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

William T. Peterson,[1] Cheryl A. Morgan,[2] Edmundo Casillas,[1] Jennifer L. Fisher[2]
and John W. Ferguson[1]

[1]Fish Ecology Division
Northwest Fisheries Science Center
National Marine Fisheries Service
Newport Research Station
2032 S Marine Science Drive
Newport, Oregon 97365-5275

[2]Cooperative Institute for Marine Resource Studies
Hatfield Marine Science Center
Oregon State University
2030 S Marine Science Drive
Newport, Oregon 97365

April 2010

CONTENTS

PROJECT OVERVIEW

Over the past three decades, physical and biological oceanographic conditions have varied greatly in continental shelf waters of the northern California Current (CC) off the Pacific Northwest. Between 1977 and 1998, the northern CC was in a warm and relatively unproductive phase; as a result, salmon numbers in the Pacific Northwest declined significantly. Two of the largest tropical El Niño events of the century occurred during these 22 years: one in 1983 and a second during 1997-1998. These remote events contributed to exceptionally warm ocean temperatures in the northern CC.

As many scientists and salmon managers have noted, variations in marine survival of both coho and Chinook salmon correspond with periods of alternating cold and warm ocean conditions. Cold conditions are generally good for Chinook and coho salmon, whereas warm conditions are not. Our research is focused on identifying the ecological linkages that accompany warm vs. cold ocean conditions, and on how changes in ocean conditions affect salmon survival. This report is drawn entirely from our project website: http://www.nwfsc.noaa.gov (click on "Ocean Index Tools").

This report provides an overview of these topics for the non-specialist. We include a discussion of basic oceanography and of the interactions between physical and biological ocean processes as appendices. Three sets of ecosystem indicators are presented to aid in understanding the ecological interactions presented here and for use in predicting adult salmon returns. The first set is based on large-scale oceanic and atmospheric conditions in the North Pacific Ocean, and consists of the Pacific Decadal Oscillation and the Multivariate El Niño Southern Oscillation Index. These metrics help gauge the influence of basin-scale winds and ocean currents on local ocean dynamics off the Pacific Northwest.

The second set of indicators is based on local observations of physical and biological ocean conditions off Newport, Oregon. These observations were recorded during oceanographic research cruises by NOAA Fisheries scientists since 1996. They include measures of upwelling, water temperature and salinity characteristics, and plankton species compositions, among other elements. The third set of indicators is based on biological sampling of plankton and juvenile salmonids. These indices were developed from recorded observations of biological conditions in coastal waters off Oregon and Washington since 1998. Additional indicators are being developed or considered for development, and their status is discussed as well.

From this combination of physical and biological indicators, we produce forecasts of adult salmon returns. At this time, these forecasts are qualitative in nature, in that we rate each indicator in terms of "good," "bad," or "neutral," based on its relative impact on marine survival of juvenile salmon. In Table 1, we summarize all of the indices discussed in this report and present a simple color system that codes the qualitative influence of each indicator. Please refer to http://www.nwfsc.noaa.gov (click on "Ocean Index Tools") for bi-annual updates for each indicator.

Table 1. Ocean ecosystem indicators of the Northern California Current. Colored squares indicate positive (green), neutral (yellow), or negative (red) conditions for salmon entering the ocean each year. In the two columns to the far right, colored dots indicate the forecast of adult returns based on ocean conditions in 2009.

	Juvenile migration year				Forecast of adult returns	
					Coho	Chinook
	2006	2007	2008	2009	2010	2011
Large–scale ocean and atmospheric indicators						
PDO (May–Sep)	yellow	red	green	yellow	green	green
MEI (annual)	yellow	green	green	yellow	yellow	yellow
Local and regional physical indicators						
Sea surface temperature anomalies	yellow	red	green	yellow	yellow	yellow
Coastal upwelling	yellow	green	green	yellow	yellow	yellow
Physical spring transition	red	green	yellow	yellow	yellow	yellow
Deep water temperature and salinity	red	yellow	green	yellow	yellow	yellow
Local biological indicators						
Copepod biodiversity	red	yellow	green	yellow	yellow	yellow
Northern copepod anomalies	yellow	green	green	green	green	green
Biological spring transition	red	green	green	green	green	green
June spring Chinook	yellow	green	green	green	—	green
September Coho	yellow	red	yellow	red	red	—

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

INTRODUCTION

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

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

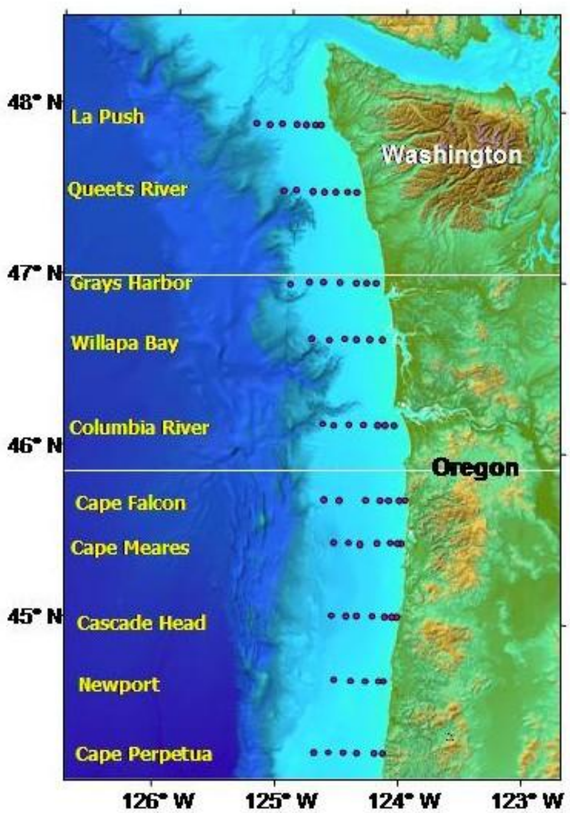


Figure 1. Transects sampled during trawling surveys off the coast of Oregon and Washington.

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

Using all of these data, we developed a suite of ocean ecosystem indicators upon which to base forecasts of salmon returns. These forecasts are presented as a practical example of how ocean ecosystem indicators can be used to inform management decisions for endangered salmon. At this time, the forecasts are qualitative in nature: we rate each in terms of its "good," "bad," or "neutral" relative impact on salmon marine survival (Table 1).

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

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

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

upwelling → nutrients → plankton → forage fish → salmon.

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

LARGE-SCALE OCEAN AND ATMOSPHERIC INDICATORS

Pacific Decadal Oscillation (PDO)

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

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

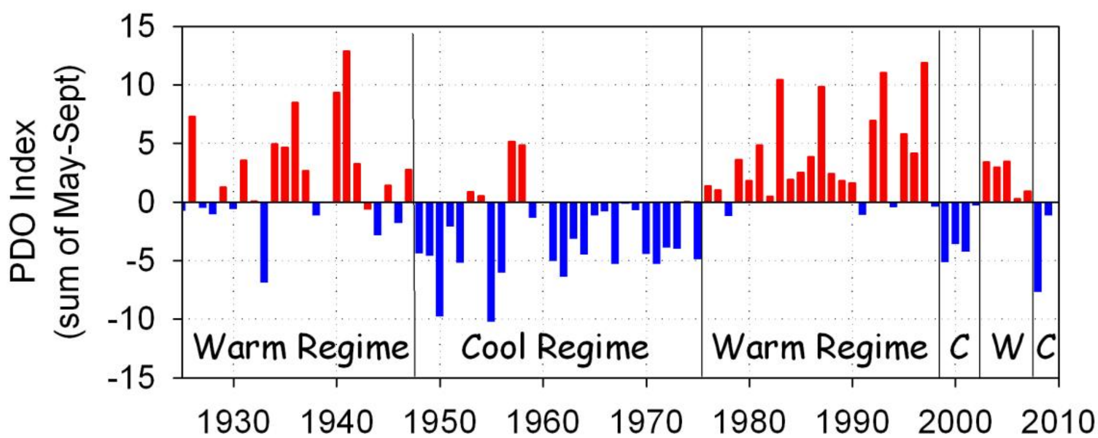


Figure 2. Time series of shifts in sign of the Pacific Decadal Oscillation (PDO), 1925 to 2009. Values are averaged over the months of May through September. Red bars indicate positive (warm) years; blue bars negative (cool) years. Note that 2008 was the most negative since 1956.

Warm and cold phases can persist for decades. For example, a warm phase continued from 1925 to 1946 (red bars in Figure 2), and a cool phase from 1947 to 1976 (blue bars). From 1977 to 1998, another 21–year warm phase occurred. Recently, however, these decadal cycles have broken down: in late 1998, the PDO entered a cold phase that lasted only 4 years followed by a warm phase of 3 years, from 2002 to 2005. The PDO was in a relatively neutral phase through August 2007, but abruptly changed to a negative phase that lasted from September 2007 through July 2009, a run of nearly 2 years. In

August 2009, the PDO again changed phase, to positive, possibly because of the El Niño event developing at the equator during fall and winter 2009–2010.

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

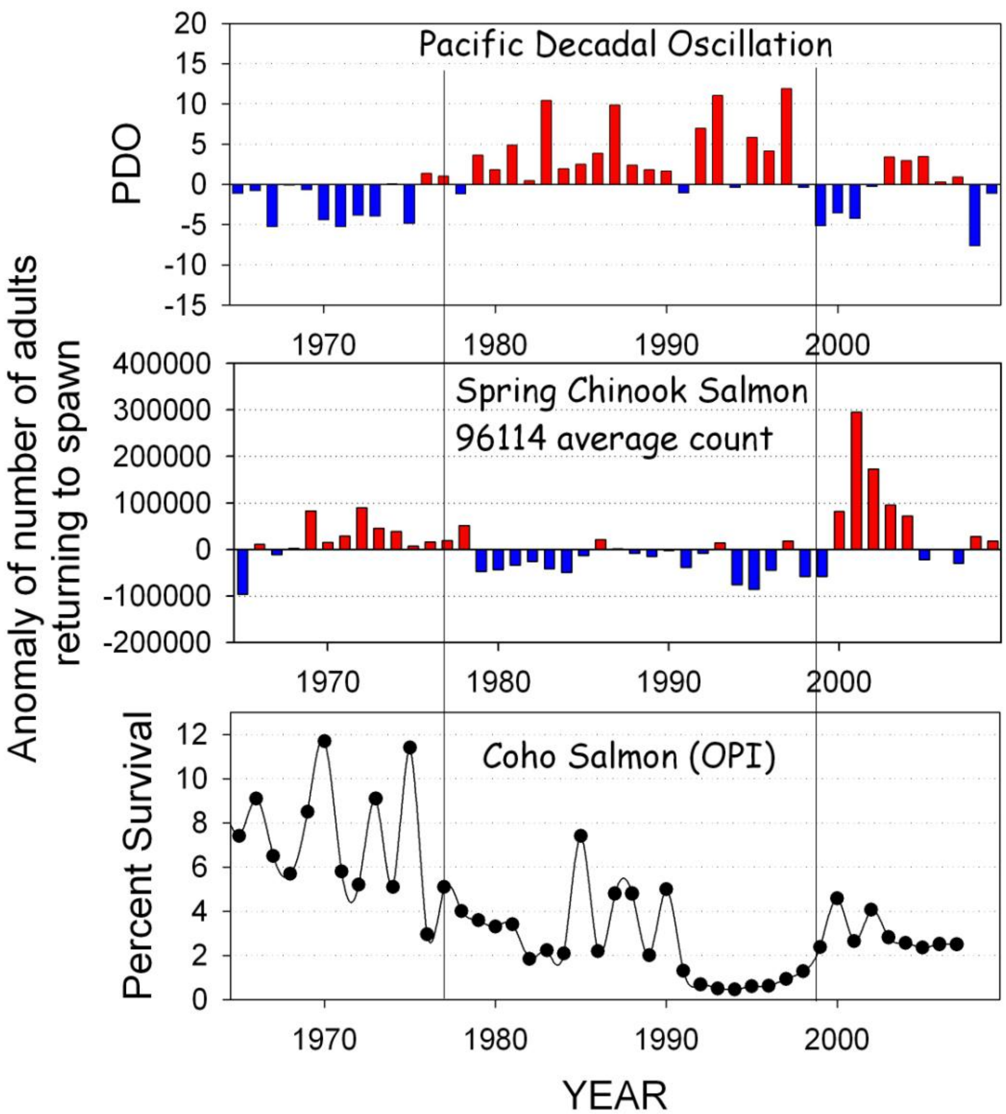


Figure 3. Upper panel shows summer average PDO, 1955–2009; middle panel shows anomalies in counts of adult spring Chinook passing Bonneville Dam for the same period; lower panel shows survival of hatchery coho salmon, also during 1955–2009. Vertical lines indicate climate–shift points in 1977 and 1998.

The listing of several salmon stocks as threatened or endangered under the U.S. Endangered Species Act coincides with a prolonged period of poor ocean conditions that began in the early 1990s. This is illustrated in Figure 3, which shows average PDO values in summer vs. anomalies in counts of adult spring Chinook at Bonneville Dam. Also shown are percentages of hatchery juvenile coho salmon that returned as adults to hatcheries in SW Washington and NE Oregon during this period. These percentages have been recorded since 1961 as the Oregon Production Index, Hatchery (OPIH).

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

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

Adult spring Chinook runs have declined recently, beginning with returns of fish that went to sea in 2003 and experienced warm ocean conditions, indicated by the positive PDO signal during 2003 to 2007. Forecasts for returns in 2010 are for large numbers of fish, and again, these anticipated returns are associated with the strongly negative PDO (and cold ocean) in effect for juvenile Chinook and coho that entered the ocean in spring 2008.

Multivariate El Niño Southern Oscillation Index (MEI)

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

These events affect weather in the Pacific Northwest as well, often resulting in stronger winter storms and 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.

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. An El Niño event developed in equatorial waters in mid–2009; however, its impacts on the Pacific Northwest during winter 2009 to spring 2010 are uncertain.

Since 1955, the presence/absence of conditions resulting from the El Niño Southern Oscillation (ENSO) has been gauged using the Multivariate ENSO Index, or MEI (Wolter and Timlin 1998). A time series of the MEI is shown in Figure 4. Prior to 1977 (during the cool phase of the PDO), El Niño conditions were observed infrequently (note the predominance of blue bars prior to 1977).

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

Beginning in September 1998, MEI values turned negative and remained so for nearly 4 years, similar to the trend observed in the PDO. The MEI returned to positive in April 2002 and remained so through September 2005, after which negative values returned. Positive values were seen once again beginning in spring 2009.

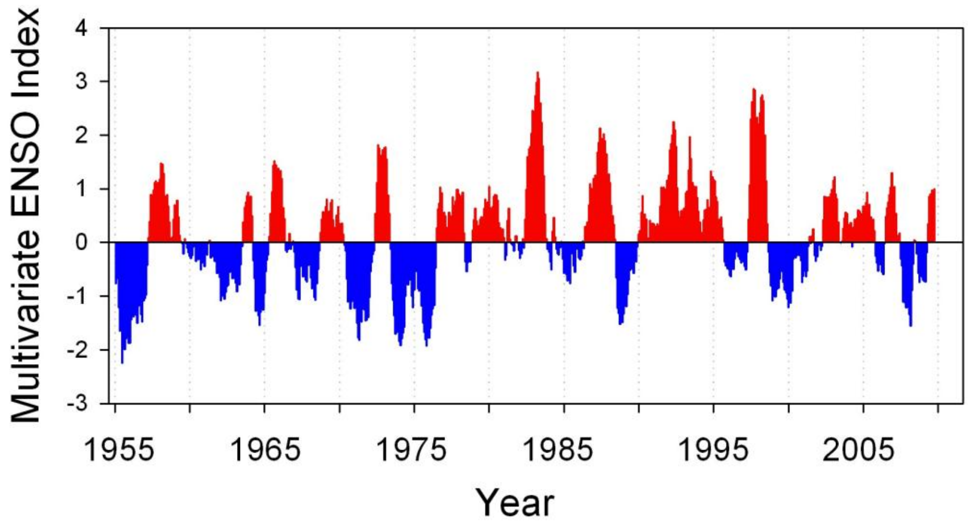


Figure 4. Values of the MEI, 1955–2009. Red bars indicate warm conditions in the equatorial Pacific, blue bars indicate cool conditions in equatorial waters. Large and prolonged El Niño events are indicated by large values of the index: note the +3 value associated with the 1983 and 1998 events and the prolonged period of warm conditions at the equator from 1977 to 1996. Note cool anomalies during 1999-2002 and 2007–spring 2009.

Both the PDO and MEI can be viewed as "leading indicators" of ocean conditions, since after a persistent change in sign of either index, ocean conditions in the California Current soon begin to change. The MEI became positive in May 2009, signaling a return to warm ocean conditions. In fact, NOAA recently issued a report that indicates El Niño conditions are now evident in the tropical Pacific and should intensify during winter 2009–2010. However, this episode is expected to be much weaker than the very strong 1997–1998 El Niño event.

Nevertheless, if the prediction of an El Niño event holds true, warm ocean conditions can be expected for the next year. The impact of El Niño events on survival of coho salmon is well documented (Pearcy 1992). For example, the large events of both 1983 and 1998 were followed by low adult return rates for coho salmon during 1983–1984 and 1999, respectively.

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

Declines in adult Chinook salmon returns from 2004 to 2007 are likely related to the period of warm ocean and weak but persistent El Niño conditions during 2003–2006.

LOCAL AND REGIONAL PHYSICAL INDICATORS

Sea Surface Temperature Anomalies

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

Figure 5 shows monthly PDO values vs. monthly average sea surface temperatures at NOAA Weather Buoy 46050 from 1996 through 2009. This is the period during which we have been measuring local ocean conditions.

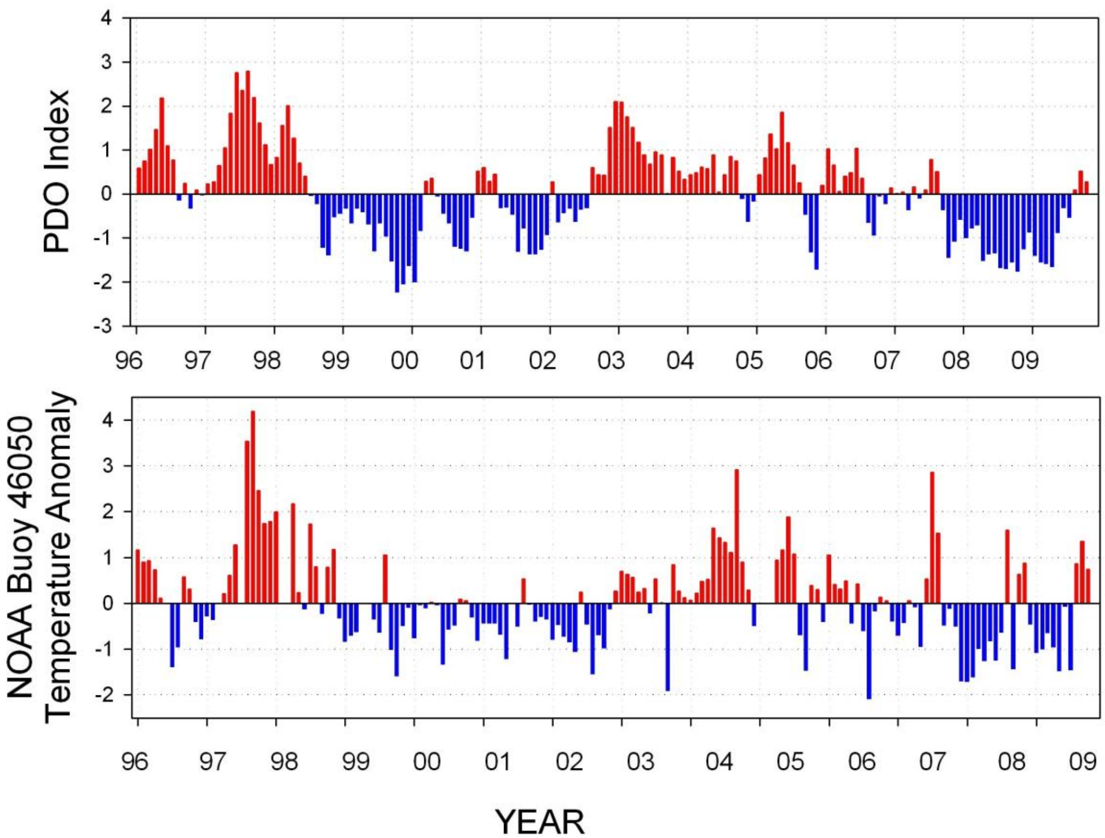


Figure 5. The PDO and monthly sea surface temperature anomalies at NOAA Buoy 46050, 22 miles west of Newport OR.

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

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

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

Note also in Figure 5 that there are time lags between a change in sign of the PDO and change in SST off Newport. In 1998, the PDO changed to negative in July, and SSTs changed to negative in December. In 2002, the opposite pattern was seen, with the PDO change in August followed by SSTs in December. Thus, it takes 5–6 months for the 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 changes associated with basin–scale indicators include the source waters that feed into the northern California Current, zooplankton and forage fish community types, and abundance of salmon predators such as hake and sea birds. Thus, local variables change in response to changes that occurs on a broad spectrum of spatial scales. These range from basin–scale changes, which are indexed chiefly by the PDO, to local and regional changes, such as those related to shifts in the jet stream, atmospheric pressure, and surface wind patterns.

Beginning in mid–May 2009, the trend of cold ocean conditions established during 2007 began to fade. Cold SSTs did continue through mid–August due to strong upwelling winds, but were interrupted by major relaxations of upwelling (and significant warming) that occurred in June, mid–July, and from mid–August to mid–September (Figure 6). The latter relaxation of winds resulted in water nearly 4°C warmer than average. The warmest temperature was observed on 19 September (17.3°C). Two brief cooling periods followed in late September and October, as well as in mid–November.

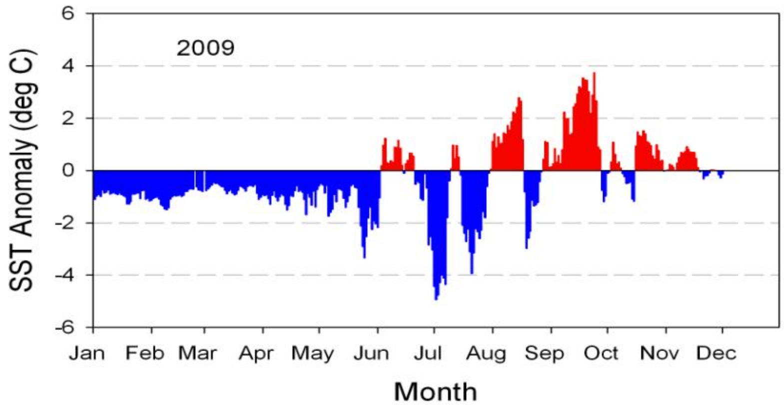


Figure 6. Daily sea surface temperature anomalies measured at NOAA Buoy 46050, located 22 miles off Newport, OR, in 2009.

Figure 7 summarizes SST measurements made during our biweekly cruises made off Newport Oregon, at station NH 05, located five miles from shore in 60 m of water. Seasonal averages for winter (October–April) and summer (May–September) show that SST during the past winter (2008/09) was about −0.5°C below normal whereas the previous two winters were colder by about −0.9°C. The summer of 2009 was about 0.3°C warmer than normal.

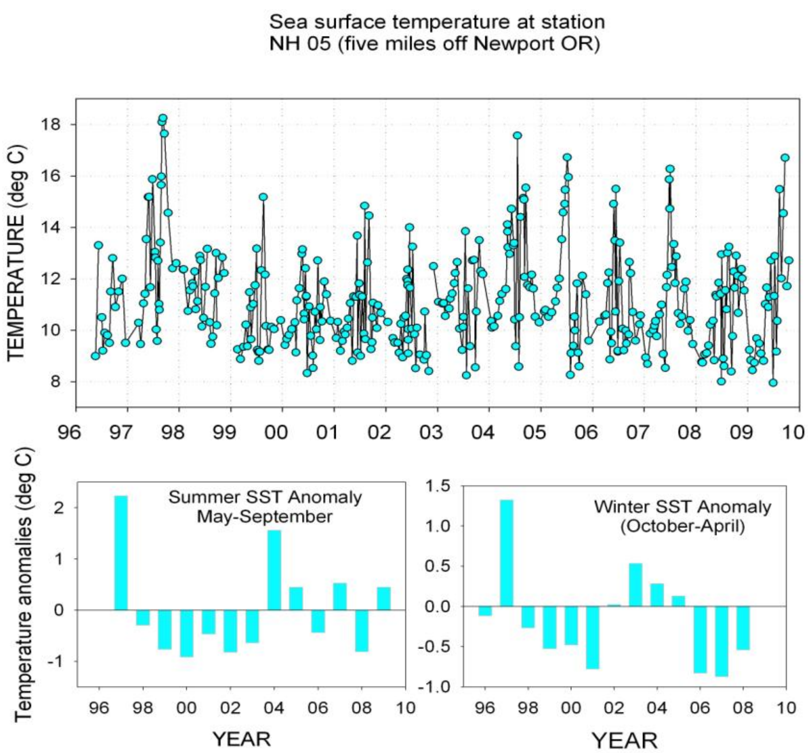


Figure 7. Upper panel shows average sea surface temperatures at Station NH 05, located 5 miles off Newport, Oregon, from 1996 through 2008. Lower panel shows temperature anomalies during the same years during summer (left) or May to September and winter (right) or October to April.

Coastal Upwelling

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

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 (CUI).

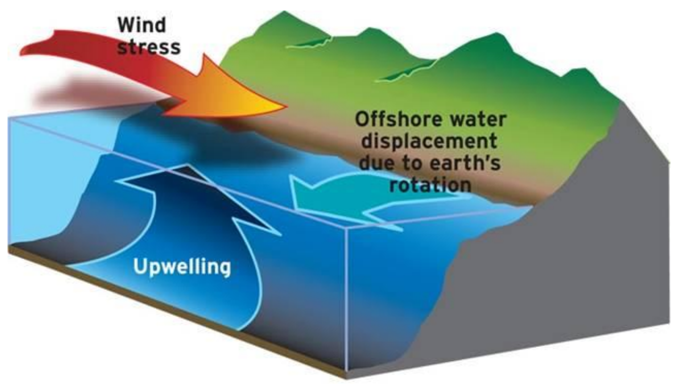


Figure 8. Forces affecting coastal upwelling. Drawing courtesy of Environmental Research Division, Pacific Fisheries Environmental Research Laboratory, NOAA.

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

The CUI is calculated in 3–degree intervals from 21°N to 60°N latitude, and data is 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 CUI anomalies in Figure 9. The years of strongest upwelling were 1965–1967.

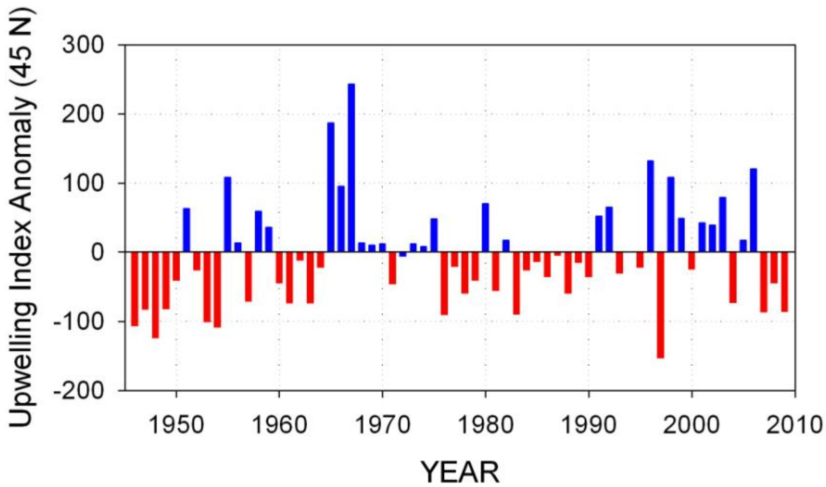


Figure 9. Anomalies of the Coastal Upwelling Index during May to September each year, 1946–2009.

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

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

Knowledge of upwelling alone does not always provide good predictions of salmon returns. For example, during the 1998 El Niño event, upwelling was relatively strong, as measured by the CUI; 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 times series, −1.0°C. These observations demonstrate that some care is required when interpreting this simple upwelling index. We hypothesize that although upwelling is necessary to stimulate plankton production, its impact is greatest during negative phase of the PDO.

Upwelling in 2009—Figure 10 illustrates the pattern of upwelling through 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 day by day. But with the onset of the spring transition and upwelling, the downward trend reverses, and the cumulative line trends upwards. One can see in Figure 10 that upwelling was initiated early in the year, on 23 March (day 82) and continued into September–October. However, a lengthy period of upwelling was never established:

rather, the process was interrupted by 5 major events during which upwelling relaxed, as indicated by the short horizontal bars in Figure 10.

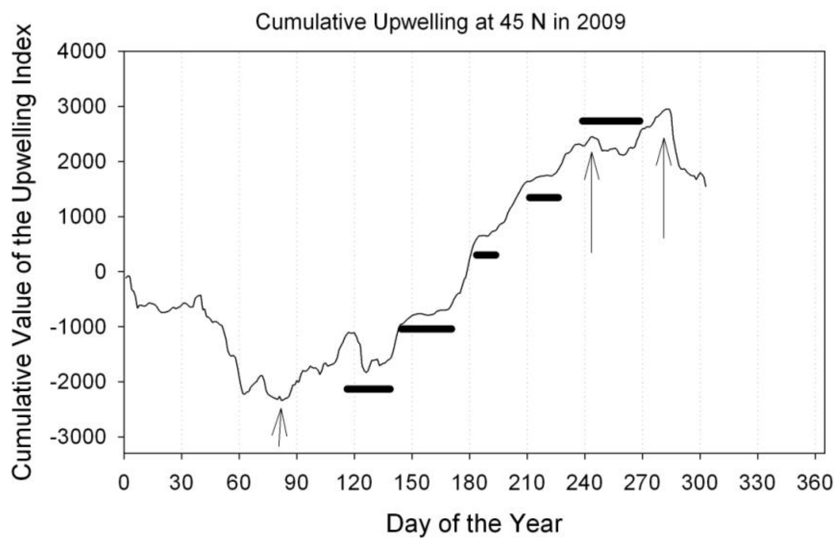


Figure 10. Cumulative upwelling index for 2009.

When Figure 10 is compared to Figure 6 (which shows SSTs in 2009), it is clear that the relaxation events initiated on day 145 (25 May 2009) and all subsequent events all resulted in onshore transport of very warm water. These warm–water "downwelling" events occurred in mid–June, mid–July, and throughout much of August and September.

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

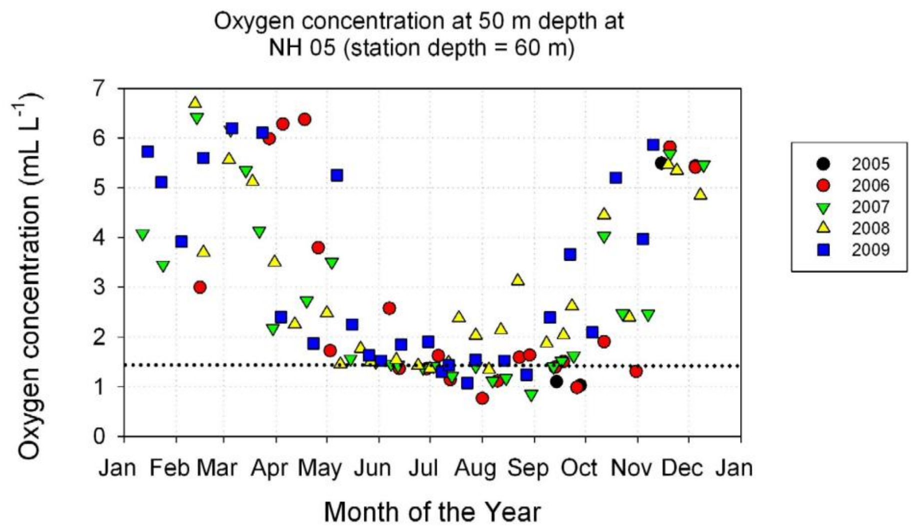


Figure 11. Oxygen concentration in bottom waters at a baseline station NH 05. Hypoxia is defined as waters with oxygen concentrations <1.4 mL/L, and is observed only during the coastal upwelling season, especially Jun–Sep. Hypoxia was particularly severe during July 2006, but relatively weak in 2008 and 2009. Values <1.4 mL/L were seen on only 3 dates in 2009: 8 and 23 July and 27 August.

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

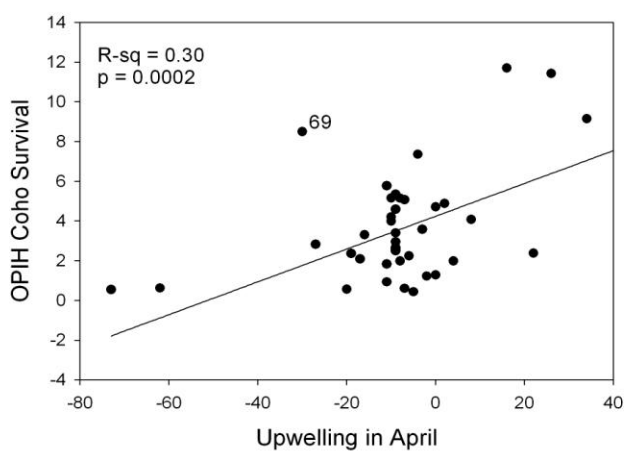


Figure 12. Scattergram of coho survival vs. CUI anomaliy for 45°N for the month of April 1969–2009. No other month produced a significant correlation. When the year 1969 was excluded from the regression, r^2 improved from 0.21 to 0.30.

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

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 from 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. If late season storms are intense, they can erase any upwelling signature that may have been initiated, thus re–setting the "seasonal clock" to a winter state. This is what occurred during summer 2005.

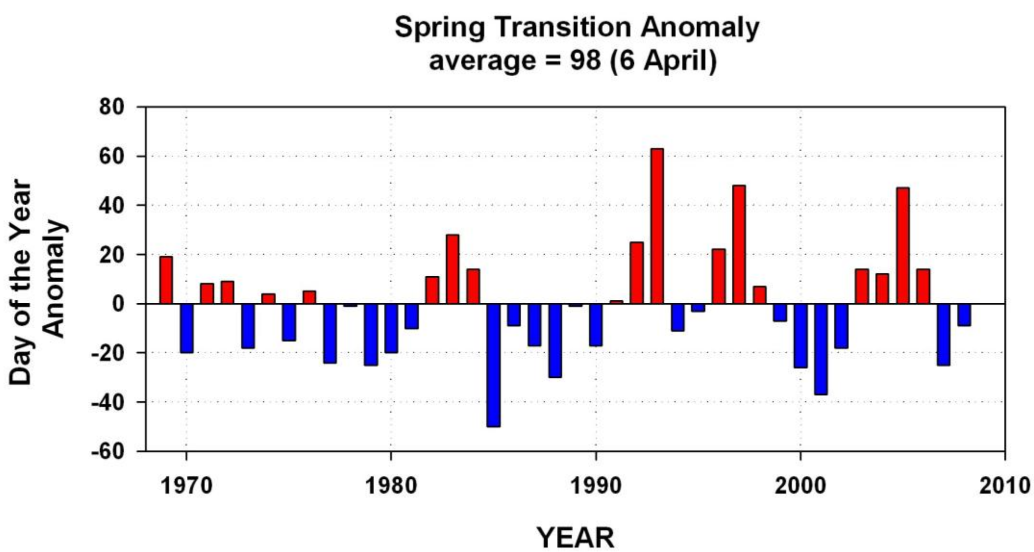


Figure 13. Anomalies in the date of the physical spring transition from 1969 to 2009. Anomalies are based on an average date of 6 April (Logerwell et al. 2003).

The date of spring transition can be indexed in several ways. Logerwell et al. (2003) has indexed the spring transition date based on the first day when the value of the 10–day running average for upwelling is positive and the 10–day running average for sea level is negative (Figure 13). Based on the index of Logerwell and her associates, the mean date of the transition is 6 April, but it can range from early February to early July. Note from Figure 13 the following four points:

- Most spring transition dates prior to the 1977 cool–phase PDO were near the average.
- Spring transition dates from the 1980s and 1990s did not reflect changes in either the PDO (Figure 2) or the Multivariate ENSO index (Figure 4).
- The brief, 4–year shift to a cool phase PDO from 1999 to 2002 was characterized by early spring transition dates, whereas the warm–phase PDO years of 2003–2005 had late spring transition dates. Transition dates have been early the past 3 years (2009 data not available).
- The period of early transition dates from 1985 to 1990 correlates well with the high salmon survival in the late 1980s (see Figure 3).

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

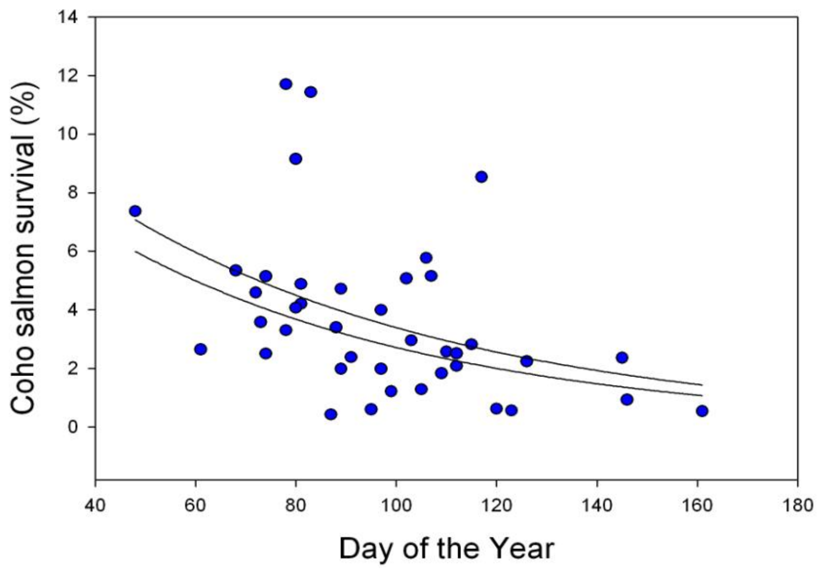


Figure 14. Coho salmon survival vs. day of spring transition, 1969–2005 (Logerwell et al. 2003). The upper curve includes all of the data; the lower curve was calculated after excluding the outlier years of 1969, 1970, 1973 and 1975. The adjusted r^2 doubled when these 4 years were excluded from the regression (r^2 adj = 0.33).

Another measure of the spring transition comes from monitoring of ocean currents on a daily basis. Dr. Mike Kosro, College of Oceanic and Atmospheric Sciences, Oregon State University, operates an array of coastal radars that are designed to track the speed and direction of currents at the sea surface. He produces daily charts showing ocean surface current vectors, and from those one can clearly see when surface waters are moving south (due to upwelling) or north (due to downwelling). By scanning progressive images, the date of transition can be visualized.

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

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

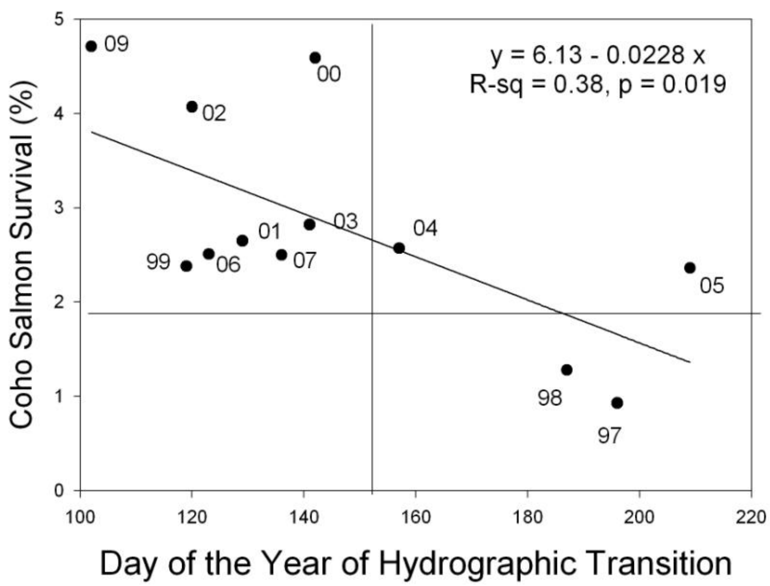


Figure 15. Coho survival vs. spring transition as indicated by the day of the year when bottom water temperature dropped below 8.0°C. The data point for 2009 is based on an expected return of 4.5%, estimated from jack returns.

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 also affect transport of water into the northern California Current. Northerly winds transport water from the north whereas southwesterly winds transport water from the west (offshore) and south.

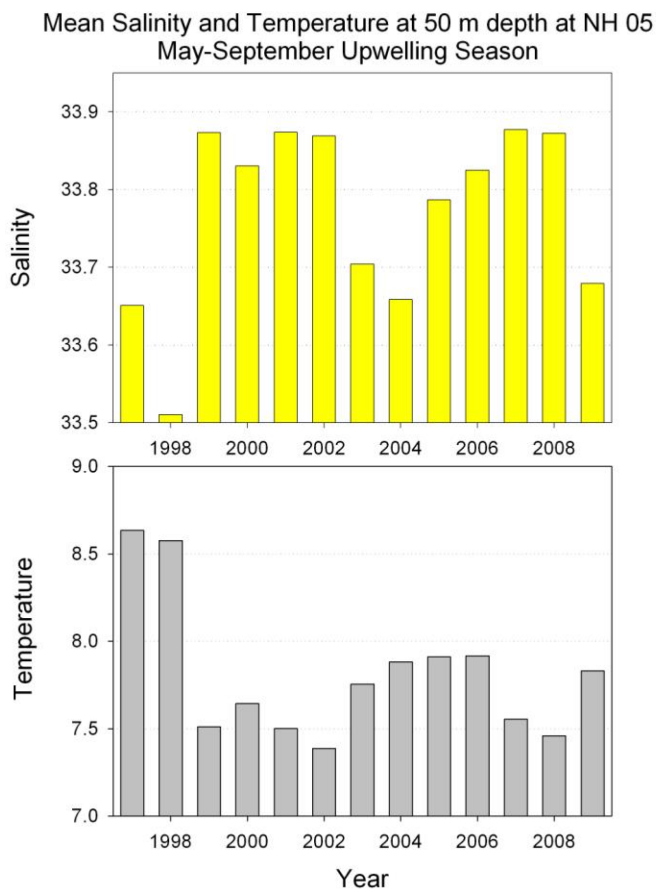


Figure 16. Salinity (upper panel) and temperature (lower panel) at the 50–m depth at station NH 05 (average water depth 60 m) averaged over all cruises from May to September each year. Note that the deeper waters of the shelf in 2009 are slightly warmer and saltier than values observed during the previous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

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 and salty water of subarctic origin is nutrient–rich, whereas the relatively warm and fresh water of the offshore west wind drift, or antarctic circumpolar current (ACC) is nutrient depleted.

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

From these data, two patterns have become clear: first, the years 1997 and 1998 (and to a lesser extent 2004 and 2005) were warmer than average, and corresponded to a warm phase of the PDO. Second, the years 1999–2002 (and to a lesser extent 2003), and especially 2008, were colder than average and corresponded to a cool phase PDO (and to negative SST anomalies at Buoy 46050). The year 2009 is classified as having intermediate values of S and T.

Figure 17 shows the same data, but as a scatter diagram. As Figure 17 illustrates, during the El Niño event of 1997–1998, deep waters on the continental shelf off Newport were warm and relatively fresh, whereas during the negative phase of the PDO (1999–2002 and 2009), they were cold and relatively salty. Note also the unusual nature of hydrographic conditions during summer 2005. This was the summer during which upwelling was not initiated until mid–July, 2–3 months later than normal.

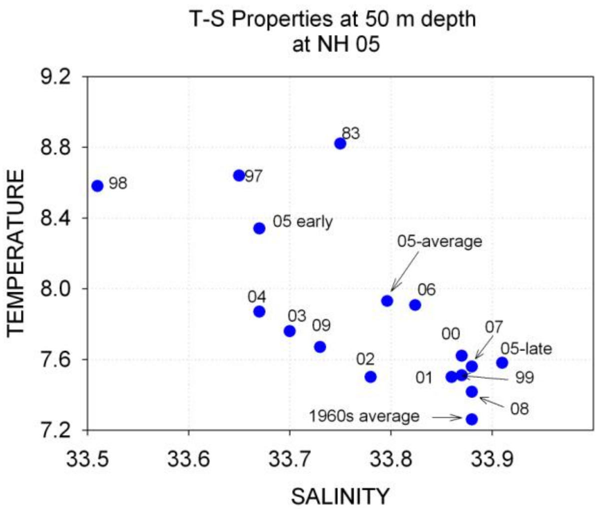


Figure 17. Scattergram of temperature and salinity from 1998 to 2008. Note that 2008 was the coldest year to date and that 2009 was a transitional year, which more closely resembled the "warm" years of 2003–2004.

During 2005, the spring/early summer months resembled summer 1997, when the coastal ocean was dominated by warm (+0.6°C anomaly) and fresher water. However, once upwelling became established, the water properties resembled the cooler conditions (−0.3°C anomaly) that were seen during 1999 and 2002.

Coho salmon survival is high when cold salty water is present in continental shelf waters, and vice versa (Figure 18). That is, during the summer when coho first enter the ocean, if deep waters are relatively cold and salty, we can expect good coho salmon survival.

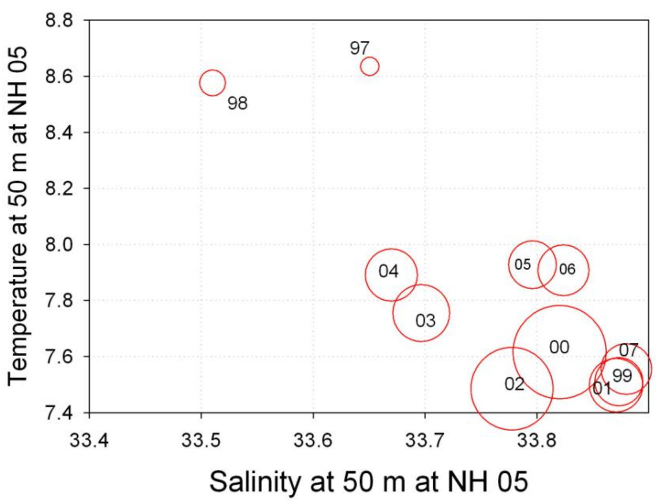


Figure 18. Coho survival shown as a bubble plot vs. temperature and salinity at the 50–m depth at hydrographic station NH 05. Coho survival is high when a "cold salty" water type is present on the continental shelf.

Conversely, if deep water is relatively warm and fresh, coho salmon survival is poor, as in 1997 and 1998. Thus, we can use presence of different water types as a leading indicator of coho survival.

Such a relationship was not as clear for spring and fall Chinook salmon, based on counts of adults at Bonneville Dam 2 years after ocean entry (Figure 19). This may be due to the differences in age class of returning Chinook salmon from the same year class: for both spring and fall life history types, length of the ocean life varies, with some fish returning as 2–year ocean fish and others as 3–year ocean or older. Coho, on the other hand, spend a maximum of 18 months in the ocean, usually entering in the spring of one year and returning in the fall of the next. The plot in Figure 19 shows counts at Bonneville Dam using data from 2 years after the fish entered the sea. Regardless of age at return, it is clear the the 1997 El Niño can probably be blamed for poor adult counts in 1999. The high adult returns in 2001–2003 were preceded by a 4–year period of very cold and salty ocean conditions, and the declining returns in 2005–2007 were preceded by a period when the PDO was positive and deep waters were relatively warm and fresh.

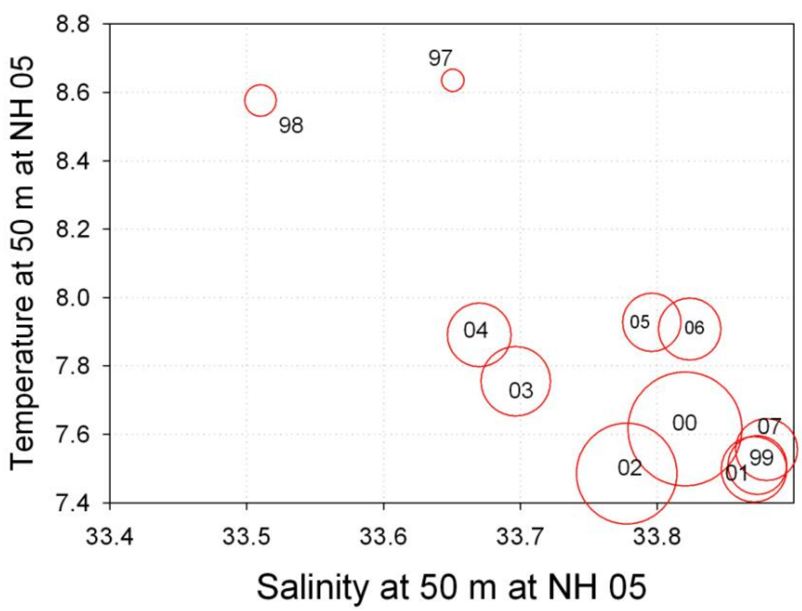


Figure 19. Bubble plot showing relationship between Chinook returns (circles) and summer average temperature and salinity measured at the 50–m depth at hydrographic station NH 05.

LOCAL BIOLOGICAL INDICATORS

Copepod Biodiversity

Being planktonic, copepods drift with the ocean currents; therefore, they are good indicators of the type of water being transported into the Northern California Current. Copepod biodiversity (or species richness) is a simple measure of the number of copepod species in a plankton sample, and can be used to index the types of water masses present in the coastal zone off Oregon and Washington.

For example, the presence of subtropical species off Oregon indicates transport of subtropical water into the northern California Current from the south. Likewise, the presence of coastal, subarctic species indicates transport of coastal, subarctic waters from the north. Thus the presence of certain copepod species offers corroborative evidence that the changes in water temperature and salinity observed during our monitoring cruises were in fact measuring different water types. Figure 20 shows average copepod species richness (i.e., the average number of species from all plankton samples) for each month from 1996 to 2004 at station NH 05.

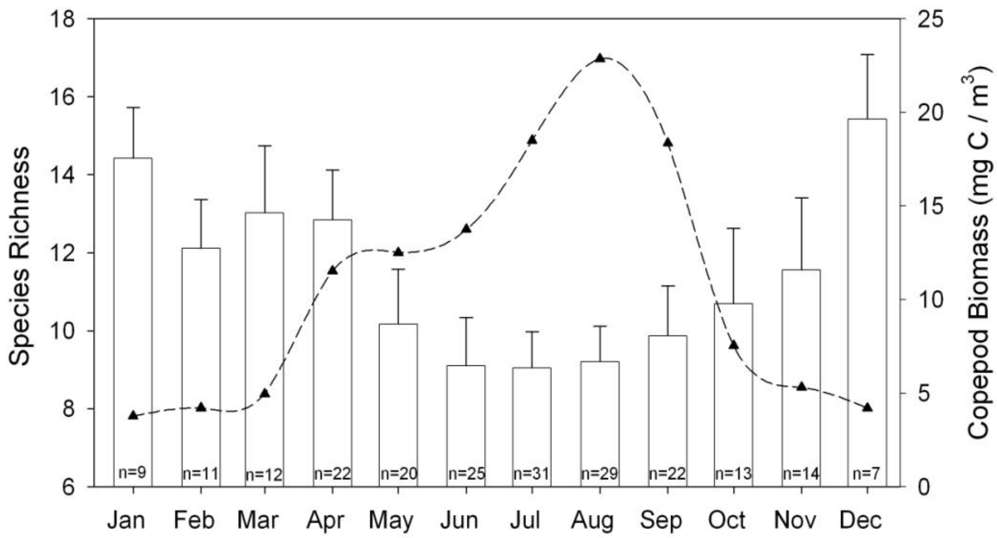


Figure 20. Vertical bars are the climatology of monthly averaged copepod species richness, a measure of biodiversity, at station NH 05 off Newport OR. Dashed line with filled triangles is the climatology of monthly averaged copepod biomass (Y–axis on right side of graph). Note the inverse relationship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

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

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

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

Figure 21 shows monthly anomalies of copepod species richness during 1996–2009. This time series is derived by taking the average number of species for each month, then subtracting the observed monthly average for that month.

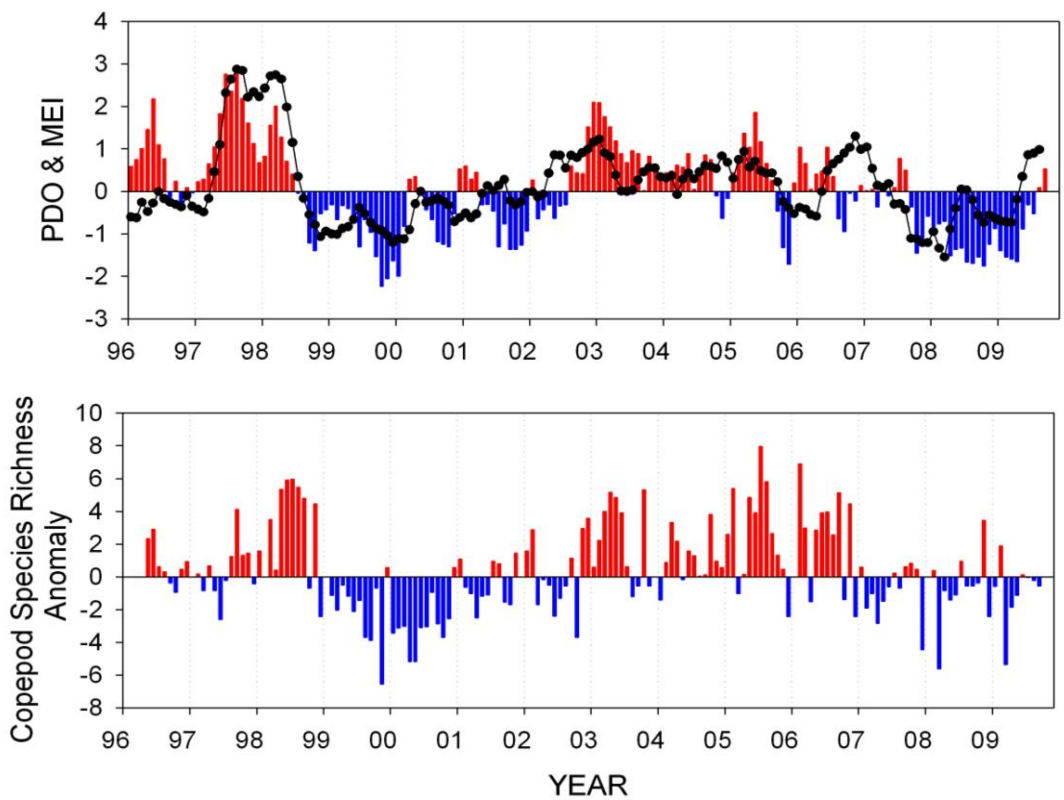


Figure 21. Upper panel shows time series of the PDO and MEI (bars and dots, respectively) from 1996 to the present. Lower panel shows copepod species richness during the same period. Note the time lag of a few months between long–term persistent shifts in the PDO/MEI and copepod species richness, as seen in mid–1998, mid–2002, and late 2007.

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

Note that three pronounced changes in copepod species richness lagged the PDO and MEI by about 6 months. The first of these was in 1998, when a change to a negative anomaly of species richness in December was preceded by sign changes of the PDO in July and the MEI in August. The second pronounced change was seen in 2002, with the shift to a positive anomaly of copepod species richness in November, which followed changes in the PDO and MEI in August and April, respectively. The third change is not as clear, but was initiated in summer 2007.

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

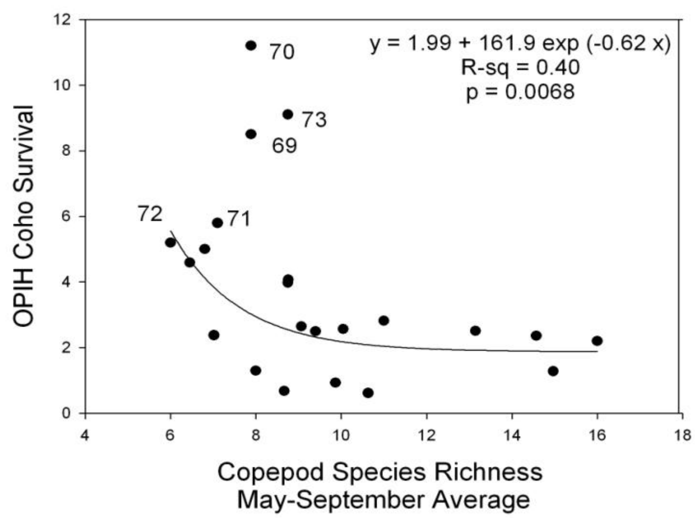


Figure 22. Scattergram showing relationship between copepod species richness and survival of OPHI coho salmon. The regression equation shown was calculated for 1969–2009 after excluding the years 1969, 1970, and 1973, years with extraordinarily high survival.

We have found that this simple measure of species richness is correlated with the OPIH survival time series (Figure 22), suggesting that copepods are reasonably good indicators of salmon survival.

The regression of OPIH coho on copepod species richness is somewhat biased and complicated by the trend towards increasing species richness with time. Figure 23 shows that species richness has increased at a rate of 4.4 species over the past 40 years. The implications of this increase in species remains unclear since the "new" species are chiefly subarctic (cold water) neritic species (see Peterson 2009).

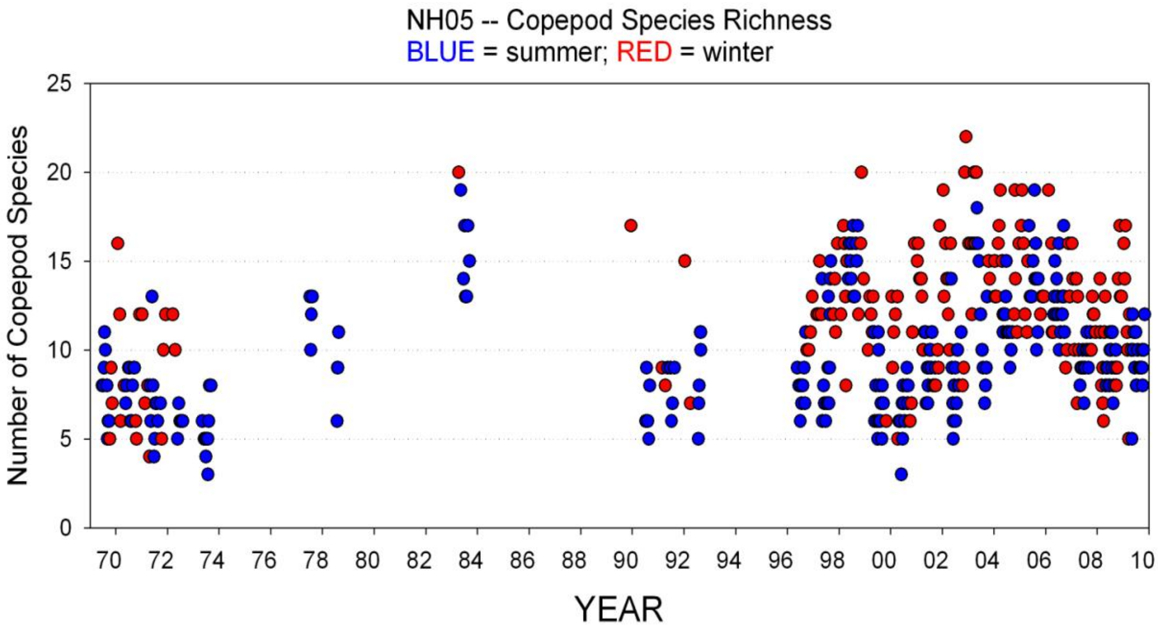


Figure 23. Time series of copepod species richness, from 1969 to present. Note that the number of copepod species has been increasing over the past decade compared to the 1970s.

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*, *C. arcuicornis* and *C. parapergens*, *Calocalanus styliremis*, and *Corycaeus anglicus*.

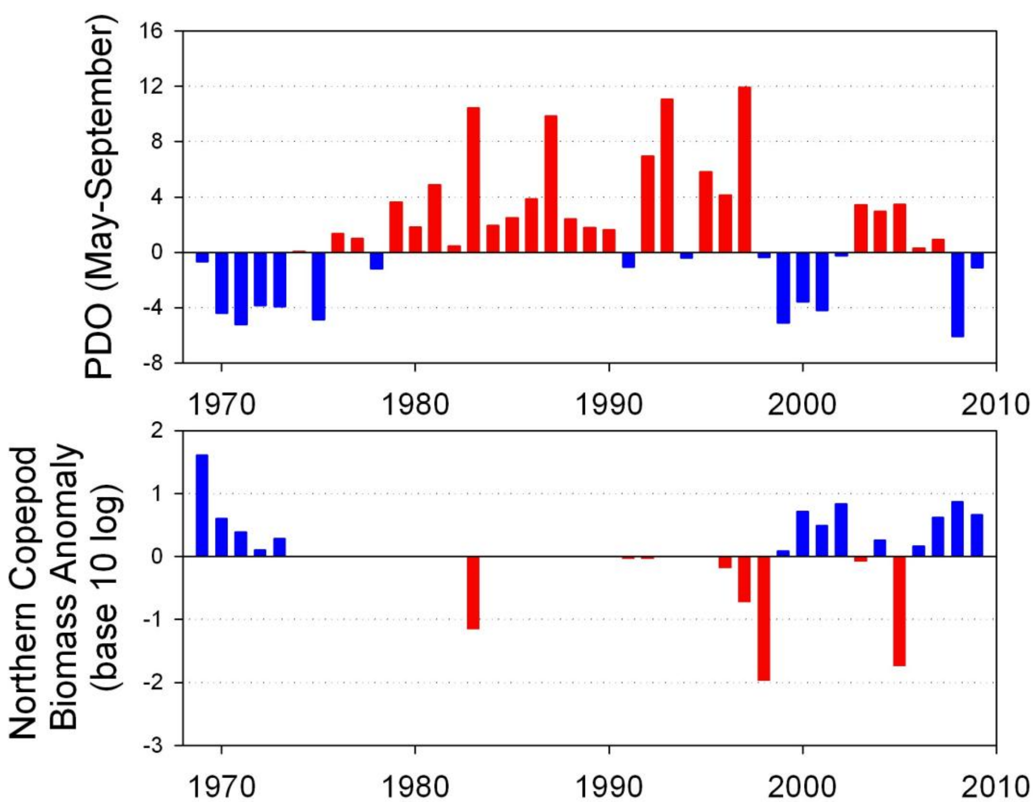


Figure 24. The Pacific Decadal Oscillation (upper), and northern copepod biomass anomalies (lower), from 1969 through 2009. Biomass values are log base–10 in units of mg carbon m^{-3}.

The cold–water group usually dominates the Washington/Oregon coastal zooplankton community in summer, whereas the warm–water group usually dominates during winter ([Peterson and Miller 1977](#); [Peterson and Keister 2003](#)). This pattern is altered during summers with El Niño events and/or when the PDO is in a positive (warm) phase. At such times the cold–water group has negative biomass anomalies and the warm group positive anomalies. Figure 24 shows a time series of the PDO, along with biomass anomalies of northern and southern copepod species averaged over the months of May through September. Changes in biomass among years can range over more than one order of magnitude. When the PDO is negative, the biomass of northern copepods is high (positive) and biomass of southern copepods is low (negative), and vice versa.

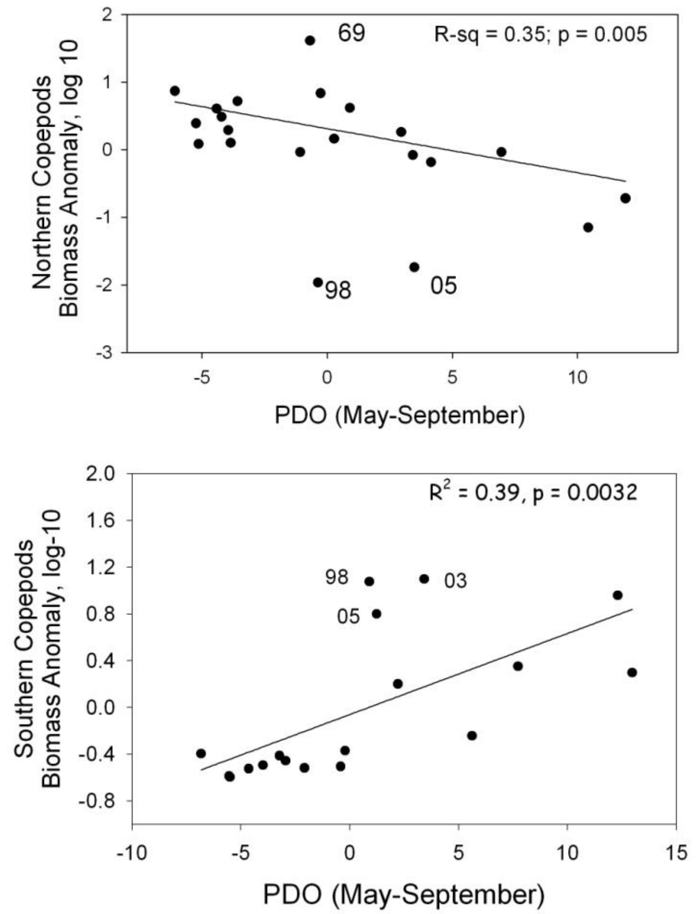


Figure 25. Regression of northern (upper) and southern copepod anomalies (lower) vs. the PDO. Units of biomass are mg carbon m^3. Strongly negative PDO values lead to high biomass of cold–water copepods and vice versa. The regression line shown was calculated after excluding the outlying data points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

Figure 25 shows the same data, but as a scatter gram, with copepod anomalies plotted against the PDO. We hypothesize that the correspondence between the PDO and northern copepod anomalies is due to physical coupling between the sign of the PDO, coastal winds, water temperatures, and the types of source water (and zooplankton which they contain) that enter into the northern California Current and the coastal waters off Oregon.

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, (such as those in 1996, 1997, 2004, and 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 species. Therefore, an index of northern copepod biomass may also index the amount of wax–esters and fatty acids being fixed in 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.

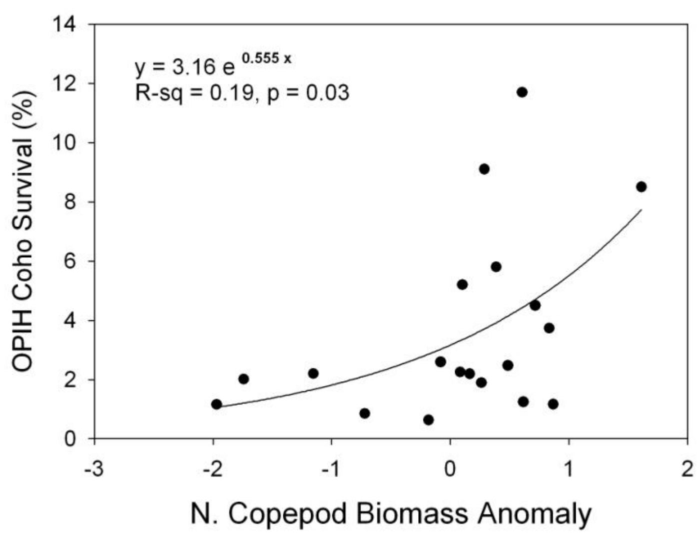


Figure 26. Regression of OPIH coho survival on the northern copepod biomass anomalies.

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 these species as opposed to cold–water species. Therefore, salmon feeding on pelagic fish, which have in turn fed on warm–water copepod species, may experience a relatively lower probability surviving the winter.

The "northern copepod index" appears to be a good predictor of the survival of hatchery coho salmon. Figure 26 shows the correlation between OPIH coho and northern copepod biomass anomalies. The correlation is based on the year of ocean entry, that is, OPIH values for year + 1 are regressed on copepod biomass in year 1. Figure 27 shows similar relationships for adult fall Chinook counts and for adult spring Chinook counts at Bonneville Dam. Both are lagged by 2 years.

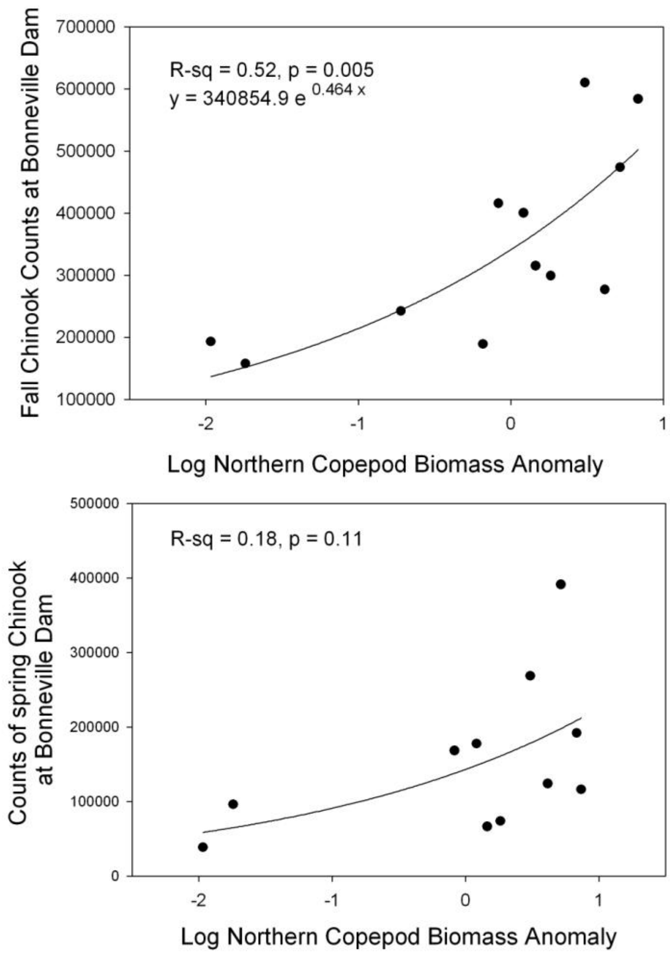


Figure 27. **Upper panel** shows relationship between counts of fall Chinook at Bonneville Dam and log of the northern copepod biomass anomaly. Counts at Bonneville are lagged by 2 years. For example, the copepod biomass anomaly in 1996 is related to counts at Bonneville in fall 1998, 2 years after ocean entry. **Lower panel** shows counts of spring Chinook at Bonneville Dam vs. northern copepod biomass anomaly. The two are somewhat related, but only at the $P = 0.11$ level.

Copepod Community Structure

We have developed a new index, as part of our "stoplight" forecasting suite, based on the presence/absence of two alternate copepod community types. Data sets upon which this index is based are from biweekly sampling of zooplankton off Newport, which has been ongoing since 1996, and from sampling during our juvenile salmonid surveys, which have been carried out each June and September since 1998.

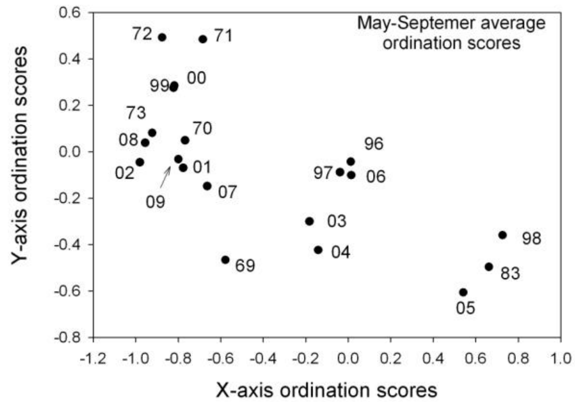


Figure 28. Ordination of average copepod community structure during May–September by year. Years when summer community structure was dominated by cold, boreal species fall into the left quadrant (1970–1973, 1999–2002, 2007–2009); years with warm subtropical species fall in to the center of the graph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

The indicator of "copepod community structure" is based on *multidimensional scaling* (MDS), an ordination technique (Figure 28). The full ordination is not shown, but rather the averaged X– and Y–axis scores: two axes alone accounted for about 90% of the variability (X–axis for 69%; Y–axis for 13%). The figure below compares summer-average X– and Y–axis scores.

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

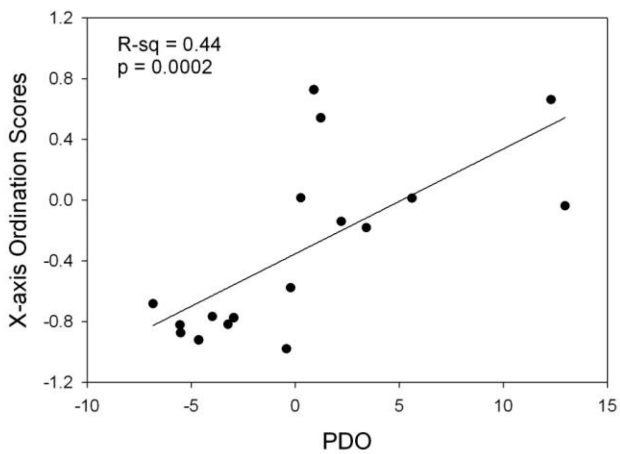


Figure 29. Relationship between the PDO and X–axis ordination scores. A "cold water zooplankton community" is associated with the negative (cold) phase of the PDO and vice versa.

Coho survival is related to the copepod community structure in that when a cold water community dominates, coho survival is often high, and vice versa (Figure 30). The link between copepods and salmon is almost certainly through the food web, in that 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, smelts and sand lance.

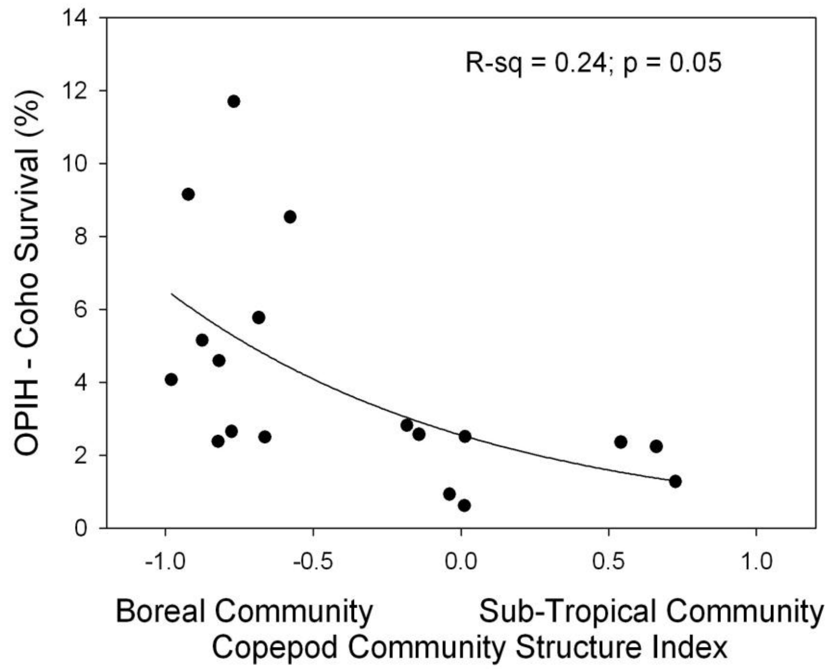


Figure 30. Relationship between coho survival and copepod community structure. The stronger the boreal community, the greater the coho survival. Note also that when a subtropical copepod community prevails, coho survival usually averages < 2%.

Biological Spring Transition

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

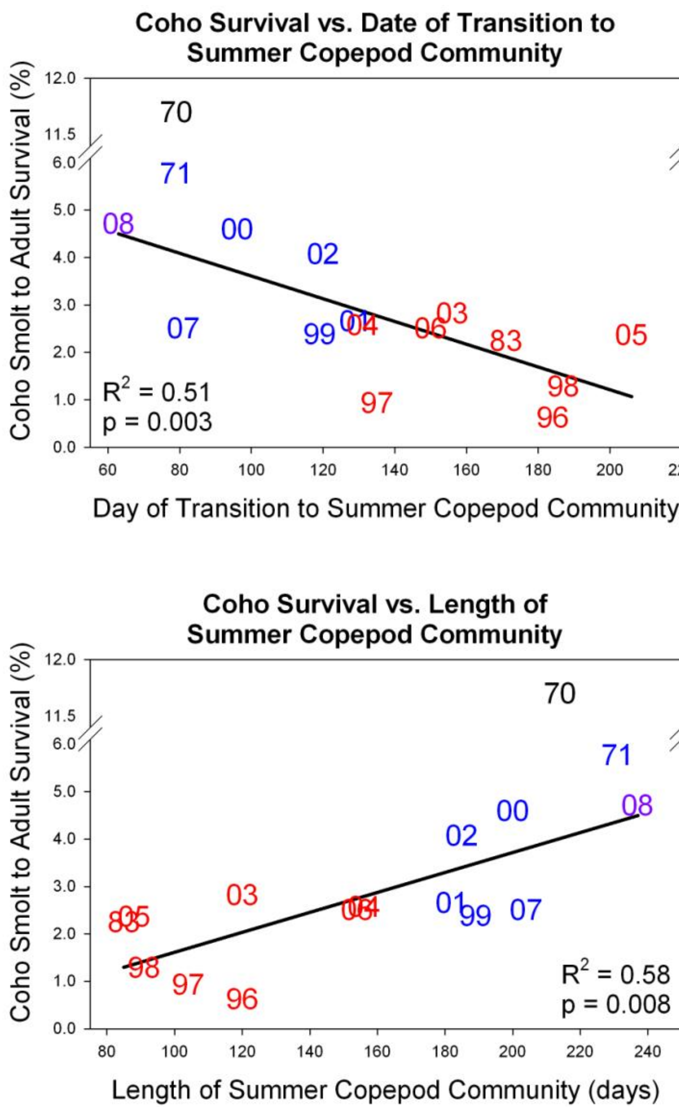


Figure 31. **Upper plot** shows regression of coho survival vs. day of the year when copepod community structure transitioned to a summer community. The earlier this transition takes place, the higher coho survival. **Lower plot** shows regression of coho survival vs. length of the "biological" upwelling season, measured as the number of days that the summer community structure persisted. Data from the year 1970 were excluded from the regression.

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 coho and Chinook salmon seem to prefer; 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 the 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 fails to correctly indicate feeding conditions.

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

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

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

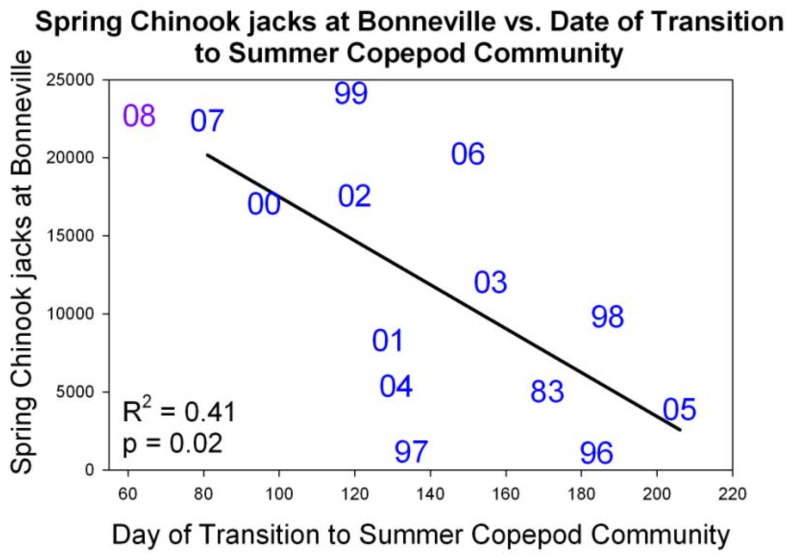
Table 6. Historical dates of the Biological Spring Transition, as measured by the timing of change in the zooplankton from a winter to a summer community.

Year	Arrival of cold–water copepod community Start date	 End date	Length of cold–water copepod presence (in days)
1970	~20 Mar	20 Oct	214
1971	20 Mar	6 Nov	231
1983	20 Jun	13 Sep	85
1996	3 Jul	31 Oct	120
1997	15 May	27 Aug	104
1998	never	never	0
1999	14 May	4 Nov	174
2000	6 Apr	4 Nov	200
2001	11 Apr	7 Nov	210
2002	30 Apr	1 Nov	185
2003	5 June	3 Oct	120
2004	25 May	14 Oct	142
2005	18 Aug	21 Oct	64
2006	30 May	31 Oct	154
2007	30 Mar	12 Oct	196
2008	4 Mar	27 Oct	237
2009	24 Mar	—	—

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

The arrival of the "northern" species in spring signals that the ecosystem is primed to begin a productive upwelling season. Also listed is the length of the upwelling season, in days, as reckoned by the zooplankton. Note that transition dates over the past 3 years have all come very early, in March.

Both the date of "biological spring transition" and "length of the biological upwelling season" correlate well with jack counts of spring Chinook salmon (1–year lag; Figure 32) and adult counts of fall Chinook salmon at Bonneville Dam (2–year lag; Figure 33). In the case of adult fall Chinook, the year 2007 was an outlier: had it not been included in the linear regression, then R^2 would have increased to 51% for the transition date ($P = 0.008$) and 63% for length of the biological upwelling season ($P = 0.0021$).



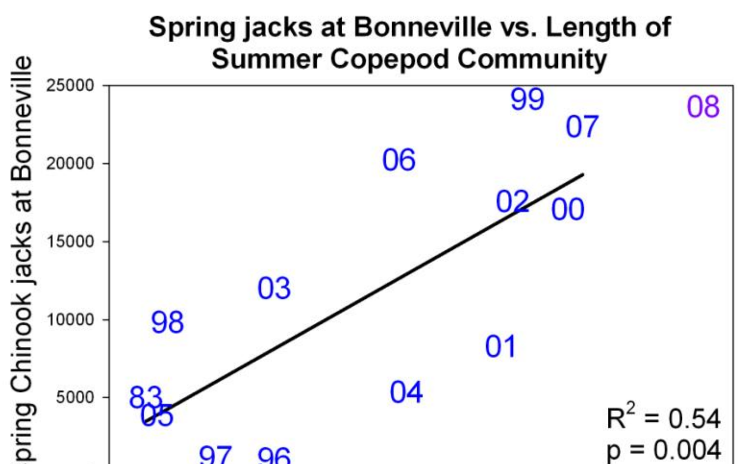
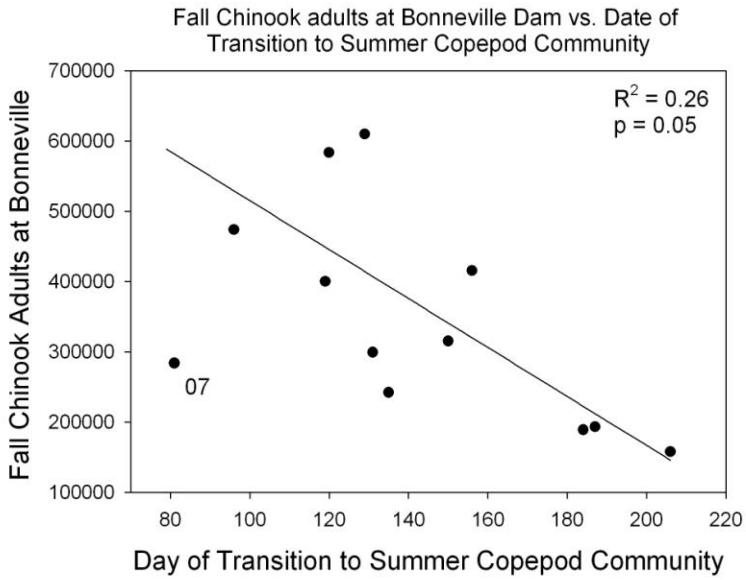


Figure 32. Counts of spring Chinook salmon jacks at Bonneville Dam vs. date of the biological spring transition and length of the biological upwelling season.



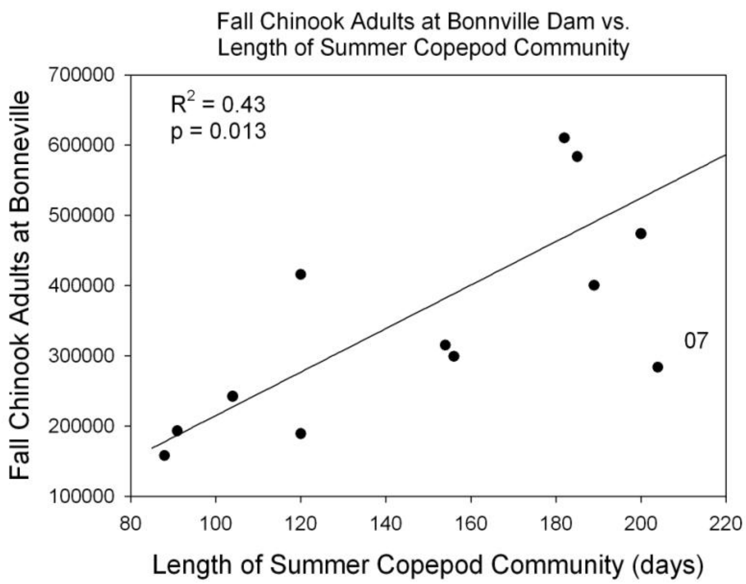


Figure 33. Fall Chinook adults counts at Bonneville Dam vs. date of the biological spring transition and length of the biological upwelling season.

Catches of Yearling Chinook in June and Coho in September

Numbers of juvenile salmon caught during our June and September trawl surveys can serve as an index or surrogate measure of ocean survival for spring Chinook and coho salmon. Figure 34 shows catch per unit effort (CPUE) during our trawl surveys from 1998 to 2009.

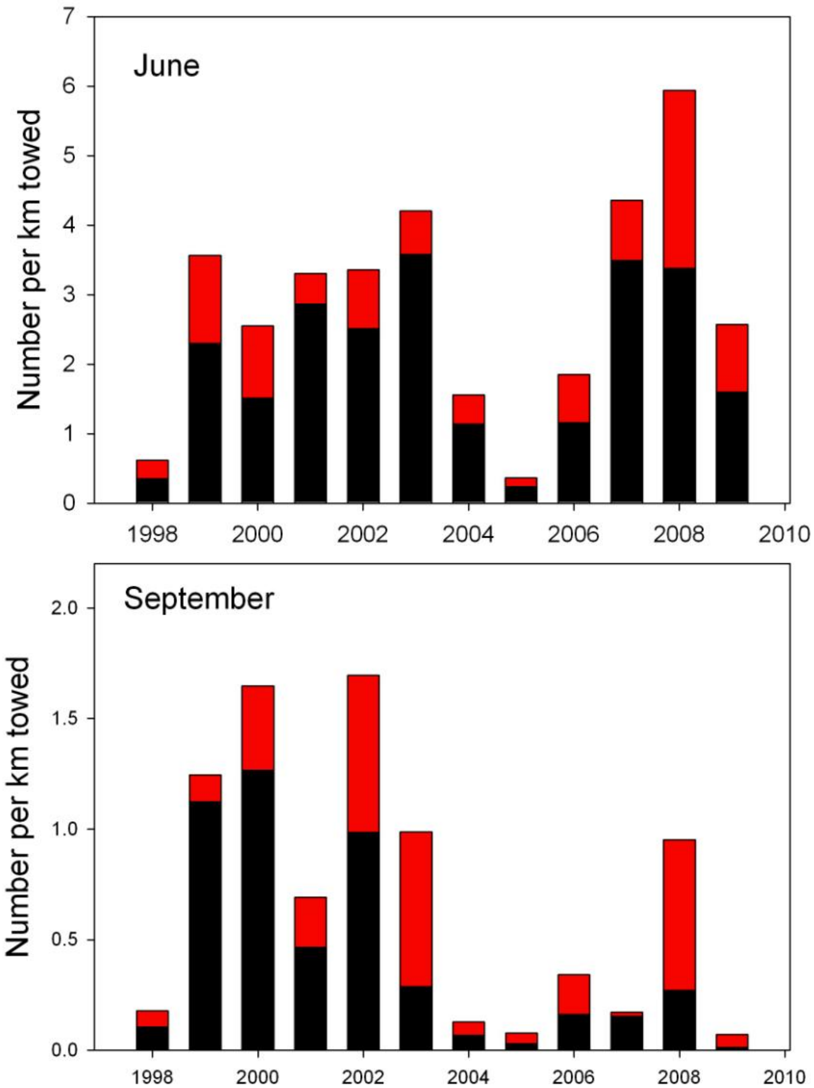


Figure 34. Average catches of juvenile coho (black bars) and spring Chinook (red bars) during trawl surveys off the coast of Washington and Oregon. Surveys were conducted in June (upper panel) and September (lower panel) from 1998 to 2009.

Catch rates were lowest for both species during 2005, but rebounded gradually during 2006–2008, only to decline again in 2009. Catches of coho in September 2009 were the lowest in our 12 years of surveys.

Figure 35 shows the relationship between catches of juvenile Chinook and coho and returns the following year of coho adults and Chinook jacks. In the upper panel, trawl catches of coho in September of year *i* are correlated with adult counts from the Oregon Production Index of hatchery coho adult returns (OPIH in year *i* + 1). Similarly, catches of yearling Chinook in June of year *i* are correlated with counts of spring Chinook jacks at Bonneville Dam in year *i* + 1.

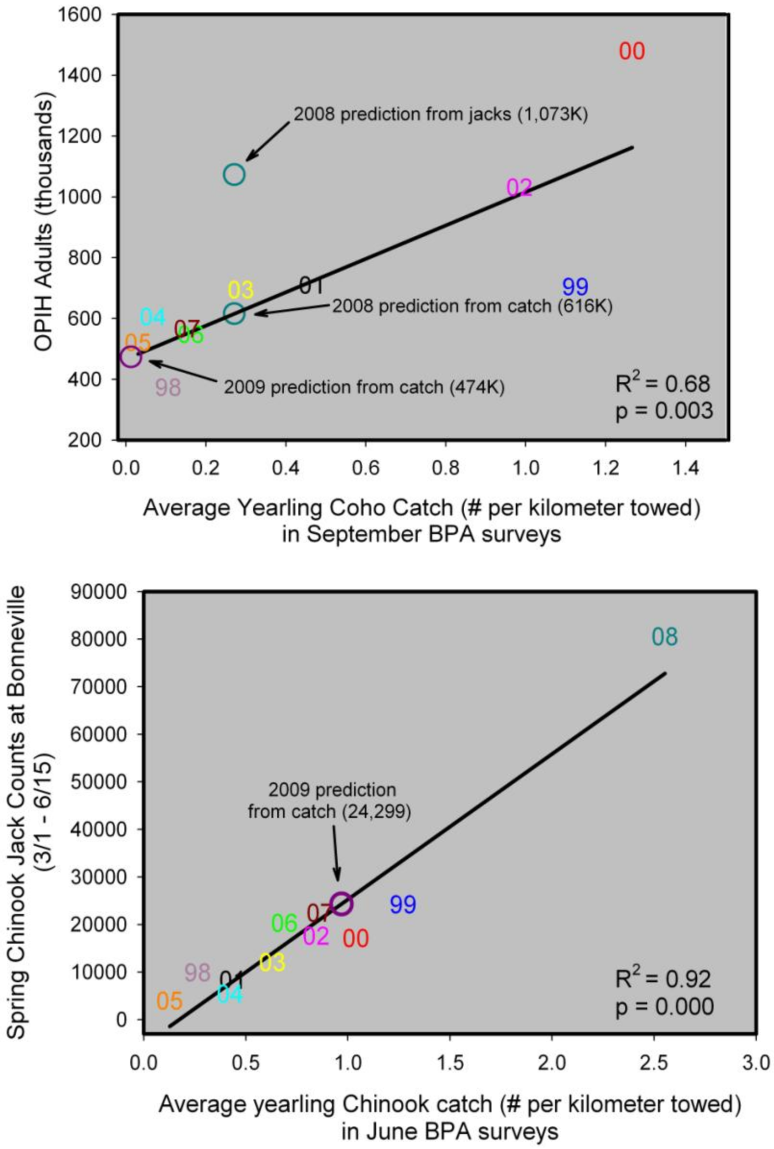


Figure 35. **Upper panel** shows regression of OPIH adult coho salmon abundance on the average CPUE of juvenile coho salmon catches in trawl surveys the previous September. Years indicated are for catches of juvenile fish. Maroon open circle indicates observed juvenile CPUE (0.02) in September 2008 and predicted OPIH from the regression (474 thousand). **Lower panel** shows regression of spring Chinook salmon jack counts at Bonneville Dam (1998–2009) vs. average CPUE of yearling Chinook salmon caught during each of our June cruises. Open point indicates observed CPUE in June 2009 (0.97) and predicted OPIH from the regression (24,299).

Zooplankton Species Composition

Zooplankton samples collected in winter 2006 and early spring 2007 show a copepod community that is dominated by cold–water subarctic species, namely *Pseudocalanus mimus* and *Calanus marshallae*. The copepods, *Neocalanus plumchrus/flemingerii* and *N. cristatus* have been unusually abundant this spring, and this has continued through May 2007. This is a very good sign, and these copepods have been found from inner shelf waters to at least 125 miles from shore.

This species composition indicates either a greater–than–average influx of subarctic waters (from the Gulf of Alaska) or a "normal" influx of subarctic waters containing a greater–than–average abundance of these copepods. Either case is good for fishes that feed on *Neocalanus*—in particular juvenile rockfish and sablefish. Thus, 2007 should be an excellent recruitment year for sablefish (black cod). Moreover, copepod biodiversity declined during winter 2007, indicating that a cold–water community has moved into the area.

INDICATORS UNDER DEVELOPMENT

North Pacific Gyre Oscillation

As discussed earlier in this document, changes in sign of the PDO (i.e., the spatial pattern in SST) tends to follow an east/west dipole such that when the North Pacific is cold in the west, it is warm in the east (negative phase), and vise versa (positive phase). There is variability in the SST pattern in a north-south direction and this is described by the second mode of the PDO (or Victoria pattern). A new index, termed the North Pacific Gyre Oscillation (NPGO), is derived from the second mode of sea surface height anomalies and accounts for most of the variability in sea surface salinity. The NPGO index is calculated from satellite altimeter data and on a ROMS model and is closely related to the second EOF of the North Pacific SST anomalies (or Victoria pattern). Positive values of the NPGO indicate stronger circulation within both the eastern and central branches of the sub-polar and sub-tropical gyres in the north Pacific, and vice versa. For details see Chhak et al. 2009.

We have not yet investigated this pattern fully because the negative phase of the first mode (the PDO) seems to apply to coastal waters north of approx 40°N whereas coastal waters south of 38-40°N seem better correlated with the NPGO. We have just begun to examine correlations between PDO, NPGO and salmon returns in the Pacific Northwest. We are examining the idea that years when the PDO is in negative phase **and** when the NPGO is in positive phase would be characterized as the best possible ocean conditions for salmon survival.

Phytoplankton Biomass

Based on samples collected along the Newport Hydrographic Line, we developed time series of both total chlorophyll, the fraction of chlorophyll smaller than 10 µm, and species composition of the phytoplankton. These data serve as estimates of phytoplankton biomass, and can 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. We have also shown that the distribution of chlorophyll is well-correlated with area of suitable habitat of juvenile salmonids (Bi et al. 2007, 2008).

Euphausiid Egg Concentration and Adult Biomass

Euphausiids are a key prey item for juvenile coho and Chinook salmon. Sampling along the Newport Hydrographic Line since 1996 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 (Bi et al. 2007, 2008). Interannual variation in potential habitat area may also serve as a correlate for salmon survival during the first summer at sea.

Forage Fish and Pacific Hake Abundance

We hope to develop an index that describes food web interactions between juvenile salmon and their fish predators, chiefly Pacific whiting, also known as Pacific hake. The index will 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: the hypothesis is that during most warm years, hake moves into continental shelf waters, where salmon may be more susceptible to predation. During cold years, hake feeds in deeper waters offshore, near the shelf break; thus they may not be actively feeding in water inhabited by juvenile salmon.

During cold conditions, where zooplankton production is high, small forage fish biomass increases. The advantage to salmon of high forage fish abundance is that predators are more likely to "see" forage fish than salmon because there are far more of them present in the water column. Since forage fish populations do well during cold conditions but tend to crash during warm conditions, there will likely be time lags of one or more years 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.

Metrics of salmon performance

All juvenile salmon collected during our pelagic trawl surveys are frozen and returned to the laboratory for analysis of a number of “performance” indicators. Length (L) and weight (W) is measured and an index of “condition” is calculated from the ratio of log W to log L. Stomach contents are examined, parasites are removed and presence of diseases such as BKD is assessed. Growth is estimated from analysis of scales, otoliths and through measurement of IGF in blood samples. Muscle samples are taken and wet and dry weights measured as a crude measure of lipid content. Each fish is typed genetically as to stream-of-origin using microsatellites, thus ultimately we could estimate habitat parameters on a stock by stock basis.

FORECAST OF ADULT RETURNS FOR COHO IN 2010 AND CHINOOK SALMON IN 2011

From the color scheme in Table 1 below, one can see that the poor ocean conditions during 2003–2006 began to improve during 2007 and greatly improved during 2008. The most negative winter PDO since 2000 and most negative summer PDO since 1955 were seen in 2008. Also in 2008, we observed the coldest winter sea surface temperatures of the past 12 years (and probably since the 1970s) and the earliest biological spring transition and highest northern copepod biomass of the past 13 years. The latter included an anomalously high biomass of the large, lipid–rich subarctic copepods, *Neocalanus plumchrus* and *N.* cristatus. During the first half of 2009, the PDO initially continued the same trend observed in 2008, that is, a strongly negative signal through winter and spring. However, the strong negative PDO began to weaken in June and abruptly turned positive in August. Key observations of ocean ecosystem indicators in 2009 included:

Positive signs

- Negative PDO through winter and spring
- Colder–than–normal sea surface temperature anomalies (–1°C) from January through May
- Early timing of coastal upwelling and the biological spring transition (both on 23 March)
- High biomass of northern copepods (4th highest since 1998)
- High CPUE of yearling Chinook salmon during the June survey (4th highest of the past 12 years)

Negative signs

- Negative PDO signal weakened in May and turned positive by August
- Discontinuous coastal upwelling (upwelling was interrupted by 5 major relaxation events)
- Warm sea surface temperatures, with respective +1, +2, and +3°C anomalies in June, August, and September
- Catches of juvenile coho were low in June (7th of 12 surveys) and ranked lowest in September (12th of 12 surveys)

Based on superior ocean conditions during spring–summer 2008, we expect spring Chinook runs in 2010 to rival the high returns of this species seen in 2001 and 2002. This was our forecast last year based on ocean indicators, and our expectation is now supported by high returns of spring Chinook jacks in fall 2009. However, expectations for returns of coho in 2010 are considerably lower due to warm sea–surface conditions throughout August 2009 and low catches of coho salmon in our June and September surveys.

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

Table 1. Ocean ecosystem indicators of the Northern California Current. Colored squares indicate positive (green), neutral (yellow), or negative (red) conditions for salmon entering the ocean each year. In the two columns to the far right, colored dots indicate the forecast of adult returns based on ocean conditions in 2009.

	Juvenile migration year				Forecast of adult returns	
	2006	2007	2008	2009	Coho 2010	Chinook 2011
Large–scale ocean and atmospheric indicators						
PDO (May–Sep)	■ yellow	■ red	■ green	■ yellow	● green	● green
MEI (annual)	■ yellow	■ green	■ green	■ yellow	● yellow	● yellow
Local and regional physical indicators						
Sea surface temperature anomalies	■ yellow	■ red	■ green	■ yellow	● yellow	● yellow
Coastal upwelling	■ yellow	■ green	■ green	■ yellow	● yellow	● yellow
Physical spring transition	■ red	■ green	■ yellow	■ yellow	● yellow	● yellow
Deep water temperature and salinity	■ red	■ yellow	■ green	■ yellow	● yellow	● yellow
Local biological indicators						
Copepod biodiversity	■ red	■ yellow	■ green	■ yellow	● yellow	● yellow
Northern copepod anomalies	■ yellow	■ green	■ green	■ green	● green	● green
Biological spring transition	■ red	■ green	■ green	■ green	● green	● green
June spring Chinook	■ yellow	■ green	■ green	■ green	—	● green
September Coho	■ yellow	■ red	■ yellow	■ red	● red	—

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

Table 2. Rank scores upon which color–coding of ocean ecosystem indicators is based. Lower numbers indicate better ocean ecoystem conditions, or "green lights" for salmon growth and survival, with ranks 1–4 green, 5–8 yellow, and 9–12 red. To arrive at these rank scores, 12 years of sampling data were compared across years (within each row), and each year received a rank between 1 and 12. Note that 2008 was characterized by the best ocean conditions over the 12–year period, whereas 2009 ranked 7th of 12, suggesting below–average returns of coho in 2010 and Chinook in 2011.

Environmental Variables	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
PDO (December-March)	11	4	2	8	5	12	7	10	9	6	3	1
PDO (May-September)	9	2	3	4	6	11	10	12	8	7	1	5
MEI Annual	12	1	3	5	11	10	8	9	6	4	2	7
MEI Jan-June	12	2	3	5	8	10	7	11	4	9	1	6
SST at 46050 (May-Sept)	10	8	3	4	1	6	12	9	5	11	2	7
SST at NH 05 (May-Sept)	8	2	1	4	6	7	12	11	5	9	3	10
SST winter before going to sea	12	7	5	6	4	8	11	10	9	3	1	2
Physical Spring Trans (Logerwell)	8	7	2	1	4	10	9	12	10	3	6	5
Upwelling (Apr-May)	7	1	11	3	6	10	9	12	7	2	4	5
Deep Temperature at NH 05	12	5	6	3	1	8	9	10	11	4	2	7
Deep Salinity at NH05	12	5	6	4	3	10	11	8	7	1	2	9
Length of upwelling season	7	3	2	10	1	11	9	12	6	5	8	4
Copepod richness	12	2	1	5	3	9	8	11	10	6	4	7
N.Copepod Anomaly	12	9	3	6	2	10	7	11	8	5	1	4
Biological Transition	11	5	4	7	6	10	8	12	9	2	1	3
Copepod Community structure	12	3	4	6	1	8	9	11	10	7	2	5
Catches of salmon in surveys												
June-Chinook Catches	11	2	3	9	6	8	10	12	7	5	1	4
Sept-Coho Catches	9	2	1	4	3	5	10	11	7	8	6	12
Mean of Ranks of Environmental Data	10.4	3.9	3.5	5.2	4.3	9.1	9.2	10.8	7.7	5.4	2.8	5.7
RANK of the mean rank	11	3	2	5	4	9	10	12	8	6	1	7

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

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

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
PDO (December-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
PDO (Sum May-September)	0.9	-5.54	-3.23	-2.95	-0.47	3.42	2.21	3.94	0.28	0.18	-6.08	-1.11
MEI Annual	0.87	-0.85	-0.51	-0.18	0.59	0.46	0.38	0.40	0.22	-0.20	-0.65	0.32
MEI Jan-June	2.28	-0.80	-0.63	-0.28	0.32	0.55	0.27	0.65	-0.42	0.49	-0.84	-0.23
SST 46050 (°C)	13.70	13.14	12.54	12.56	12.30	12.92	14.59	13.43	12.60	13.88	12.5	13.02
SST NH 05 Summer (°C)	11.34	10.89	10.62	10.91	11.14	11.2	12.99	12.24	11.02	11.55	10.9	12.00
SST NH 05 Winter Before Entering (°C)	12.11	10.52	10.26	10.31	10.01	10.81	11.32	11.07	10.92	9.96	9.03	9.63
SST NH 05 Winter After Entering (°C)	10.52	10.26	10.31	10.01	10.81	11.32	11.07	10.92	9.96	9.03	9.63	
Physical Spring Trans Logerwell (day of yr)	105	91	72	61	80	112	110	145	112	74	89	82
Upwelling Anomaly (April-May)	-14	19	-36	2	-12	-34	-27	-55	-14	9	0	-5
NH 05 Deep T (°C)	8.566	7.58	7.643	7.522	7.386	7.754	7.882	7.911	7.916	7.555	7.46	7.70
NH 05 Deep S	33.53	33.85	33.83	33.86	33.87	33.7	33.66	33.79	33.82	33.88	33.9	33.73
Length of upwelling season (days)	191	205	208	173	218	168	178	132	194	200	180	201
Copepod richness (no. of spp.)	5.49	-2.46	-3.03	-0.41	-0.72	1.52	0.57	5.02	3.67	-0.39	-0.53	-0.35
Northern Copepod Biomass (log biomass)	-1.97	0.084	0.717	0.486	0.834	-0.08	0.262	-1.74	0.163	0.617	0.87	0.662
Biological Transition (day of year)	187	119	96	129	120	156	131	206	150	81	63	83
Copepod Community structure (x-axis ordination)	0.726	-0.82	-0.82	-0.78	-0.98	-0.18	-0.14	0.541	0.15	-0.66	-0.96	-0.8
June-Chinook Catches (fish per km)	0.26	1.27	1.04	0.44	0.85	0.63	0.42	0.13	0.69	0.86	2.55	1.00
Sept-Coho Catches (fish per km)	0.11	1.12	1.27	0.47	0.98	0.29	0.07	0.03	0.16	0.15	0.27	0.01

In figure 36 below, counts of adult salmon at Bonneville Dam are compared to the "Rank of mean ranks" from Table 2. Using "Rank of the mean ranks" is a simple integrative index that we suggest expresses ocean conditions in the year that the salmon went to sea. As can be seen in the figure below, this integrative index correlates well with adult counts at Bonneville.

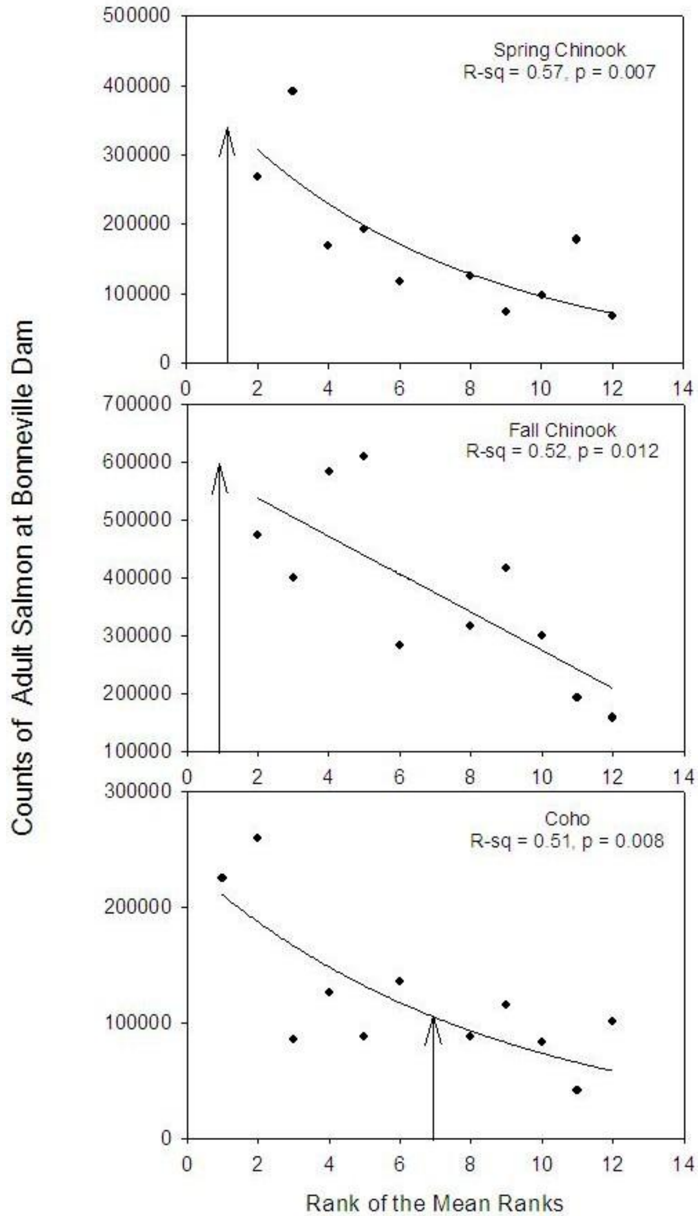


Figure 36. Counts of adult salmon vs. rank of mean ranks for ocean indicators. Vertical arrows indicate expected returns based on the year of ocean entry (2008 for Chinook salmon, when overall ocean conditions were ranked 1st, and 2009 for coho salmon, when overall ocean conditions ranked 7th).

ADULT RETURNS OF CHINOOK AND COHO SALMON

For specific stocks of Chinook and coho, the proportion of adult returns from a particular juvenile year class is not often available. To obtain this information, one would first need to know the number of juveniles that survived to the smolt stage and migrated to the ocean, and then wait 0.5–2 years for coho or 1–5 years for Chinook to obtain the total number of returning adults (Healy 1991; Sandercock 1991).

Even then, it would be difficult to distinguish the proportion of fish that died during migration prior to entering the ocean vs. those that died at sea. Therefore, adult return data that is available, such as counts at dams or traps, can be used only as an index or surrogate measure of abundance. With these caveats in mind, we present adult return data from various sources with which to compare forecasts based on ocean indicators.

The table below is color–coded according to ranks of adult return data from each ocean-entry year for which we have corresponding ocean indicator data. Note that the adult data lags behind the year of ocean entry by 1 year for coho and 2-3 years for spring and fall Chinook salmon. Therefore, 3 fewer years of data are available for comparison in ranking adult returns among years than in ranking ocean ecosystem indicators. For example, as of 2009 we have 12 years of indicator data and 9 years of adult return data. This is why the color–coding system for adult data is slightly different than that of the ocean indicators, with rankings of 1−3 coded green, 4−6 yellow, and 7−9 red.

Table 4. Ranks among years for adult returns by year of ocean entry from 1998 to 2006. With 9 years of available data, color-coded ranks are 1−3 green, 4−6 yellow, and 7−9 red.

Adult returns by Year of Ocean Entry[1]

	OPIH Coho (adults:smolts)	Bonneville spring Chinook (n)	Bonneville fall Chinook (n)	Klamath River fall Chinook (n est.)
1998	**9**	**4**	**5**	**1**
1999	**5**	**1**	**3**	**3**
2000	**2**	**2**	**1**	**4**
2001	**3**	**3**	**2**	**2**
2002	**1**	**5**	**4**	**6**
2003	**4**	**8**	**7**	**8**
2004	**7**	**7**	**9**	**9**
2005	**6**	**9**	**6**	**5**
2006	**8**[2]	**6**	**8**	**7**[2]

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

2 Estimate based on jack returns.

Data used in the rank scores above are shown in the chart below. Again, counts of spring and fall Chinook salmon at Bonneville Dam are shown lagged by 2 and 3 years, respectively. For example, for fish that entered the ocean in 1998, the number listed for spring Chinook indicates adults that returned in 2000, while the number for fall Chinook indicates adults that returned in 2001. For Chinook salmon, return numbers may also change during the 2-5 years of adult returns due to the different age classes of returning adults. For example, spring Chinook that entered the ocean in 2000 may return to spawn in 2002, 2003, or 2004. Comparison of adult return rankings for the years 2007–2009 will be possible when adult returns from these years are complete (2010-2012).

Table 5. Adult–return data used for ranking among years, as shown in Table 4. Note that the full data set for the year of ocean entry requires a lag time of at least 3 years: thus though we have 12 years of ocean ecosystem indicator data, we have only 9 years of adult–return data.

Adult returns by Year of Ocean Entry[1]

	OPIH Coho (adults:smolts)	Bonneville spring Chinook (n)	Bonneville fall Chinook (n)	Klamath River fall Chinook (n est.)
1998	0.0142	177,741	400,205	218,100
1999	0.0304	391,367	473,786	187,400
2000	0.0447	268,813	610,075	160,800
2001	0.0371	192,010	583,224	191,900
2002	0.0468	168,656	415,684	79,200
2003	0.0333	74,038	299,161	65,200
2004	0.0252	96,456	157,784	61,400
2005	0.0253	66,624	315,279	132,100
2006	0.0246	124,336	283,691	70,600[2]
2007	0.0326	114,525	—	—
2008	0.0122[2]	—	—	—

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

[2] Estimate based on jack returns.

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

Estimates of SARs for OPIH coho and adult counts for Klamath River fall Chinook were provided by the Pacific Fishery Management Council (PFMC 2008). Counts of spring and fall Chinook at Bonneville were provided by the Columbia River DART project (1996–present). These sources are publicly available via the internet.

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

SUMMARY OF OCEAN ECOSYSTEM INDICATORS FOR 2009

During the second half of 2009, the trend of cold ocean conditions that began in 2007 and continued through 2008, changed noticeably. After June, the ocean began to warm significantly, leading to detrimental changes in the pelagic food web and likely high mortality of juvenile salmonids. Here we discuss each ocean ecosystem indicator in terms of how measurements in 2009 compared to those made by our research team since 1998. Values for each indicator for all years since 1998 are listed in Table 3.

Pacific Decadal Oscillation—During 2009, the PDO continued strongly negative through April (Figure 5), became less negative after June, and turned positive by August. However, the signal turned once again, becoming slightly negative by November. In comparing mean winter PDO (Dec–Mar) behavior over the past 13 years, we find the coldest (most negative) signal in winter 2008–2009, the second coldest in winter 1999–2000, and the third coldest in winter 2007–2008. Winter PDO value is an important leading indicator of ocean conditions: as shown by Logerwell et al. (2003), one prerequisite for good coho salmon survival is a cold winter ocean preceding the spring when juvenile coho arrive. We assume that the same is true for yearling Chinook salmon.

In August 2009, PDO values changed sign, from negative to positive; this signaled a change from the very productive ocean conditions of the past two years to poor ocean conditions. The 2008 summer−average PDO (May–Sep) was the most negative of our time series, with a value of –6.08 (Figure 2). In contrast, the 2009 summer−average PDO was only our 5th highest, with a value of −1.11.

Multivariate ENSO Index—The MEI became negative in June 2007 and continued negative through 2008 (indicating good conditions for salmon). In May 2009, the MEI switched to positive (indicating poor conditions for salmon; Figure 4). This indicates that the La Niña, and cold ocean conditions in equatorial waters of the eastern Pacific, have come to an end. It is clear that an El Niño is developing in equatorial waters, and climate scientists at NOAA are predicting that the effects of this El Niño will be felt in the Pacific Northwest during winter 2009 and spring 2010 (see this report from the Climate Prediction Center). However, at the time of this writing (January 2010) there are as yet no clear signs of an El Niño event in the coastal waters off Oregon or Washington.

Sea Surface Temperature (SST)—Although the recent trend of cold ocean conditions began to fade beginning in mid-May 2009, the cold period did continue intermittently through mid-August. The cold period extension was aided by strong upwelling winds, which were interrupted by several major relaxations of upwelling (and significant warming). Upwelling relaxations occurred in June, mid-July, and from mid-August to mid-September (Figure 6). The latter relaxation of winds resulted in water that was nearly 4°C warmer than average, with the warmest temperature observed on 19 September (17.3°C).

Summertime SST values at NH 05 were measured biweekly during our hydrographic cruises. At station NH05, summer SSTs were only slightly warmer than normal during 2009 (+0.44°C; Figure 7), as would be expected with weakly negative PDO and strongly positive MEI indices.

Coastal Upwelling—Upwelling began early in 2009, on 23 March (day 82) and continued into September and October. Unfortunately, the upwelling process was repeatedly interrupted by relaxation events, and an extensive period of upwelling was never established. During each of these major relaxation events, upwelling slackened, causing downwelling at the coast (as indicated by horizontal bars in Figure 10). The first downwelling event in early April did not result in anomalously warm water (see Figure 10). However, the following four events resulted on onshore transport of very warm water, and this was seen clearly in the SST time series (Figure 6). These warm–water "downwelling" events occurred in mid–June, mid–July, throughout much of August, and in September.

Deep Water Temperature and Salinity—Temperature and salinity profiles are recorded every 2 weeks during our biweekly monitoring cruises off Newport. During summer 2009, deep waters were warmer and fresher than in other years (Figures 16 and 17). The presence of warm water of lower salinity was consistent with the lack of consistent and strong upwelling in that it indicated that surface waters from offshore dominated the continental shelf in 2009.

Physical Spring Transition—During winters off the Pacific Northwest, winds often originate from the south or southwest, driven by the Aleutian Low pressure system, which persists over the Gulf of Alaska. These winds cause coastal currents to flow northward and onshore, raising sea level at the coast and transporting plankton from the south (central California Current) and from offshore. In spring, the Aleutian Low recedes, and the North Pacific High pressure system begins to build. Winds in the region reverse direction and begin blowing from the north towards the equator. Coastal currents also reverse direction, sea level drops, and north Pacific waters (from the coastal Gulf of Alaska) begin to appear off the Pacific Northwest. This signals the start of the upwelling season. The "date" when this transition takes place is known as the "spring transition."

The spring transition came early in 2009, on 23 March (day 82); however, winds were weak and inconsistent, especially after May. An early start to the upwelling season is a necessary condition for good survival; however, despite the early start of the 2009 upwelling season, upwelling was weak, and had ended by early September.

Length of the Upwelling Season—In 2009, the upwelling season began on 23 March (day 82); however, the date marking the end of the upwelling season was more ambiguous. One could select 1 September (Figure 10); however, the warm period that persisted through much of September was interrupted by a strong upwelling event that lasted for three weeks, from 19 September to 10 October. It was only after this date that upwelling ceased completely; thus we select 10 October as the end of the upwelling season.

Copepod Species Biodiversity (Species richness)—Copepod biodiversity, or species richness, is simply the number of copepod species observed in our monthly plankton samples. Monthly average values for copepod species richness continue to track quite closely with the PDO and SSTs (Figure 21). That is, when the PDO is negative, surface waters are cold (see Figure 5), and the copepod community is dominated by only a few cold–water, subarctic species. Conversely, when the PDO is positive, SSTs are warm, and the copepod community is dominated by a greater number of warm–water, subtropical species. During 2009, we found moderately low biodiversity, though not as low as in 2008. Copeopod species richness in the year prior to the return of adult coho salmon is also strongly correlated with indices of survival for this species (Figure 22), thus providing a potentially useful forecasting tool.

Northern Copepod Anomalies—Copepods are transported to the Oregon coast, either from the north or from the east and south. Copepods that arrive from the north are cold–water species. They originate in the coastal Gulf of Alaska and are referred to as "northern copepods." The presence of northern copepods indicates that waters from the coastal Gulf of Alaska are being fed into the coastal California Current. The "northern copepod index" is the log biomass anomaly of three species of cold–water copepods: *Calanus marshallae*, *Pseudocalanus mimus*, and *Acartia longiremis*. We recently recalculated this index, using monthly anomalies of the log biomass of these three species, with the averaging period based on samples collected from 1996 to 2008. In the past, we used quarterly anomalies as the basis for making this calculation; therefore, the values now (based on monthly anomalies) are somewhat different from the old values (based on quarterly anomalies).

Figure 24 shows time series of the PDO and of northern copepod biomass anomalies. The year 2008 had the second highest biomass of northern copepods since 1996 (a value of 0.75), with the highest value observed in 2002 (0.83). In contrast, the smallest biomass observations were during the 1998 El Niño event (−1.96) and the summer of 2005 (−1.78). Biomass of northern copepods has been steadily increasing since the dismal summer of 2005. For example, the difference in log10 biomass between 2005 and 2008 was 1.89 + 0.75 = 2.64, or 436 times greater in 2008 than in 2005 (antilog 2.64 = 436). Values for 2009 were still strongly positive (0.54), simlar to values seen in 2007 (0.499).

Biological Spring Transition—The biological spring transition is defined as the date when the zooplankton community has transitioned from a warm–water "winter" community to a cold–water "summer" community. In most years, there is a time–lag between the date when coastal currents begin to reverse (the physical spring transition) and the date when animals from distant sources arrive in waters off the Oregon coast (distant sources being the coastal Gulf of Alaska in spring and coastal central California in autumn). During 2009, the biological transition came very early, in early March (day 83), as shown in Table 3. This is a positive sign for fisheries because it means that the food chain was populated by northern species very early in the year. Several methods are used to calculate dates of the spring and fall transition, and a compilation of the different methods is available from Columbia River DART (Data Access in Real Time), a project of the University of University of Washington School of Aquatic and Fishery Sciences.

Catches of Spring Chinook in June—Pelagic trawl surveys have been carried out for 12 years (since 1998). In the June 2008 survey, we collected the highest number of juvenile spring Chinook salmon of the entire time series (Figure 34); this was a harbinger for strong returns of Columbia River Chinook beginning in 2010. Catches in June 2009 were lower, but still relatively high, ranking 4th of 12 years.

Catches of Coho in September—Catches of juvenile coho salmon in our September trawl surveys have been another good indicator of rates of return of coho the following year. We were surprised that catches in our September 2008 survey were only average (ranked 6th of 11), even though ocean conditions during summer 2008 (their first summer at sea) were the best (1st of 11).

If adult returns in autumn–winter 2009–2010 are only average, as the catch suggests, then the reason might be the 35–day period of warm ocean conditions observed during 22 July–22 August 2008. This period of warm conditions may have led to their demise because coho salmon reside within the upper few meters of the water column. Thus warm SSTs could have been a factor contributing to low survival through both increases in metabolism of fish and relatively low availability of prey. We suspect that a similar scenario was experiened by coho during summer 2009 due to two extended periods of warm ocean conditions: one during most of August, and a second during much of September (Figure 6).

REFERENCES

Bakun, A. 1973. Coastal upwelling indices, west coast of North America, 1946–71. U.S. Department of Commerce, NOAA Technical Report NMFS–SSRF–671.

Bakun, A. 1996. Patterns in the ocean: ocean processes and marine population dynamics. University of California Sea Grant, La Jolla.

Beamish, R. J., and C. Mahnken. 2001. A critical size and period hypothesis to explain natural regulation of salmon abundance and the linkage to climate and climate change. Progress in Oceanography 49:423–437.

Bi, Hongsheng, R. E. Ruppell, W. T. Peterson. 2007. Modeling the salmon pelagic habitat off the Pacific Northwest coast using logistic regression. Mar. Ecol. Prog. Ser. 336:249-265

Bi, Hongsheng, R.E.Ruppel, W.T.Peterson and E. Casillas. 2008. Spatial distribution of ocean habitat of yearling Chinook (*Oncorhynchus tshawytscha*) and coho (*Oncorhynchus kisutch*) salmon off Washington and Oregon, USA Fish Oceanogr. 17: 463-476

Bond, N. A., J. E. Overland, M. Spillane, and P. Stabeno. 2003. Recent shifts in the state of the North Pacific. Geophysical Research Letters 30(23)2183.

Chhak, K.C., E. Di Lorenzo, N. Schneider and P.F.Cummins. 2009. Forcing of low-frequency ocean variability in the Northeast Pacific. Journal of Climate, doi:10.1175/2008JCLI2639.1

Columbia River DART (Data Access in Real Time). 1995—. Online interactive database of the Columbia Basin Research group, University of Washington School of Aquatic & Fishery Sciences. Available at www.cbr.washington.edu (September 2008).

Emmett, R. L. 2006. The relationships between fluctuations in oceanographic conditions, forage fishes, predatory fishes, predator food habits, and juvenile salmonid marine survival off the Columbia River. Ph.D. Thesis, Oregon State University, Corvallis.

Fessenden, L. M. 1996. Calanoid copepod diet in an upwelling system: phagotrophic protists vs. phytoplankton. Ph.D. Thesis, Oregon State University, Corvallis.

Gunsolus, R. T. 1978. The status of Oregon coho and recommendations for managing the production, harvest, and escapement of wild and hatchery–reared stocks. Oregon Department of Fish and Wildlife, Clackamas, OR.

Healey, M. C. 1991. Life history of Chinook salmon (*Oncorhynchus tshawytscha*). Pages 311–394 *in* C. Groot and L. Margolis, editors. Pacific salmon life histories. University of British Columbia Press, Vancouver.

Hooff, R. C., and W. T. Peterson. 2006. Copepod biodiversity as an indicator of changes in ocean and climate conditions of the northern California current ecosystem. Limnology and Oceaonography 51(6).

Logerwell, E. A., N. J. Mantua, P. W. Lawson, R. C. Francis, and V. N. Agostini. 2003. Tracking environmental processes in the coastal zone for understanding and predicting Oregon coho (*Oncorhynchus kisutch*) marine survival. Fisheries Oceanography 12(6):554–568.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis. 1997. A Pacific decadal climate oscillation with impacts on salmon. Bulletin of the American Meteorological Society 78:1069–1079.

Miller, C. B., H. P. Batchelder, R. D. Brodeur, and W. G. Pearcy. 1985. Response of the zooplankton and ichthyoplankton off Oregon to the El Niño event of 1983. Pages 185–187 *in* Worster, W. W., and D. L. Fluharty, editors. El Niño North. Washington Sea Grant Program, University of Washington, Seattle.

Myers, J. M., R. G. Kope, G. J. Bryant, D. J. Teel, L. J. Lierheimer, T. C. Wainwright, W. S. Grant, F. W. Waknitz, K. Neely, S. Lindley, and R. S. Waples. 1998. Status review of Chinook salmon from Washington, Idaho, Oregon, and California. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-35.

Nickelson, T. E. 1986. Influences of upwelling, ocean temperature, and smolt abundance on marine survival of coho salmon (*Oncorhynchus kisutch*) in the Oregon Production Area. Canadian Journal of Fisheries and Aquatic Sciences 43:527 535.

Pearcy, W. G. 1992. Ocean Ecology of North Pacific Salmonids. Washington Sea Grant Program, University of Washington Press, Seattle.

Peterson, W. T. 2009. Copepod species richness as an indicator of long–term changes in the coastal ecosystem of the northern California Current. California Cooperative Oceanic Fisheries Investigations (CalCOFI) Report 50:73-81.

Peterson, W. T., and J. E. Keister. 2003. Interannual variability in copepod community composition at a coastal station in the northern California Current: a multivariate approach. Deep Sea Research Part II: Topical Studies in Oceanography 50(14–16):2499–2517.

Peterson, W. T., and C. B. Miller. 1975. Year–to–year variations in the planktology of the Oregon upwelling zone. Fishery Bulletin, U.S. 73:642–653.

Peterson, W. T., and C. B. Miller. 1977. Seasonal cycle of zooplankton abundance and species composition along the central Oregon coast. Fishery Bulletin, U.S. 75:717–724.

PFMC (Pacific Fishery Management Council). 2008. Preseason report I: stock abundance analysis for 2008 ocean salmon fisheries. Internal report. Pacific Fishery Management Council. Portland, Oregon.

Sandercock, F. K. 1991. Life history of coho salmon (*Oncorhynchus kisutch*). Pages 395–446 *in* C. Groot and L. Margolis, editors. Pacific salmon life histories. University of British Columbia Press, Vancouver.

Scheuerell, M. D., and J. G. Williams. 2005. Forecasting climate induced changes in the survival of Snake River spring/summer Chinook salmon (*Oncorhynchus tshawytscha*). Fisheries Oceanography 14(6):448–457.

Ware, D. M., and G. A. McFarlane. 1989. Fisheries production domains in the Northeast Pacific Ocean. Pages 359–379 *in* Beamish, R. J., and G. A. McFarlane, editors. Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models. Canadian Special Publications of Fisheries and Aquatic Sciences 108.

Weitkamp L. A., T. C. Wainwright, G. J. Bryant, G. B. Milner, D. J. Teel, R. G. Kope, and R. S. Waples. 1995. Status review of coho salmon from Washington, Oregon, and California. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-24.

Whiteaker, J. J., and K. Fryer. 2007. Age and length composition of Columbia Basin Chinook and sockeye salmon and steelhead at Bonneville Dam in 2006. Internal report. Columbia River Inter–Tribal Fish Commission 07–4.

Wolter, K., and M. S. Timlin. 1998. Measuring the strength of ENSO events: How does 1997/98 rank? Weather 53:315-324.

APPENDIX A: INTRODUCTION TO THE LOCAL 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 boad scale variations both in 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 offshort 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 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 climate regime" or "cold–water regime," with a warm ocean being less productive than a cold ocean (Figure 37).

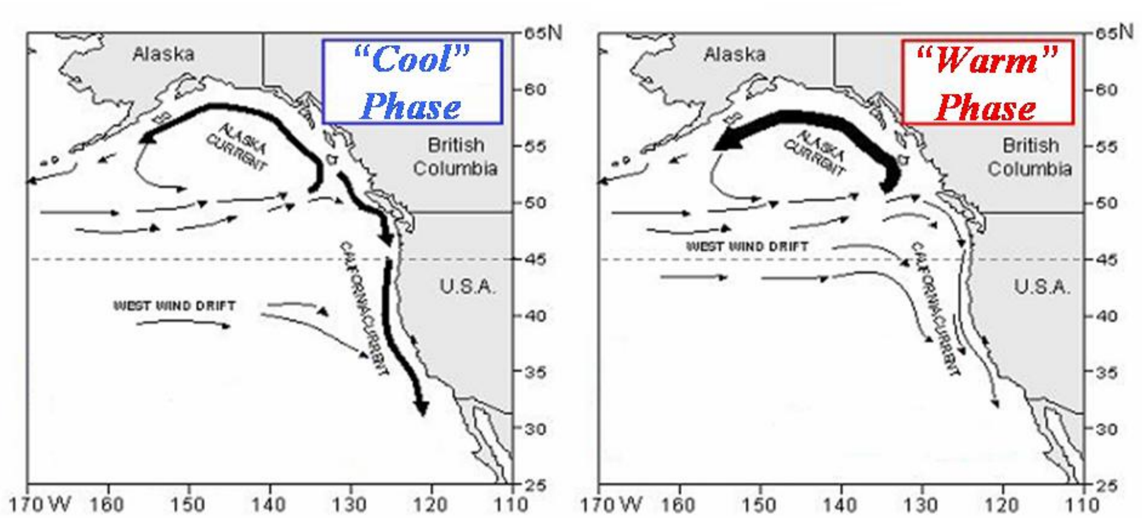


Figure 37. A working hypothesis on how changes in the Pacific Decadal Oscillation affect productivity in the northern California Current.

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 Orgeon. Zooplankton biomass was higher than average during the cool regime prior to 1977 and lower than average durring 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: 1976–1977, 1982–1983, 1986–1987, 1991–1992, 1997–1998 and again in 2002–2004. 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 it appears that another regime shift may have been initiated in late 1998. Thus, the California Current now appears to have returned to a cool, productive phase. The shift to productive conditions was interrupted for 3 years (late 2002–late 2005), but the ocean has once again cooled (in early 2006). Whether or not short–term (3–4 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 7. 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)

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 West Wind Drift offshore or from the south. The changes in the type of source water yield the results shown in Table 7.

These simple relationships only hold during years of persistent recurrence of one phase of the PDO or the other. During transitional years, such as 1998–1999, 2002–2003, and possibly 2006, 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 two years. Similarly, increases in abundances of forage fish and juvenile salmon lagged the PDO index changes by 1–2 years. If the year 2006 is classified as a "cool phase" year, we might expect a 1–year time–lag in response by the salmon to a renewal of "good ocean conditions."

APPENDIX B: AT-SEA SAMPLING METHODS

Hydrography, Zooplankton, and Ichthyoplankton

Much of the oceanographic data shown in this report came from sampling along the Newport Hydrographic Line (Figure 38). We sample the coastal waters off Newport at biweekly intervals during the upwelling season in spring, summer, and fall. Sampling cruises are conducted monthly during stormy winter months. This program began in 1996, but we also have data from these same stations from sampling conducted in 1973 (Peterson and Miller 1975), 1983 (Miller et al. 1985), and summer 1990–1992 (Fessenden 1995). Most data presented here were collected during these cruises, which initiated in May 1996.

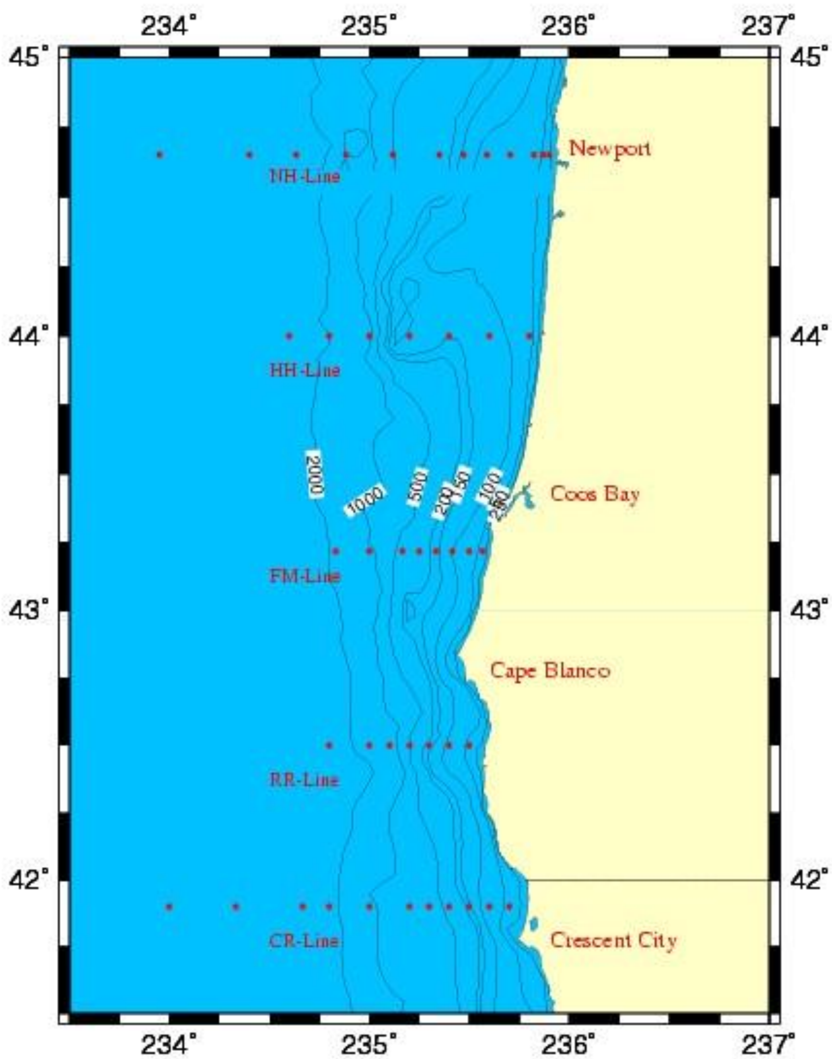


Figure 38. Transects and stations sampled during cruises by the NOAA Fisheries Service.

From May 1996 through September 2001, all cruises were made during daylight hours because our research vessel, the *RV Sacajawea* was only 37 ft in length, rendering it unsafe to work at night. With the acquisition of a new (and larger, 55 ft) research vessel in September 2000, we were able to sample at night. Thus in fall 2000, we began collecting data for an adult euphausiid time series.

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

At each station, a CTD profile (conductivity, temperature, and depth) is taken (Seabird SBE 19+ CTD), and transparency of surface waters is measured (Secchi disc). A bucket of seawater is collected from the surface for analysis of chlorophyll–a and nutrients. A vertical plankton net fitted with a flowmeter is towed from near the sea floor to the surface (or from 100 m to the surface in deeper waters). The plankton net is 0.05 m in diameter with a mesh size of 202 micrometers (µ). A double oblique tow is made for ichthyoplankton (1–m diameter net with 333–µm mesh) over the upper 20 m. Since 2005, CTD casts have included fluorometry (WetLabs fluorometer) and oxygen (Seabird oxygen sensor).

From 1998 to 2003, we sampled each transect line five times per year as part of the U.S. Global Ocean Ecosystem Dynamics (GLOBEC) program (Figure 38). Since the GLOBEC project ended, we have continued to sample these same transect lines as frequently as possible. Thus far, we have been able to sample each transect in May (2004 2006), along with several visits to the Newport Line, out to 85 miles from shore, in summer 2004. As a result, the Newport biweekly data are nested within larger scale quarterly surveys, an approach that is useful in helping us interpret locally derived data from the inner portions of the Newport Line.

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

JUVENILE SALMON SAMPLING PROGRAM

Methods

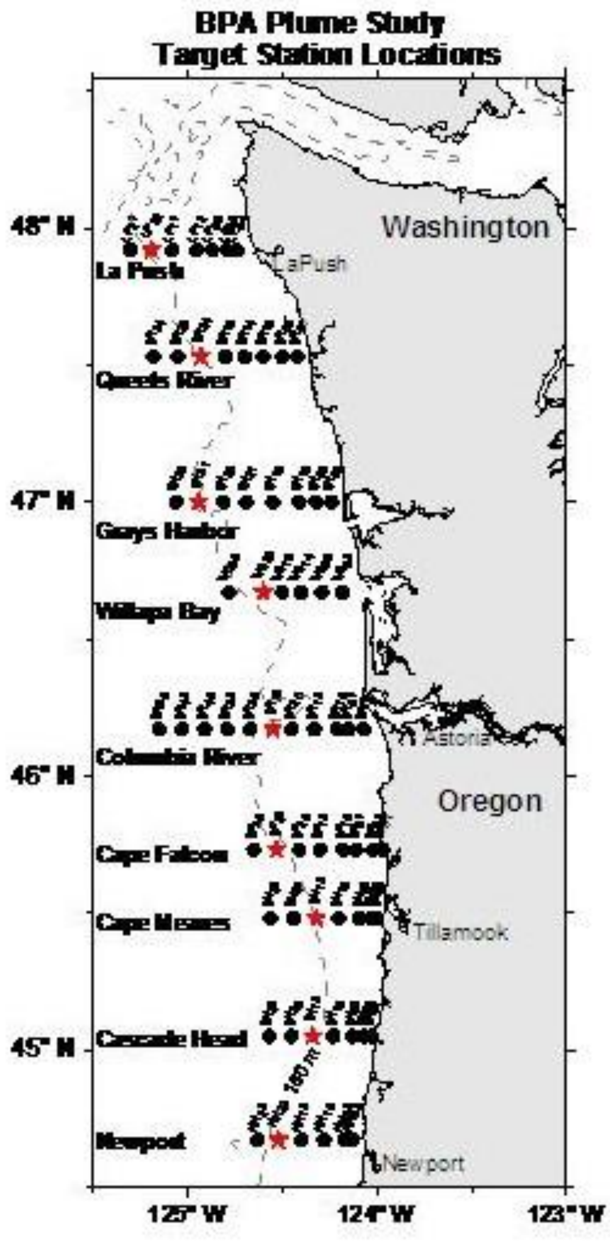


Figure 39. Transects sampled for coho and yearling and subyearling Chinook salmon, 1998–2006.

We have been sampling juvenile salmon off the coasts of Washington and Oregon at the stations shown in Figure 39, in June and September, since 1998. Pelagic fish are collected within the upper 20 m of the water column with a NET Systems Model 264 rope trawl (30 m wide x 20 m high x 100 m long), at stations ranging from Newport, Oregon north to La Push, Washington (Figure 39).

For each trawl sample, all fish and invertebrates are identified and enumerated. Lengths of 50 randomly selected individuals are measured. For juvenile salmon, up to 200 individuals of each species and size class (i.e., subyearling and yearling Chinook based on size) are measured and individually frozen at –20°C.

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

We (Robert Emmett) also carry out cruises every 10 days during which pelagic fish are sampled at night along transects off the Columbia River and Willapa Bay. This work provides data to index the abundance of fish predators (such as hake) and forage fish (which can serve as an alternate prey of the fish predators).

From 1998 to 2005, 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), under very high Columbia River flows (June 1999) and extremely low flows (June 2001), and during anomalously warm conditions in the coastal ocean due to lack of upwelling (June 2005). Also during this 8–year period, the Pacific Decadal Oscillation moved from warm phase (pre–1999), to cool phase (1999–2002), then to warm phase again (2003–2005). Thus, nature has handed us a grand experiment that allows us to determine in what ways and how quickly salmon and other ecosystem components respond to short–term climate variability.

Results

Salmon Distribution—Average juvenile salmon abundance over all June cruises has been highest in the vicinity of the Columbia River and off the Washington coast (Figure 40). Distributions of coho salmon have been more widespread, whereas both yearling (spring) and subyearling (fall) Chinook salmon were far less common off Oregon than Washington.

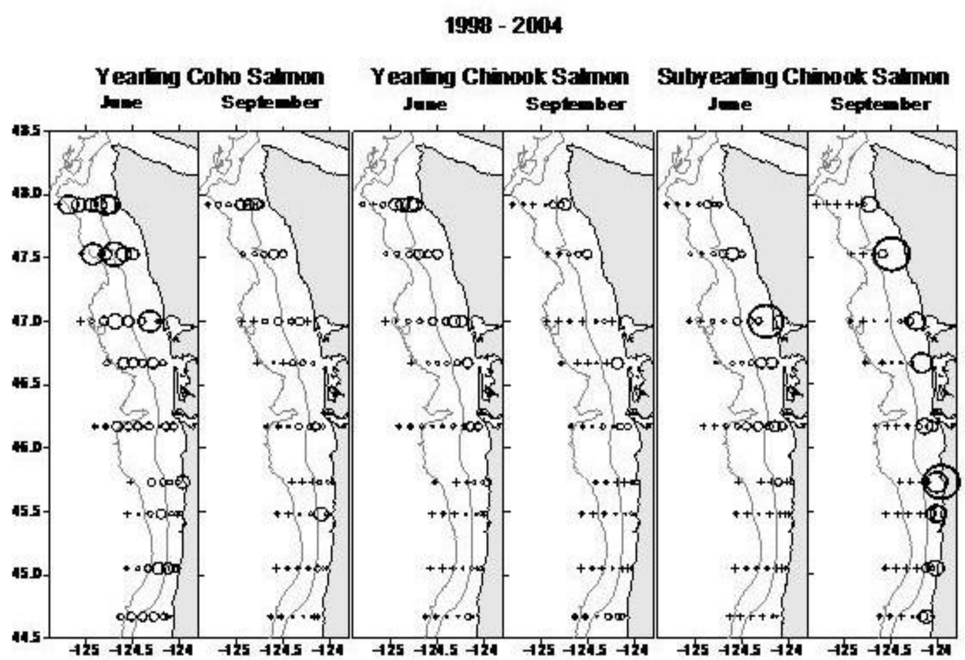


Figure 40. Average catch of salmonids per km towed at stations in June and September, for each life history type, averaged over 1998–2004. A (+) represents locations where trawls were attempted but no fish were caught. The very largest diameter circle represents an average catch of >50 fish/tow/km^{-1}.

In September, salmon catches were lower overall, and their distributions shifted to the north with the exception of fall Chinook, which was found mainly inshore throughout the study area. Large catches were consistently made at several stations along the La Push (48°N), Queets River (47.5°N) and Grays Harbor (47°N) transects, as well as at two stations associated with the plume: one 5 miles off Willapa Bay (46.6°N), and the other 7 miles off the mouth of the Columbia River (46.2°N).

Catches in both June and September were also very patchy in that we generally caught half of the fish in less than 5 trawls per cruise and did not catch any fish in 40% of the trawls. Patches most generally occurred for both yearling Chinook and coho off the Washington coast in and very near shore for yearling and subyearling Chinook in September.

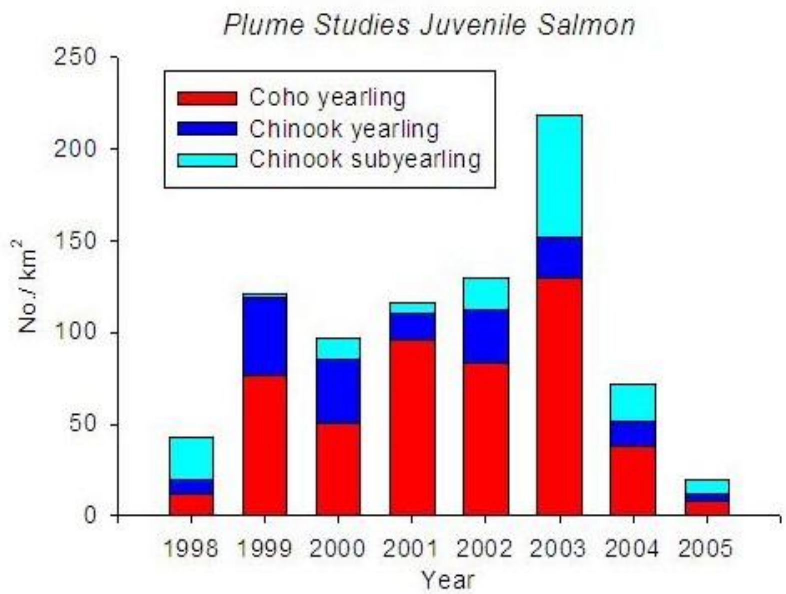


Figure 41. Annual variation in catches of juvenile coho and Chinook salmon during June trawl surveys, 1998–2005.

Year–to–year variations in salmon abundance—The lowest June catches of Chinook and coho salmon were associated with an El Niño event in 1998 and an anomalously low upwelling period during May and June 2005 (Figure 41). Highest catches were during the cold phase of the Pacific Decadal Oscillation (1999 2003). Catches of yearling Chinook began to decline in September 2003 in concert with persistent warming, which began that summer and continued through 2005. The number of yearling Chinook caught in September was lower than in June, whereas subyearling Chinook was more abundant in September than June.