

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

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Project Summary

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

As many scientists and salmon managers have noted, variations in marine survival of salmon often correspond with periods of alternating cold and warm ocean conditions. For example, cold conditions are generally good for Chinook (*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 for salmon survival outlooks 1–2 years in advance, as shown in [Table 1](#). This information is presented for the non-specialist; additional detail is provided via links when possible.

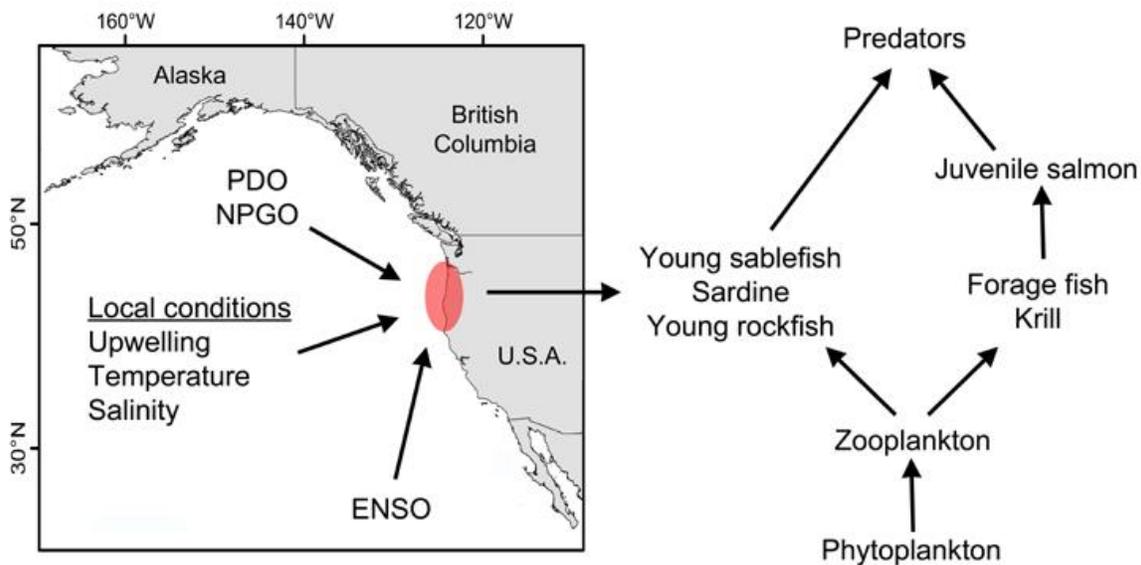


Figure HP-01. Illustration of how basin-scale and local-scale physical forces influence the northern California Current and resultant food web structure. PDO = Pacific Decadal Oscillation. NPGO = North Pacific Gyre Oscillation. ENSO = El Niño–Southern Oscillation. Figure from Peterson et al. [2014 Oceanography 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 these data, we developed a suite of ocean ecosystem indicators upon which to base outlooks of salmon returns. These outlooks are presented as a practical example of how ocean ecosystem indicators can be used to inform management decisions for endangered salmon. We provide a qualitative 'stoplight' table where we rate each indicator in terms of its "good," "bad," or "neutral" relative impact on salmon marine survival ([Table 1](#)). We also use these ocean ecosystem indicators to predict adult salmon returns which complement other methods, 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 salmon return outlooks, 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 2019

While 2018 was fairly neutral, 2019 showed indicators that ranked on the warmer side—especially the basin scale indices (PDO, ONI), the local temperature metrics, and the winter ichthyoplankton metrics. While many of the biological variables were neutral, the May–Sept northern copepod anomalies were much higher than normal, ranking second highest in our time series. Even though the high abundance of northern copepods is generally an indicator of good feeding conditions in the Northern California Current, the majority of the other indicators point to a more neutral and/or poor year for outmigrating juvenile salmon.

PDO and ONI. The PDO turned positive (warm phase) in January 2014 and has remained positive through September of 2019. The PDO value in October 2019 was -0.45, was the first negative value since 2013, but then returned to positive (0.15) in November of 2019. Weak El Niño conditions (positive Ocean Niño Index values greater than or equal to -0.5) persisted during the fall/winter of 2018/2019 from October through April, then became neutral throughout the remainder of 2019.

Upwelling Index at 45°N. The winter downwelling period was close to the climatological mean. The onset of upwelling occurred on April 19, 2019, and was relatively strong at the beginning of the season but decreased mid-June and remained weaker than normal through the season. Weak upwelling favorable winds continued through November, which is rare, but also occurred in 2013.

Sea Surface Temperatures (SST) from NOAA Buoys. Positive temperature anomalies occurred during the winter from mid-October through May punctuated by brief periods of negative anomalies during the beginning of March and May ([Figure TA-02](#)). After the onset of upwelling in mid-April, SST anomalies remained positive until June when negative SST anomalies persisted. However, SST anomalies became strongly positive (+2.5°C) from July through at least October.

Hypoxia. Hypoxic oxygen concentrations below 1.4 ml/L were [observed](#) on the shelf off Newport, OR only in August of 2019 ([Figure HYP-01](#)). However, hypoxic conditions were observed further north from Grays Harbor, WA to Cape Meares, OR during late June, and the area of hypoxia was 6th out of the 13 years, so about average ([Figures HYP-02 & HYP-03](#)).

Zooplankton. During the anomalously warm years in 2015 and 2016, the copepod community remained in a warm state and never transitioned to a cold water (upwelling) community during those years. During January through May of 2017, the copepod community was still anomalously warm, however the community did shift to a cold water community in late June 2017, 2 months later than the 1998–2014 climatology. In both 2018 and 2019, the community shift from winter to summer occurred about one month later than the climatology. However, in 2019, the fall transition (the shift from an upwelling to a downwelling copepod community) was very early, which together with the late start, resulted in a 2.5-month shorter duration of the cold water copepod

community. During the summer of 2019, the northern copepod anomalies were much higher than normal, ranking second highest in our time series ([Figure NSC-01](#)).

Pyrosomes. [Colonial tunicates called Pyrosomes](#) were a common occurrence in our plankton nets from fall 2016 through midsummer 2018. We did not encounter pyrosomes in 2019.

Winter Ichthyoplankton. The winter biomass of larval stages of fish species common in salmon diets in 2019 was the 20th lowest in the 22-year time series ([Figure WI-01](#)). The community composition of ichthyoplankton in 2019 was dominated by offshore taxa, similar to that seen in 2015-2017, with the community indicator suggesting poor food conditions for piscivorous juvenile salmon that out-migrate into the ocean in 2019.

Forecast of Adult Returns for coho salmon and Chinook salmon

Our annual summary of ecosystem indicators is [here](#), and our "stoplight" rankings and predictions are shown below in [Table SF-01](#), [Table SF-02](#), and [Figure SF-01](#).

	Juvenile Migration Year				Adult Return Outlook	
	2016	2017	2018	2019	coho 2020	Chinook 2020
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 biomass	■	■	■	■	●	●
Winter ichthyoplankton community	■	■	■	■	●	●
Juvenile Chinook salmon catch – June	■	■	■	■	●	●
Juvenile coho salmon catch – June	■	■	■	■	●	●
Key ■ good conditions for salmon ● good returns expected ■ intermediate conditions for salmon ● intermediate returns expected ■ poor conditions for salmon ● poor returns expected						

Ecosystem Indicators	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
PDO (Sum Dec-March)	19	6	3	13	7	21	12	17	14	9	5	1	16	4	2	8	10	22	20	18	11	15
PDO (Sum May-Sept)	10	4	6	5	11	17	16	18	12	14	2	9	7	3	1	8	20	22	21	15	13	19
ONI (Average Jan-June)	21	1	1	7	14	16	15	17	9	12	3	11	18	4	6	8	10	19	22	13	5	20
SST NDBC buoys (°C; May-Sept)	17	6	8	4	5	11	22	12	2	14	1	10	3	7	9	16	20	19	18	13	15	21
Upper 20 m T (°C; Nov-Mar)	21	11	8	10	6	15	16	13	12	5	1	9	18	4	3	7	2	22	20	19	14	17
Upper 20 m T (°C; May-Sept)	16	11	13	4	1	3	22	19	8	10	2	5	17	7	6	18	20	9	14	12	15	21
Deep temperature (°C; May-Sept)	22	6	8	4	1	10	12	16	11	5	2	7	14	9	3	15	21	19	13	18	20	17
Deep salinity (May-Sept)	21	3	11	4	5	18	19	12	7	1	2	16	20	15	14	13	22	17	9	8	6	10
Copepod richness anom. (no. species; May-Sept)	20	2	1	7	6	15	14	19	16	10	8	9	18	4	5	3	11	21	22	17	13	12
N. copepod biomass anom. (mgC m ⁻³ ; May-Sept)	20	15	11	12	4	17	14	21	16	13	7	10	9	1	3	5	6	18	22	19	8	2
S. copepod biomass anom. (mgC m ⁻³ ; May-Sept)	22	2	5	4	3	15	16	21	14	10	1	7	17	9	8	6	11	19	20	18	13	12
Biological transition (day of year)	19	11	6	7	8	15	12	20	14	3	1	2	17	4	9	5	10	21	21	18	13	15
Nearshore Ichthyoplankton Log(mgC 1,000 m ⁻³ ; Jan-Mar)	17	4	11	6	1	21	22	16	8	18	3	13	2	7	5	10	19	14	15	12	9	20
Nearshore & offshore Ichthyoplankton community index (PCO axis 1 scores; Jan-Mar)	11	6	5	9	8	13	16	20	1	14	3	12	15	4	2	7	10	18	21	22	17	19
Chinook salmon juvenile catches (no. km ⁻² ; June)	20	4	5	17	8	12	18	21	13	11	1	6	7	16	2	3	10	14	19	22	15	9
Coho salmon juvenile catches (no. km ⁻² ; June)	20	8	14	6	7	3	17	21	18	4	5	10	11	16	19	1	13	9	15	22	2	12
Mean of ranks	18.5	6.3	7.3	7.4	5.9	13.9	16.4	17.7	10.9	9.6	2.9	8.6	13.1	7.1	6.1	8.3	13.4	17.7	18.3	16.6	11.8	15.1
Rank of the mean rank	22	4	6	7	2	15	17	19	11	10	1	9	13	5	3	8	14	19	21	18	12	16
<i>Ecosystem Indicators not included in the mean of ranks or statistical analyses</i>																						
Physical Spring Trans. UI based (day of year)	3	7	21	18	4	13	16	22	13	1	6	2	8	11	19	9	20	10	5	17	11	13
Physical Spring Trans. Hydrographic (day of year)	21	3	13	8	5	12	15	22	6	9	1	9	19	3	11	2	17	7	18	20	15	14
Upwelling Anomaly (April-May)	11	3	18	7	10	15	14	22	11	5	8	9	16	18	16	13	20	1	2	21	6	4
Length of Upwelling Season UI based (days)	6	2	20	13	1	15	11	22	5	3	9	3	17	19	17	16	21	12	8	14	7	10
Copepod Community Index (MDS axis 1 scores; May-Sept)	21	3	5	8	2	16	14	20	17	10	1	7	13	9	6	4	11	19	22	18	12	15

Table SF-02 Rank scores derived from ocean ecosystem indicators data found in [Table SF-03](#) and color-coded to reflect ocean conditions for salmon growth and survival (green = good; yellow = intermediate; red = poor). Lower numbers indicate better ocean ecosystem conditions, or "green lights" for salmon growth and survival. To arrive at these rank scores for each ocean ecosystem indicator, all years of sampling data from [Table SF-03](#) were compared (within each row).

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	2016	2017	2018	2019
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	6.69	3.38	1.52	2.01
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	6.6	1.86	0.45	3.94
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	1.23	0.12	-0.45	0.72
SST NDBC buoys (°C; May-Sept)	13.77	13.2	13.33	12.98	13.05	13.56	14.68	13.58	12.73	13.64	12.45	13.44	12.76	13.23	13.34	13.72	14.03	13.89	13.83	13.59	13.71	14.68
Upper 20 m T (°C; Nov-Mar)	12.30	10.31	10.12	10.22	10.08	10.70	10.86	10.61	10.59	10.04	9.33	10.19	11.01	10.02	9.62	10.12	9.62	12.73	12.03	11.47	10.63	10.99
Upper 20 m T (°C; May-Sept)	10.40	10.07	10.16	9.76	8.97	9.62	11.32	10.73	9.97	10.07	9.30	9.90	10.42	9.95	9.92	10.43	10.95	10.05	10.18	10.14	10.34	11.31
Deep temperature (°C; May-Sept)	8.59	7.63	7.74	7.56	7.46	7.81	7.89	7.97	7.83	7.58	7.48	7.73	7.89	7.81	7.56	7.94	8.38	8.08	7.89	8.06	8.11	8.04
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	33.76	33.53	33.71	33.83	33.85	33.85	33.79
Copepod richness anom. (no. species; May-Sept)	4.54	-2.58	-3.41	-1.03	-1.12	1.99	1.42	4.39	2.68	-0.63	-0.76	-0.65	3.12	-2.13	-1.31	-2.51	-0.11	7.42	8.15	2.79	0.39	0.05
N. copepod biomass anom. (mg C m ⁻³ ; May-Sept)	-0.76	0.04	0.15	0.15	0.29	-0.13	0.05	-0.85	-0.01	0.14	0.26	0.15	0.16	0.44	0.39	0.28	0.26	-0.28	-0.90	-0.63	0.22	0.40
S. copepod biomass anom. (mg C m ⁻³ ; May-Sept)	0.60	-0.23	-0.21	-0.22	-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	0.41	0.50	0.31	0.002	-0.004
Biological transition (day of year)	209	134	97	101	108	156	146	214	150	81	64	65	169	82	125	91	126	365	365	179	149	156
Nearshore ichthyoplankton (Log(mg C 1,000 m ⁻³ ; Jan-Mar)	0.48	1.64	0.97	1.27	1.95	0.40	0.32	0.49	1.16	0.48	1.64	0.62	1.87	1.21	1.55	1.09	0.46	0.51	0.49	0.64	1.12	0.43
Nearshore/offshore Ichthyoplankton community index (PCO axis 1 scores; Jan-Mar)	-8.74	-19.07	-27.84	-13.56	-14.02	-1.58	20.43	33.77	-34.18	10.37	-31.33	-3.26	11.79	-28.79	-32.28	-16.00	-13.55	31.50	34.14	39.67	29.53	33.00
Chinook salmon juvenile catches (no. km ⁻¹ ; June)	0.26	1.30	1.04	0.46	0.91	0.71	0.42	0.15	0.71	0.86	2.60	1.02	0.95	0.50	1.36	1.35	0.87	0.58	0.37	0.07	0.50	0.88
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	4.92	1.63	1.96	1.42	0.22	4.04	1.68
Principal Components scores (PC1)	4.59	-2.99	-2.69	-2.14	-2.79	1.07	2.30	3.51	-0.60	-1.02	-5.23	-1.67	0.28	-2.59	-3.32	-2.26	0.72	5.01	5.21	2.78	-0.02	1.86
Principal Components scores (PC2)	0.25	-0.54	0.77	-0.98	-1.86	-0.45	2.54	-0.41	-1.38	0.24	-1.68	0.84	-0.81	0.61	0.07	1.31	3.25	-1.49	-2.30	-0.87	0.40	2.47
<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	86	116	105	109
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	164	179	157	156
Upwelling Anomaly (Sum April-May)	-14	19	-36	2	-12	-34	-27	-55	-14	9	0	-5	-35	-36	-35	-21	-37	50	28	-45	8	14
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	186	172	189	178
Copepod Community Index (MDS axis 1 scores; May-Sept)	0.63	-0.95	-0.93	-0.87	-0.96	-0.25	-0.26	0.50	-0.14	-0.73	-0.98	-0.87	-0.31	-0.75	-0.89	-0.93	-0.49	0.41	0.76	0.34	-0.37	-0.26

Data for rank scores of ocean ecosystem indicators. Download [data for rank scores of ocean ecosystem indicators 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 2019a) 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).

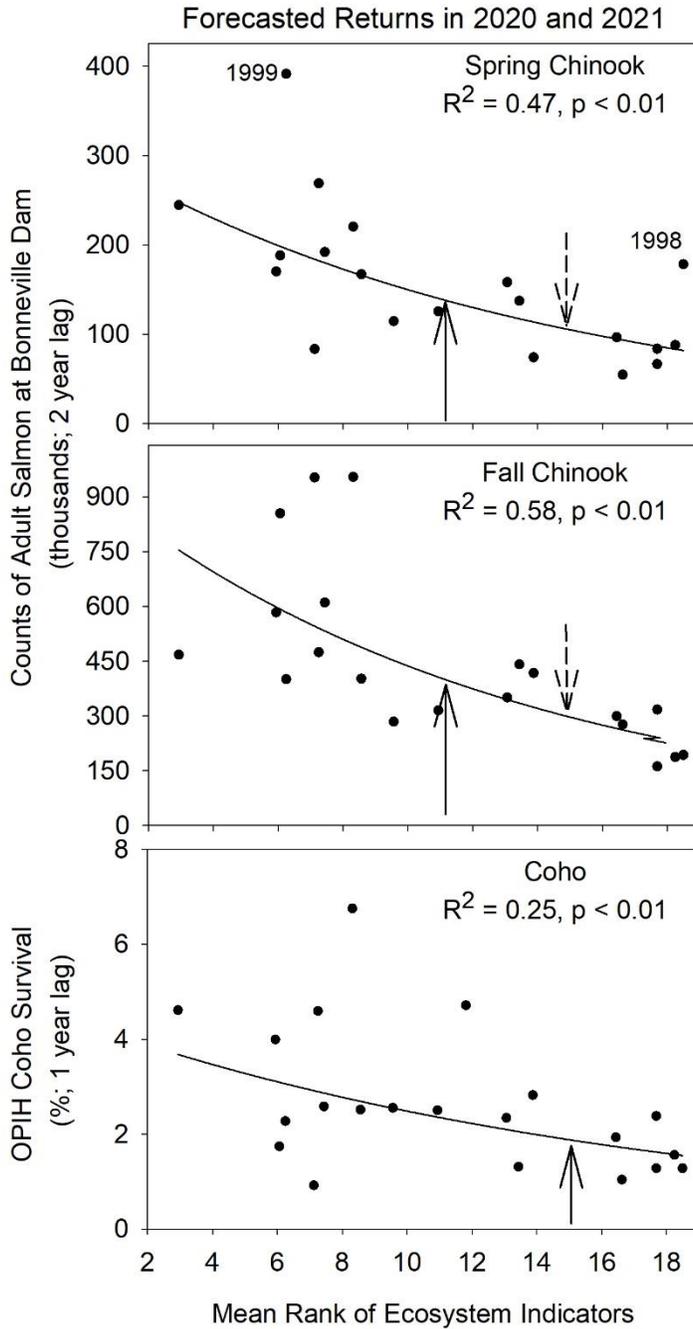


Figure SF-01. Salmon returns versus the mean rank of ecosystem indicators. Arrows show the forecasted returns for Chinook salmon in 2020 (solid line) and 2021 (dashed line). The mean rank of the ocean ecosystem indicators in 2018 was 11.8 forecasting a return of 131,000 and 379,000 adult spring and fall Chinook salmon to the Bonneville Dam respectively in 2020 (top two panels). The mean rank of the ocean ecosystem indicators in 2019 was 15.1 forecasting lower adult returns in 2021 of 104,000 and 294,000 spring and fall Chinook salmon respectively (top two panels- dashed lines). Using the rank of the ecosystem indicators of 15.1 from 2019, the forecast of the smolt to adult survival of coho salmon to Oregon coastal streams is 1.9 percent in 2020..

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 54% of the ecosystem variability among years while the second principal component explains only 14%. 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.

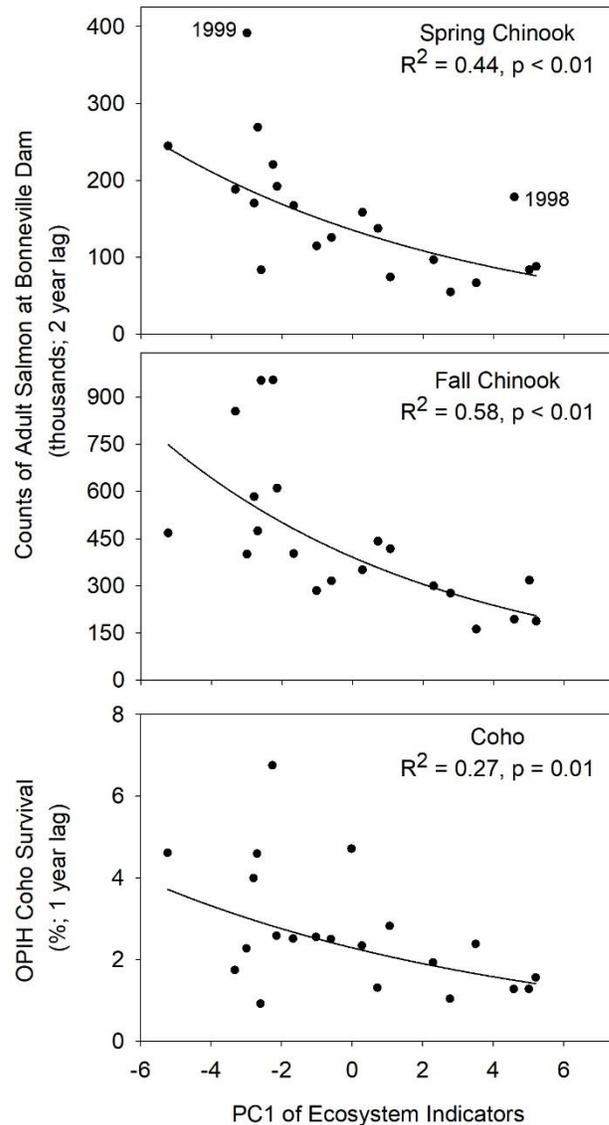
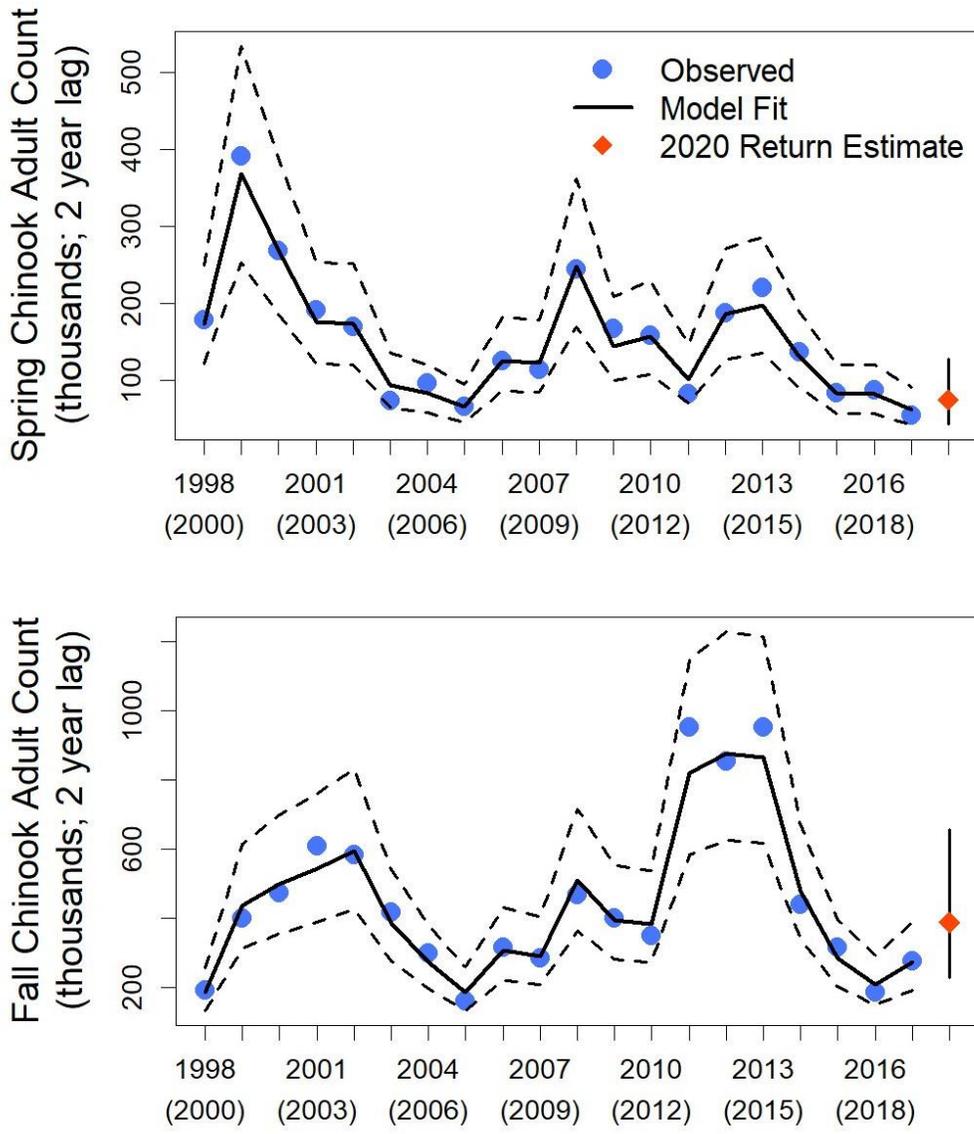


Figure SF-02. Salmon returns versus the first principal axis scores (PC1) from a Principal Component Analysis on the environmental indicators from [Table SF-02](#).

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 & Williams 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. In all models, we allowed the coefficients for siblings and PC1 to vary, but kept a constant model intercept.

The best model for both spring and fall Chinook salmon showed support for a dynamic effect of jack counts, but not of PC1. For coho salmon, there was no support for any parameter to vary, resulting in a simple linear regression model (of logit-transformed SAR).



[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 the model fit and lighter lines represent 95% confidence intervals. Forecasts were created from a DLM (Dynamic Linear Models) with log of sibling counts (for the Chinook models only) and PC1 as predictor variables.

We are working towards stock-specific salmon return outlooks 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 outlooks 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 2019, we have up to 22 years of indicator data but only 19 - 21 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 2019b](#)).

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 Entry ¹				
Year	OPIH Coho (adults:smolts)	Bonneville spring Chinook (n)	Bonneville fall Chinook (n)	Klamath River fall Chinook (n est.)
1998	18	7	18	8
1999	13	1	11	3
2000	4	2	6	5
2001	7	5	4	2
2002	5	8	5	13
2003	6	18	9	16
2004	14	14	15	17
2005	11	19	20	7
2006	10	12	14	15
2007	8	13	16	10
2008	3	3	7	12
2009	9	9	10	9
2010	12	10	12	1
2011	21	17	2	4
2012	15	6	3	6
2013	1	4	1	14
2014	17	11	8	19
2015	18	16	13	18
2016	16	15	19	11 ²
2017	20	20	17	—
2018	2 ²	—	—	—

¹Counts of spring and fall Chinook salmon are lagged by 2 years and return ratios 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 22 years of ocean ecosystem indicator data, we have only 20–21 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	583,332	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	161,256	132,131
2006	0.0250	125,543	314,995	70,554
2007	0.0255	114,525	283,691	100,644
2008	0.0461	244,385	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	0.0174	188,078	854,503	160,396
2013	0.0675	220,250	954,140	77,821
2014	0.0131	137,176	440,945	24,582
2015	0.0128	83,616	316,833	33,232
2016	0.0156	87,890	186,862	92,293 ²
2017	0.0104	54,656	275,632	—
2018	0.0471 ²	—	—	—

¹ Counts of spring and fall Chinook salmon are lagged by 2 years and 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 2019b). 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 on the continental shelf (station NH-05) and slope (station NH-25) off Newport, Oregon (Figure TSP-01).

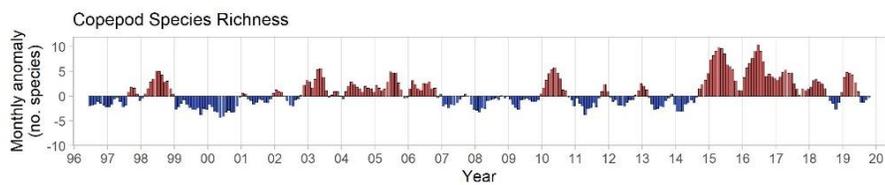
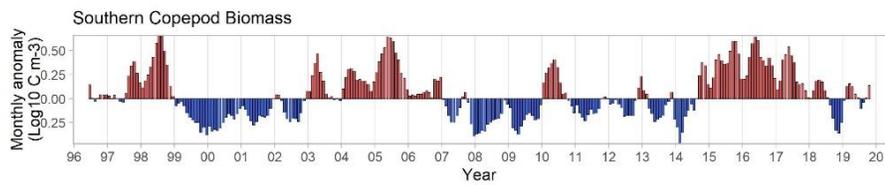
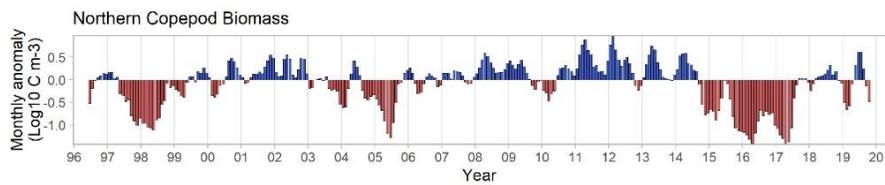
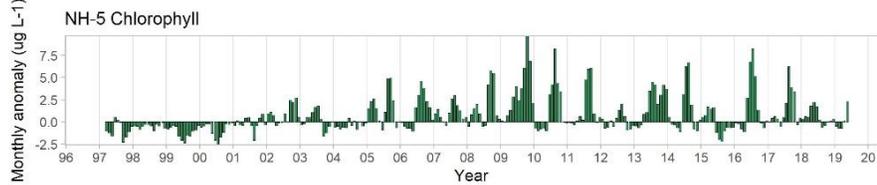
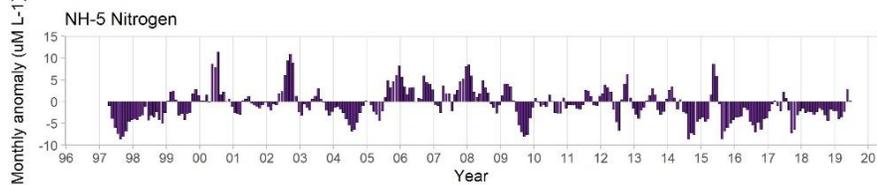
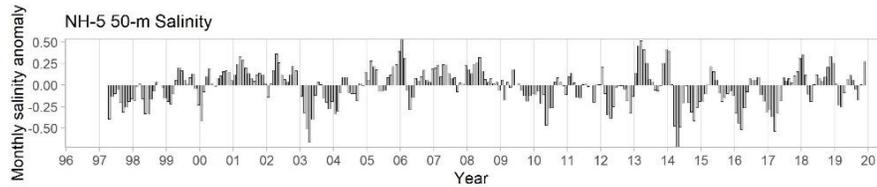
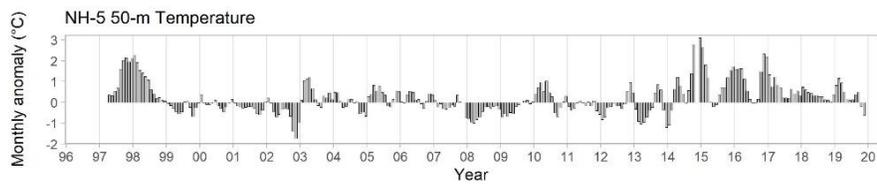
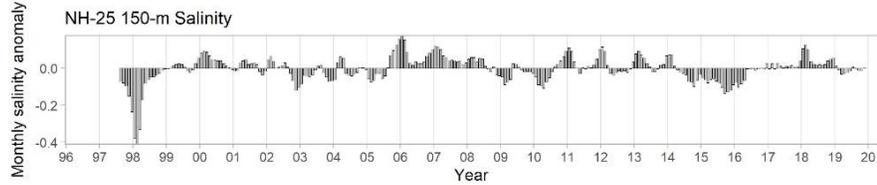
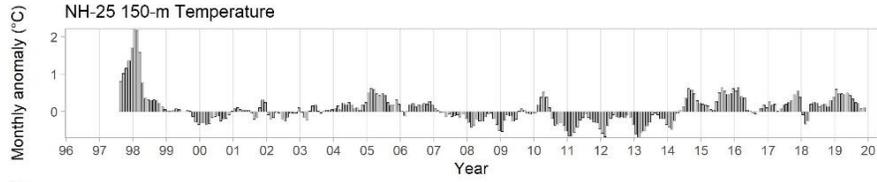
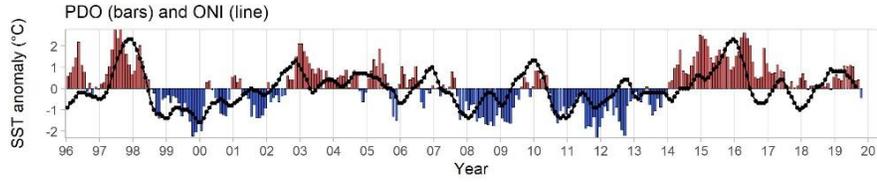


Figure TSP-01. Time series plots of large-scale atmospheric forcing and local physical and biological indicators from 1997 - present. All local indicators were smoothed with a 3-month running mean to remove high frequency variability.

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.

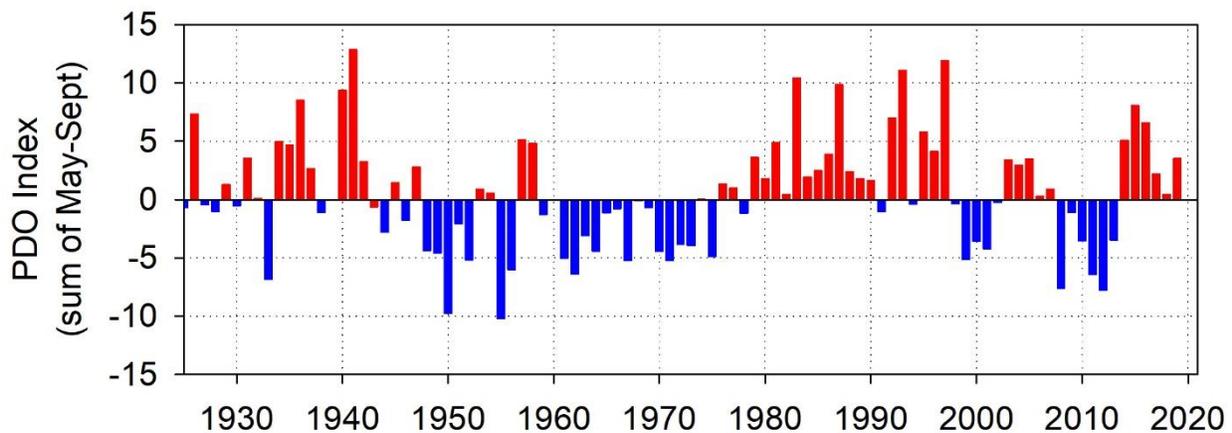


Figure PDO-01. Time series of shifts in sign of the Pacific Decadal Oscillation (PDO), 1925 to present. Values are summed over the months of May through September. Red bars indicate positive (warm) years; blue bars negative (cool) years. Note that 2008 and 2012 were the most negative values recorded 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). In 2014, the PDO switched phase again and remained strongly positive until more neutral conditions in 2018.

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.

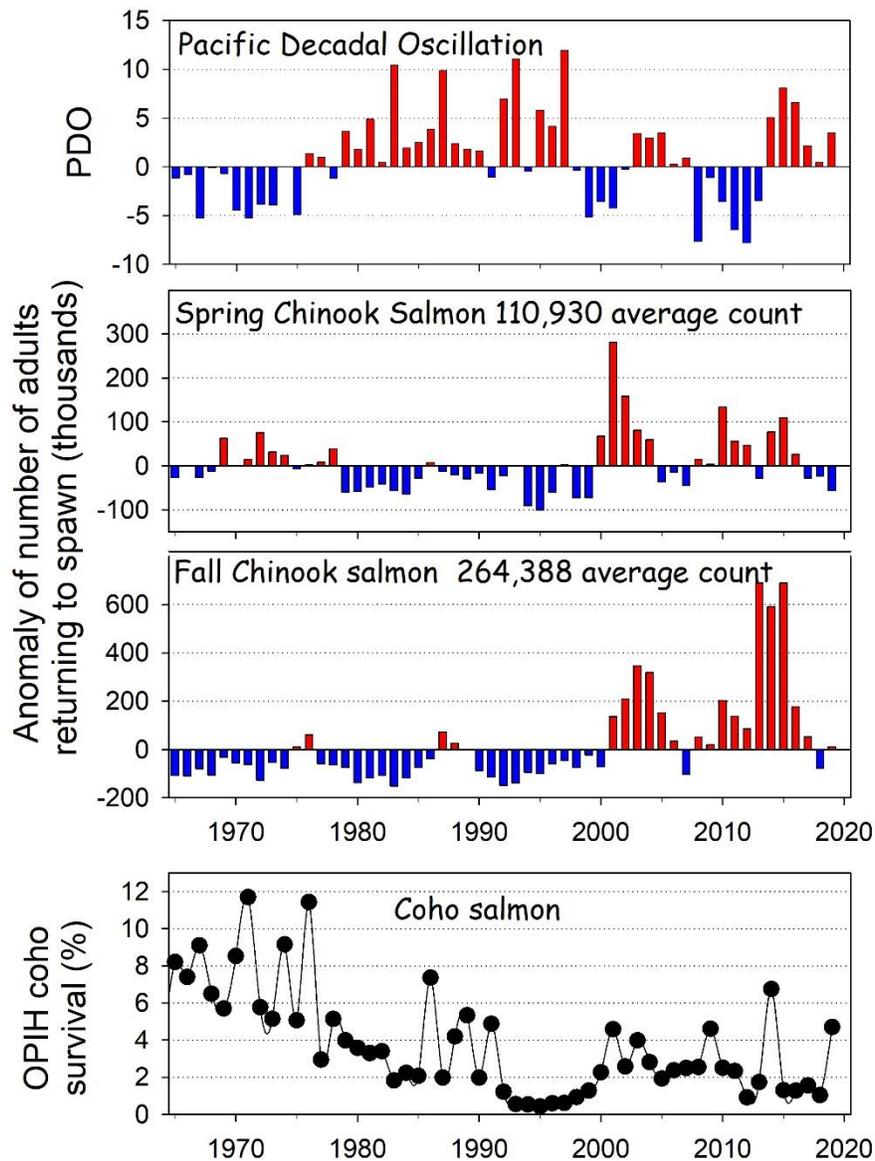


Figure PDO-02. Figure PDO-02. Upper panel shows summer PDO (sum of May-Sept), 1965-present; middle panels show anomalies in counts of adult spring and fall Chinook salmon passing Bonneville Dam from 1965-present; lower panel shows survival of hatchery coho salmon from 1965-present.

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, 1960, 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. Returns of both spring and fall Chinook declined from 2017 to present, likely from poor ocean conditions associated with the marine heatwave that affected feeding conditions for outmigrating juveniles in 2015 onward.

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.

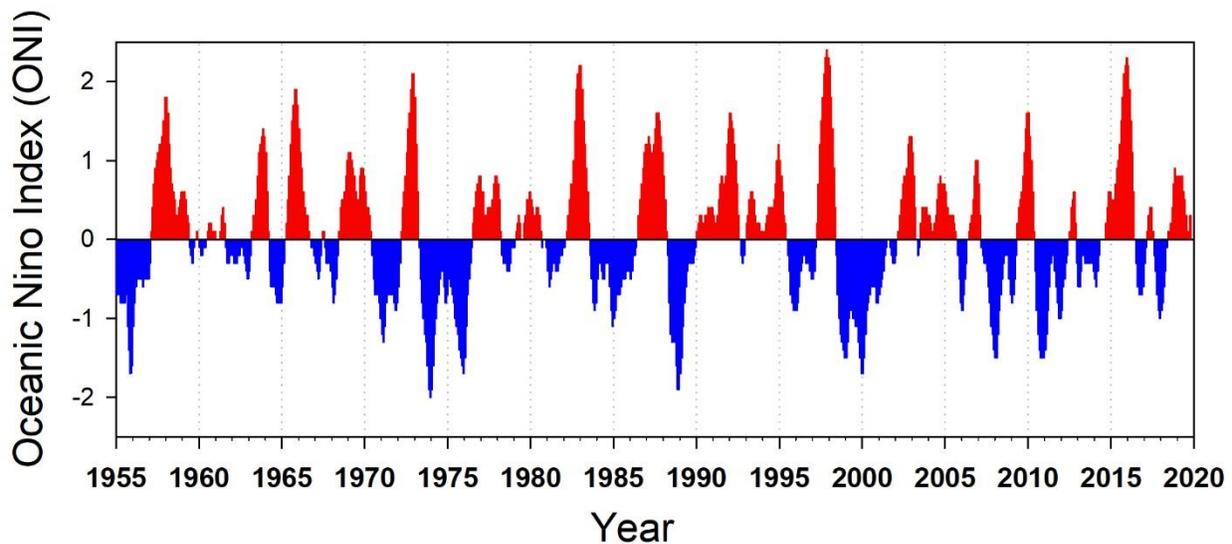


Figure ONI-01. Values of the ONI, 1955 - present. Red bars indicate warm conditions in the equatorial Pacific, blue bars indicate cool conditions in equatorial waters. Large and prolonged El Niño events are indicated by large, positive values of the index: note the $> +2$ value associated with the 1972, 1983, 1998, and recent strong even in 2015-2016. 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.

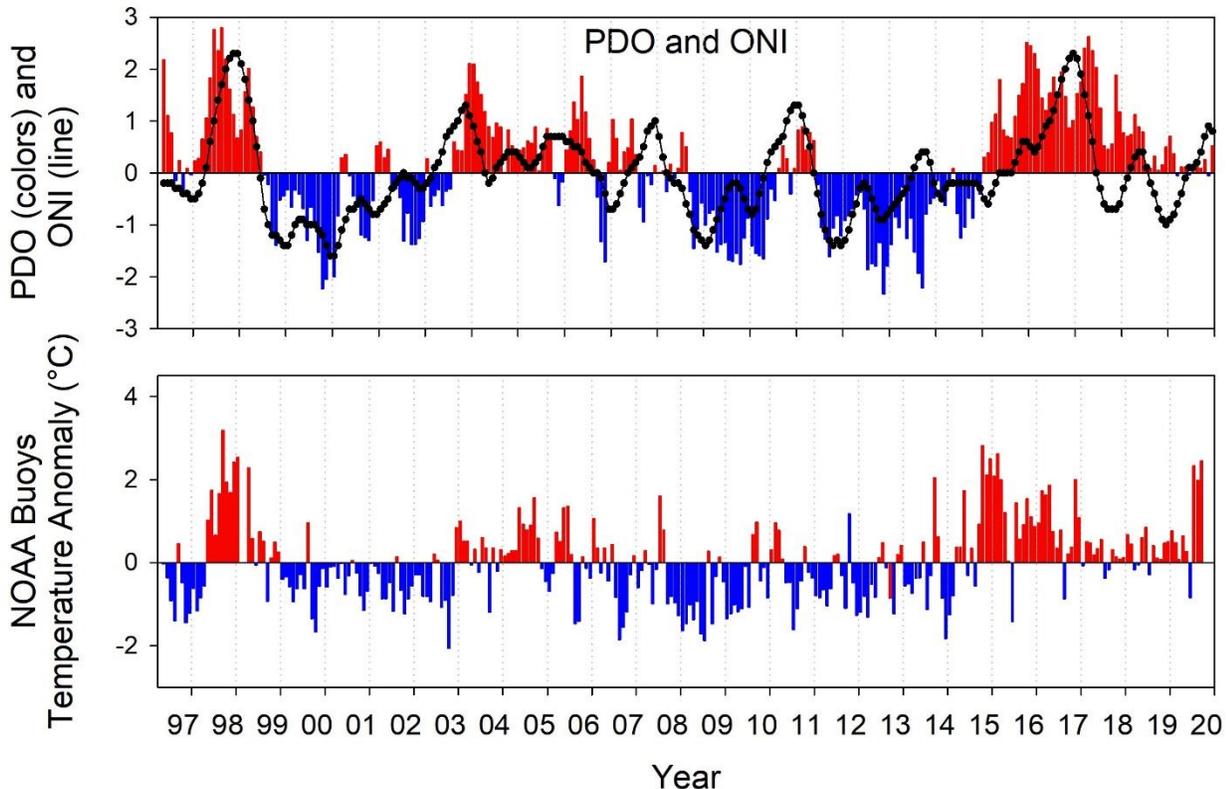


Figure TA-01. The PDO (upper panel, colored bars), ONI (upper panel, line) and monthly sea surface temperature (SST) anomalies calculated using an average of seven NOAA NDBC buoys (46229, 46211, 46041, 46029, 46050, 46097, 46098) located off coastal Oregon and Washington (bottom panel).

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 coastal Oregon and Washington. 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 remained high, higher than the strong El Niño event in 1998, until 2017. This most recent increase in SST anomalies was associated with the anomalously warm water dubbed the warm “Blob”, which had persisted in the NE Pacific since the end of 2013. During 2017 and 2018, SST anomalies fluctuated from moderately negative to moderately positive, signaling more neutral ocean conditions.

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.

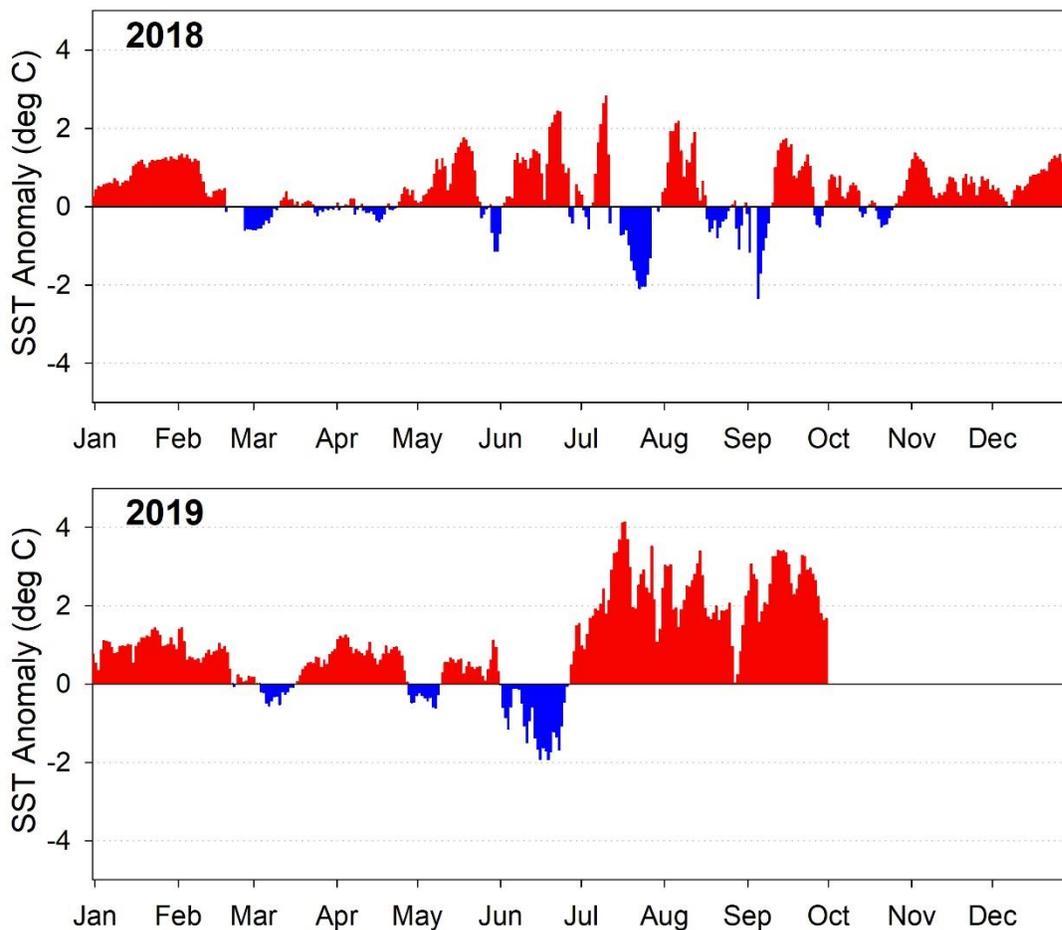


Figure TA-02. Daily sea surface temperature anomalies measured at seven NOAA Buoys located off coastal Oregon and Washington.

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.

[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.

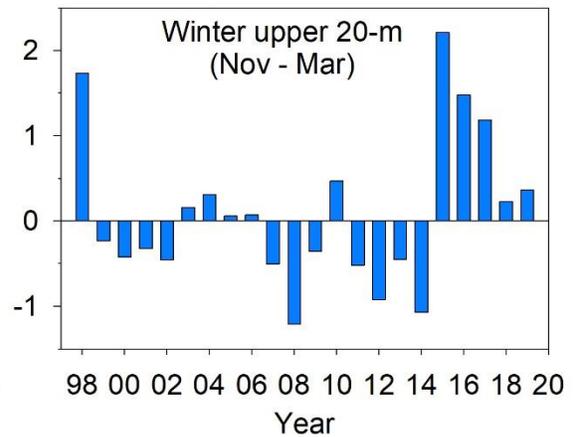
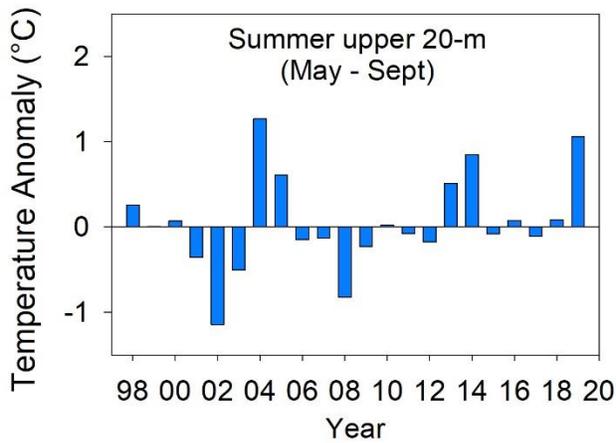
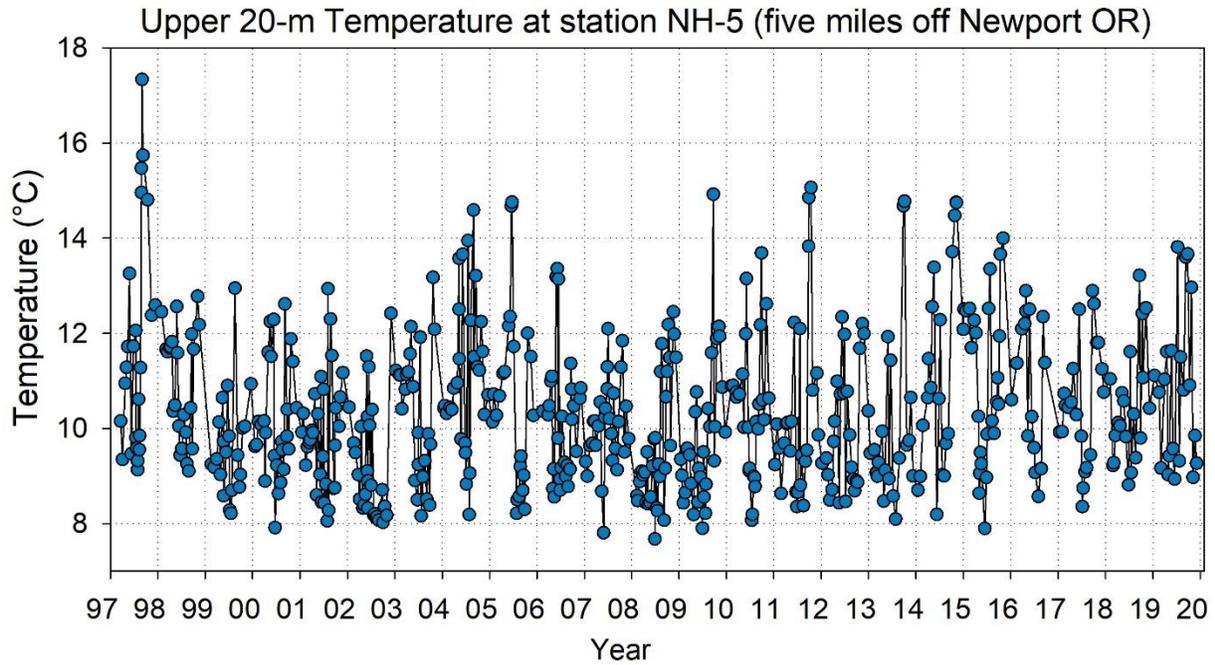


Figure TA-03. Upper panel shows the average temperature in the upper 20 m of the water column at Station NH-5 (located 5 miles off Newport, Oregon) since 1996. The lower panels depict the upper 20 m temperature anomalies over the same years during summer (left; May–Sept) and winter (right; Nov – Mar).

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).

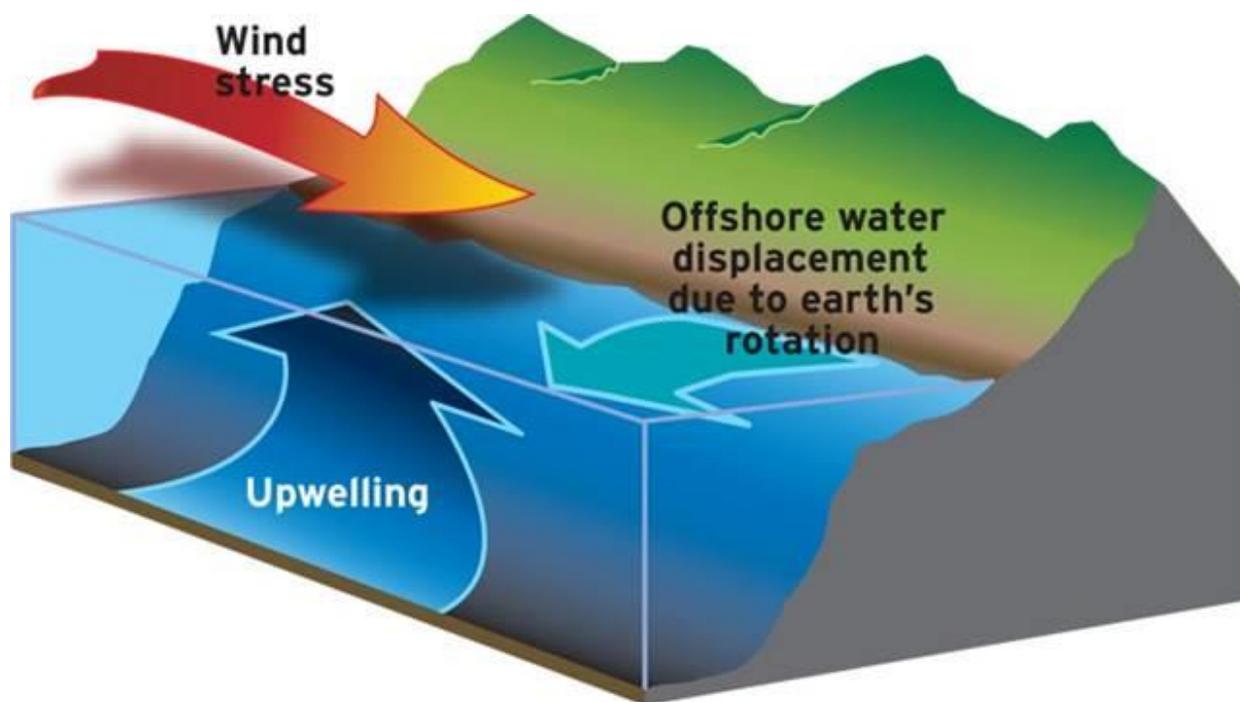


Figure CU-01. Forces affecting coastal upwelling.

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 windfields](#). 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.

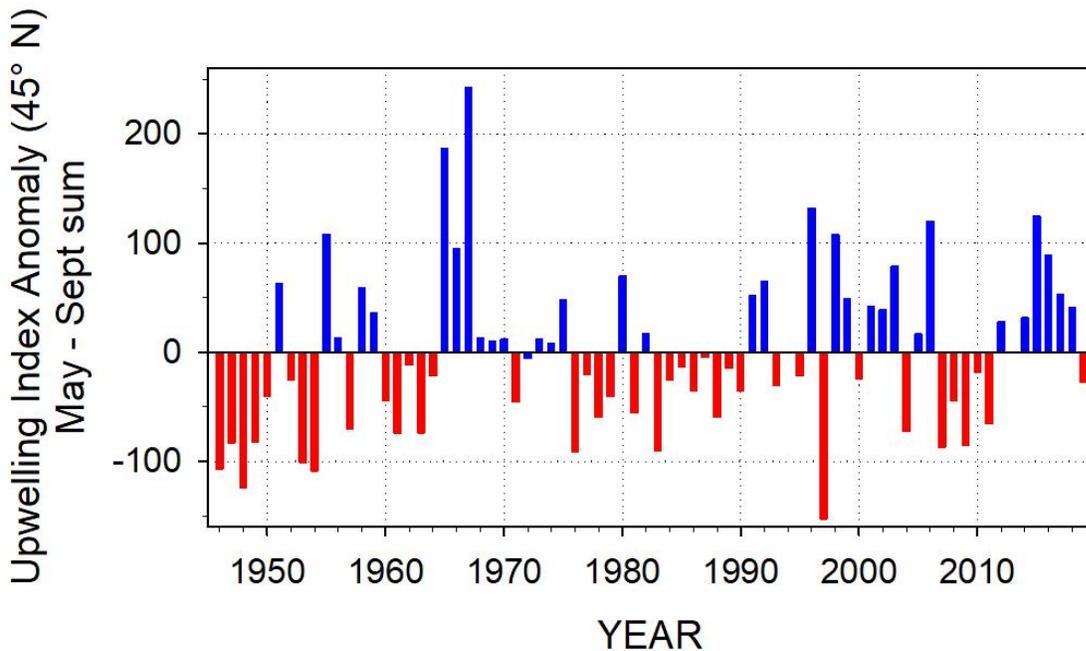


Figure CU-02. Anomalies of the coastal Upwelling Index during May to September each year, 1946 – present.

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](#). Although there was weak relationship between spring Chinook salmon returns and summed upwelling in April and May, this relationship has fallen apart during the recent warm years of 2015 and 2016.

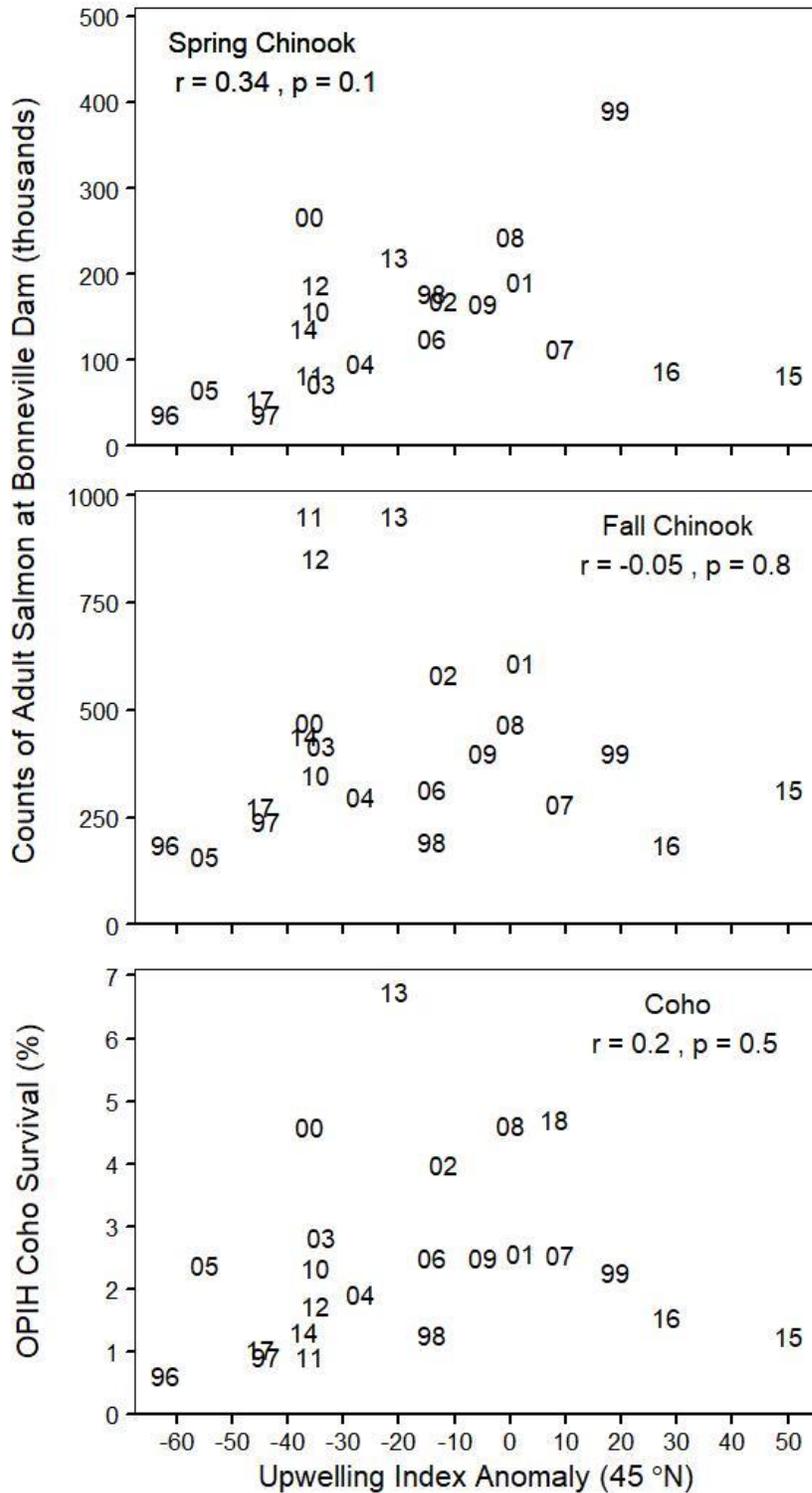


Figure CU-03. Relationship of spring and fall adult Chinook salmon returns (lag 2 years) to the Bonneville dam (top two panels) and coho salmon survival (OPIH, bottom panel, lag 1 year) with the April and May sum of upwelling at 45°N from 1996-present. Number symbols indicate the year of juvenile salmon outmigration.

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.

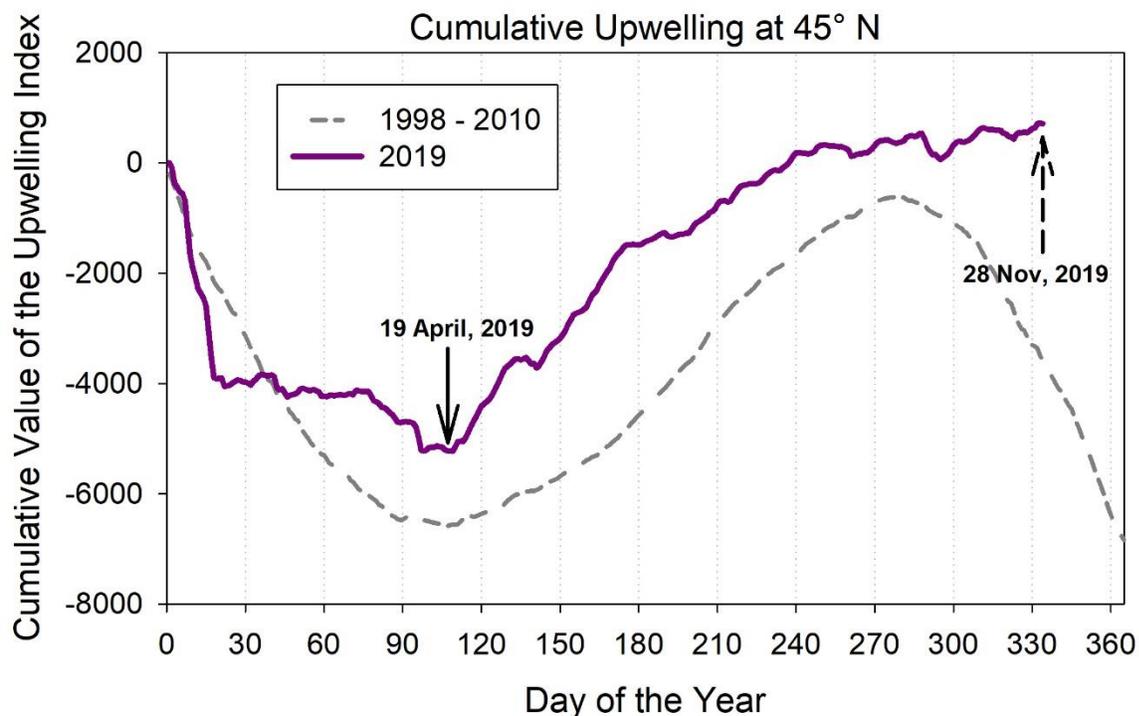


Figure CU-04. : Cumulative upwelling index. Vertical arrows indicate the date of physical spring transition (solid line) and fall transition (dashed line).

One can see in [Figure CU-04](#) that the winter downwelling period was close to the climatological mean. The onset of upwelling occurred on April 19, 2019, and was relatively strong at the beginning of the season but decreased mid-June and remained weaker than normal through the season. Weak upwelling favorable winds continued through November, which is rare, but also occurred in 2013.

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](#)).

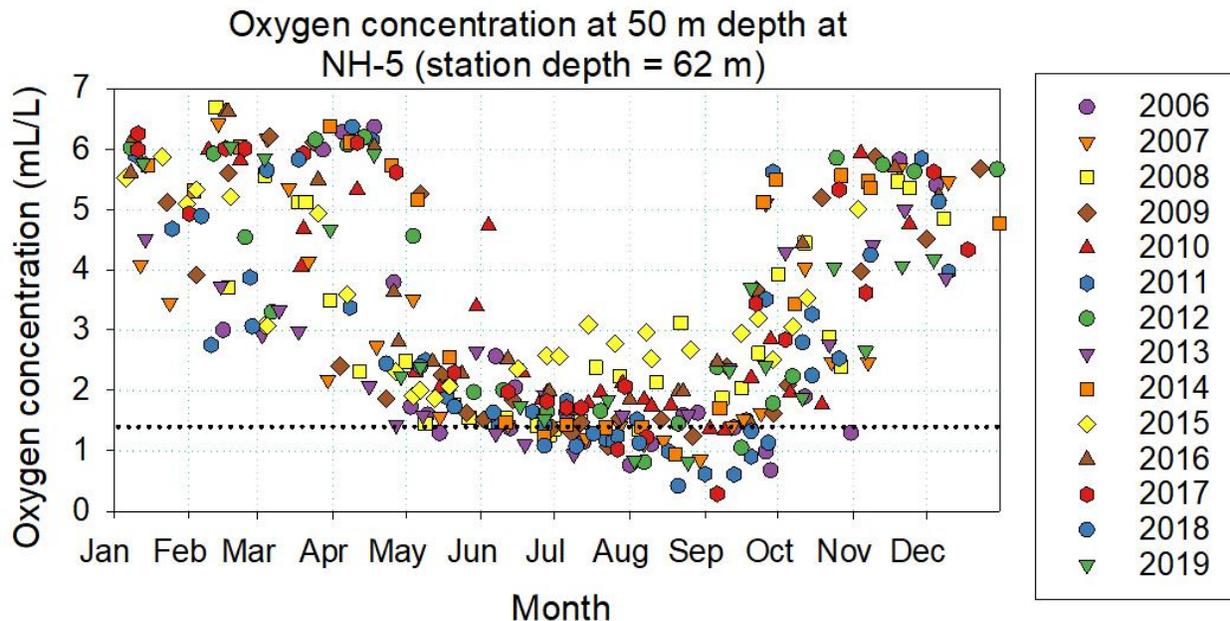


Figure HYP-01. Oxygen concentration in bottom waters at a baseline station [NH 05](#). Hypoxia is defined as waters with oxygen concentrations < 1.4 ml/L, and is observed only during the coastal upwelling season, especially during Jun-Sep.

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.

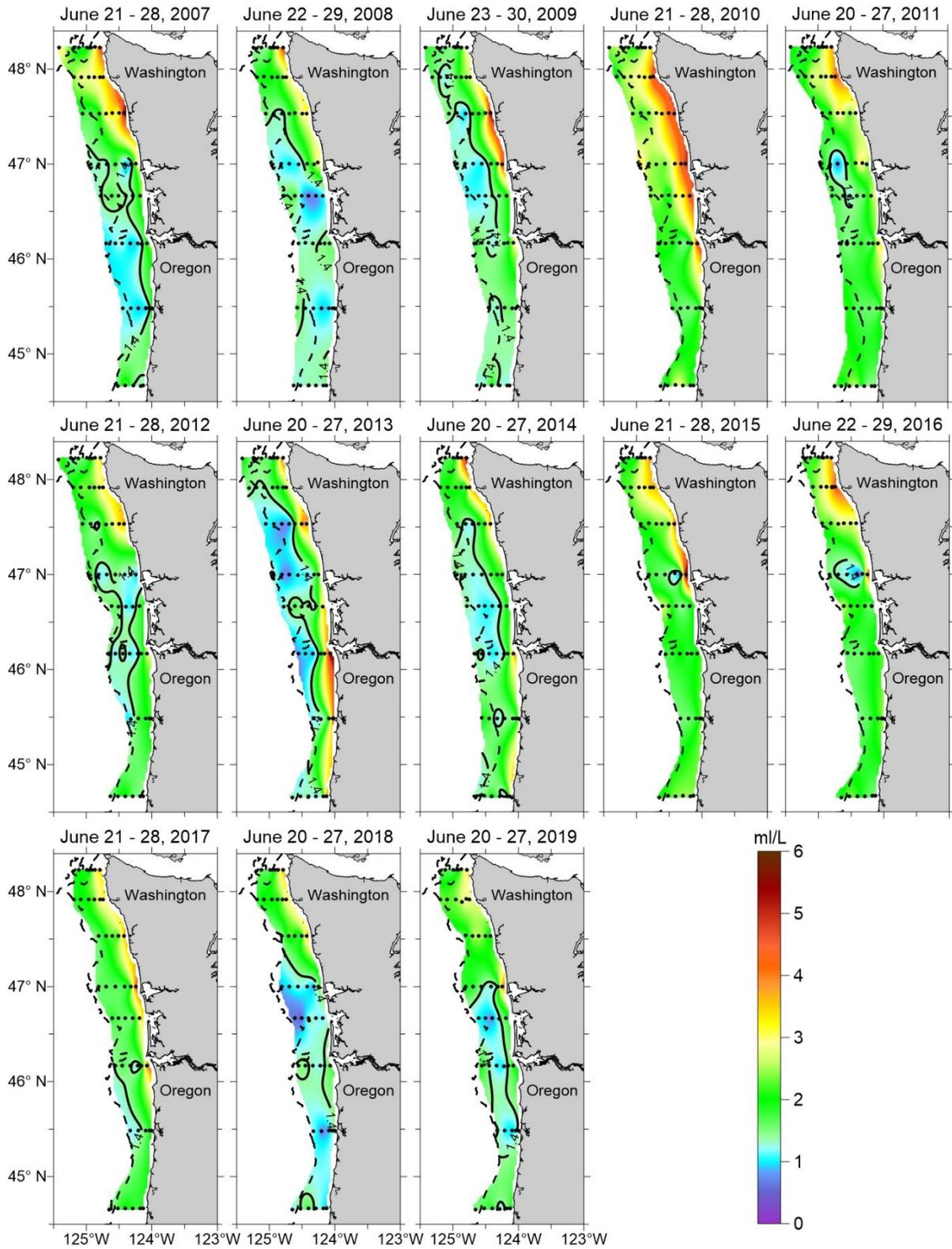


Figure HYP-02. Dissolved oxygen maps. Distribution of the minimum dissolved oxygen values (ml/L) during the June BPA surveys from 2007 - present. A level of 1.4 ml/L dissolved oxygen is used to identify hypoxic waters (outlined with bold contour line).

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).

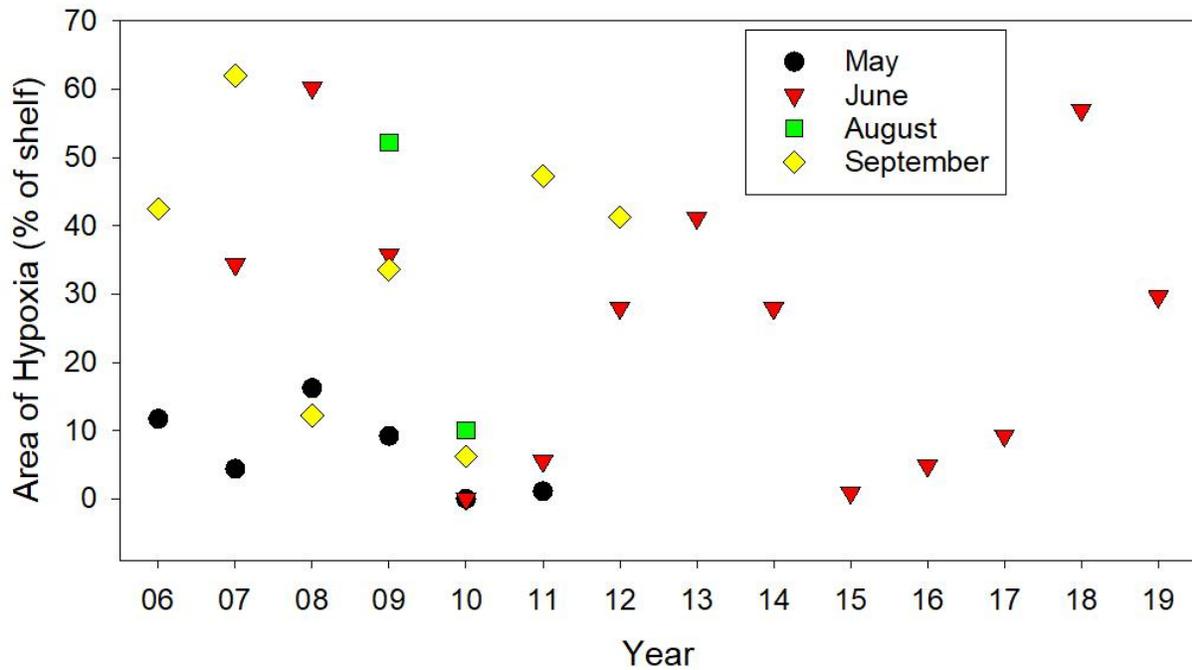


Figure HYP-03. The area of the shelf containing hypoxic bottom waters during the May, June, August and September surveys. The shelf area surveyed is 15,750 km². The shelf area and region of hypoxia were calculated from maps similar to those shown in Figure HYP-02.

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.

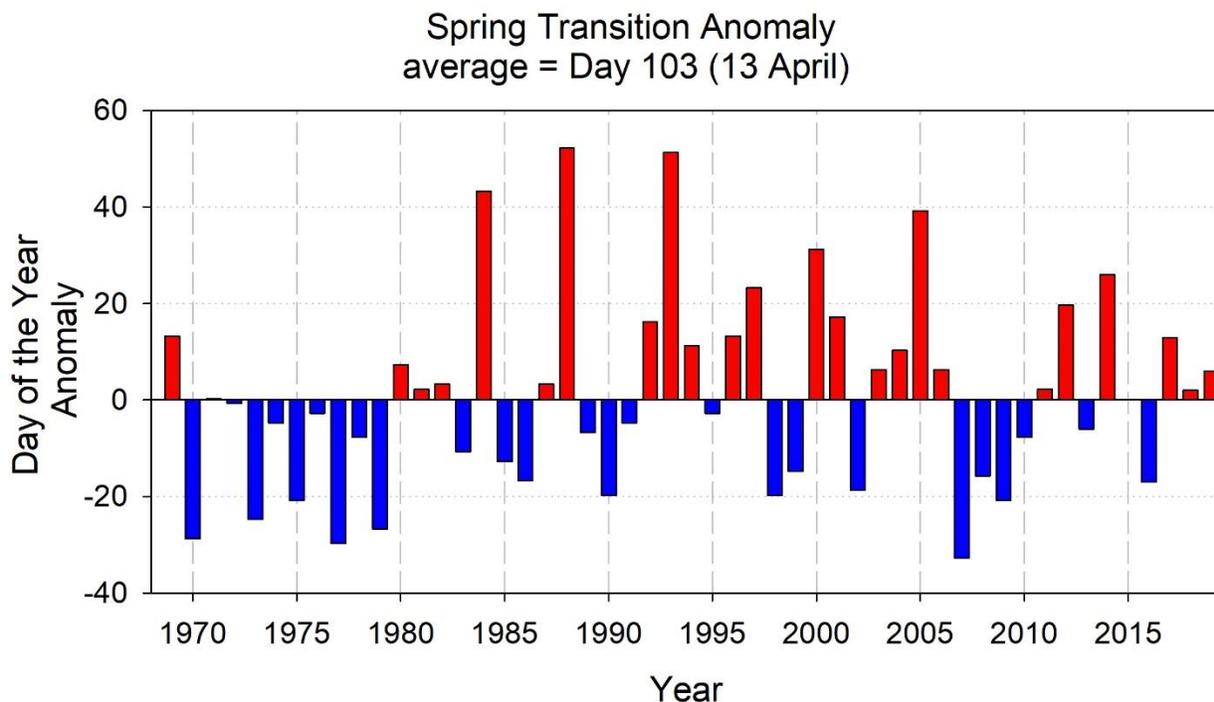


Figure PST-01. Anomalies in the date of the physical spring transition from 1969 to present. Anomaly is based on an average date of 13 April using the minimum cumulative upwelling index (CUI) climatology from 1969 – 2017.

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.

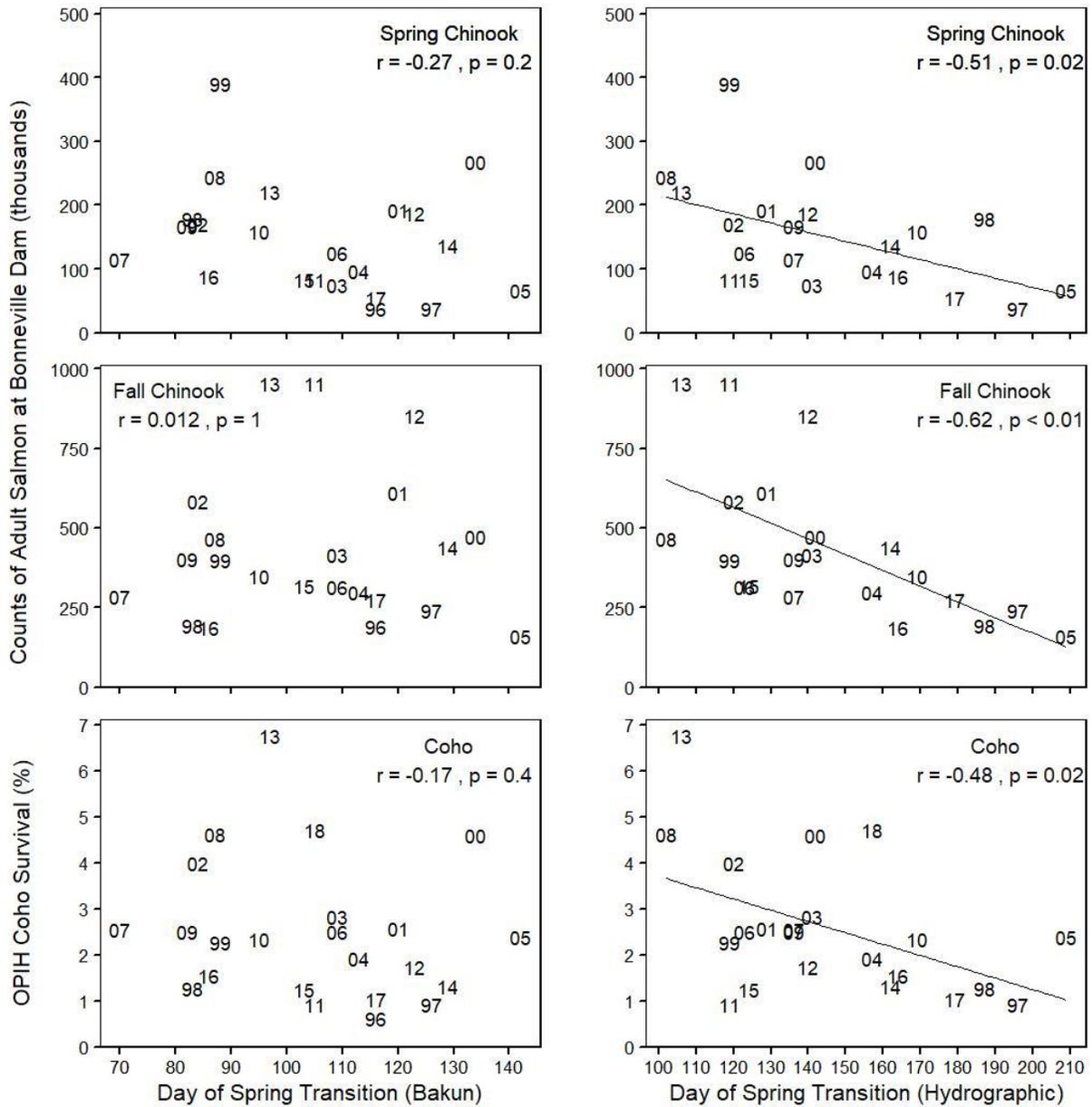


Figure PST-02. Plot showing the relationship between spring Chinook salmon adult returns at Bonneville dam (lag 2 years, top), fall Chinook salmon adult returns at Bonneville dam (lag 2 years, middle), and coho salmon survival (OPIH, lag 1 year, bottom) versus the date of spring transition using the Bakun upwelling method (left) and the hydrographic method (right). Number symbols indicate the year of juvenile salmon outmigration.

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](#) 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.

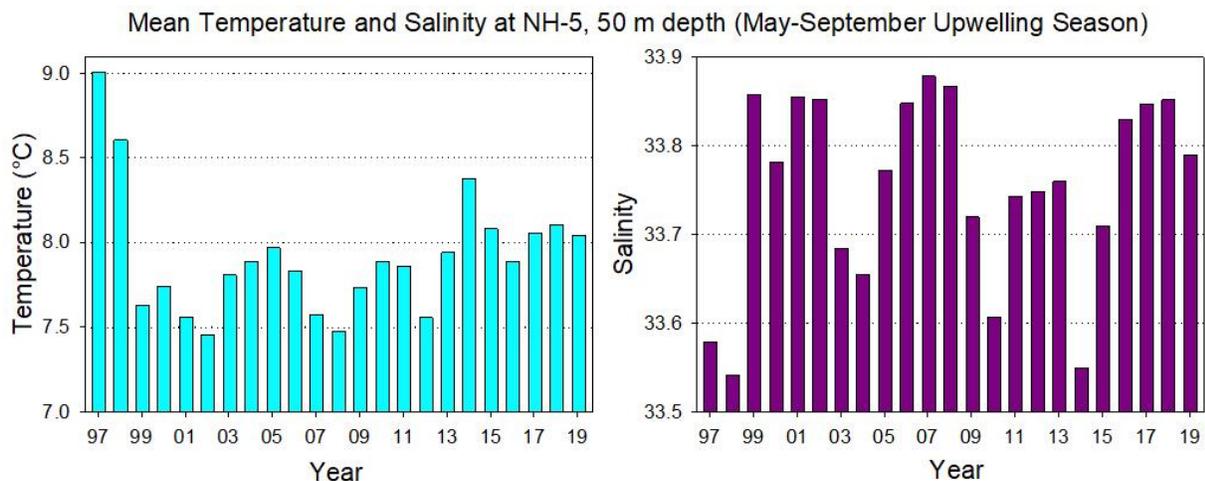


Figure DTS-01. Mean temperature (left panel) and salinity (right panel) at the 50–m depth at station NH-5 (average water depth 60 m) averaged over all cruises from May to September each year.

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.

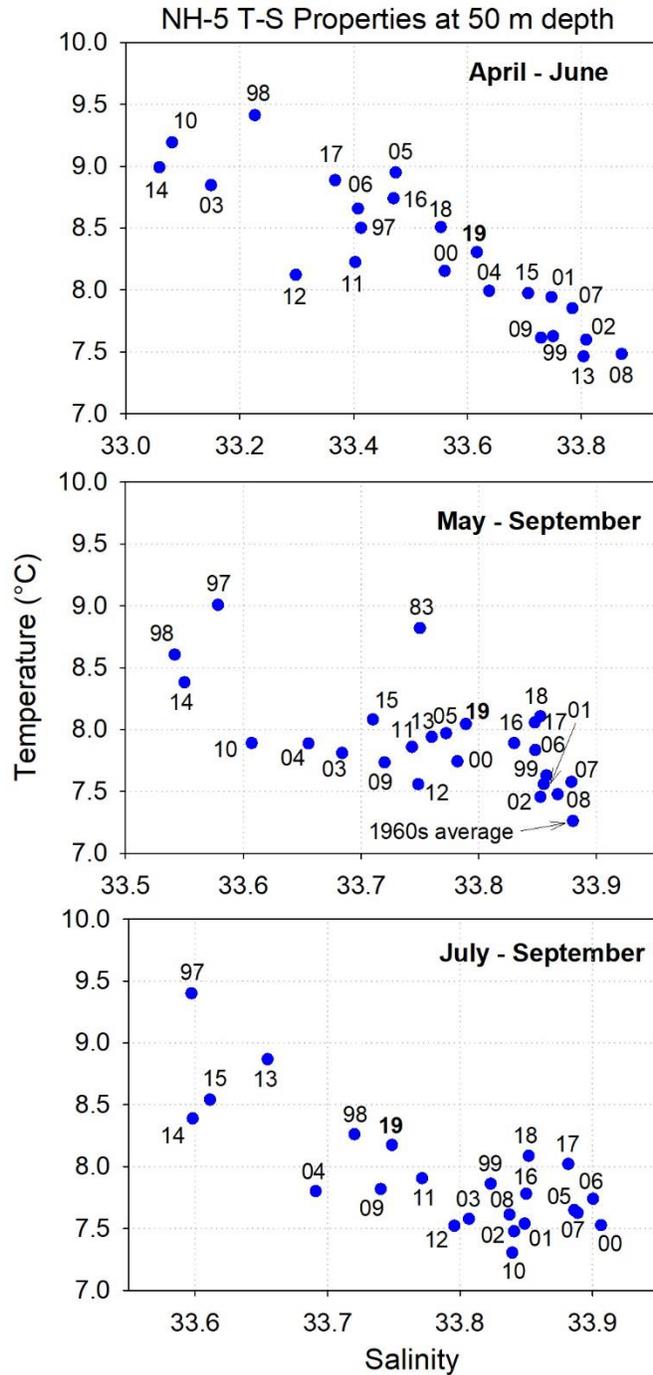


Figure DTS-02.

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.

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.

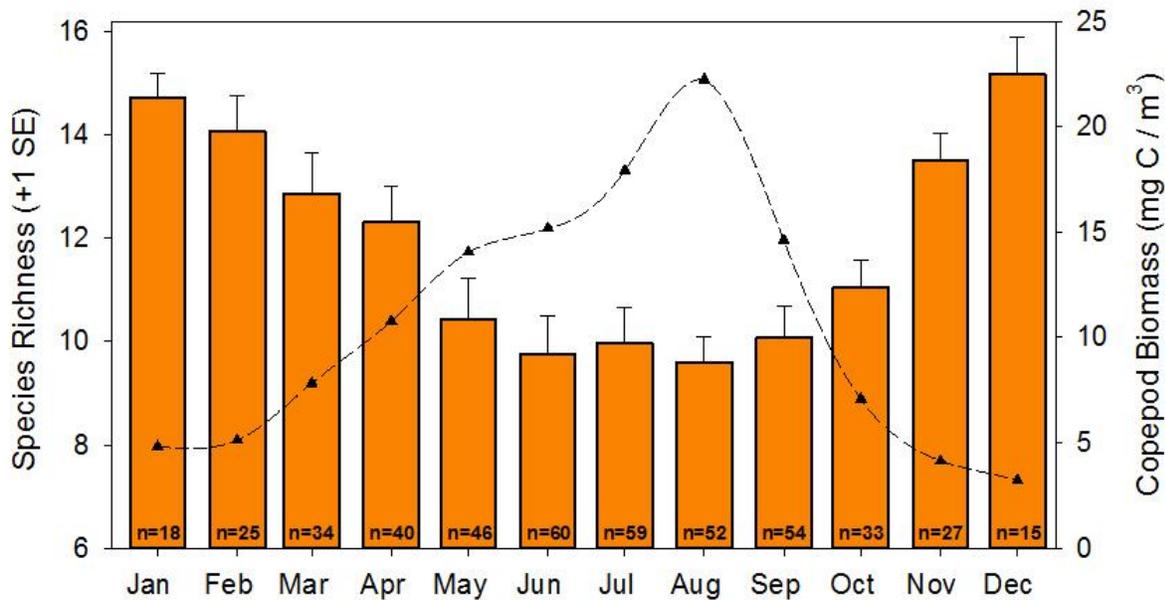


Figure CB-01. Vertical bars are the climatology of monthly averaged copepod species richness, a measure of biodiversity, at station NH-5 off Newport OR. Dashed line with filled triangles is the climatology of monthly averaged copepod biomass (Y-axis on right side of graph). Note the inverse relationship 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.

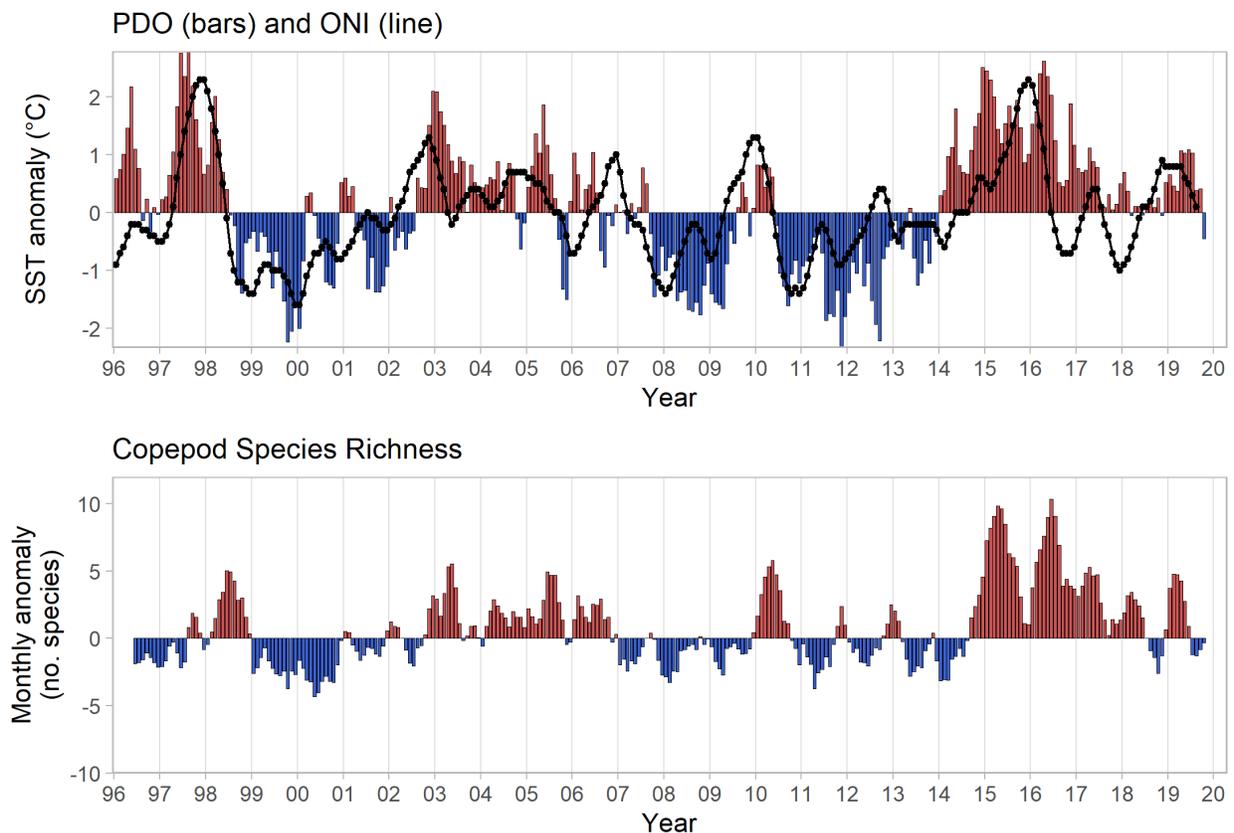


Figure CB-02. Upper panel shows time series of the PDO (bars) and ONI (line) during 1996-present. Lower panel shows anomalies in copepod species richness during the same period. Note that high species richness occurs during positive PDO years and the opposite during negative PDO years.

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 from the autumn of 2014 through 2016 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 ([Peterson et al. 2017](#)).

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.

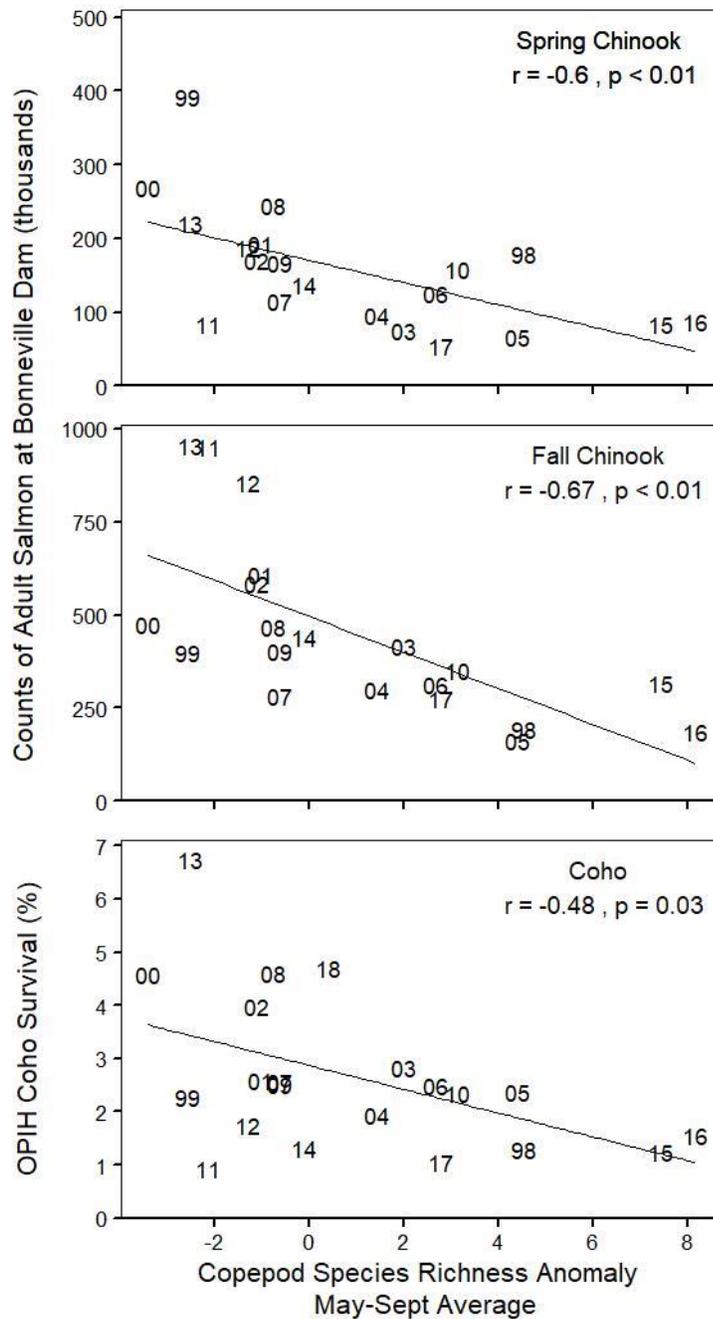


Figure CB-03. Relationship of spring and fall Chinook salmon adult returns to the Bonneville Dam, and coho salmon survival (OPIH) to the copepod species richness anomaly when these fish first enter the ocean 2 and 1 years prior (Chinook and coho salmon respectively) from 1998 - present. Number symbols indicate the year of juvenile salmon outmigration.

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](#)).

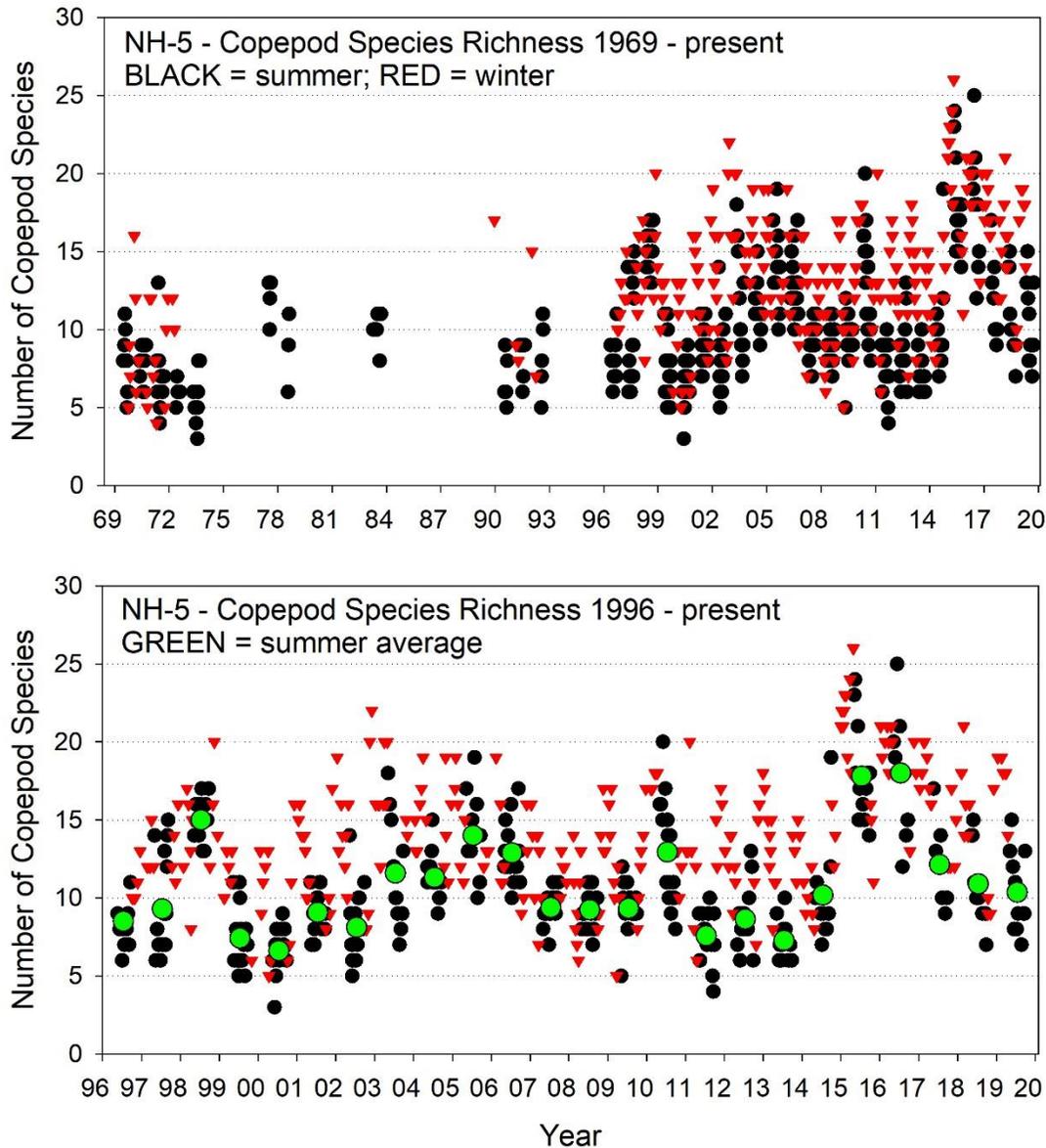


Figure CB-04. *Upper panel* shows time series of copepod species richness from 1969 to present. Note that the number of copepod species has been increasing over the past decade compared to the 1970s. Red triangles represent winter (Oct - April) and black circles represent summer (May - Sept). *Lower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

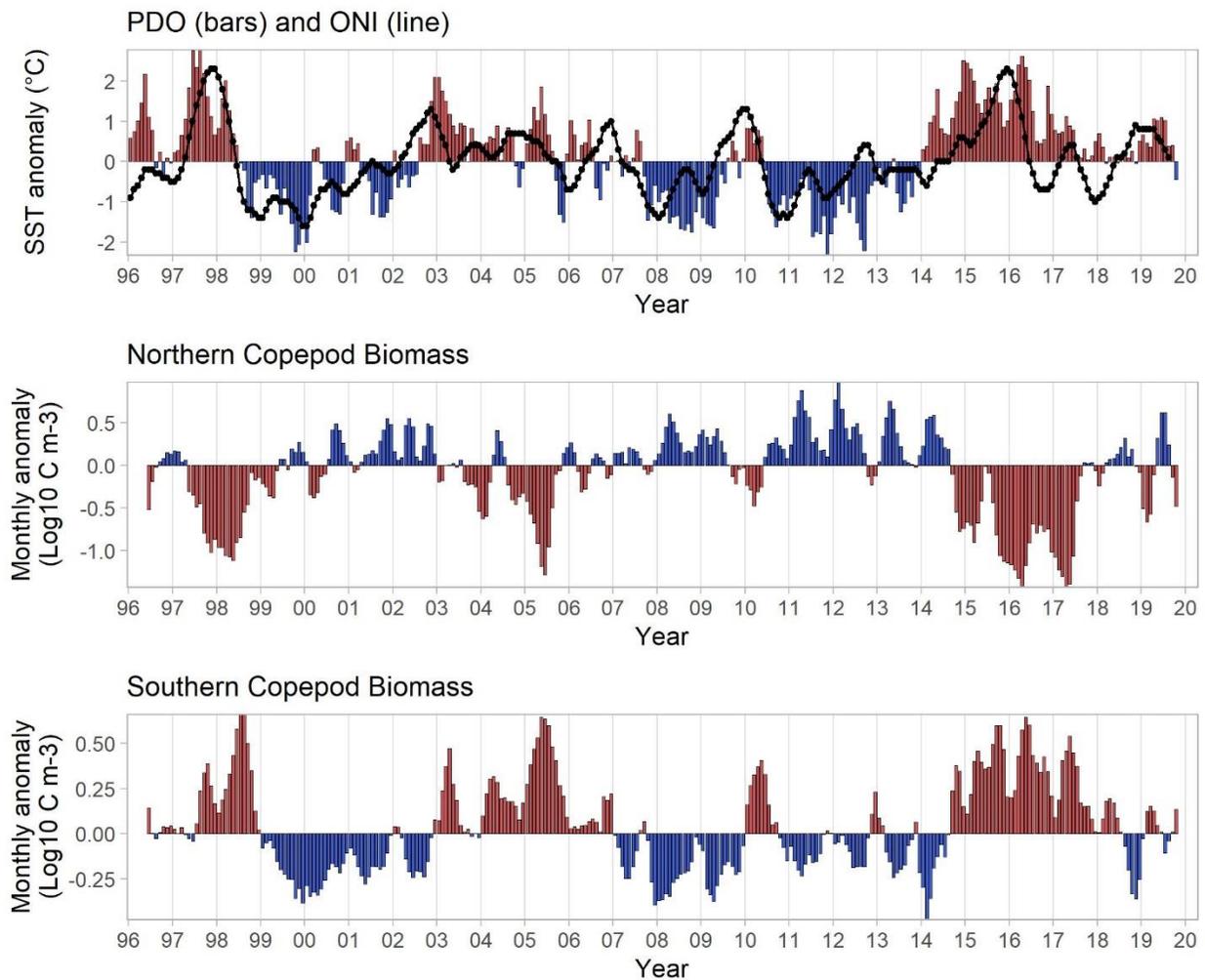


Figure NSC-01. The Pacific Decadal Oscillation (upper), and northern copepod biomass anomalies (lower), from 1969 to present. Biomass values are log base-10 in units of mg carbon m⁻³.

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 and the monthly biomass anomalies of northern and southern copepod species. 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 relationship between the PDO and the northern and southern copepod anomalies during the summer upwelling season (May – Sept). Data are from 1969 - 1973, 1983, and 1996 - present. Units of copepod biomass are Log10 mg carbon m⁻³. Strongly negative PDO values lead to high biomass of cold-water copepods and vice versa.

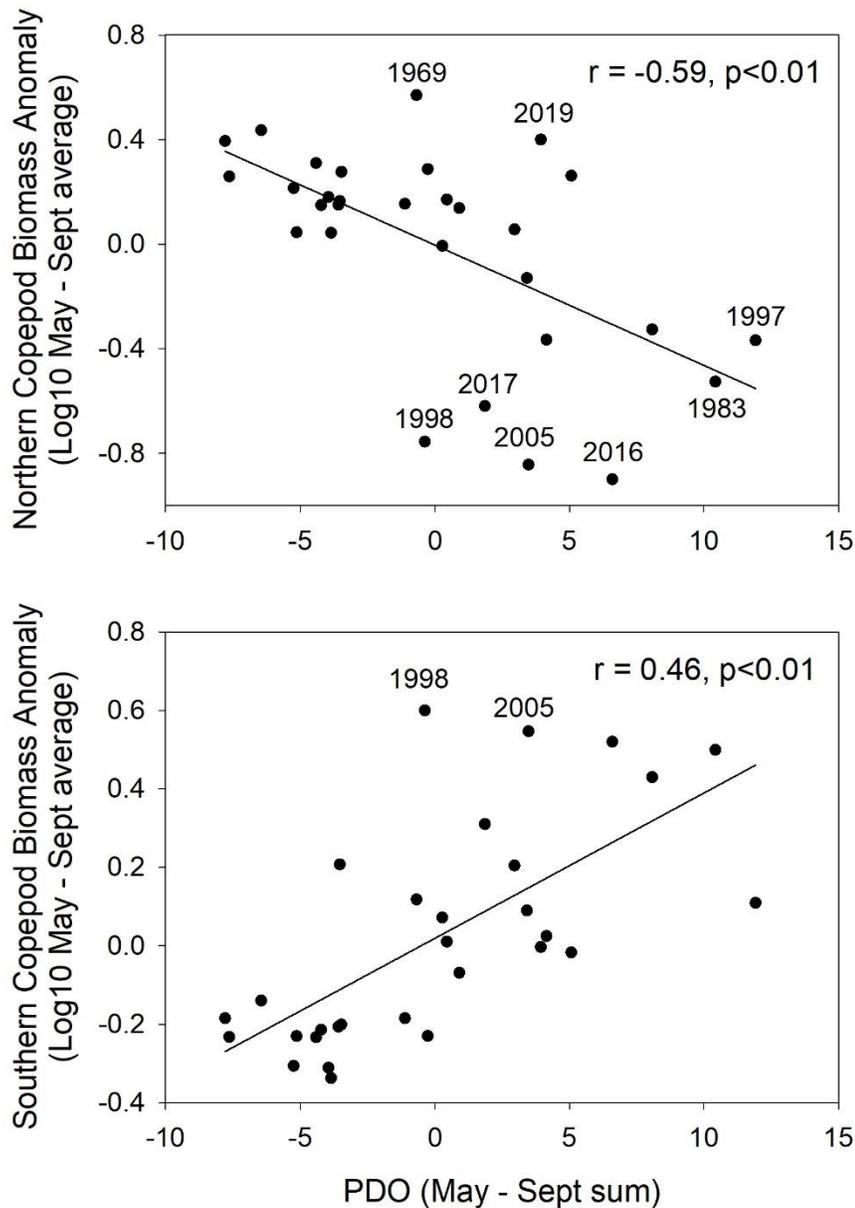


Figure NSC-02. Relationship of northern copepod anomalies and the PDO during the summer upwelling season (May - Sept). Data are from 1969 - 1973, 1983, and 1996 - present. Units of copepod biomass are $\text{Log}_{10} \text{ mg carbon m}^3$. Strongly negative PDO values lead to high biomass of cold-water 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. [Figure NSC-03](#) shows the relationship between the lipid rich northern copepods and salmon returns. Indeed, for all salmon species, there is a positive relationship between the biomass of lipid rich northern copepods and adult salmon returns.

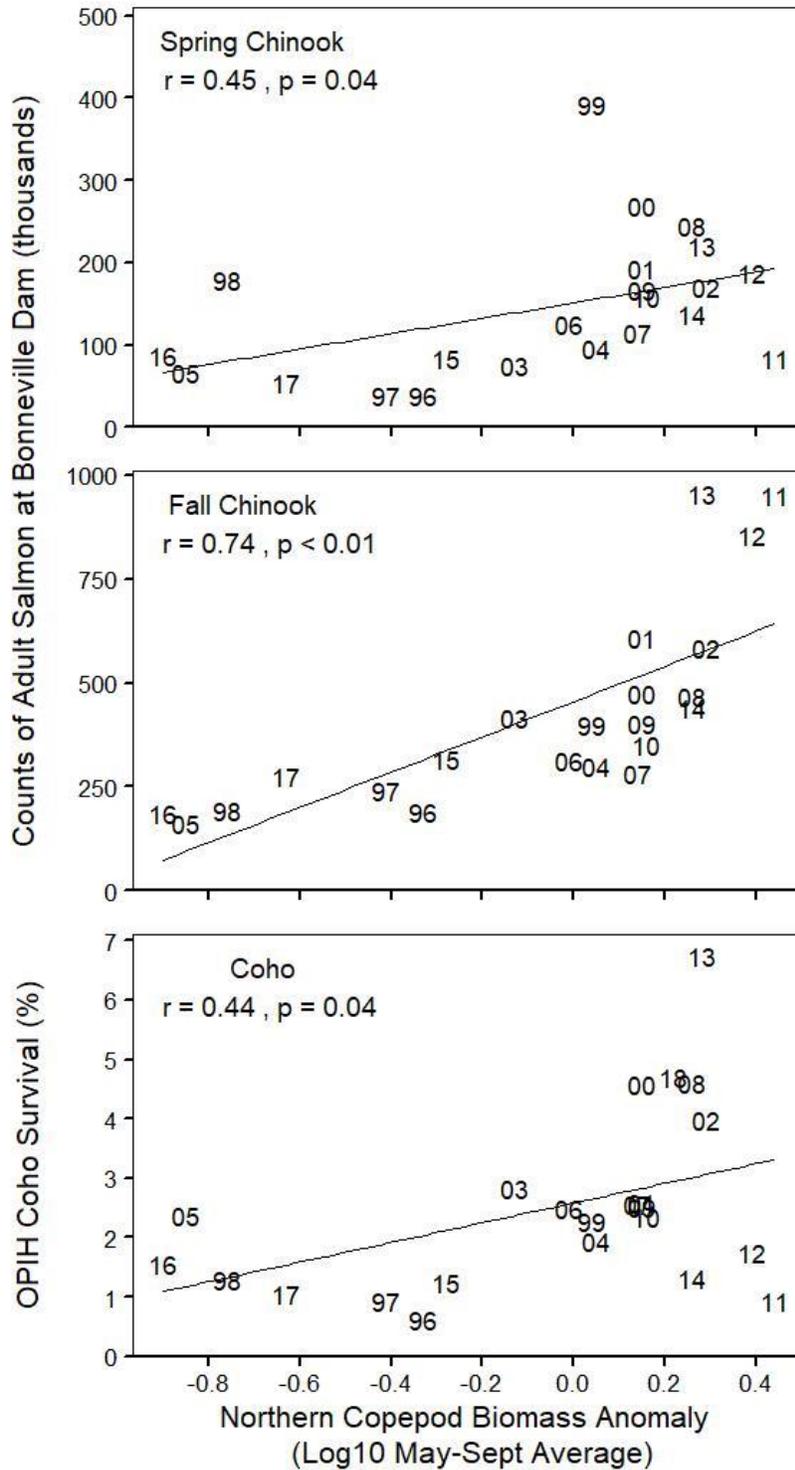


Figure NSC-03. Relationship between counts of adult spring Chinook (upper panel) and fall Chinook salmon (middle panel) at Bonneville Dam and coho salmon survival (OPIH, bottom panel) vs. the northern copepod biomass anomaly during the year of ocean entry. Counts at Bonneville are lagged by 2 years and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

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 salmonids.

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 75% and the Y-axis for 8%. CCI-01 compares these summer-average scores.

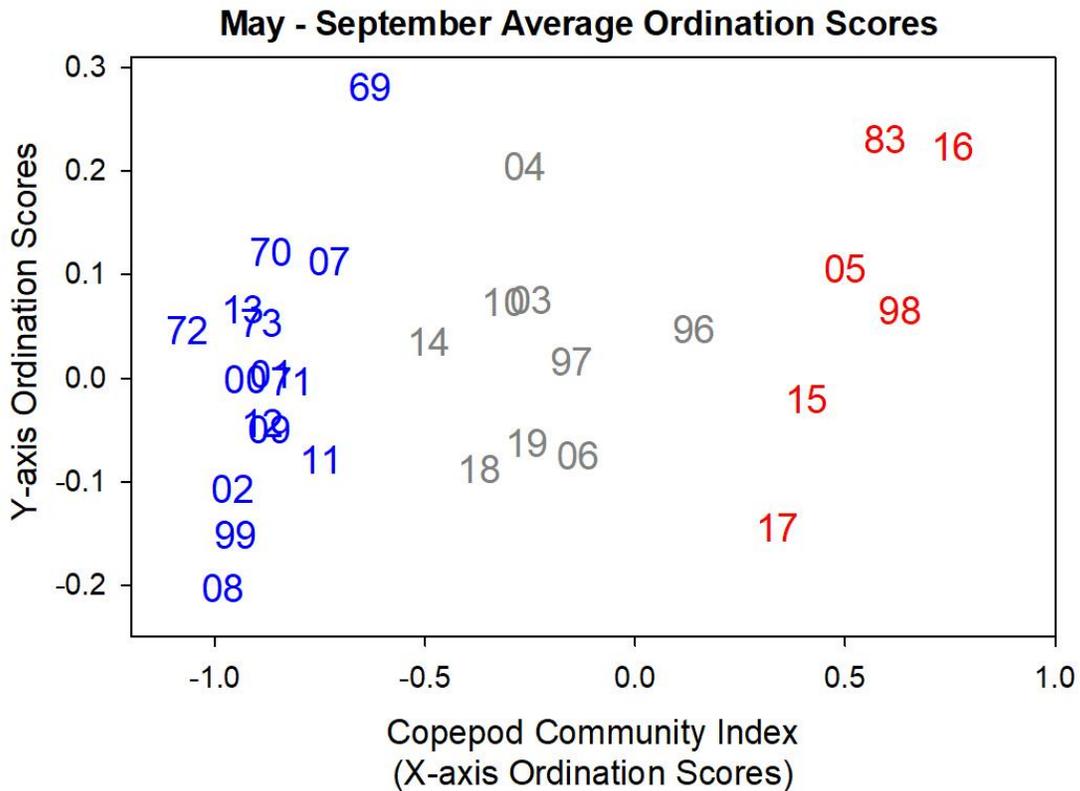


Figure CCI-01. Ordination of copepod community structure averaged over May-September, by year (symbols). Number symbols indicate the warm (red) neutral (gray) and cold (blue) years.

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).

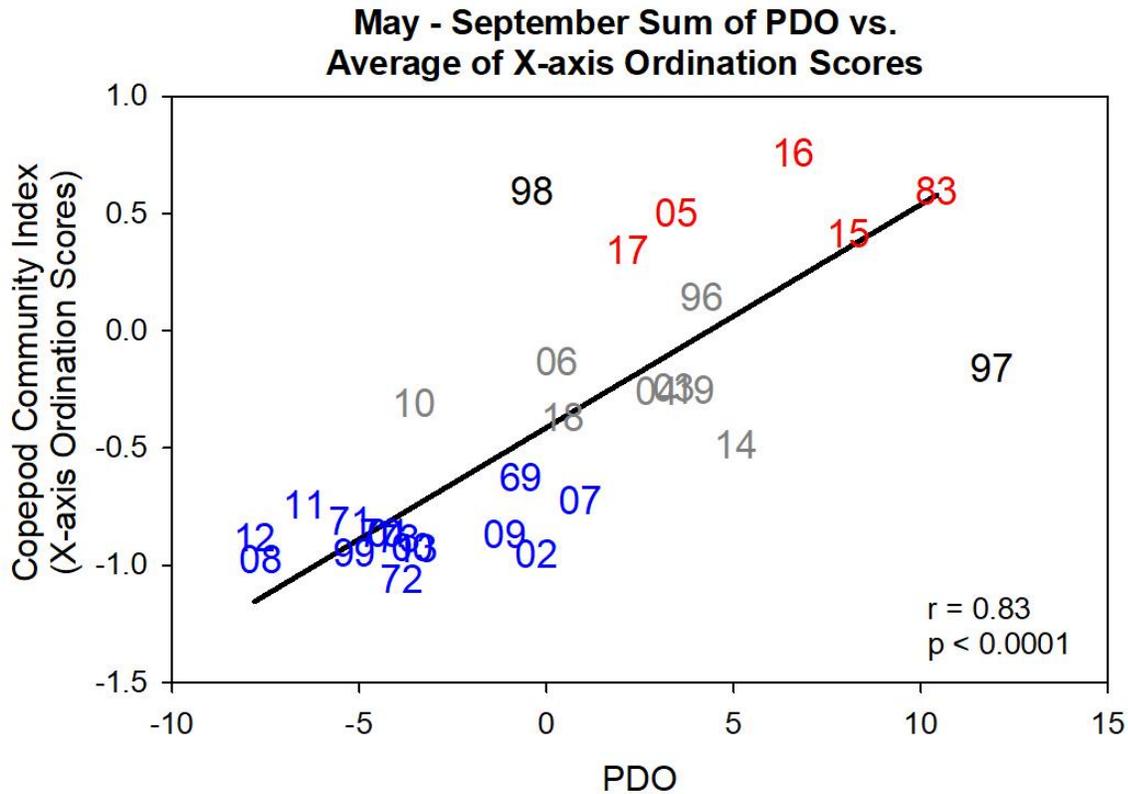


Figure CCI-02. Relationship between the PDO and X-axis ordination scores. A "cold-water zooplankton community" is associated with the negative (cold) phase of the PDO and vice versa. Number symbols indicate the warm (red) neutral (gray) and cold (blue) years. Years in black were outliers and were excluded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

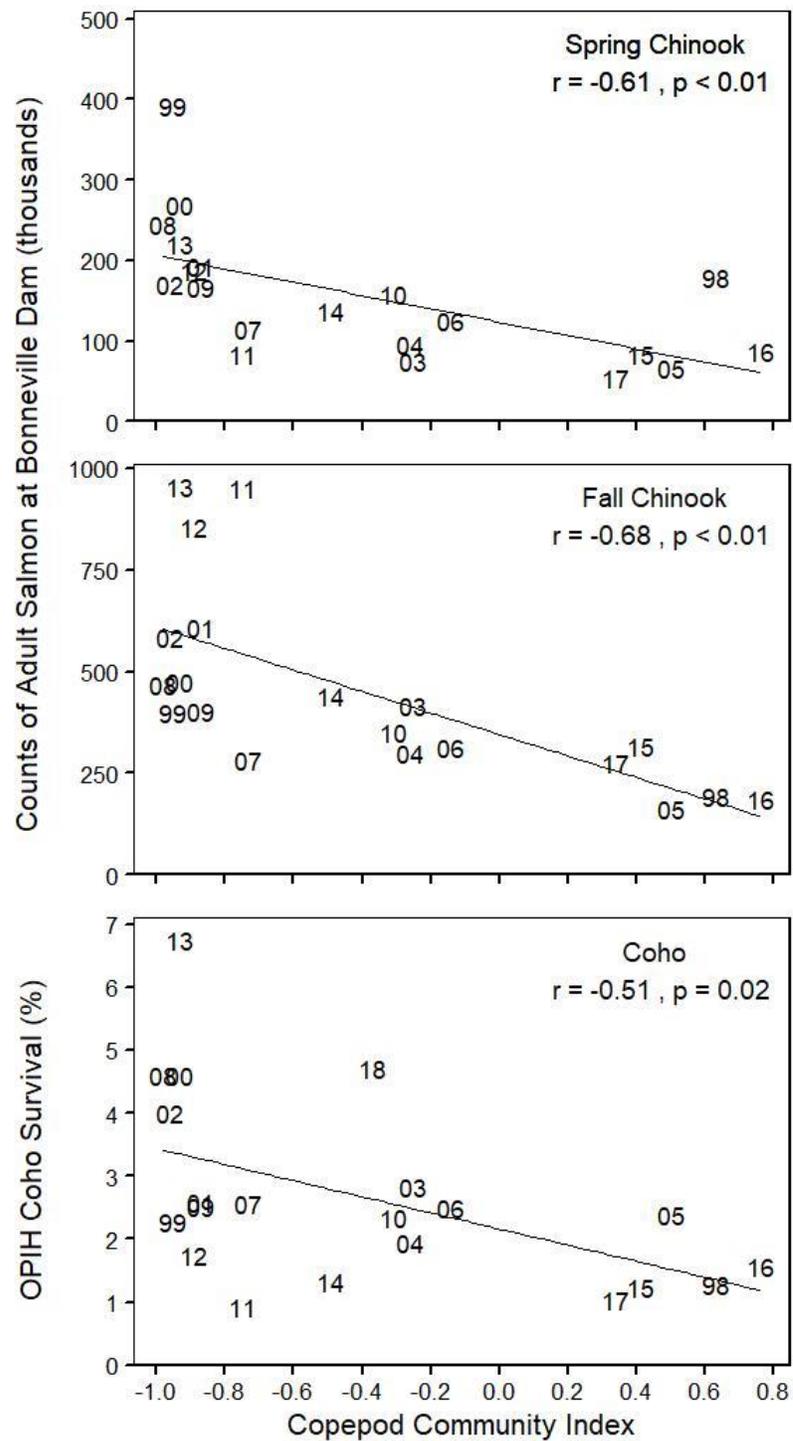


Figure CCI-03. Plot showing the relationship between spring Chinook salmon adult returns at Bonneville dam (lag 2 years, top panel), fall Chinook salmon adult returns at Bonneville dam (lag 2 years, middle panel), and coho salmon survival (OPIH, lag 1 year, bottom panel) versus the copepod community structure index (X-axis ordination score). The X-axis ordination score for May-September 2019 was -0.26, which indicates a transition back to more average salmon survival. Number symbols indicate the year of juvenile salmon outmigration.

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*.

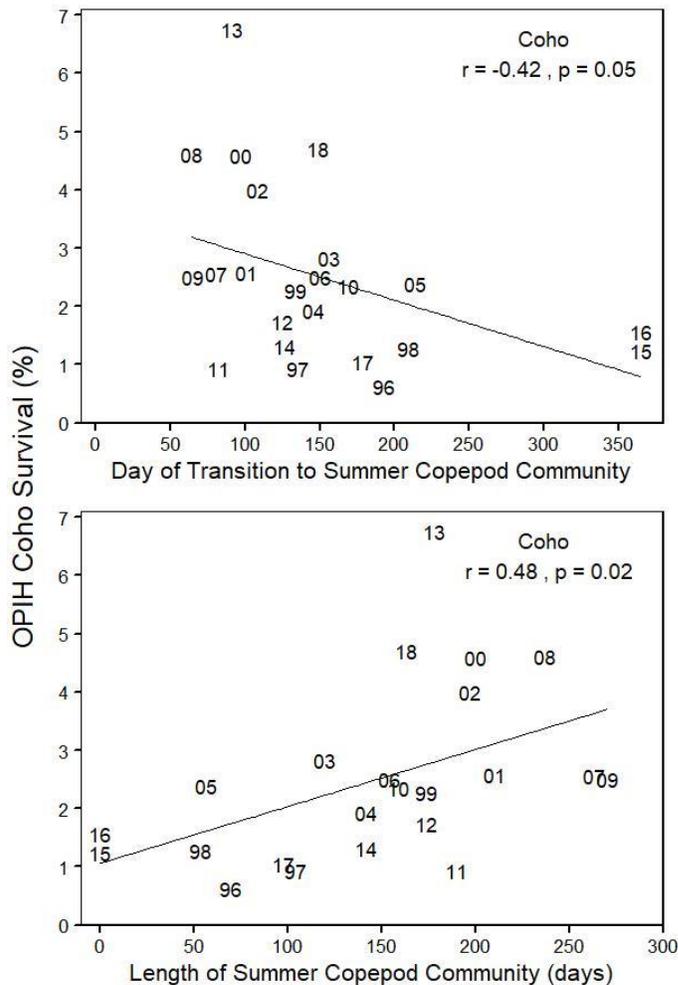


Figure BST-01. *Upper panel:* Relationship of coho salmon survival (OPIH, lag 1 year) vs. day of the year when copepod community structure transitioned to a summer community. The earlier this transition takes place, the higher the coho salmon survival.

Lower panel: Relationship of coho salmon survival (OPIH, lag 1 year) vs. length of the biological upwelling season, measured as the number of days that the summer community structure persisted. Number symbols indicate the year of juvenile salmon outmigration.

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.

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	11 Jun	19 Sep	70
1997	15 May	27 Aug	104
1998	28 Jul	20 Sep	54
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	25 May	14 Oct	142
2005	2 Aug	28 Sep	57
2006	30 May	31 Oct	154
2007	22 Mar	10 Dec	263
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 Apr	26 Sep	178
2014	6 May	25 Sep	142
2015	Never	Never	0
2016	Never	Never	0
2017	28 June	4 Oct	98
2018	29 May	8 Nov	163
2019	5 Jun	11 Sep	98

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 and 2013, the transition date came very early, in March, whereas in 2015 and 2016 for the first time in our time series, the biological spring transition never occurred. Although in 2017, the biological spring transition did happen again, it was very late, which indicated poor ocean conditions for outmigrating juvenile salmonids. However, in 2018 and 2019, the biological spring transition was just a little later than average, indicating a return to more neutral conditions for outmigrating juvenile salmonids.

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.

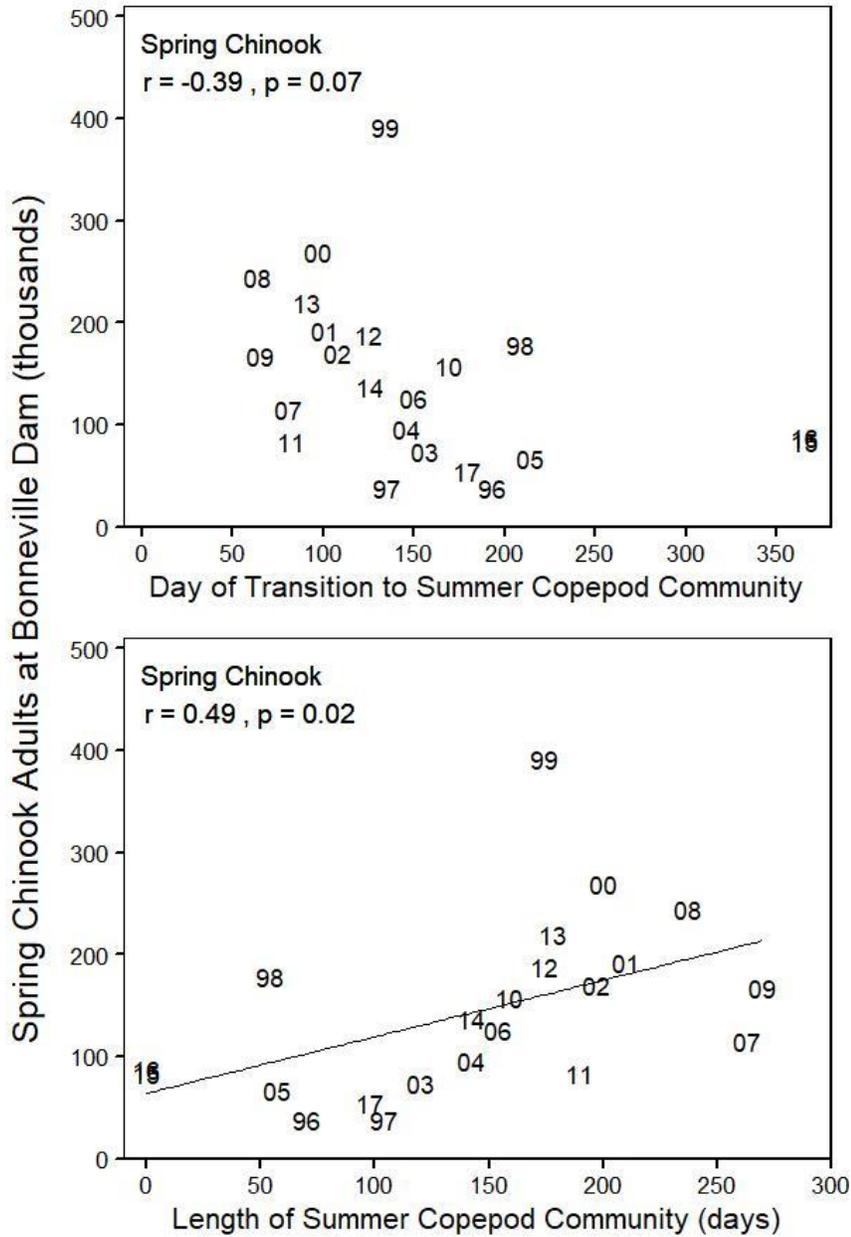


Figure BST-02. Spring Chinook salmon adult counts at Bonneville (lagged by 2 years) vs. date of biological spring transition (upper panel) and length of the biological upwelling season (lower panel). Number symbols indicate the year of juvenile salmon outmigration.

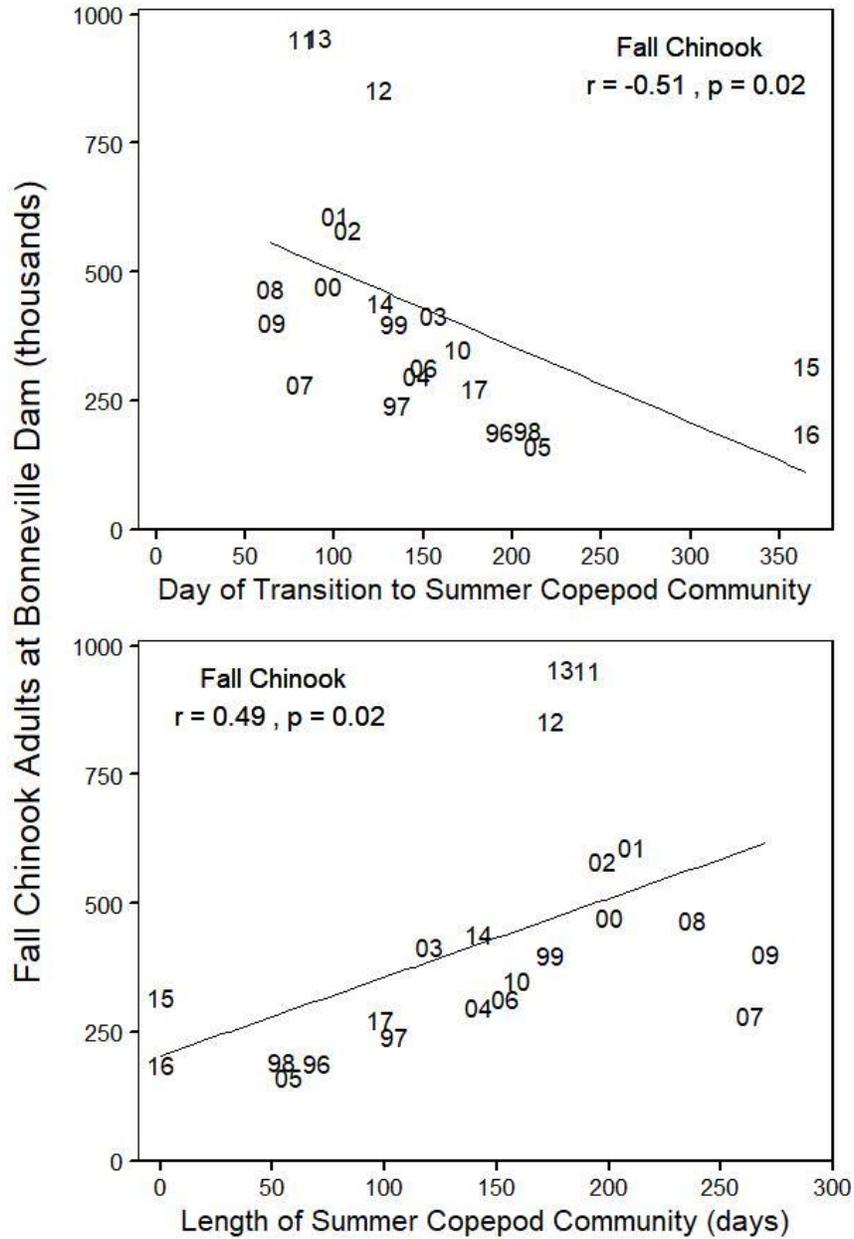


Figure BST-03. Fall Chinook salmon adult counts at Bonneville (lagged by 2 years) vs. date of biological spring transition (upper panel) and length of biological upwelling season (lower panel). Number symbols indicate the year of juvenile salmon outmigration.

Winter Ichthyoplankton

Juvenile coho and Chinook salmon, and steelhead feed primarily on late-larval and early-juvenile fishes when they enter coastal waters in early summer (Brodeur et al. 2007; Daly et al. 2009; Daly et al. 2014). The late-larval and early-juvenile life stages of most marine fishes are difficult to sample effectively (Brodeur et al. 2011), which led us to explore alternative indices of potential fish prey. The majority of marine fishes in the northern California Current (NCC) spawn in late winter and early spring (Brodeur et al. 2008). Winter-spawned fish larvae that grow and survive through spring provide a food base for juvenile coho and Chinook salmon, and steelhead during their first marine summer. Therefore, we proposed using the winter [ichthyoplankton](#) biomass as a proxy for potential salmon food during this critical growth period (Daly et al. 2013).

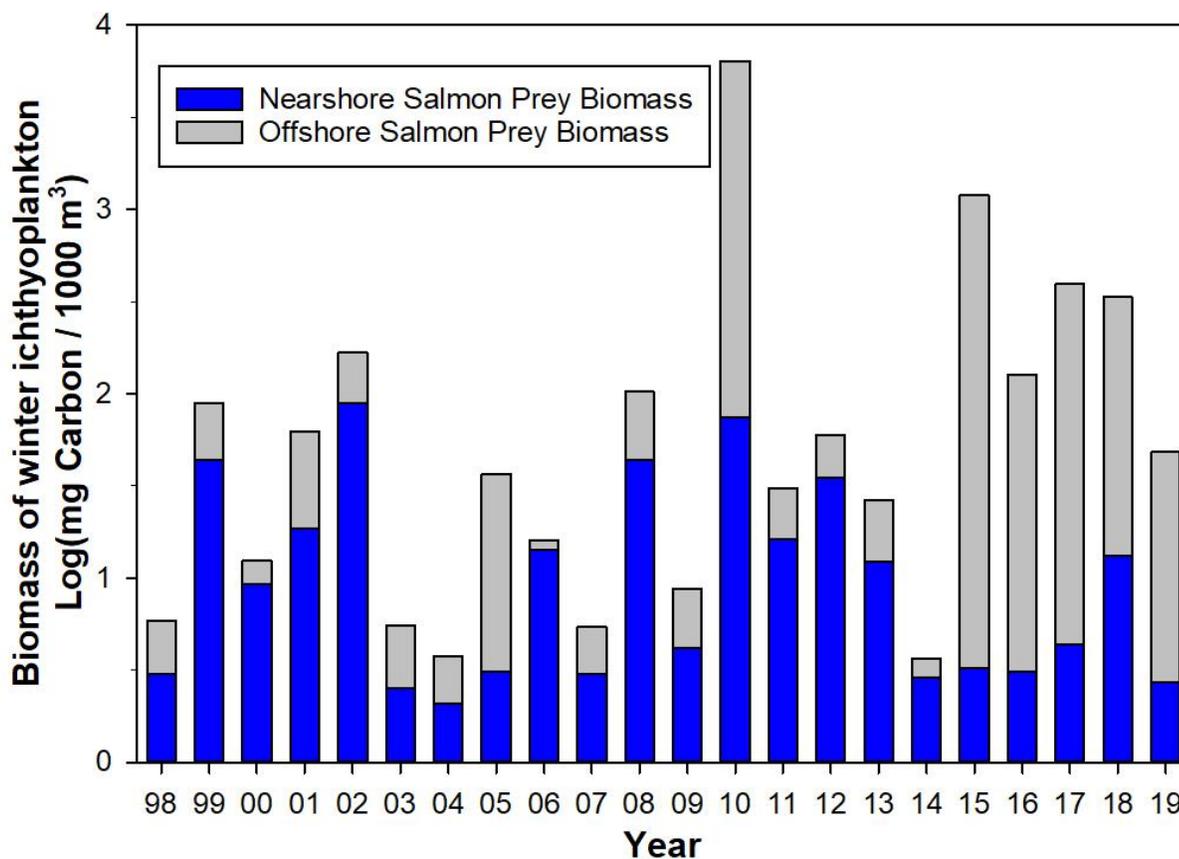


Figure WI-01. Estimates of total winter [ichthyoplankton](#) biomass from 1998 to present. Proportions composed of fish larvae considered prey items for juvenile salmon are represented by blue bars.

The ichthyoplankton data used for the index come from five stations sampled bi-weekly along the Newport Hydrographic (NH) line in January-March of 1998-present. The stations in the index are fixed and are located from 9.3 km offshore to just off the shelf at 46.3 km (Peterson et al. 2014). 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. Rarely-sampled ichthyoplankton taxa (present in < 2.5% of the samples) and rarely- (or never-) eaten taxa (e.g., myctophids) were omitted from the biomass index. With inconsistent station and bi-weekly sampling, the biomass of each taxon was first averaged by station within each month/year, then by each month/year, and finally by each year for an overall annual average for each taxon. To account for the unusual ocean conditions seen in the NCC since 2015, which resulted in a high proportion of offshore larval taxa found in our sampling ([Figure WI-01](#)), the taxa included in the winter ichthyoplankton biomass index changed in 2019 (see Daly et al. [2019] for a detailed description of the changes). [Table WI-01](#) lists common prey eaten by juvenile salmon in their first marine summer and provides data on their life-history traits and the size and availability of each. While Pacific herring are commonly eaten by juvenile salmonids, they are not present in the ocean in January-March (they occur as larvae in the estuaries at this time), and are thus not part of the biomass index. Our new Index of the Coastal Prey Biomass (ICPB) is related to adult returns of spring and fall Chinook to Bonneville Dam and this relationship is not significant for coho survival (OPIH; $p = 0.1$); [Figure WI-02](#).

Table WI-01. Life history information for the 11 dominant larval fish taxa used in the winter ichthyoplankton-salmon prey index (Matarese et al., 1989; Auth, 2009; Doyle et al., 2009; Auth, unpublished data; Daly, unpublished data).

Taxon	Common name	Coastal/ offshore taxa	Peak larval abundance (season)	Larval habitat	Length at hatching (mm)	Size at transformation to juvenile (mm)	Mean size when eaten by salmonids (mm)
<i>Ammodytes personatus</i>	Pacific sand lance	Coastal	Jan.-April	Coastal/ Shelf	4-7	30	42
Cottidae	Sculpin	Coastal	Year round	Coastal/ Shelf	1.5-5	8-20	22
Osmeridae	Smelt	Coastal	Jan.-June	Coastal/ Shelf	3-7	30	39
Hexagram- midae	Greenling/ lingcod	Coastal	Jan.-Mar.	Coastal/ Shelf	7-10	30	45
<i>Microgadus proximus</i>	Pacific tomcod	Coastal	Mar.-May	Coastal/ Shelf	3	22-28	39
<i>Ronquihus jordani</i>	Northern ronquil	Coastal	Mar.-May	Coastal/ Shelf	4	20	29
Pleuro- nectidae	Flatfish	Both- species dependent	Oct.-July	Coastal/ Shelf/ Offshore	1.7-6	12-60	27
<i>Liparis fucensis</i>	Slipskin snailfish	Offshore	Year round	Coastal/ Shelf/ Offshore	2-3	20-23	16
<i>Sebastes</i> spp.	Rockfish	Offshore	Year round	Coastal/ Shelf/ Offshore	2.5-7.5 ^a	19-30	34
<i>Engraulis mordax</i>	Northern anchovy	Offshore	May-July	Coastal/ Shelf/ Offshore	1.5-3	30	60
<i>Sardinops sagax</i>	Pacific sardine	Offshore	Mar.-July	Coastal/ Shelf/ Offshore	2.3-3.7	35	38

^a Length at which *Sebastes* spp. larvae are extruded.

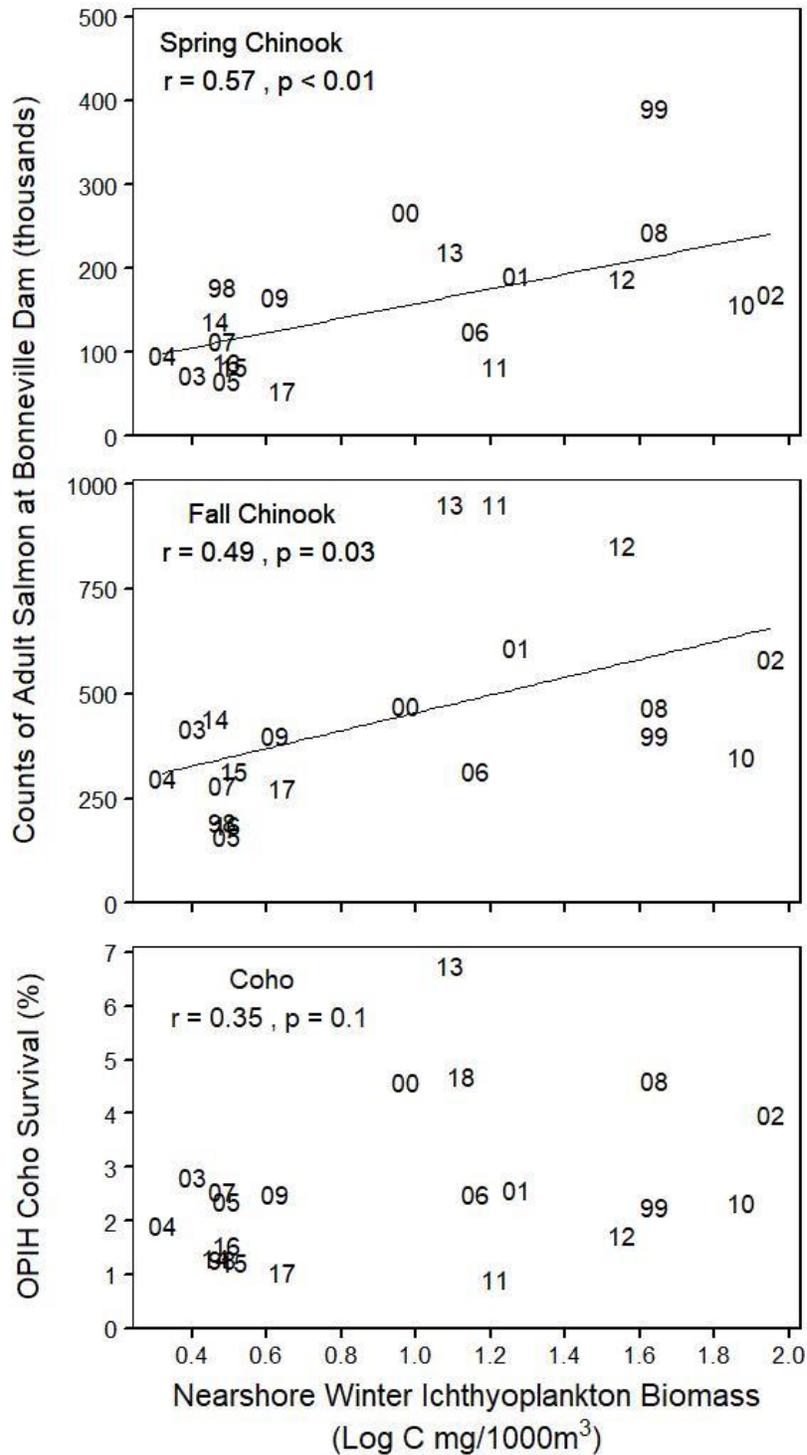


Figure WI-02. Spring and fall Chinook salmon adult counts at Bonneville (lagged by 2 years), and coho salmon survival (OPIH, lag 1 year) vs. the log of the nearshore winter ichthyoplankton salmon prey biomass. Number symbols indicate the year of juvenile salmon outmigration.

Since 2014, the ICPB has been below average with the exception of 2018 (which was somewhat of a warm average year) and the coastal biomass index in 2019 was the 20th lowest in the 22-year time series. The community composition of ichthyoplankton in 2019 was once again dominated by offshore taxa (Figure WI-01), similar to that seen in 2015-17 (Auth et al. 2018), with the community indicator suggesting poor food conditions for piscivorous juvenile salmon that out-migrate into the ocean in 2019. In contrast to the winter ichthyoplankton biomass in 2018, the overall community composition of winter ichthyoplankton in 2019 suggests that conditions for outmigrating juvenile salmon were poor.

Recent work (Daly et al. 2017) has shown that the type of fish that are available for salmon to consume is also an important predictor of food conditions and success of salmon. Below is the Principal Coordinate (PCO) community analysis of the winter ichthyoplankton prey that are important for juvenile salmon (Figure WI-03). Warmer years are positive on axis 1 (PCO1), including 2019. This new index relates well to returns of spring and fall Chinook but not coho salmon (Figure WI-04).

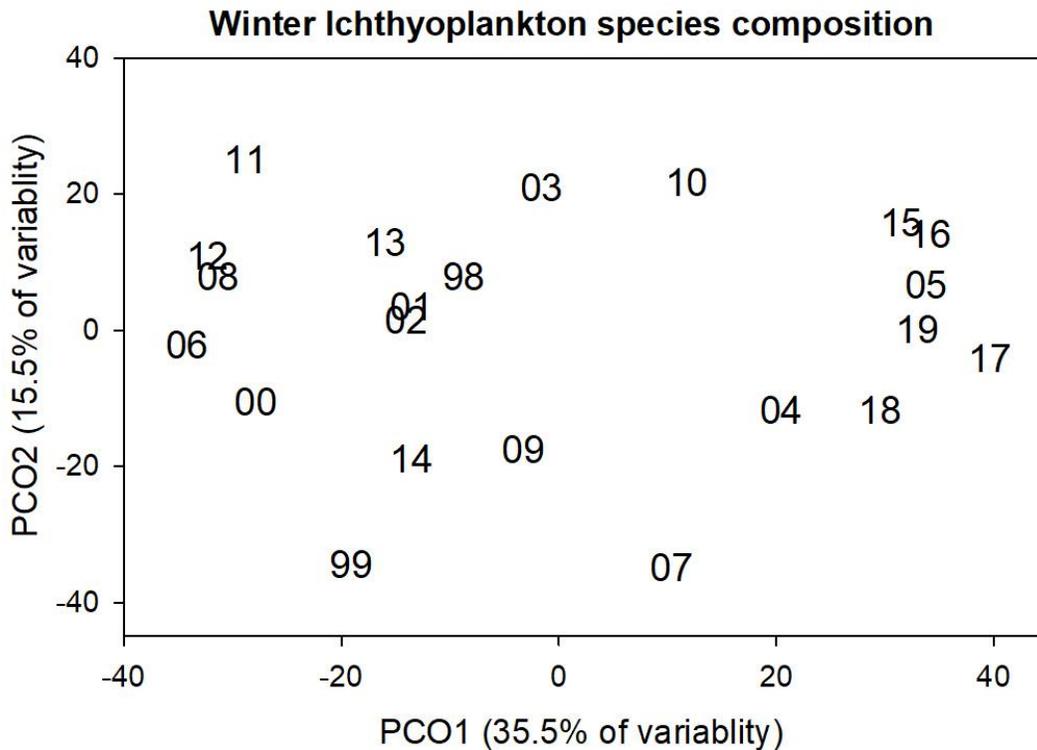


Figure WI-03. Principal Coordinate Analysis (PCO) of annual composition of winter ichthyoplankton typically eaten by salmon averaged over January-March with warm years on the right side of PCO axis 1.

The overall community composition of winter ichthyoplankton in 2019 suggests that conditions for outmigrating juvenile salmon were poor due to high composition of offshore taxa ([Figure WI-04](#)).

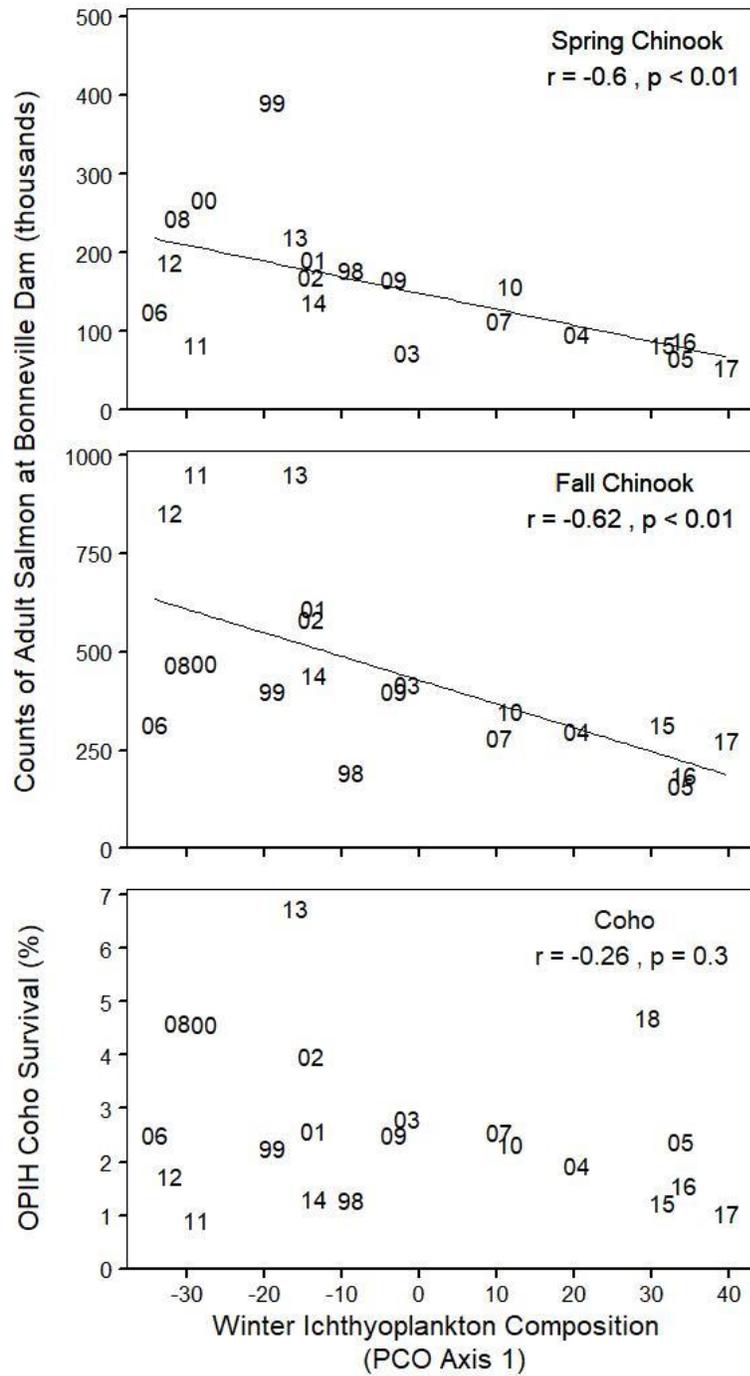


Figure WI-04. Relationship of spring and fall Chinook salmon adult counts at Bonneville (lagged by 2 years), and coho salmon survival (OPIH, lag 1 year) vs. the PC1 ichthyoplankton species composition value from Figure WI-03. Number symbols indicate the year of juvenile salmon outmigration.

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.

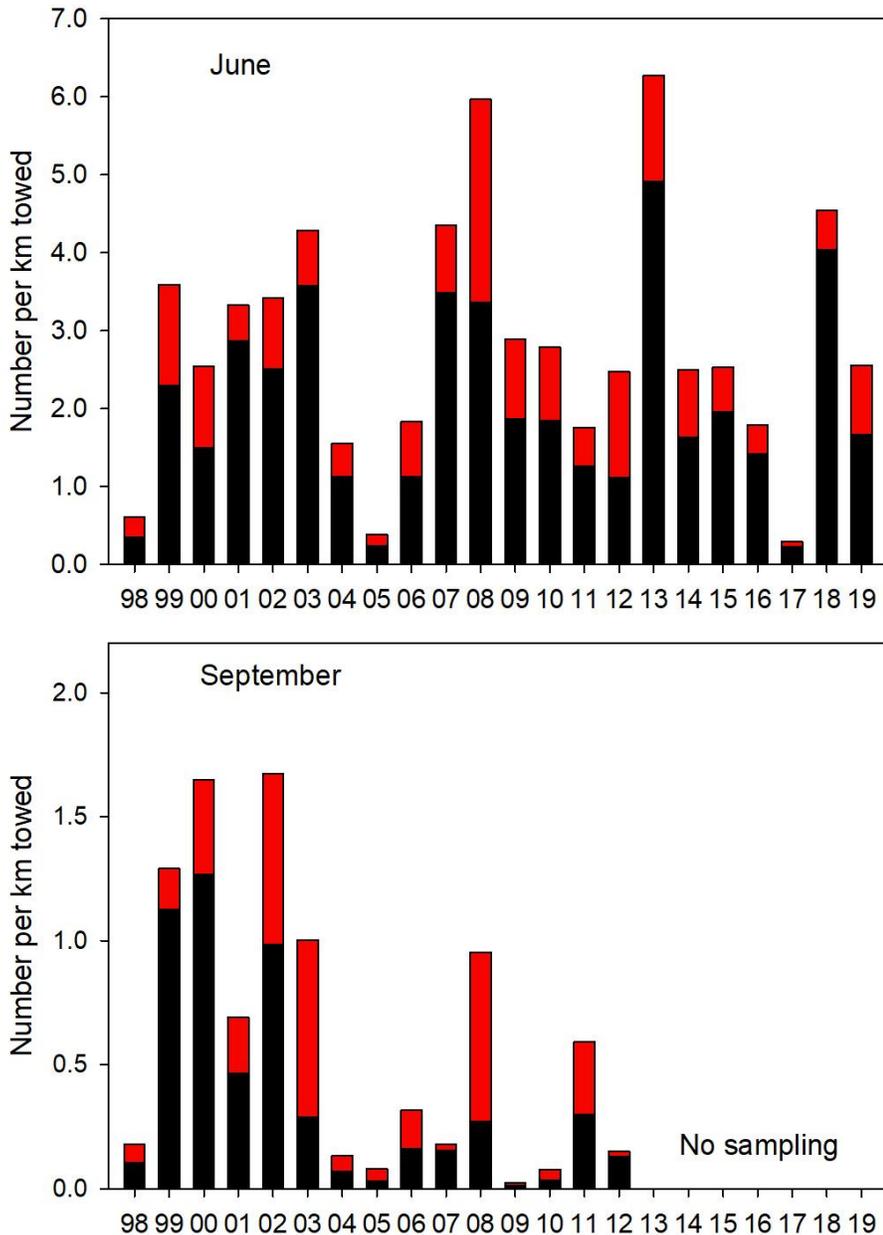


Figure JSC-01. Average catches of juvenile coho (black bars) and yearling Chinook (red bars) during trawl surveys off the coast of Washington and Oregon. Surveys were conducted in June (upper panel) and September (lower panel) from 1998 to present. Note the difference in the scale of the y-axis between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

Catch rates in June were very low for both species during 2005, but rebounded gradually from 2006-2008 and 2013, only to decline again and were the lowest for both species in June 2017. Catches in June 2019 were ranked 9th out of 22 for yearling Chinook, and 12th out of the 22 years for yearling coho salmon. Due to funding constraints, there were no surveys in September after 2012.

Abundance of yearling Chinook salmon during June surveys has a significant and positive relationship to spring Chinook jack counts at Bonneville the following spring and to adult spring Chinook counts at Bonneville two years later ([Figure JSC-02](#)). Abundance of yearling coho salmon during June surveys also has a significant and positive relationship to coho smolt to adult survival ([Figure JSC-02](#)). Thus, catches of yearling salmon in June may be a good indicator of first year ocean survival of yearling Chinook and coho salmon. There was no relationship between June catches of subyearling Chinook and Bonneville fall Chinook salmon jack counts or adults (not shown). Based on June 2018 catches of yearling Chinook salmon, jack counts at Bonneville in spring 2019 and adult returns of spring Chinook at Bonneville in 2020 should be about average for the survey years of 1998 – 2018. However, coho salmon survival in the fall of 2019 should be well above average of the survey years of 1998 – 2018.

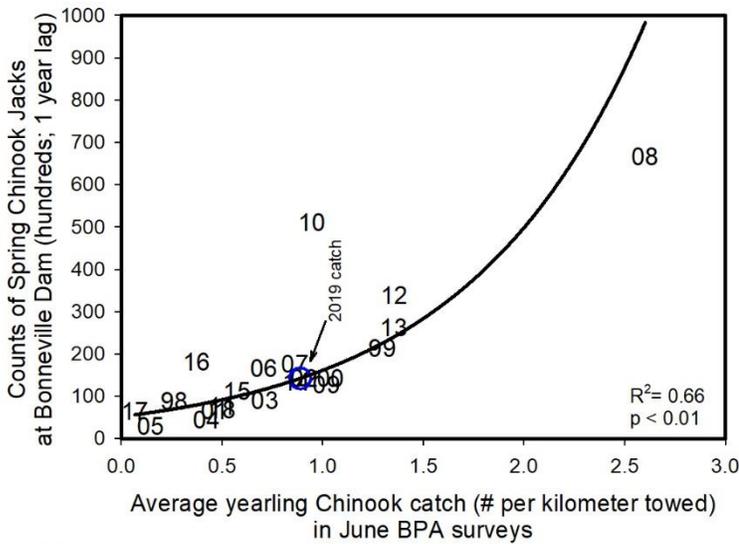
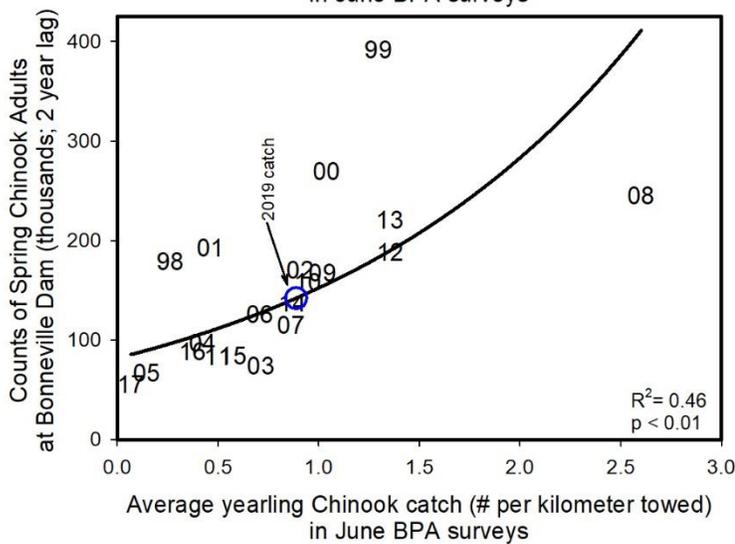
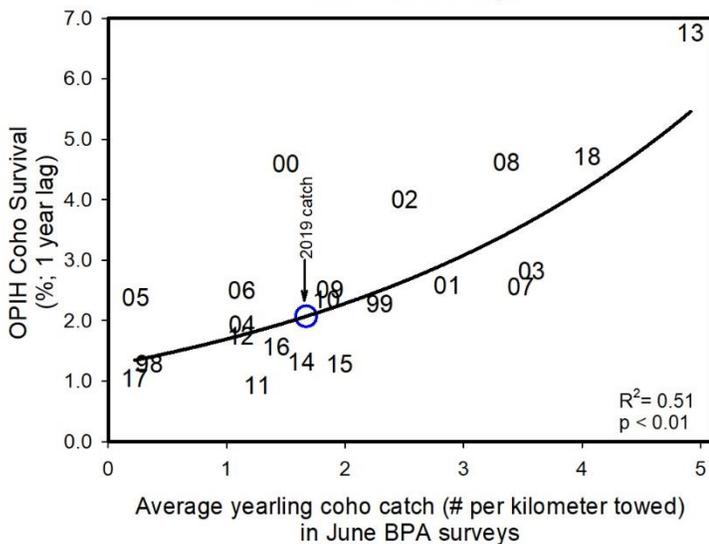


Figure JSC-02. *Upper panel* shows the regression of spring Chinook salmon jack counts (lag 1 year) at Bonneville Dam vs. average CPUE of yearling Chinook salmon caught during each June cruise. Years indicated are for catches of juvenile fish. Open blue circle indicates observed CPUE in June 2019 (0.88) and predicted jacks from the regression (14,237) and was predicted from a linear regression model of log-transformed counts of jack Chinook salmon. Number symbols indicate the year of juvenile salmon outmigration.



Middle panel shows the regression of spring Chinook salmon adult counts (lag 2 years) 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 2019 (0.88) and predicted adult from the regression (142,064) and was predicted from a linear regression model of log-transformed counts of adult Chinook salmon. Number symbols indicate the year of juvenile salmon outmigration.



Lower panel shows the regression of the OPIH smolt-to-adult survival (SAR, lag 1 year) 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 2019 (1.67) and predicted coho salmon survival from the regression (2.1%) and was predicted from a linear regression model of log-transformed coho survival. Number symbols indicate the year of juvenile salmon outmigration.

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.

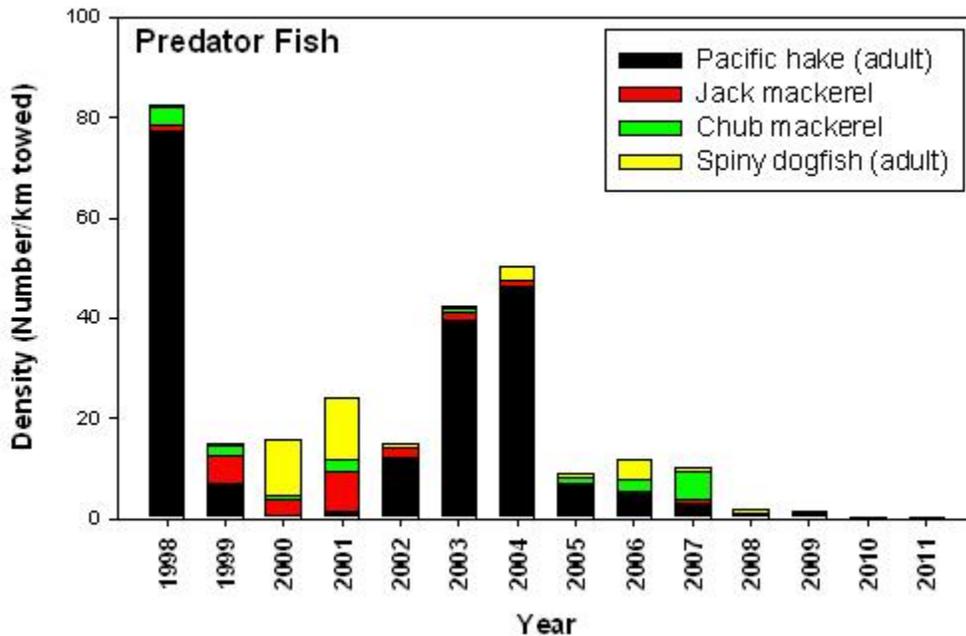


Figure AD-01. Catches of potential piscivores that prey on juvenile salmon. Pacific hake numbers are usually very high during "warm years" such as the 1998 El Niño event and during the first 2 years of a warm-phase PDO (2003-2004). However, numbers were surprisingly low from 2008-present, despite the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

In 2011, Pacific hake, ([Figure AD-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 AD-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.

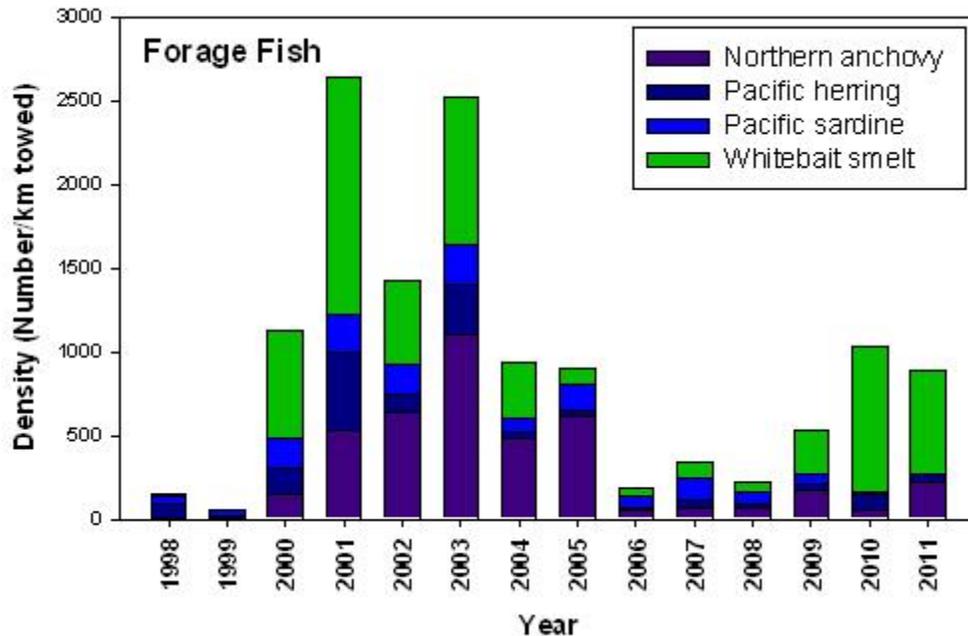


Figure AD-02. Catches of forage fish along the Columbia River and Willapa Bay [transects](#), 1998-present. Note low numbers of forage fish in 2006; note also low numbers in 1999, demonstrating that there can be time lags of at least 1 year following a crash before forage fish numbers begin to increase. 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

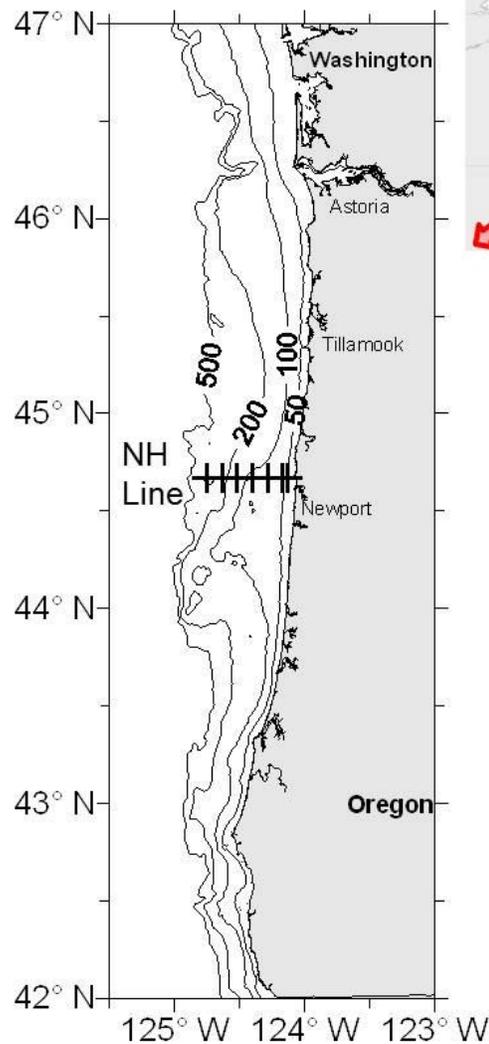
Hydrography, Zooplankton, and Ichthyoplankton

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. Additionally, we also sample north of the Newport Line at least 3 times per year as part of the [Juvenile Salmon sampling program](#). As a result, the Newport biweekly data are nested within



larger scale semi-annual to quarterly surveys, an approach that is useful in helping us interpret locally derived data from the inner portions of the Newport Line.

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

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

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

Juvenile Salmon Sampling Program

Methods

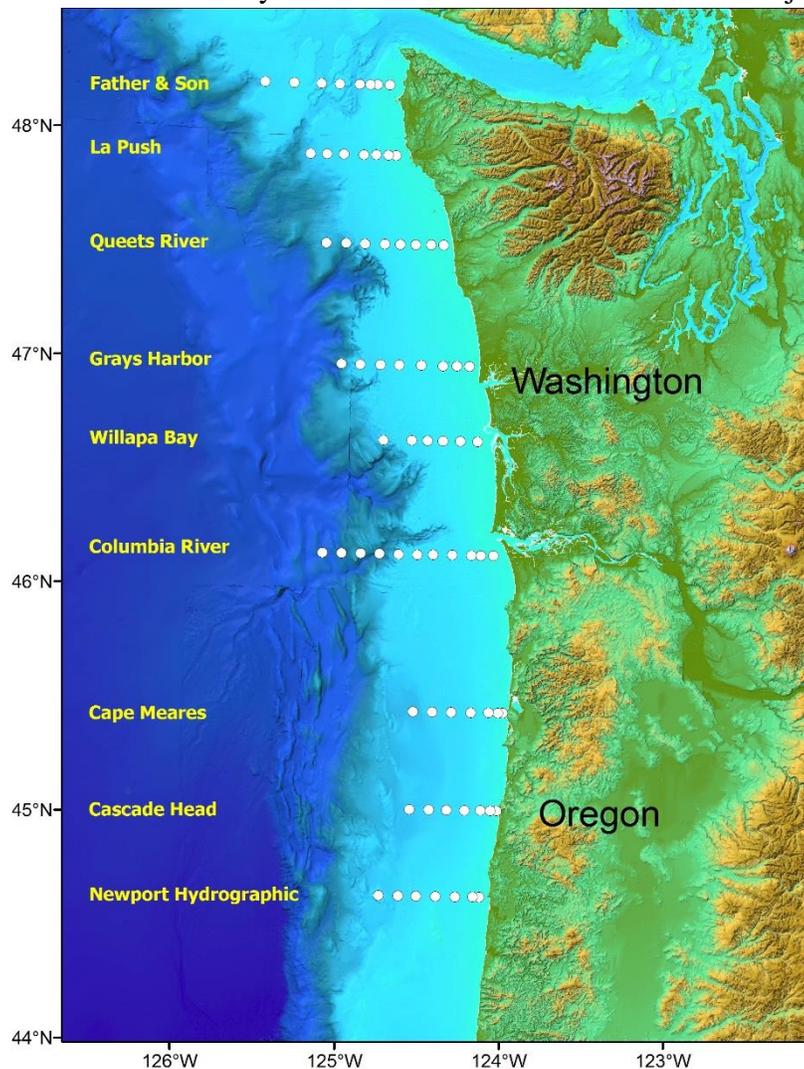
We have sampled juvenile salmon in May, June, and September since 1998 at offshore stations ranging from Newport, Oregon, to Father and Son, Washington (Figure JSS-01). Pelagic fish are collected from the upper 20 m of the water column using a 264 rope trawl (NETSystems, Inc.; 30 × 20 × 100 m).

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 and SBE-25 CTD), and water transparency (measured with a Secchi disk and/or a transmissometer).

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.

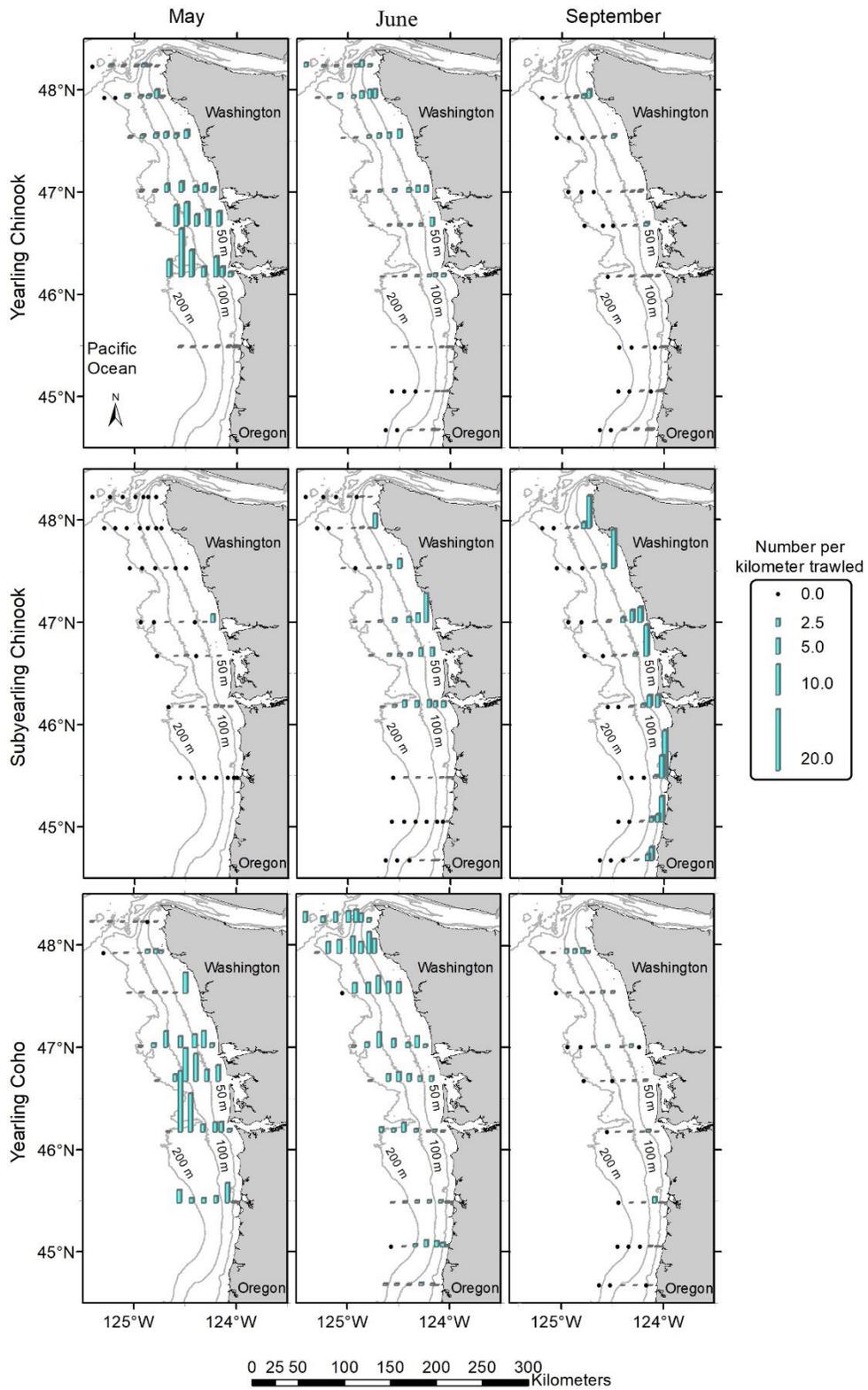


Figure JSS-02. Average catch of salmonids per km towed at stations in May 1999, 2006 – 2012, June 1998 – present, and September 1998 – 2012 for each life history type.

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. Due to funding constraints, September sampling ended in 2012.

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, anomalously low upwelling period during May-June 2005, and the warm “Blob” in 2017 (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 2019 catches of subyearling Chinook salmon were on the high side, whereas catches of yearling Chinook and coho salmon were about average, and catches of mixed-age juvenile were below average. Subyearling Chinook salmon catch were the 5th highest of the 22 years, yearling Chinook salmon were ranked 9th, yearling coho salmon were the 12th highest catches, and mixed-age juvenile Chinook salmon were the 26th highest of the 22 June survey catches..

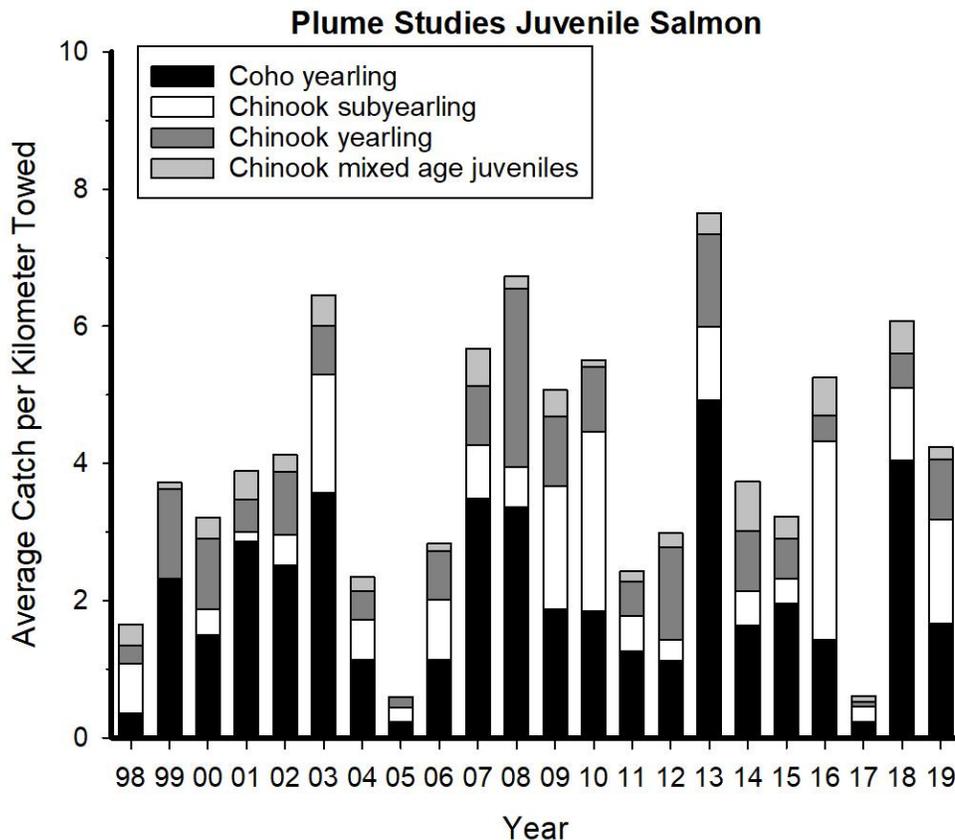


Figure JSS-03. Annual variation in catches of juvenile coho and Chinook salmon during June trawl surveys, 1998-present.

Introduction to Pacific Northwest Oceanography

Physical Oceanographic Considerations

The marine and anadromous faunae 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](#).

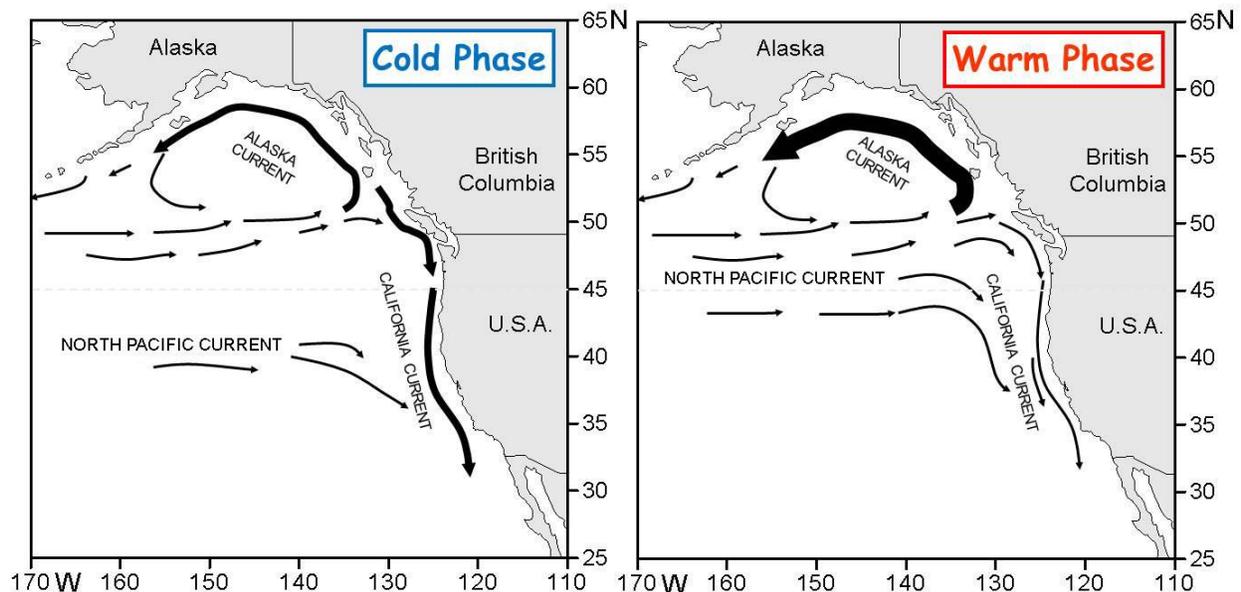


Figure CPV-01. A working hypothesis on how changes in the Pacific Decadal Oscillation affect productivity in the northern California Current.

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-01. Summary of the manner in which the sign of the PDO influences broad-scale 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 ([Kenyon 1999](#)). 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 the 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 our 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.