The Pacific Decadal Oscillation and Pacific Salmon Production

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Abstract. Retrospective analyses of Pacific Basin climate records highlight the existence of a pan-Pacific interdecadal climate oscillation. We find strong evidence for coherent patterns of interdecadal variability in Pacific winds, sea level pressures, and upper ocean temperatures. Collectively, the ocean-atmosphere pattern of variability has been labeled the "Pacific Decadal Oscillation", or PDO. An index for the PDO has been developed from an empirical orthogonal function (EOF) analysis of north Pacific SST records dating back to 1900.

An analysis of Pacific coast salmon catch records suggests that the dominant pattern of salmon production is driven by low-frequency climate variations associated with the PDO. The characteristics of this salmon production pattern of variability include a preferentially interdecadal time scale of variation that is coherent with our PDO index, and a north-south inverse production pattern in which Alaska stocks tend to be productive while those in the Pacific northwest are relatively unproductive (and vice versa).

1. Introduction

A growing body of research documents coincident changes in both the large-scale marine environment and ecosystems of the North Pacific. For example, *Francis et al.* (1998) present a synthesis of studies linking marine biotic variations to those in the sea surface temperature (SST) and sea level pressure (SLP) fields over the North Pacific. Generally speaking, most studies addressing issues of biotic impacts of climate variations have been limited to analyses that examine correlations between environmental variables (like SST or SLP) and indices of marine productivity (such as records of commercial fish landings). It is generally agreed that such studies provide only indirect (and sometimes misleading!) insights into the biophysical processes that give rise to climate impacts on marine ecosystems. However, it is also evident that integrative studies of marine biota and the physical environment are yielding valuable clues to some of the major drivers of variability in living marine resources.

This article focuses on an overview of the large-scale physical climate characteristics associated with the Pacific Decadal Oscillation (PDO) and the dominant pattern of salmon production in the NE Pacific Ocean. For more complete descriptions of the climate anomalies associated with the PDO see *Zhang et al.* (1997) and *Mantua et al.* (1997). For an in-depth discussion of the characteristics and management implications of the dominant (PDO-related) pattern in salmon production the reader is referred to *Hare et al.* (1998).

2. Analysis

2.1. Characteristics of the PDO

An empirical orthogonal function (EOF) analysis of 20th century monthly SST variability over the North Pacific sector (poleward of 20°N) produces what Dr. Steven Hare labeled the "Pacific (inter)Decadal Oscillation", or PDO, as the leading eigenvector/principal component (PC) pair. A loading pattern for the PDO has been extended to the global oceans by regressing Nov.-Mar. mean grid point SST data onto the principal component time series. Also shown in the top panels of Figure 1 are Nov.-Mar. SLP (middle panel) and wind stress (right panel) PDO-regression patterns. The maps in the top panel of Figure 1 depict the amplitude of SST, SLP, and surface wind stress anomalies typical of a positive unit standard deviation in the PDO index (shown in Figure 2). The positive-phase PDO pattern include these characteristics:

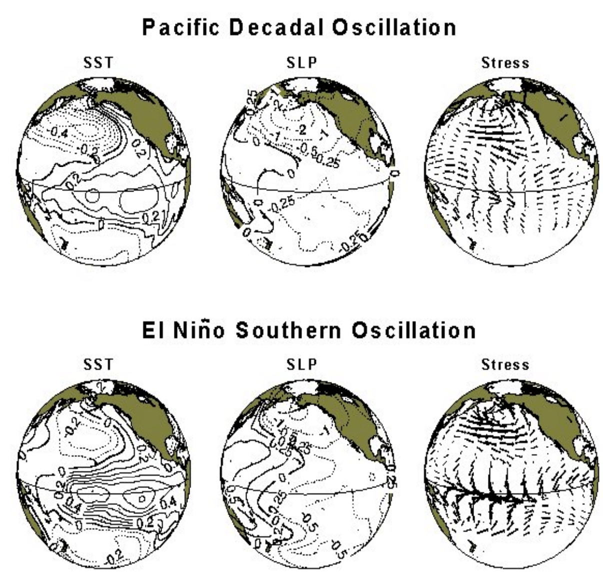

Figure 1. Regression patterns associated with positive phases of the PDO (top row) and ENSO (bottom row). Positive (negative) contours are solid (dashed). SST is in ºC; SLPs in millibars, and the largest vectors correspond to pseudo stresses of 10 m^2/s^2. After *Hare et al.* (1998).

- anomalously cool SSTs in the western and central North Pacific, with anomalously warm SSTs along the Pacific coast of the Americas and throughout the central and eastern tropical Pacific
- negative SLP anomalies over the entire North Pacific basin centered on the Aleutian Islands (resulting in an intensified wintertime Aleutian Low), low SLP in the eastern tropical Pacific and high SLP in the western tropical Pacific and Indonesia
- surface wind stress anomalies with enhanced counterclockwise flow over the North Pacific, westerly wind stress anomalies in the west-central equatorial Pacific, and easterly wind stress anomalies in the eastern equatorial Pacific

Because the EOF/PC analysis is a linear statistical method, the signs of the regression patterns shown in Figure 1 are simply reversed when the PDO index is negative.

Additionally, the atmospheric circulation anomalies associated with the PDO give rise to surface climate anomalies over North America. Typical of positive PDO years are warmer than average Nov.-Mar. temperatures in the northwest half of North America and cooler than average temperatures in the southeast US. Wintertime precipitation tends to be above average along the southern US, northern Mexico and coastal Gulf of Alaska regions, but below average in the Pacific Northwest, the Great Lakes region, and over the Hawaiian Islands (*Mantua et al.* 1997).

Spatial patterns of SST, SLP and wind stress anomalies associated with warm phases of the El Niño Southern Oscillation (ENSO), commonly referred to as El Niño, are shown in the bottom panels of Figure 1. Note that the patterns associated with the positive phases of the PDO are quite similar to those associated with El Niño. Major differences between the El Niño and PDO signatures include:

- SST anomalies associated with ENSO are largest in the tropical Pacific, and focused on the equator, while those associated with the PDO are strongest in the North Pacific
- ENSO SLP anomalies are weaker and more confined to the central North Pacific than those associated with the PDO, and ENSO SLP anomalies in the tropics are stronger than those associated with PDO
- Tropical wind stress anomalies associated with ENSO are more intense than those associated with PDO

Time series for ENSO and the PDO, derived from instrumental SST records, and an index for the intensity of the Nov.-Mar. Aleutian Low pressure cell, are shown in Figure 2. Note that the ENSO index (NINO3.4) shows a strong tendency for large amplitude year-to-year swings. On the other hand, the PDO index shows much more year-to-year persistence. The PDO was predominantly in its negative phase from the mid-1940s to 1976, and primarily in its positive phase from about 1925 to 1945 and from 1977 to 1988. Since 1989 the PDO index has fluctuated between positive and negative values, making its status difficult to characterize. Also note that the AL index is correlated with both ENSO and PDO, reflecting the combined influences of strong interannual ENSO and interdecadal PDO fluctuations, as well as other sources of variability.

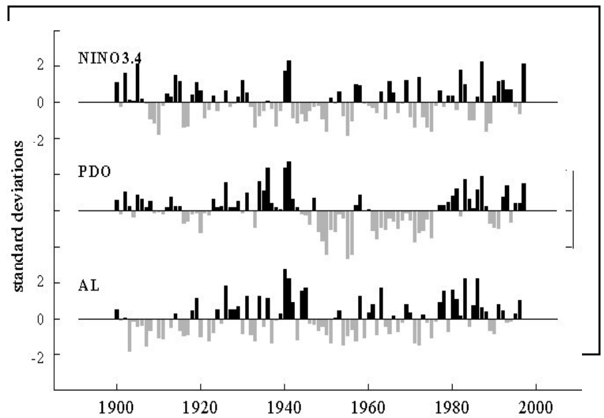

Figure 2. Annual mean indices for the ENSO, PDO, and Nov.-Mar. Aleutian Low pressure pattern. The NINO3.4 index depicts SST anomalies in the eastern equatorial Pacific (5ºN-5ºS, 170W-120ºW). The PDO and AL indices are defined in *Mantua et al.* (1997) and *Hare et al.* (1998).

The time variability of ENSO and PDO is what truly set these patterns of Pacific climate variability apart. ENSO has emerged as the Earth's dominant pattern of seasonal to interannual variability, with preferred time scales ranging from 2- to 7-year periods. On the other hand, the PDO index varies at preferentially interdecadal time scales. *Minobe* (1997) has a pre-instrumental PDO index dating to the 17th century. This index is based upon reconstructed North American temperature records derived from tree-ring chronologies. A spectral analysis performed on Minobe's index suggests that the PDO has had peak spectral power at 50 to 70 periods over the last few centuries.

2.2 Salmon production in the northeast Pacific

Pacific salmon production has a long history of confounding expectations. Predictability of stock sizes is of great interest to management and fishing interests for both economic and conservation purposes. Presently, most run-size prediction methods utilize information on known populations of juvenile salmon as they migrate from freshwater to marine environments and from "cohort" adult population estimates. These forecast methods have demonstrated some skill, but are notoriously poor at capturing much of the large year-to-year fluctuations in abundance that characterizes many marine species.

Several recent studies have focused on the relationships between fluctuations in climate and Pacific salmon abundance. For example, *Beamish and Boullion* (1993*), Hare and Francis* (1994) and *Francis and Hare* (1995) all attributed trends in North Pacific salmon production to interdecadal climate variations in the North Pacific that are partly expressed as changes in the intensity of the wintertime Aleutian Low.

Hare (1996) used time series analysis to show that the best relationships between North Pacific climate parameters and Alaska salmon stock abundance were realized when the salmon time series were shifted in time to reflect the year of ocean entry. This analysis suggests that the strongest biophysical interactions take place when juvenile salmon are migrating from freshwater to marine environments. Other evidence for strong climate influences on marine survival comes from coded wire tag (*Coronado-Hernandez* 1995) and ocean field studies (*Pearcy*, 1992).

In the analysis of salmon catch data reported here, our goals were the following: (1) to objectively identify regionally coherent patterns in Pacific salmon catch data (indicative of production) that explain large fractions of the overall variance; and (2) to provide insights into the causes for the existence of such patterns, should they exist.

For this analysis we assembled regionally stratified historical catch records of northeast Pacific salmon since 1925. We grouped the catch data by the five commercially harvested Pacific salmon species (pink, sockeye, chinook, coho, and chum) and seven regions (western, central and southeast Alaska, British Columbia, Washington, Oregon, and California). We believe that, to a first order approximation, catches are generally indicative of salmon abundance. Several other studies have adopted this approach and offer justification for the use of catch data as an index of abundance (*Quinn and Marshall* 1989, *Beamish and Bouillon* 1993, *Francis and Hare* 1994, *Hare and Francis* 1995, *Jaenicke et al.*. 1998, *Noakes et al.* 1998). Also note that we made no attempts to consider the influence of hatchery production of Pacific salmon. Generally speaking, most Alaska salmon are wild spawners in pristine watersheds while most stocks from California, Oregon, and Washington are heavily influenced by hatcheries and have been increasingly so since the 1960s (NRC 1996).

To identify the dominant pattern of variability in our catch data matrix, we used principal component analysis (PCA). Because age at capture varies among the species, we used a modified catch matrix. The catch records were lagged such that the year of catch represented fish that had, on average, entered the ocean in the same year (Table 1). Sockeye catches were shifted one year, those for chinook and chum were shifted two years, relative to pink and coho salmon. This step was included to match the year of ocean entry for each species because we hypothesize that it is at the beginning of a salmon's marine life that climate-driven changes to ocean environment most affect survival to adulthood (*Pearcy* 1992, *Hare and Francis* 1995, and *Hare* 1996). The resulting catch matrix contains 71 years of catches for the ocean entry years of 1924-1994, with 1924 representing 1925 catches of pink and coho, 1926 catches of sockeye, and 1927 catches of chinook and chum.

Table 1. Typical ocean residence times for Pacific salmon species (*Randall et al.*. 1985).

Species	years (range)
sockeye	2 (1-3)
pink	1 (1)
chum	3 (2-4)
coho	1 (1-3)
chinook	3 (1-5)

The results of the PCA provide evidence for an inverse production relationship between Alaska and West Coast (California, Oregon and Washington) salmon stocks with a time history that is coherent with the PDO (Figure 3). The leading PC-eigenvector pair from this analysis explains 36% of the variance from the normalized catch data matrix. Higher modes have overlapping eigenvalues and are thus statistically insignificant and physically non-interpretable (see *Hare et al*. 1998 for a more complete discussion).

The low-frequency variability in the principal component time series (Figure 3) bears a striking resemblance to that in the PDO index (compare with Figure 2). The loadings on the

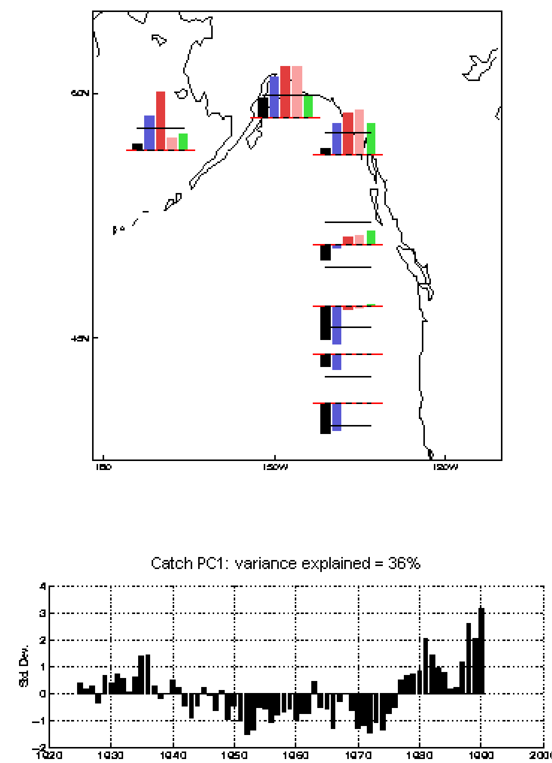

Figure 3: The leading principal component (bottom panel) and eigenvector (top panel) from the PCA of regional salmon catch data. Each bar in the top panel corresponds to one species in each specific region, ordered as follows: chinook, coho, sockeye, chum then pink for each region, respectively.

leading PC, shown in the top panel of Figure 3, are uniformly of one sign for each stock and each region in Alaska and of the opposite sign for coho and chinook in Washington, Oregon, and California. Loadings on British Columbia stocks are relatively small and statistically insignificant. We interpret the leading loading vector to mean that Alaska salmon catches of all five species have, in large measure, varied synchronously throughout the past 70 years. Chinook and coho salmon from Washington, Oregon, and California have also tended to vary synchronously but in the opposite sense of Alaska stocks.

The PC reflects the well-documented fact that catches of Alaska salmon were relatively high from the mid-1920s to mid-1940s, relatively low from the mid-1940s to the mid-1970s, and then exceptionally high from the late 1970s to 1990. Salmon landings in California, Oregon and Washington have varied in the opposite sense.

3. Discussion

We hypothesize that large scale, low frequency climate variations are driving the alternating regimes of salmon production identified in the PC analysis of Pacific salmon catch data. The production regimes identified here appear to be especially sensitive to interdecadal time scale environmental variations. The salmon production cycles are coherent with the slowly varying climate of the north Pacific captured by the PDO index.

Although the PDO index is derived from North Pacific SST, other PDO-related environmental parameters may be playing more important roles in the biophysical interactions that connect fluctuations in climate with those in salmon production. For instance, *Gargett* (1997, also see Gargett's article in this volume) suggests that PDO influences on coastal upper ocean stability may be a unifying link that gives rise to the observed north-south inverse production regimes.

Historical climate data are notoriously sparse for the world's oceans. This fact makes SST data the most attractive parameter for characterizing ocean climate variability. However, for studies of biotic impacts of climate variability it seems vitally important to acknowledge the coherence between variations in SST and other environmental parameters (e.g. eddies, horizontal advection, turbulent mixing, salinity, mixed layer depths and stratification). Hopefully, improved monitoring and modeling will lead to advances in our theories and understanding of biophysical interactions in marine ecosystems.

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