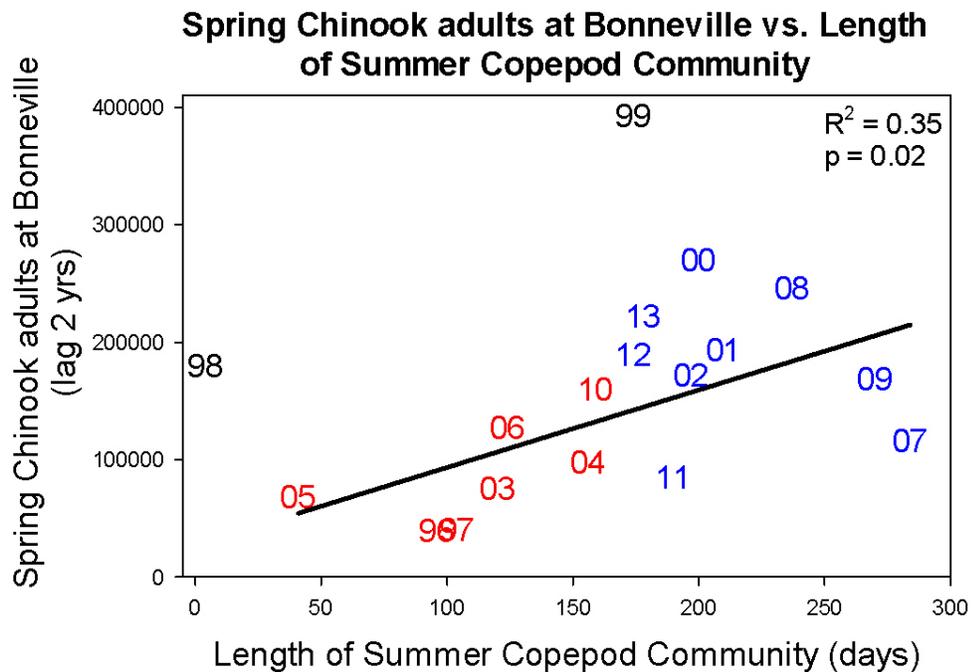
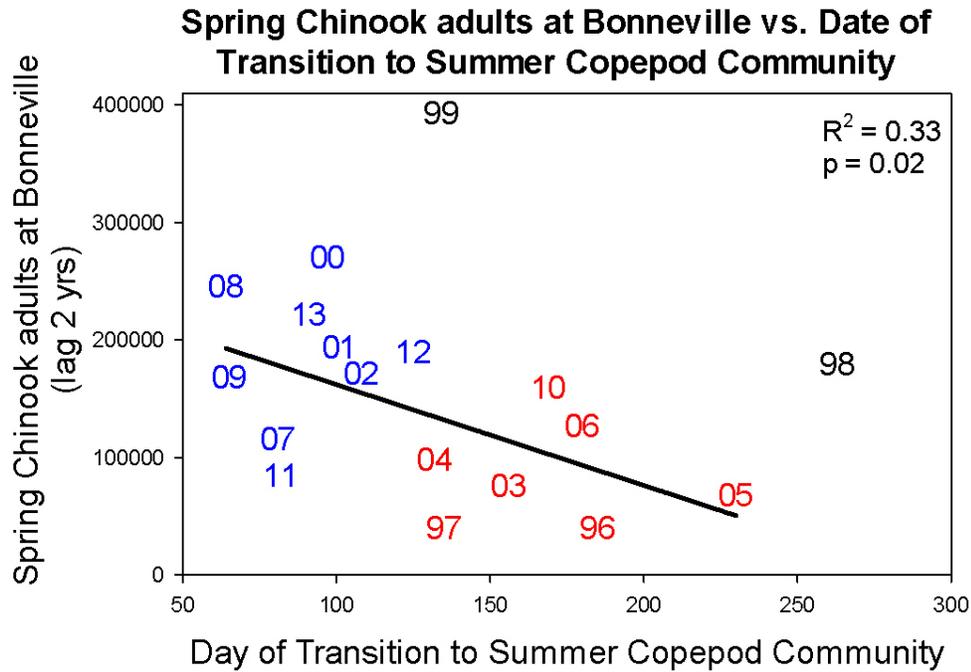


Figure BST-02. Spring Chinook salmon adult counts at Bonneville (lagged by 2 years) vs. date of biological spring transition (upper panel) and length of the biological upwelling season (lower panel). Numbers indicate the warm (red) and cold (blue) years. Numbers indicate the warm (red) and cold (blue) years. Years in black were outliers and were excluded from the regression.

* outliers were excluded using [Cook's Distance](#)

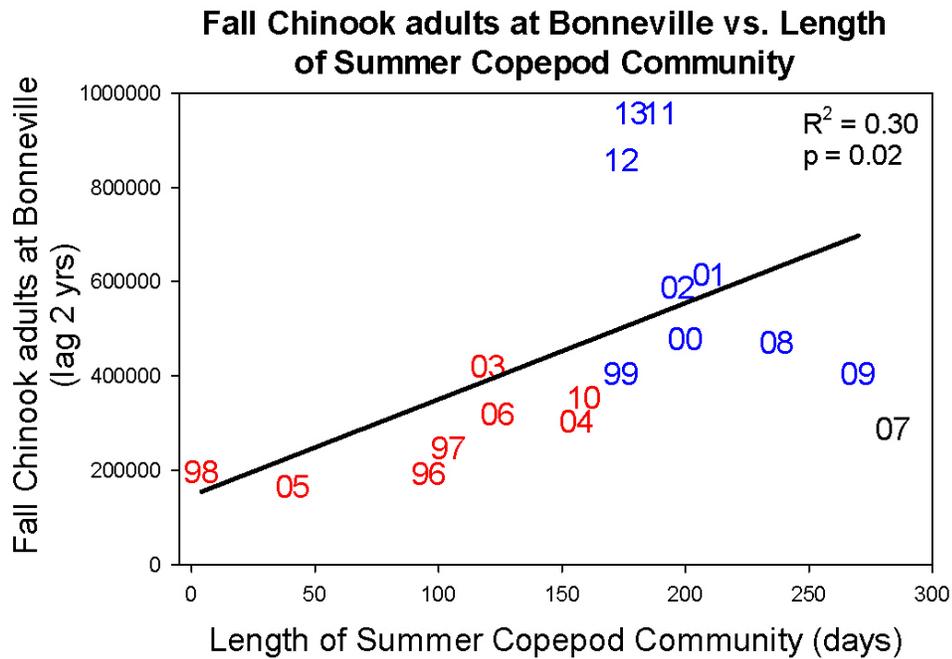
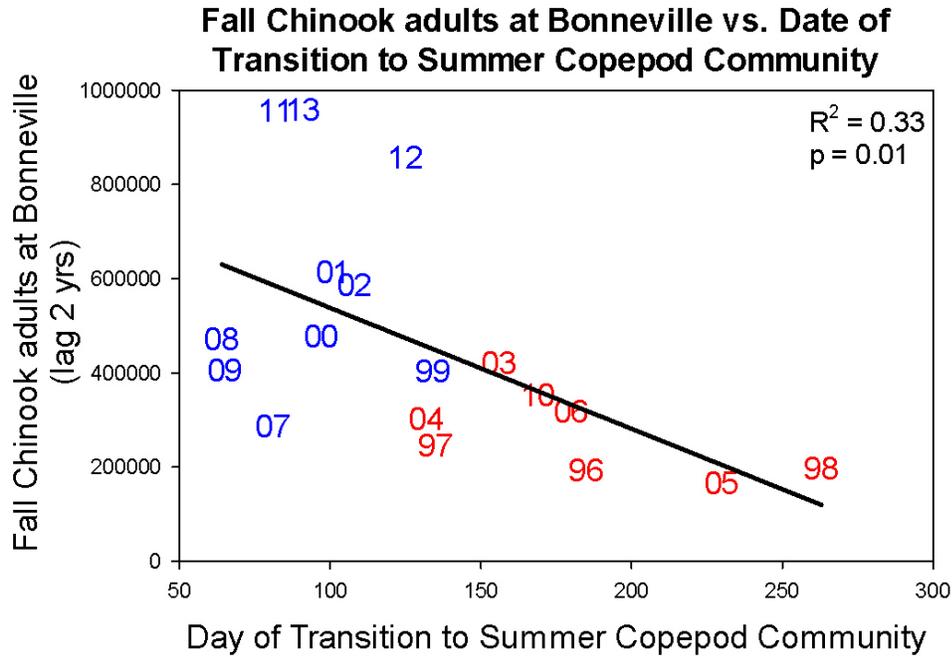


Figure BST-03. Fall Chinook salmon adult counts at Bonneville (lagged by 2 years) vs. date of biological spring transition (upper panel) and length of biological upwelling season (lower panel). Numbers indicate the warm (red) and cold (blue) years. Numbers indicate the warm (red) and cold (blue) years. Years in black were outliers and were excluded from the regression.

* outliers were excluded using [Cook's Distance](#)

Winter Ichthyoplankton

Marine diets of juvenile coho and Chinook salmon are primarily made up of age zero winter—spawning juvenile fish such as rockfish, Pacific sand lance, cottids, Northern anchovies and smelts ([Brodeur et al. 2007](#); [Daly et al. 2009](#); [Table 7](#)). Measures of [ichthyoplankton](#) biomass prior to the ocean entry of juvenile salmon is currently a good indicator of adult salmon returns ([Daly et al. 2013](#)). Annual biomass 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 WI-01](#) shows the proportions of total winter ichthyoplankton biomass composed of food items for juvenile salmon.

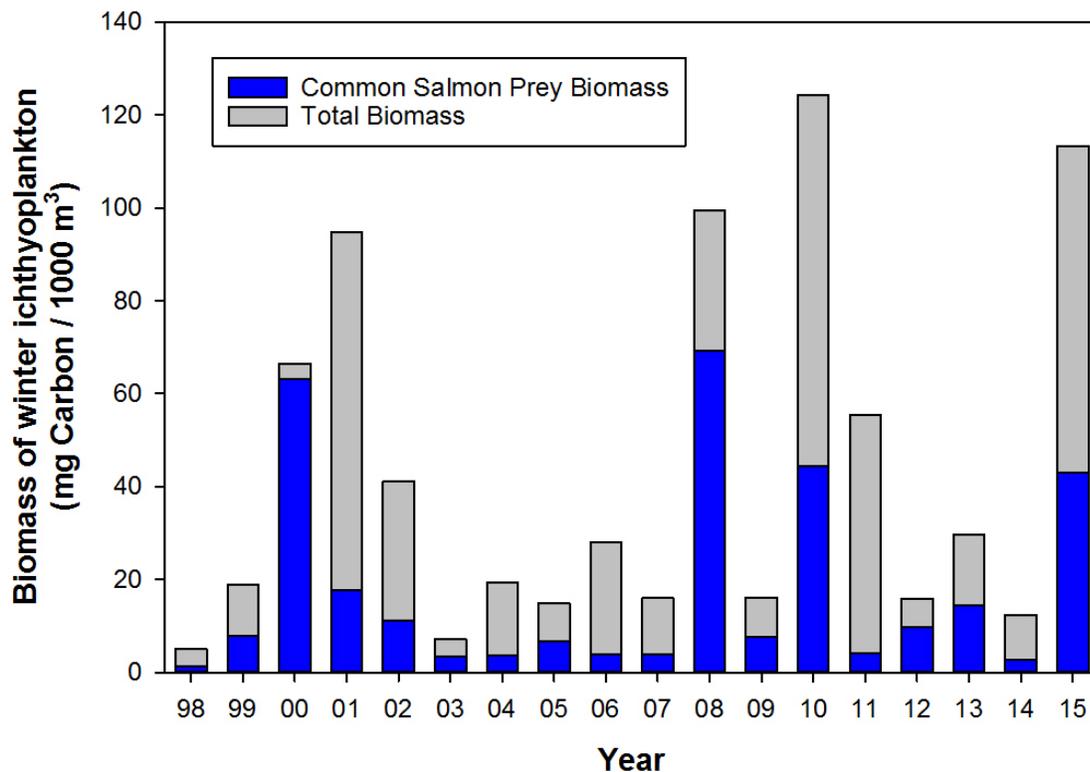


Figure WI-01. Estimates of total winter [ichthyoplankton](#) biomass from 1998 to present. Proportions composed of fish larvae considered prey items for juvenile salmon are represented by blue bars.

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 m³ 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 WI-01](#) lists common prey eaten by juvenile salmon in their first marine summer and provides data on the size and availability of each.

Table WI-01. Common prey eaten by juvenile salmon during their first marine summer. Shown are the peak spawning season, hatch time and size, estimated days to reach the juvenile stage and average size of prey when eaten by juvenile salmon.

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

Total winter ichthyoplankton biomass was highest in 2001, 2008, 2010, and 2015 and lowest in 1998, an El Niño year ([Figure WI-01](#)). Years with the highest biomass of the ichthyoplankton typically eaten by juvenile salmon were 2008 and 2000; those with low biomass were 1998 and 2003–2007 and 2014. The proportion of total ichthyoplankton biomass considered common salmon prey fluctuated from a low of 7.4% in 2011 to a high of 95.0% in 2000.

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 WI-02](#).

Food biomass for out-migrating juvenile salmon in 2015 was predicted to be above average based on the winter ichthyoplankton biomass index primarily due to high biomass of Northern anchovy and rockfish larvae. The 2015 winter (January to March) biomass of fish larvae that salmon prey upon was the fourth highest in 18 years. The biomass of fish larvae in late winter provides an index of juvenile fish that are the common prey of juvenile salmon when they enter the ocean in spring and summer. Due to the anomalously warm ocean conditions, which typically predict lower salmon survival of early ocean migrants, we are uncertain about the accuracy of our current prediction using winter ichthyoplankton biomass.

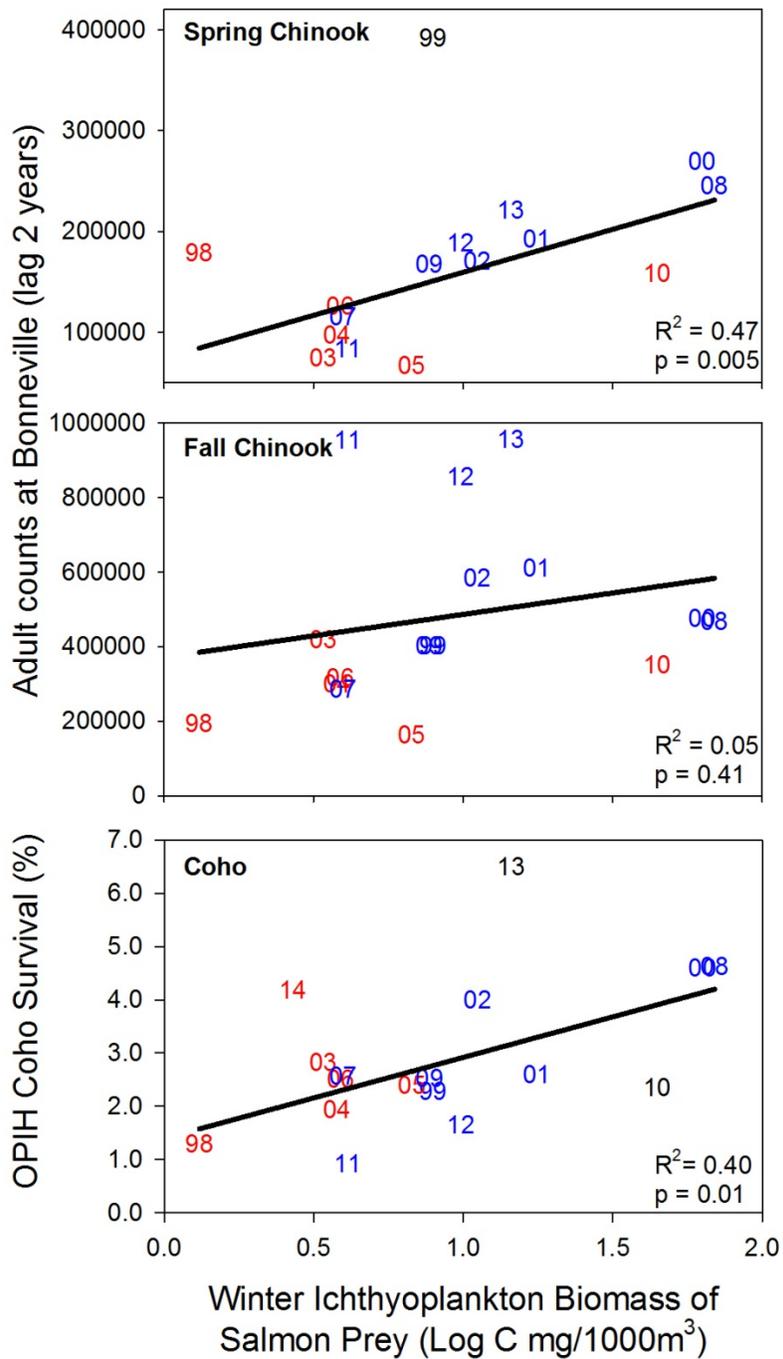


Figure WI-02. Spring and fall Chinook salmon adult counts at Bonneville (lagged by 2 years), and coho salmon smolt-to-adult survival (SAR, lag 1 year) vs. the log of the winter ichthyoplankton salmon prey biomass. Numbers indicate the warm (red) and cold (blue) years. Years in black were outliers and were excluded from the regression.

*outliers were excluded using [Cook's Distance](#)

This year we have added a second predictor based on the prey composition of winter ichthyoplankton which predicts lower returns of salmon in 2017. This second indicator also has a relationship with salmon survival. This index suggests that in addition to the quantity of the prey (biomass), the type of fish prey (composition) is also important. Below is the Principal Coordinate community analysis of the winter ichthyoplankton prey that are important for salmon (WI-03). Warmer years are positive on axis 1 (PC1), including 2015. This new index relates well to returns of spring and fall Chinook and coho salmon (Figure WI-04).

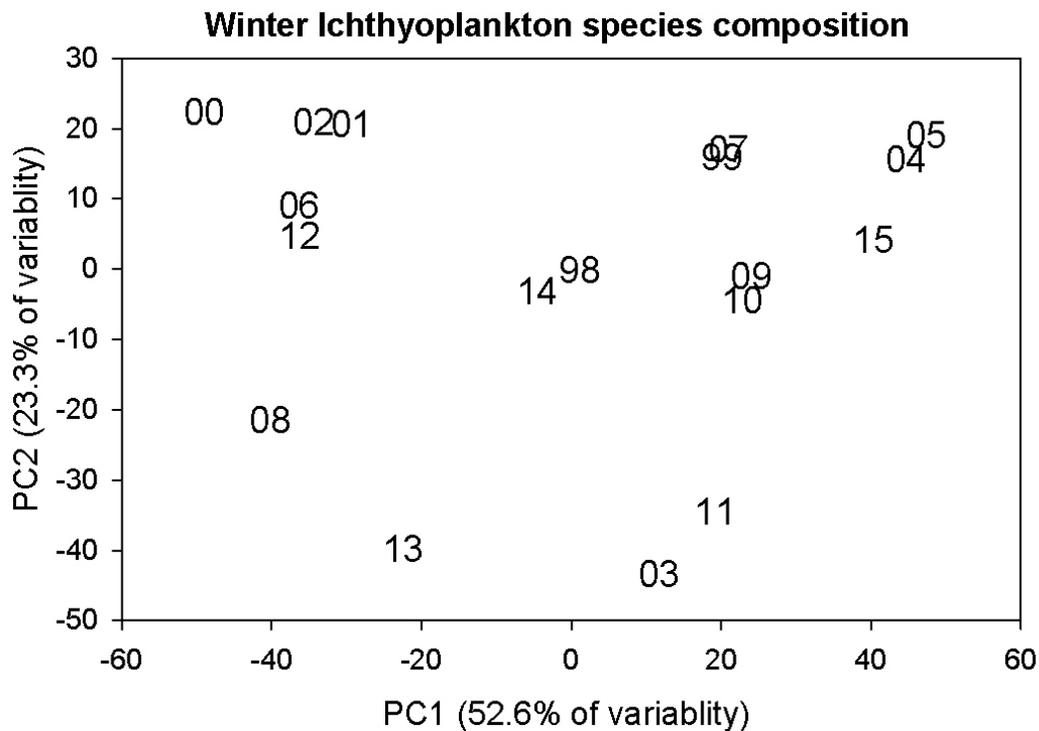


Figure WI-03. Principal Coordinate Analysis (PCA) of annual composition of winter ichthyoplankton typically eaten by salmon averaged over January-March with warm years on the right side of PCA axis 1

While the ichthyoplankton biomass from the winter of 2015 (Figure WI-02) suggests returns of spring Chinook salmon in 2017 will be slightly over 210,000, the ichthyoplankton composition suggests it will be lower, around 93,000 (Figure WI-04). There has not been a year in the 18 year time series with such a discrepancy of return prediction between the two indices.

Of particular note during Jan-March of 2015 were:

1. Presence of larvae at every sampling station in high concentrations.
2. Extremely high concentration and biomass of sardine larvae in February and March from NH-01 (most inshore station) to NH-25. This is unprecedented in the time series.
3. While Northern anchovy larvae have been collected in Jan-March along the NH line (1998 & 2003), 2015 biomass was over 100 times greater and again present inshore to offshore (NH-01 to NH25).
4. 3 new taxa were collected, including a Pacific saury larva

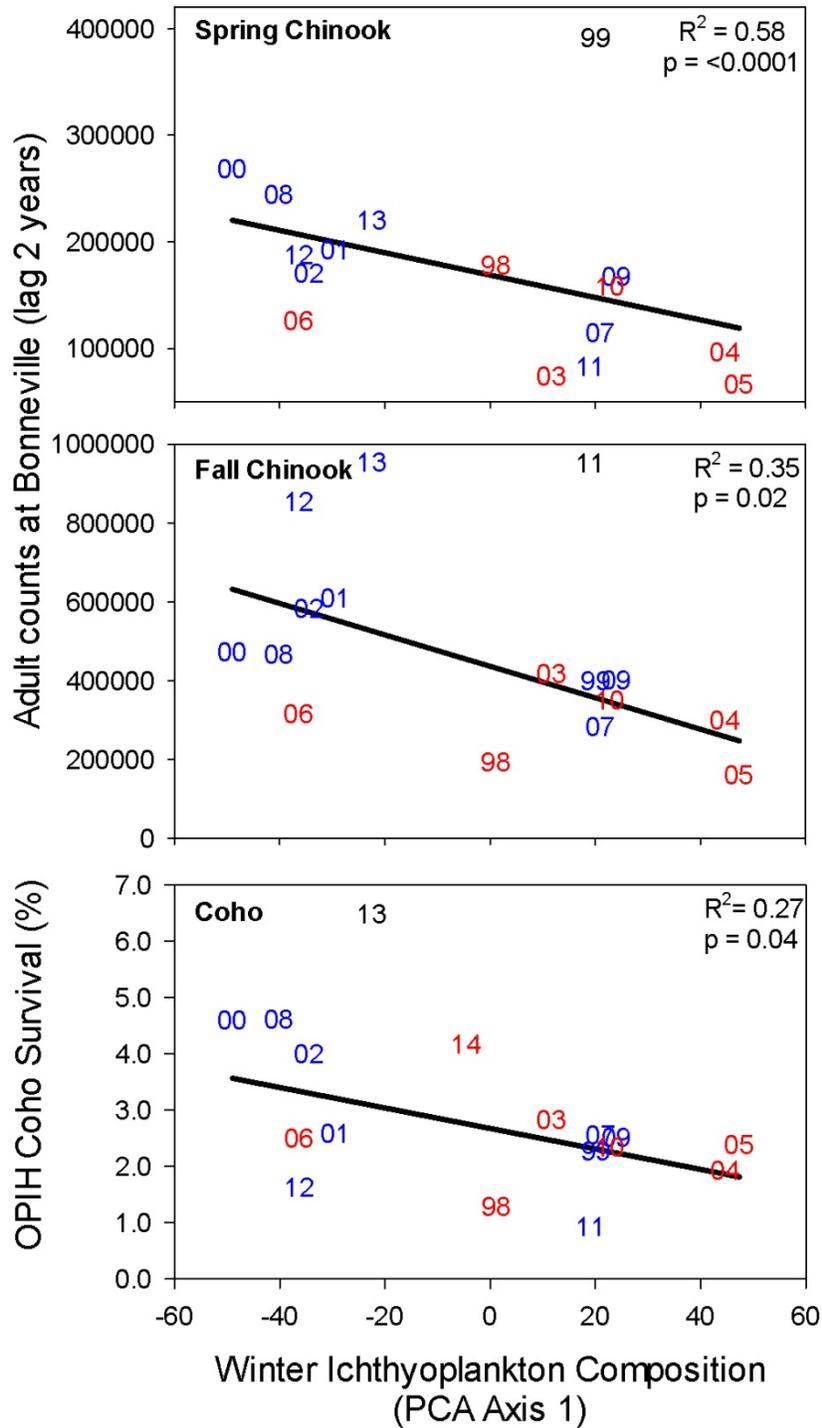


Figure WI-04. Spring and fall Chinook salmon adult counts at Bonneville (lagged by 2 years), and coho salmon smolt-to-adult survival (SAR, lag 1 year) vs. the PC1 ichthyoplankton species composition value from Figure WI-03. Numbers indicate the warm (red) and cold (blue) years. Years in black were outliers and were excluded from the regression.

Juvenile Salmon Catch

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 JSC-01](#) shows catch per unit effort (CPUE) during our trawl surveys from 1998 to present.

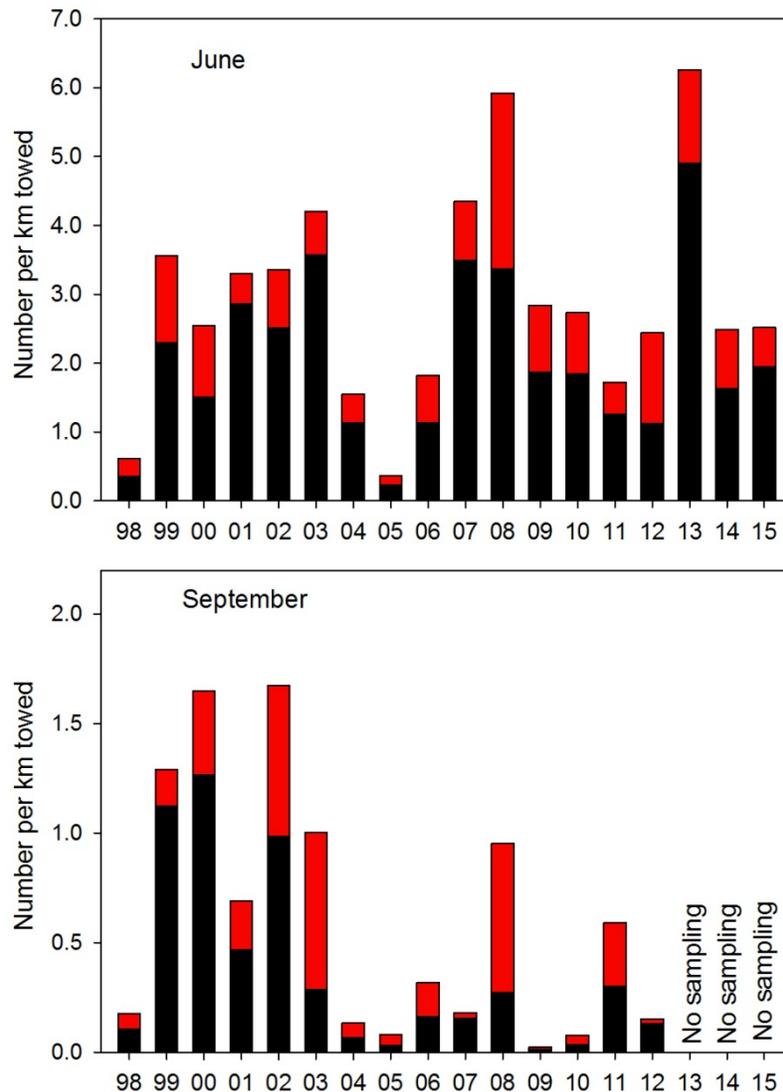


Figure JSC-01. Average catches of juvenile coho (black bars) and yearling Chinook (red bars) during trawl surveys off the coast of Washington and Oregon. Surveys were conducted in June (upper panel) and September (lower panel) from 1998 to present. Note the difference in the scale of the y-axis between plots.

Catch rates in June were lowest for both species during 2005, but rebounded gradually from 2006-2008 and 2013, only to decline again. Catches in June 2015 were ranked 13th out of 18 for yearling Chinook salmon, and 8th out of the 18 years for yearling coho salmon. Due to funding constraints, there were no surveys in September after 2012.

[Figure JSC-02](#) *Upper panel* shows the regression of spring Chinook salmon jack counts at Bonneville Dam vs. average CPUE of yearling Chinook salmon caught during each June cruise. Years indicated are for catches of juvenile fish. Open blue circle indicates observed CPUE in June 2015 (0.57) and predicted jacks from the regression (9,220). Numbers indicate the years. 2010 (red) was an outlier and was excluded from the regression.

Lower panel shows the regression of the OPIH smolt-to-adult survival (SAR) of coho salmon on the average CPUE of juvenile coho salmon catches in trawl surveys the previous June. Years indicated are for catches of juvenile fish. Open blue circle indicates observed CPUE in June 2015 (1.95) and predicted coho salmon survival from the regression (2.8%). Numbers indicate the years.

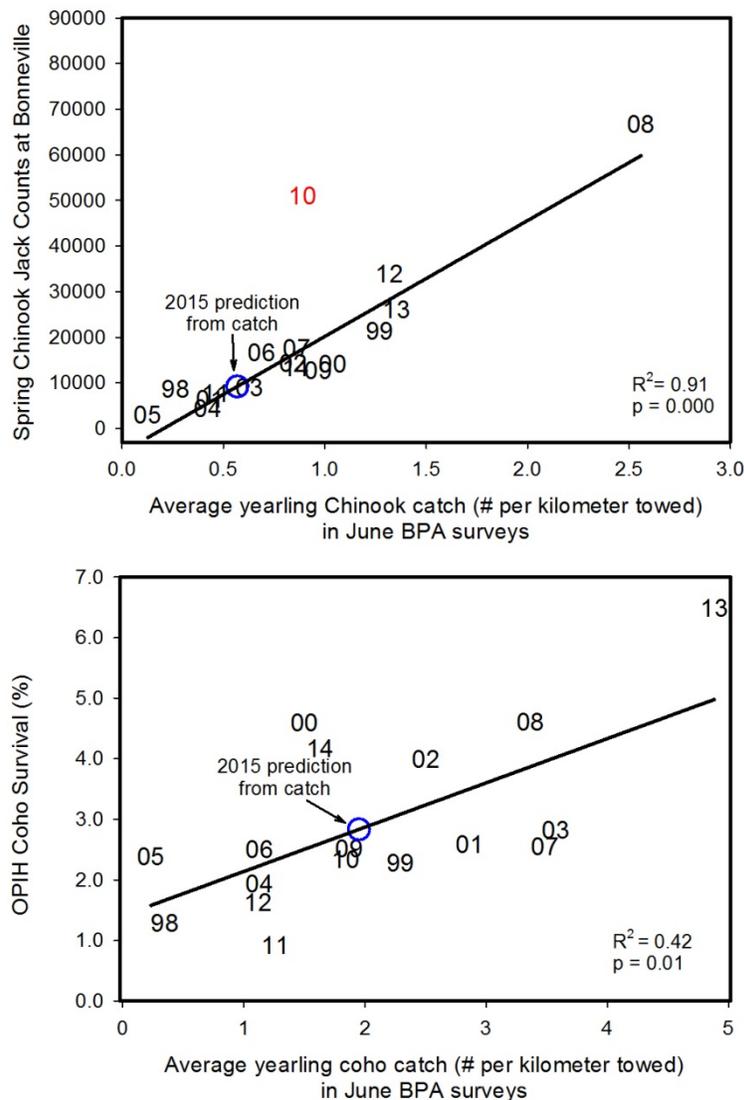


Figure JSC-02.

Upper panel shows the regression of spring Chinook salmon jack counts at Bonneville Dam vs. average CPUE of yearling Chinook salmon caught during each June cruise. Years indicated are for catches of

juvenile fish. Open black circle indicates observed CPUE in June 2014 (0.86) and predicted jacks from the regression (16,772). Numbers indicate the warm (red) and cold (blue) years. Years in black were outliers and were excluded from the regression.

Lower panel shows the regression of the OPIH smolt-to-adult survival (SAR) of coho salmon on the average CPUE of juvenile coho salmon catches in trawl surveys the previous June. Years indicated are for catches of juvenile fish. Open black circle indicates observed CPUE in June 2014 (1.6) and predicted coho salmon survival from the regression (2.5%). Numbers indicate the warm (red) and cold (blue) years. Years in black were outliers and were excluded from the regression.

* outliers were excluded using [Cook's Distance](#)

Ancillary Data

Forage Fish and Pacific Hake Abundance

We have also explored developing an index that describes food–web interactions between juvenile salmon and their fish predators, chiefly Pacific whiting, aka Pacific hake. This would be 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 [IUD-01](#) and [IUD-02](#) 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.

Due to funding constraints, we were unable to conduct any forage fish/predator study cruises in 2012. We believe that this is a promising indicator and hope to resume sampling in the near future.

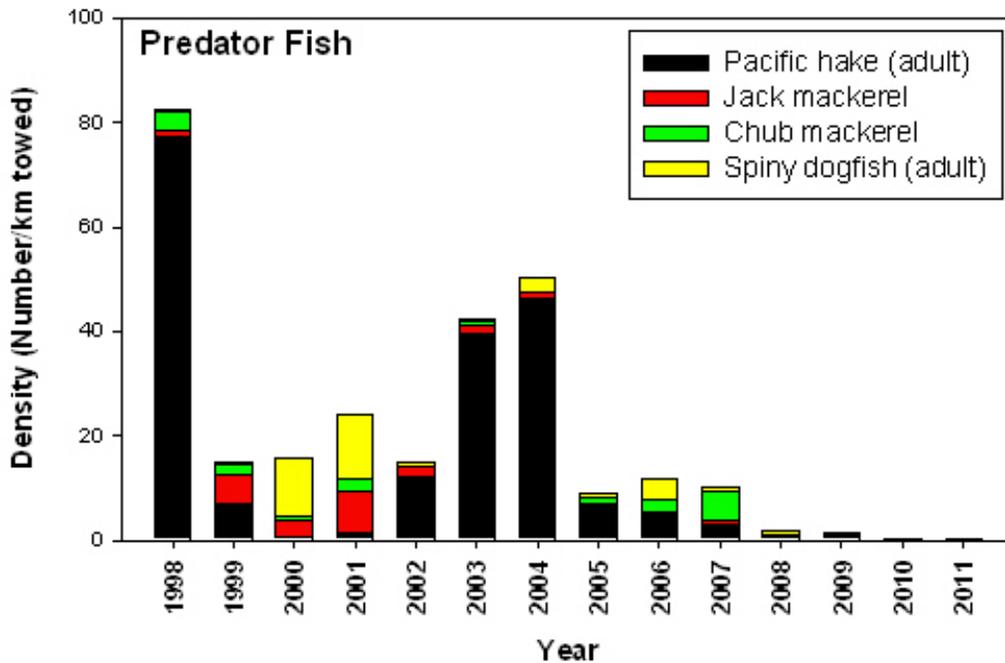


Figure IUD-01. Catches of potential piscivores that prey on juvenile salmon. Pacific hake numbers are usually very high during "warm years" such as the 1998 El Niño event and during the first 2 years of a warm-phase PDO (2003-2004). However, numbers were surprisingly low from 2008-present, despite the 2009 El Niño. Data shown are from the surveys of R. Emmett, conducted May-August 1998-present.

In 2011, Pacific hake, ([Figure IUD-01](#)) continued to be found in very low abundances compared to 1998, 2003, and 2004. Low densities were observed during the cool, negative-PDO phases of 1999-2002 and 2008-2011. Conversely, high abundances occurred during the warm, positive-PDO years of 1998, 2003, and 2004. Probably not coincidentally, these years correspond respectively to "good" and "poor" periods for coho survival. We expected high abundance levels for hake in 2005 and 2006 (warm years), but this expectation was not met, due possibly to the timing of their northward migration. That is, hake may have moved further north (off Canada) during the warm years of 2004 and 2005, and thus would have been preying on salmon earlier (May) rather than later (Jun-Jul) in the season.

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

Forage fish numbers continued to be relatively high in 2011 (Figure IUD-02), probably as a result of relatively good recruitment in 2010. These high densities comprise a positive indicator, since juvenile forage fish (ages 0 and 1) are among the favored prey of both coho and Chinook salmon. Thus salmon were probably not food limited in either 2010 or 2011. High numbers of forage fish in 2011 and a probable cold ocean in spring 2012 (which is good for forage fish recruitment) indicates favorable ocean survival for coho and Chinook salmon in 2012.

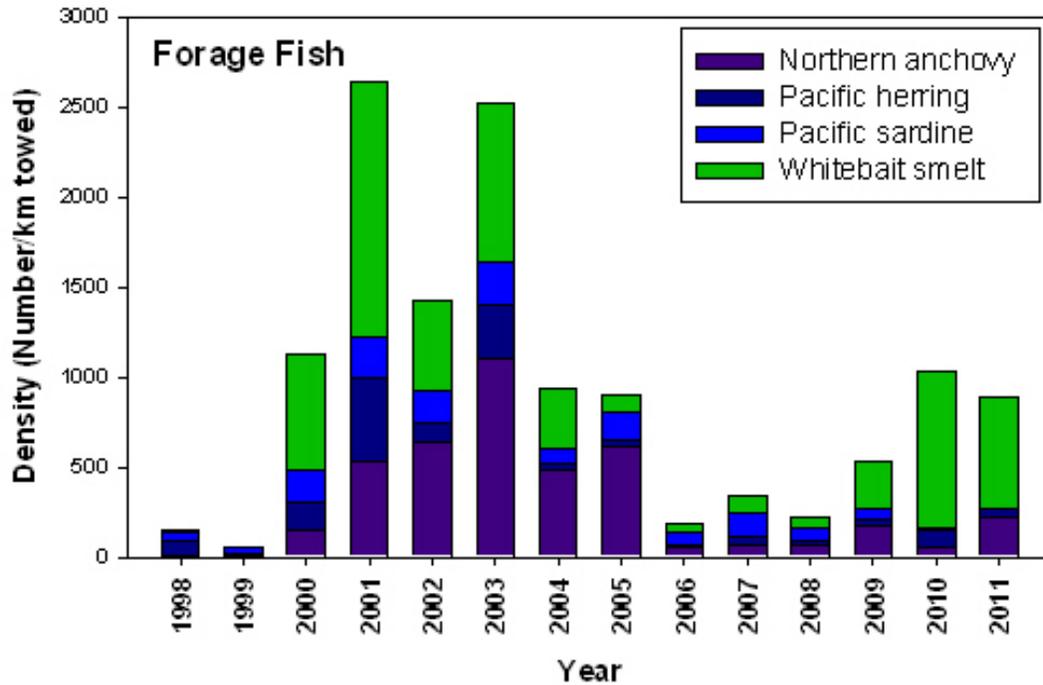


Figure IUD-02. Catches of forage fish along the Columbia River and Willapa Bay transects, 1998-present. Note low numbers of forage fish in 2006; note also low numbers in 1999, demonstrating that there can be time lags of at least 1 year following a crash before forage fish numbers begin to increase. Data shown are from the surveys of R. Emmett, conducted May-August 1998-present.

A Second Mode of North Pacific Sea Surface Temperature Variation

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

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 would integrate four variables previously found to influence predation rates of Columbia River salmon in the ocean ([Emmett 2006](#)). These variables were based on the following spring (May/June) measurements from 1998 - 2012:

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 were estimated annually from the Predator/Forage Fish Survey, and turbidity was estimated using satellite imagery, Secchi disc readings, and transmissometer measurements, each of which was collected from 1998 – 2012. Initial analyses indicated that during years when hake abundance was low and forage fish abundance, turbidity, and Columbia River flows were high, salmon marine survival was high. However, if even one variable had an opposite value, salmon marine survival declined. Sampling of predator and forage fish was ceased after 2012 due to funding constraints.

Potential Indices for Future Development

Some additional indices that could be developed 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 HZI-01). We sample the coastal waters off Newport at biweekly intervals during the upwelling season in spring, summer, and fall. Sampling cruises are conducted monthly during stormy winter months. This program began in May 1996, but we also have data from these same stations from sampling conducted in 1973 (Peterson and Miller 1975), 1983 (Miller et al. 1985), and summer 1990-1992 (Fessenden 1995).

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

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

From 1998 to 2003, we sampled a group of transects from Newport, Oregon down to Crescent City, California five times per year as part of the U.S. Global Ocean Ecosystem Dynamics (GLOBEC) program. Since the GLOBEC project ended, we have continued to sample these same transect lines as frequently as possible. Thus far, we have been able to sample this region in 2004, 2006 and 2008-present, and have extended the Newport Line out to 200 miles from shore.

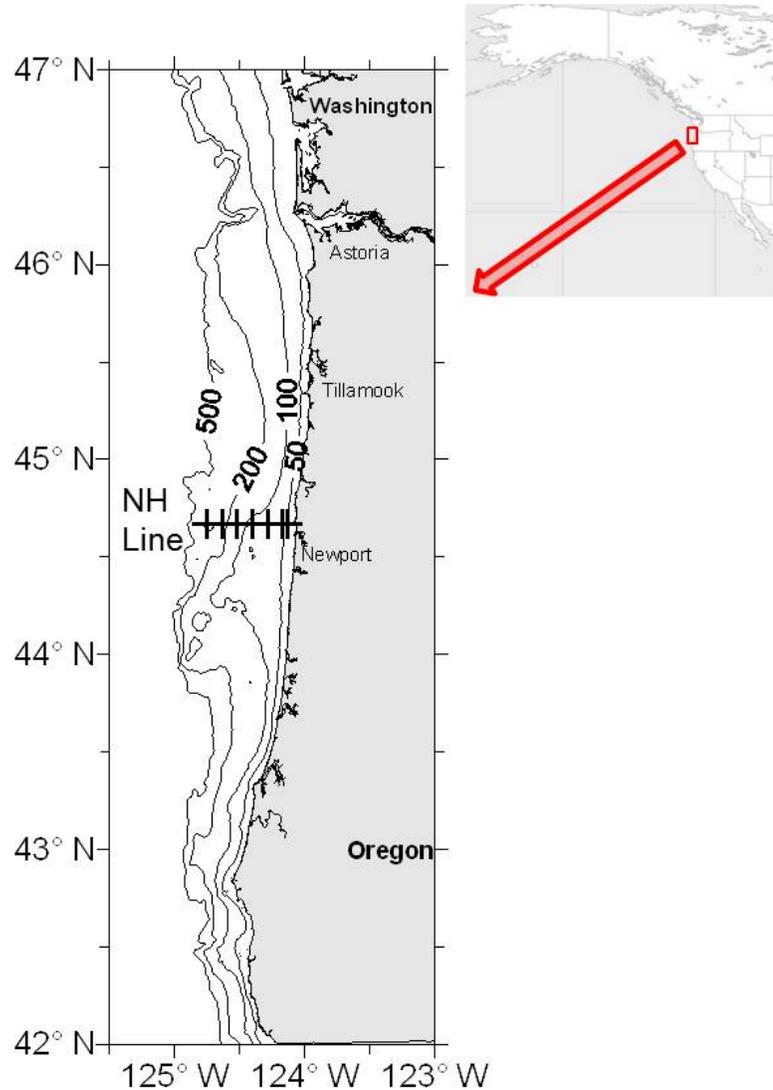


Figure HZI-01. Transects and stations sampled during cruises by the NOAA Fisheries Service.

Additionally, we also sample north of the Newport Line at least 3 times per year as part of the [Juvenile Salmon sampling program](#). As a result, the Newport biweekly data are nested within larger scale semi-annual to quarterly surveys, an approach that is useful in helping us interpret locally derived data from the inner portions of the Newport Line.;

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

Nutrients are analyzed using a Technicon Autoanalyzer. Chlorophyll-a is extracted from glass-fiber filters in 90% acetone then analyzed using a Turner Designs Fluorometer. Zooplankton samples are processed in the laboratory by subsampling with a Stempel pipette. Species and developmental stage of copepods are enumerated with the aid of a dissecting microscope. Counts are converted to number of individuals per m³ of water using appropriate conversion factors. Biomass is estimated by multiplying the number of individuals per m³ by the dry weight of the taxa (using values from either literature or our own measurements). Carbon content is calculated assuming carbon is 40% of dry weight.

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

Juvenile Salmon Sampling Program

Methods

We have sampled juvenile salmon each June and September since 1998 at offshore stations ranging from Newport, Oregon, to La Push, Washington (Figure JSS-01). 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).

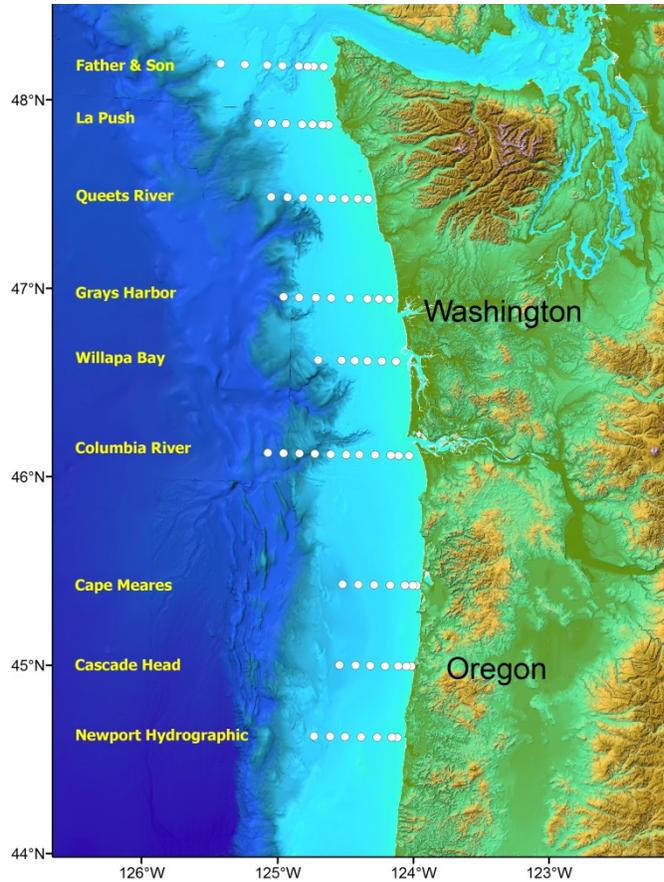


Figure JSS-01. Transects sampled for coho and yearling and subyearling Chinook salmon, 1998 –

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

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

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

During each year since 1998, we have collected samples over a wide range of ocean conditions. These data have provided many insights into the role of ocean conditions in controlling survival and growth of coho and Chinook salmon. For example, we sampled during a very strong El Niño

(June 1998) and a strong La Niña (cold water) (1999 & 2008), under very high Columbia River flows of June 1999, 2008, and 2010 – 2013 during extremely low flows of June 2001, and during anomalously warm conditions in the coastal ocean due to lack of upwelling in June 2005. During this period, the Pacific Decadal Oscillation moved from a warm phase (pre-1999) to a cool phase (1999–2002), then to warm phase again (2003-2007) and then back to a cool phase (2008-2013). Thus, nature has handed us a grand experiment that allows us to observe how salmon and other ecosystem components respond to short-term climate variability and on what temporal scales these responses occur.

Results

Salmon Distribution— Average juvenile salmon abundance over all May cruises has been highest in the vicinity of the Columbia River for both yearling (spring) Chinook and coho salmon, whereas subyearling (fall) Chinook salmon are rarely caught in May [Figure JSS-02](#)).

In June, average abundance has been highest in the vicinity of the Columbia River and off the Washington coast ([Figure JSS-02](#)). Distributions of coho salmon have been more widespread, whereas both yearling and subyearling Chinook salmon were far less common off Oregon than Washington.

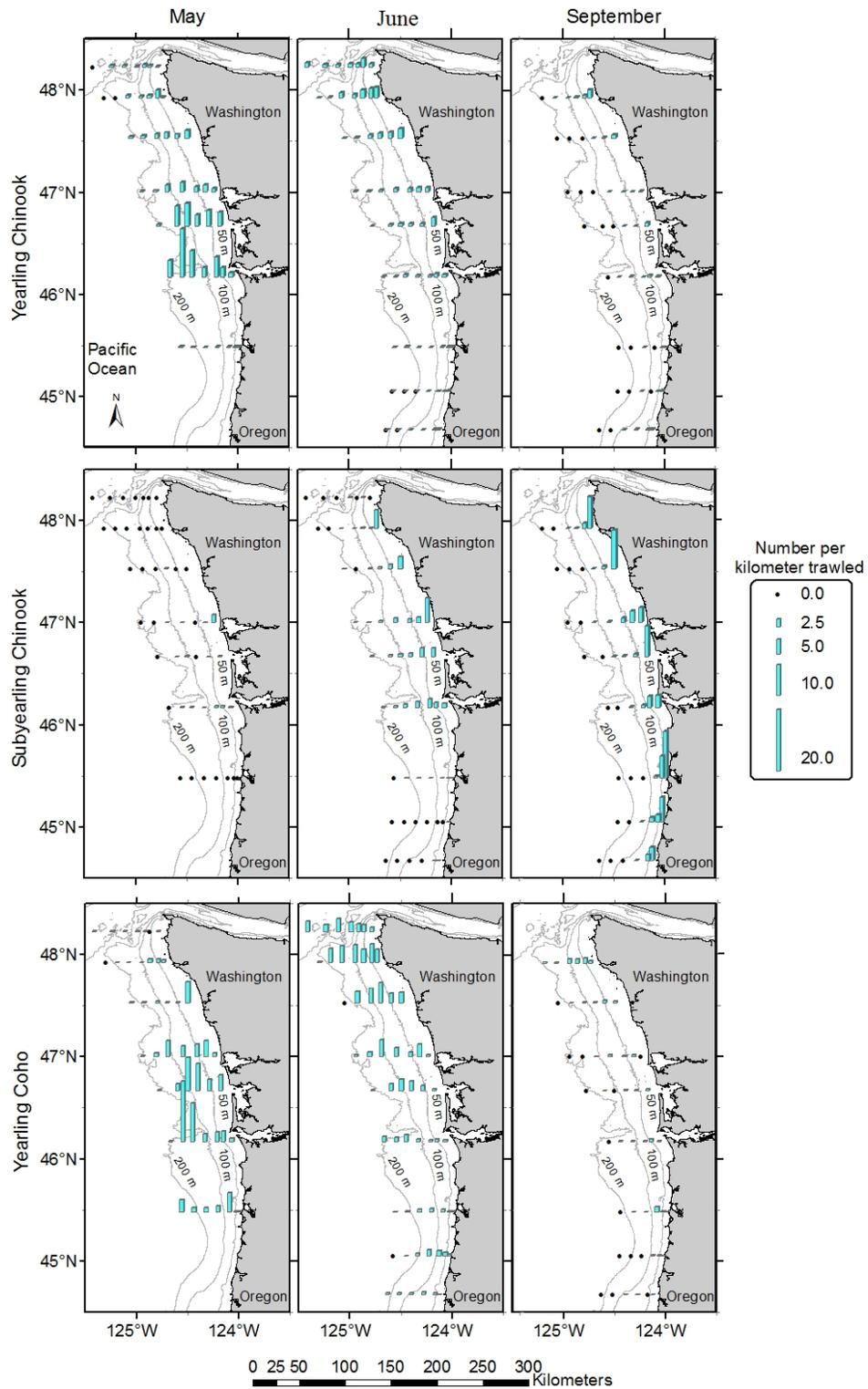


Figure JSS-02. Average catch of salmonids per km towed at stations in May 1999, 2006 – 2012, June 1998 – present, and September 1998 – 2012 for each life history type.

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. June 2014 catches were below average for subyearling and yearling Chinook and coho salmon, but the highest in our seventeen June surveys for mixed-aged juvenile Chinook salmon.

Catches in all months were 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 salmon off the Columbia River and the Washington coast in May and June (Figure JSS-02) and very near shore for yearling and subyearling Chinook salmon in September.

Annual variation in salmon abundance—The lowest June catches of Chinook and coho salmon were associated with an El Niño event in 1998 and an anomalously low upwelling period during May-June 2005 (Figure JSS-03). Conversely, the highest June catches occurred during years with a negative signal (cold phase) of the Pacific Decadal Oscillation (1999-2003 and 2008-2013). June 2013 catches were high for subyearling and yearling Chinook and coho salmon, but about average for mixed-aged juvenile Chinook salmon.

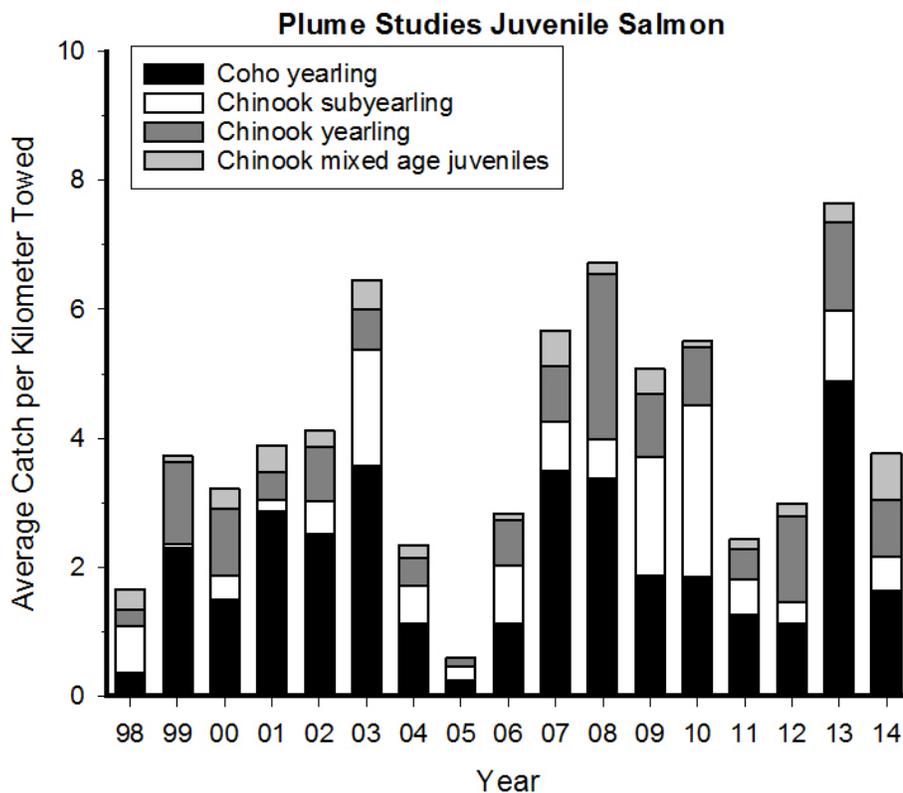


Figure JSS-03. Annual variation in catches of juvenile coho and Chinook salmon during June trawl surveys, 1998-present.

Introduction to Pacific Northwest Oceanography

Physical Oceanographic Considerations

The marine and anadromous faunas over which NOAA Fisheries exercises stewardship occupy diverse habitats in the coastal ocean off Washington, Oregon, and California. This biogeographic region has been collectively termed the Coastal Upwelling Domain ([Ware and McFarlane 1989](#)). Dominant fisheries species within this domain include market squid, northern anchovy, Pacific sardine, Pacific hake, Pacific mackerel, jack mackerel, Pacific herring, rockfish, flatfish, sablefish, and coho and Chinook salmon.

Within this domain, several smaller-scale physical zones are recognized, including:

- a. A near shore zone where juvenile fall Chinook salmon, sand lance, and smelts reside
- b. The upper 10–20 m of the water column across the continental shelf and slope, where many pelagic fishes reside, including juvenile coho and Chinook
- c. The benthic and demersal habitats on the continental shelf (English sole), at the shelf break (whiting, rockfish), and beyond the shelf break to depths of 1500 m (sablefish, Dover sole, and thornyheads)

Each of these physical zones has unique circulation patterns that affect spawning and larval transport, and each is subject to different physical conditions. These differing conditions lead to species-specific variations in growth, survival, and recruitment. Moreover, since many species have pelagic larvae/juvenile stages, recruitment is affected by broad-scale variation in both ocean productivity, which affects the feeding environment of larval and juvenile fish, and in ocean circulation, which affects the transport of eggs and larvae.

The Coastal Upwelling Domain is part of the California Current system, a broad, slow, meandering current that flows south from the northern tip of Vancouver Island (50°N) to Punta Eugenia near the middle of Baja, California (27°N). The California Current extends laterally from the shore to several hundred miles from land. In deep oceanic waters off the continental shelf, flows are usually southward all year round. However, over the continental shelf, flows are southward only in spring, summer, and fall: during winter, flow over the shelf reverses, and water moves northward as the Davidson Current.

These biannual transitions between northward and southward flow over the shelf occur in during March April and October November and are respectively termed the "spring transition" and "fall transition." Another important feature of circulation within the Coastal Upwelling Domain is the deep, poleward flowing undercurrent found year round at depths of 100–300 m over the outer shelf and slope. This current seems to be continuous from Southern California (33°N) to the British Columbia coast (50°N).

Coastal upwelling is the dominant physical element affecting production in the Coastal Upwelling Domain. In the continental shelf waters off Washington and Oregon, upwelling occurs primarily from April to September, whereas upwelling can occur year round off the coasts of northern and central California. Upwelling in offshore waters also occurs through Ekman

pumping and surface divergence in the centers of cyclonic eddies, but these processes will not be discussed further here.

Coastal upwelling works as follows: winds that blow from the north (towards the equator) result in the offshore transport of waters within the upper 15 m of the water column. This offshore transport of surface waters is balanced by onshore movement of cold, nutrient rich waters from a depth of about 100–125 m at the shelf break region. When winds are strong, this cold (8°C), nutrient rich water surfaces within 5 miles of the coast. The result is high production of phytoplankton from April through September fueled by a nearly continuous supply of nutrients and concomitant high biomass of copepods, euphausiids, and other zooplankton during summer.

Coastal upwelling is not a continuous process. Rather, it is episodic, with favorable (equatorward) winds blowing for 1–2 week periods, interspersed by periods of either calm or reversals in wind direction. These pulses in the winds produce what are called "upwelling events." Interannual variations in the length and number of upwelling events result in striking variations in the level of primary and secondary production. Thus, the overall level of production during any given year is highly variable, and is dependent on local winds.

We do not yet know if there is an optimal frequency in upwelling event cycles, but one can easily imagine scenarios in which prolonged periods of continuous upwelling would favor production in offshore waters because nutrient rich waters would be transported far to sea. The other extreme is one in which winds are weak and produce upwelling only in the very nearshore zone, within a mile or two of the coast. In this case, animals living in waters off the shelf would be disadvantaged. Any process that leads to reduction in the frequency and duration of northerly winds will result in decreased productivity and vice versa. The most extreme of these processes is El Niño, which disrupts coastal ecosystems every 5–10 years.

Despite the existence of high plankton biomass and productivity, coastal upwelling environments present unique problems to fish and invertebrate populations who must complete their life cycles there. This is because the upwelling process transports surface waters and the associated pelagic larvae and juvenile life stages away from the coast and towards the south, away from productive habitats. Typical transport rates of surface waters are 1 km per day in an offshore direction and 20–30 km per day southward.

Zooplankton and larval and juvenile fishes, which live in the food-rich surface layers (i.e., the upper 15 m of the water column), can be transported rapidly offshore, out of the upwelling zone, and into relatively oligotrophic waters. Bakun ([1996](#)) argues that for any animal to be successful in such environments, the adults must locate habitats that are characterized by enrichment, with some mechanism for concentrating food (for larvae), and that offer a way for larvae to be retained within the system.

Perhaps because of its problems related to transport (and loss), many species do not spawn during the upwelling season. Species such as Dover sole, sablefish, Dungeness crab, and pink shrimp each spawn during the winter months, before the onset of upwelling. Other species perform an extended migration to spawn in regions where there is no upwelling.

Hake, for example, undertakes an extended spawning migration, during which adults swim south to spawn in the South California Bight in autumn and winter, outside of the upwelling region and season. This migration extends from Vancouver Island (ca. 49°N) to southern California (35°N), a distance of several thousand kilometers. The return migration of adults and the northward drift of larvae and juveniles take place at depth, where fish take advantage of the poleward undercurrent.

Still other species, such as English sole, spawn in restricted parts of an upwelling system where advective losses are minimized, such as in bays or estuaries. Salmonids and eulachon smelt spawn in rivers, completely outside the upwelling system. Finally, species such as rockfish simply bypass the egg and larval stages and give birth to live precocious "juvenile" individuals.

Climate–Scale Physical Variability

Variability in productivity of the California Current occurs at climatic time scales, each of which must be taken into account when considering recruitment variability and fish growth. The North Pacific Ocean experiences dramatic shifts in climate every 10–20 years. These shifts occurred in 1926, 1947, 1977, and 1998 and were caused by eastward/westward jumps in the location of the [Aleutian Low](#) in winter, which result in changes in wind strength and direction. Changes in large-scale wind patterns lead to alternating states of either a "warm-ocean" or "cold-ocean" regime, with the warm ocean being less productive than the cold.

We hypothesize that during "cold PDO" (such 1999–2002), a larger amount of water enters the California Current from the Gulf of Alaska, whereas during "warm PDO" such as 2003–2005, smaller amounts of water enter from the Gulf of Alaska and more enters from the [North Pacific Current](#) offshore or from the south ([Figure CPV-01](#)). The changes in the type of source water yield the results shown in [Table CPV-01](#).

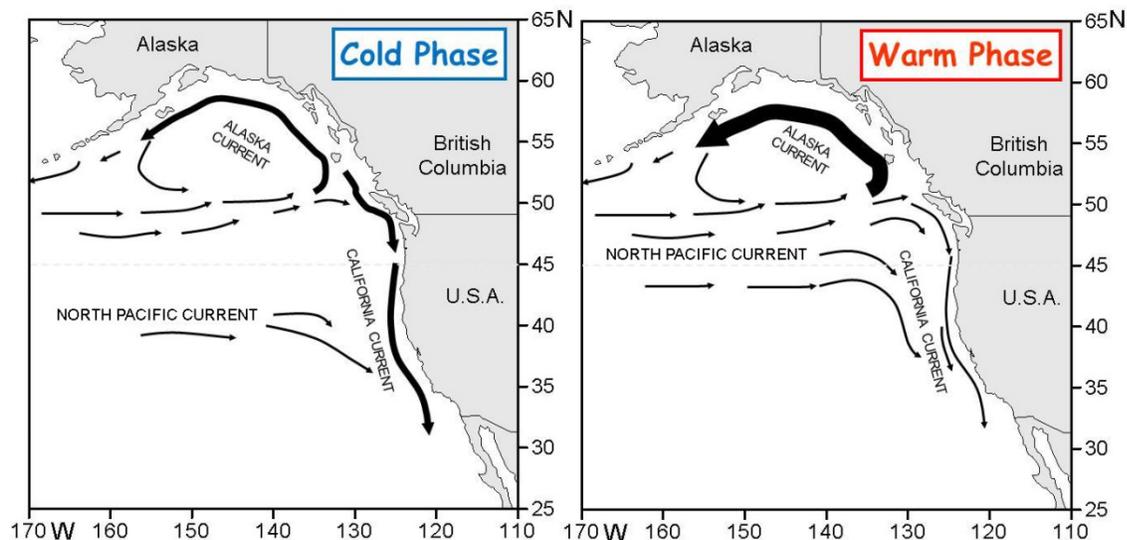


Figure CPV-01. A working hypothesis on how changes in the Pacific Decadal Oscillation affect productivity in the northern California Current.

Changes in biological productivity are best documented for the period since the 1950s, and this understanding is largely due to measurements made by the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program. Zooplankton biomass, for example, was high from the 1950s through 1977, but during the warm regime of 1977–1998, zooplankton biomass in the southern sector of the California Current declined by nearly one order of magnitude. In the northern California Current, the change in zooplankton biomass between regimes was not as dramatic, ranging just over one half an order of magnitude in coastal waters off Newport Oregon. Zooplankton biomass was higher than average during the cool regime prior to 1977 and lower than average during the warm regime from 1977 to 1998. During 2000–2004, zooplankton biomass rebounded to levels comparable to those seen prior to 1977.

Since the early 1980s, the California Current has been experiencing an increased frequency of El Niño events, with large El Niño events occurring every 5-6 years: 1976-77, 1982-83, 1986-87, 1991-92, 1997-98, 2002-03 and again in 2009-10. A higher frequency of El Niño events appears to be a characteristic of the extended periods of warm ocean conditions. From 1992 to 1998, the Oregon and Washington coasts experienced almost continuous El Niño-like conditions during summer (i.e., reduced upwelling and warmer ocean conditions). Since 1998, ocean conditions have improved markedly, and another regime shift may have been initiated in late 1998. This shift to productive conditions was interrupted for 3 years (late 2002-late 2005), and again in 2013-14. Whether or not short-term (3-5 year) variability will become the norm remains to be seen.

It is unclear why ENSO activity has a variable impact on the Pacific Northwest, but one problem is that we do not know precisely how ENSO signals are transmitted from the equator to the PNW. Signals can arrive through the ocean via [Kelvin waves](#), which propagate up the coast of North America. ENSO signals can also be transmitted through atmospheric teleconnections. El Niño conditions can strengthen the Aleutian Low pressure system 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. This results in more frequent large storms in winter and disruption of upwelling winds in spring and summer. A summary of these interactions is available from NOAA's [Earth Systems Research Laboratory](#).

Table CPV- Summary of the manner in which the sign of the PDO influences broad-scale
01. and local physical ocean condition indicators as well as biological indicators.

	Cool PDO	Warm PDO
Broad-scale ocean indicators		
Pacific Decadal Oscillation values	negative	positive
Multivariate ENSO Index values	negative	positive
Local physical indicators		
Upwelling	may not be related to PDO	
Physical spring transition ^a	may not be related to PDO	
Sea surface temperatures	cold	warm
Continental shelf water type	cold and salty	warm and fresh
Local and regional biological indicators		
Copepod species richness	low	high
Northern copepod biomass	positive anomaly	negative anomaly
Southern copepod biomass	negative anomaly	positive anomaly
Euphausiid egg abundance in shelf water	usually high	usually low
Biological spring transition	early	late
Trawl surveys		
Coho abundance	high	low
Chinook abundance	high	low
Coho survival ^b	high	low
Developing indicators		
Snake River Chinook SARs ^c	high	low
Forage fish abundances	many	few
Pacific hake abundances	few	many

a ([Logerwell et al. 2003](#))

b (OPIH) [Oregon Production Index](#), Hatchery

c Smolt to adult returns (see [Scheurell and Williams 2005](#))

These simple relationships only hold during years of persistent recurrence of one phase of the PDO. During transitional years, such as 1998-1999, 2002-2003, and 2006-07, there are time lags in the ecosystem responses. For example, after the 1998 and 2002 climate shifts, water temperatures lagged the PDO by 1-2 months, changes in copepod biodiversity lagged the PDO index by 4-6 months, and changes in copepod biomass lagged the PDO by 2 years. Similarly, increases in abundances of forage fish and juvenile salmon lagged the PDO index changes by 1-2 years. The strongly negative "cool phase" PDO of 2008 yielded good returns of salmon (particularly coho salmon) in 2009.

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Glossary

Age Class

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

Aleutian Low

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

California Current

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

CPUE

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

Geostrophic Wind

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

Escapement

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

Ichthyoplankton

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

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 a region of high sea-level pressure that occurs over the sub-tropical eastern North Pacific Ocean (Trewartha 1954). It is the dominant atmospheric pressure system influencing the northern California Current during the summer months, whereas the Aleutian Low is dominant from late fall to late spring.

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.

Oceanic Nino Index (ONI)

The temperature anomaly within the Niño 3.4 region, averaged over a 3-month period. Values, and additional information, can be found at http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml

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.

Outlier

The factors influencing salmon marine survival or adult return numbers are numerous. We recognize that the primary drivers of mortality may vary from year to year. Although any given indicator may be correlated with survival, there may be years where the correlation does not hold (ie, years when the primary driver of mortality is a set of conditions unrelated to this indicator). Therefore, we expect many of the indicators to have outlier years, where the value of thee indicator does not reflect the mechanisms of mortality. Because we do not know the exact mechanism driving mortality each year, we chose a statistical measure to identify and remove outlier years from many of our analyses. Specifically, we calculated Cook's Distance (Cook 1979) and used a cutoff of $4/N$ (Bollen and Jackman 1990) to identify outlier years. Although we show these years in our plots, we excluded them from analyses when creating out outlooks.

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.