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Inverse production regimes:
Alaska and West Coast Pacific Salmon

by

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Abstract

A principal component analysis reveals that Pacific salmon catches in Alaska have varied inversely with catches from the United States West Coast during the past 70 years. If variations in catch reflect variations in salmon production, then results of our analysis suggest that the spatial and temporal characteristics of this "inverse" catch/production pattern are related to climate forcing associated with the Pacific Decadal Oscillation, a recurring pattern of pan-Pacific atmosphere-ocean variability. Temporally, both the physical and biological variability are best characterized as alternating 20- to 30-year-long regimes punctuated by abrupt reversals. From 1977 to the early 1990's, ocean conditions have generally favored Alaska stocks and disfavored West Coast stocks. Unfavorable ocean conditions are likely confounding recent management efforts focused on increasing West Coast Pacific salmon production. Recovery of at-risk (threatened and endangered) stocks may await the next reversal of the Pacific Decadal Oscillation. Managers should continue to limit harvests, improve hatchery practices and restore freshwater and estuarine habitats to protect these populations during periods of poor ocean productivity.

Introduction

Since 1978 at least $3 billion has been spent to increase, or at least maintain, Pacific salmon production on the West Coast (Washington, Oregon, California) of the United States (Harrison 1998). Managers generally spend this money to construct and operate hatcheries, monitor harvest, and restore natural habitat. Despite these expenditures, the outlook for West Coast Pacific salmon continues to be grim. Nehlsen et al. (1991) listed 214 West Coast stocks whose populations were severely depleted, with 101 of those at "high risk of extinction." By mid-1998, 15 evolutionary significant units (ESUs) of Pacific salmon had been placed on the federal threatened or endangered species lists with at least another 12 ESUs proposed for listing (NMFS 1998).

In stark contrast to the West Coast situation, Pacific salmon production in Alaska has been extraordinarily high during most of the past 20 years. In particular, the two most productive species, pink salmon (*Oncorhynchus gorbuscha*) and sockeye salmon (*O. nerka*), have had several successive record return years in the 1990s. In fact, in a few exceptionally productive years, Alaska salmon landings have been so large that millions of pink and chum salmon (*O. keta*) have been discarded or left unharvested for lack of a market (ADFG 1996). Twenty years ago, however, many of the now abundant Alaska stocks were at alarmingly low population levels, while some West Coast stocks such as the Columbia River chinook (*O. tshawytscha*) and coastal Oregon coho salmon (*O. kisutch*) were enjoying prolonged periods of high productivity.

Salmon production is impacted by environmental conditions at each stage of a salmon's life cycle (Lawson 1993). Unfavorable freshwater, estuarine, or ocean conditions all act as limiting factors. At present, the freshwater life of salmon is much better understood than that in the marine environment, and most efforts to increase natural salmon production have focused on restoring and enhancing freshwater and estuarine habitat that has been damaged by land use practices. Where habitat has been lost (to dam building, for instance), hatcheries have been constructed with hopes of replacing and/or supplementing natural smolt production via artificial propagation. However, a growing body of evidence from field, tagging, and correlation studies shows that Pacific salmon experience large year-to-year fluctuations in survival rates of juvenile fish making the transition from the freshwater to the marine environment (Pearcy 1992; Coronado-Hernandez 1995).

What causes year-to-year changes in the marine survival of Pacific salmon? A number of recent studies indicate that fluctuations in climate are the ultimate source of widespread, regionally-coherent changes in marine survival rates for many salmon species. Mysak (1986) showed that Bristol Bay and Fraser River sockeye salmon populations were impacted by El Niño events. Francis and Sibley (1991) noted an apparent climate-related inverse decadal-scale relationship between the abundances of Alaska pink and West Coast coho salmon. Beamish and Bouillon (1993) and Hare (1996) examined trends in North Pacific salmon production and linked these to variations in the intensity of the Aleutian Low atmospheric pressure cell and North Pacific marine environment. Hare and Francis (1995) and Francis and Hare (1994) used time series analysis to connect dramatic changes in Alaska sockeye and pink salmon production to decadal-scale climate shifts in the North Pacific. Mantua et al. (1997) labeled the aforementioned climate phenomenon as the “Pacific Decadal Oscillation” or PDO. They described the PDO as a pan-Pacific, recurring pattern of ocean-atmosphere variability (also see Minobe 1997 and Zhang et al. 1997). Of most immediate interest to the work reported here, Mantua et al. (1997) found evidence of an inverse relationship between landings of major stocks of Alaska Pacific salmon and those of US West Coast coho and Columbia River spring chinook salmon. Finally, Francis et al. (1998) examined PDO-driven broad-scale changes in the marine ecosystems of the North Pacific.

In this work we explored the following questions:

(1) Are there regionally coherent patterns in Pacific salmon catch data (indicative of production)? If so, what do they look like, and what is their time history?

(2) If there are dominant patterns, what explains them?

To address these questions, we assembled Pacific salmon catch data along with three indices for large scale features of Pacific climate. First, we statistically examined the catch data to identify recurring patterns that explain large fractions of the overall variance. Second, we repeated our analysis also including the Pacific climate indices in the data matrix. Our results support the notion that Pacific salmon production in Alaska is inversely related to that on the West Coast and is climate-driven. Specifically, our work suggests that at the scale of the Pacific coast of North America, salmon production is strongly influenced by decadal-scale changes in the phase of the PDO. These changes in the PDO are, in turn, capturing the low-frequency changes in the intensity of the atmospheric circulation and properties of the coastal and interior North Pacific Ocean.

Data and Methods

We assembled regionally stratified historical commercial, recreational and subsistence catch records of Northeast Pacific salmon since 1925 (Fig. 1). We grouped the catch data by the five commercially harvested Pacific salmon species [pink, sockeye, chinook, coho, and chum (*O. keta*)] and seven regions (western, central and southeastern Alaska, British Columbia, Washington, Oregon, and California). Five of the species-area combinations had no history of catches, resulting in a total of 30 time series. The inclusion of recreational and subsistence data is particularly important for recent years when a number of commercial fishing restrictions were implemented.

Most of the harvest data was obtained from publications of the International North Pacific Fisheries Commission (INPFC) and its successor, the North Pacific Fisheries Anadromous Commission (NPFAC). Data for the period 1925-1976 was taken from INPFC (1978). Data for subsequent years was taken from the annually- issued Statistical Yearbooks (e. g. INPFC 1990). Data for 1993 and 1994 were taken from NPAFC (1997) and NPAFC (1998), respectively. British Columbia recreational catch estimates from 1977-1996 were obtained from the Department of Fisheries and Oceans (Sweeting, pers. comm.). Commercial catch data for 1995-1997 were taken from Pacific Fishing (1996, 1997, 1998). Alaskan catch data were corrected for high seas interceptions between 1952 (start of the Japanese mothership fishery) and 1992 (demise of high seas fishing) using interception rate estimates of Harris (1989).

Estimates of recreational catch generally do not exist prior to 1950 and estimates of subsistence catch do not exist prior to 1970. While in most cases these do not contribute much to the total annual catches within a species/region combination in early years, we wanted to avoid having those catches enter as step increases. To estimate earlier non-commercial catches, we computed the average recreational-to-commercial and subsistence-to-commercial catch ratios for the first 10 years they exist in the database. In general, the recreational catch ratios showed an exponential increase in the early years while subsistence catches showed neither an increasing nor decreasing trend. We fit exponential curves to the 10 earliest recreational catch ratios of the form:

$$\text{Ratio}_{\text{year}} = a \times \exp(b \times \text{year})$$

Annual recreational catches prior to actual estimates were computed using the empirically derived coefficients and multiplying the estimated catch ratio and appropriate species/region commercial catch value. For subsistence catches we used the average ratio for the 10 years and applied that ratio to the commercial catches for years prior to actual estimates. The two exceptions to these rules were British Columbia recreational coho and chinook catches. These two fisheries were well established by the 1950s and the catch ratios were relatively stable at 13% and 6% of the commercial catch for the period 1953-1962. We used those fixed ratios in computing the early years of recreational catch data. The only other non-commercial catches of significance (i. e., greater than 10% of commercial catch) prior to the 1970s were western Alaska chinook (33%) and chum (24%) salmon. It is worth noting that we conducted the analyses without correcting for recreational and subsistence catches prior to including them and found that their addition had little influence on the results.

We used catch data in this analysis, rather than productivity (catch + spawning escapement) or survival data, because it is the only abundance measure that has been systematically collected on all five species and in all seven regions over the past 70 years. Our intent in this study was to elucidate large-scale, long-term patterns of Pacific salmon abundance variability. Neither productivity nor survival data were available in sufficient breadth for such an analysis, and even now such data are not routinely collected for many Pacific salmon stocks. Another pitfall in using productivity data is that errors in estimating escapement are often so large as to give misleading estimates of trends in stock size over time (Larkin 1988). We contend that, to a first order approximation, catches are generally indicative of salmon abundance. Pacific salmon have been fully exploited for most of this century during which time they have been intensively managed (Larkin 1988). Further justification for the use of catch data as an index of abundance (for Pacific salmon) can be found in several other studies that have also examined large-scale patterns of variability (Quinn and Marshall 1989; Beamish and Bouillon 1993; Francis and Hare 1994; Hare and Francis 1995; Jaenicke et al. 1998; Noakes et al. 1998). Finally, we did not make any attempt to correct for the influence of hatchery production of Pacific salmon. There is considerable debate over the impact of hatcheries on total Pacific salmon production (Hilborn 1992; Smoker and Linley 1997). Generally speaking, most Alaskan Pacific salmon are wild spawners in pristine watersheds while stocks from the West Coast are mostly of hatchery origin and have been increasingly so since the 1960s (NRC 1996). Hatchery construction and hatchery smolt releases have generally paralleled freshwater habitat degradation. For this analysis we are assuming that hatcheries have essentially replaced natural smolt production that has been lost to habitat degradation. If survival rates of hatchery and wild smolts are similarly affected by climate factors, the hatchery releases should help prevent the recent catch data from being negatively biased with respect to production.

In addition to the Pacific salmon data, we also used three different time series representing large-scale aspects of Pacific climate variability. The environmental indices we selected are commonly used measures of

(1) The El Niño - Southern Oscillation (ENSO)

(2) The Pacific Decadal Oscillation (PDO)

(3) The winter Aleutian Low (AL) pressure cell.

ENSO is the dominant pattern of global climate variability (after the seasonal cycle) and arises from air-sea interactions in the tropical Pacific region (NOAA 1994). The climatic signature of the PDO superficially resembles ENSO. Anomalous sea surface temperatures (SST), atmospheric sea level pressures (SLP), and surface winds associated with warm phases of ENSO and the PDO are shown in Fig. 2. Note that the warm phases of ENSO and PDO share the following characteristics: above average SSTs in the tropics and along the coast of the Americas, cooler than average SSTs in the central north Pacific; anomalously low atmospheric SLP over the north Pacific and eastern tropical Pacific, with high pressure anomalies in the western tropical Pacific centered over northern Australia. Surface winds reflect the SLP patterns, with enhanced westerlies in the central north Pacific, and enhanced southerly winds along the west coast of North America. Cold phases of ENSO and PDO are simply mirror (negative) images of the patterns shown in Fig. 2. The AL is a quasi-permanent atmospheric pressure cell that overlays much of the North Pacific from late fall to spring. The size and intensity of the AL show substantial intraseasonal, interannual and interdecadal variability.

The indices we used as measures of ENSO, PDO and the AL are illustrated in Fig. 3. We used the "Nino3.4" index as our historical measure for ENSO variability. This is an area average (5° N - 5° S, 170° W - 120° W) of Pacific SST anomalies (see Trenberth 1997). Nino3.4 values for the 1900-1950 period of record were obtained from Kaplan et al. (in press), while those for 1951-1997 were obtained from the Climate Prediction Center.[1] We averaged the 12 monthly anomalies within each calendar year to obtain an annual index and then standardized this time series to unit variance. For the PDO, we used a slightly different index from that published in Mantua et al. (1997). The original PDO index is a winter (Nov. - Mar.) average of the leading monthly principal component from a principal component analysis of Pacific Ocean SSTs north of 20° N. We created an annual PDO index by averaging the 12 monthly anomalies within each calendar year and then standardized this time series to unit variance. The AL pressure index is a measure of the size of the Aleutian Low each winter (Dec. - Mar.) (Beamish and Bouillon 1993). It is computed by summing across the four winter months, the surface area (km^2) of the North Pacific where the atmospheric pressure averaged less than 1000 millibars. We standardized the index so it had a variance equal to that of the ENSO and PDO indices.

To extract the dominant pattern of variability in the data, we conducted two principal component analyses (PCA). The first analysis, hereafter referred to as the "catch-only" PCA, was done using only the 30 Pacific salmon catch time series. In the second analysis, the "catch-climate" PCA, we used the catch data plus the three climate indices described above. Because age at capture varied among the species, we used a modified catch matrix for each analysis. We lagged the catch records such that the year of catch represented fish that had, on average, entered the ocean in the same year (Table 1). Thus, sockeye salmon catches were shifted one year, and chinook and chum salmon 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 the ocean environment most affect survival to adulthood (Pearcy 1992; Hare and Francis 1995; 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 salmon, 1926 catches of sockeye salmon, and 1927 catches of chinook and chum salmon.

A common use of PCA is to extract simultaneous patterns of variability among a number of time series (Von Storch and Zwiers, in press, p. 305). PCA, and other related "eigentechniques" such as factor analysis, canonical correlation analysis and principal pattern oscillation analysis, is routinely used in the earth sciences to document and describe spatial and temporal patterns of climate variability (Richman 1986). The PCA is generally based on either the covariance or correlation matrix. Vastly different results can emerge depending on which matrix is used if the input data series have unequal variances (Jolliffe 1986). With a covariance matrix, the time series with the greatest variance most influences the results. Thus, the large Alaska Pacific salmon runs would carry much more weight than the West Coast Pacific salmon runs. Using a correlation matrix – which is equivalent to normalizing each of the time series - gives equal weight to all of the time series regardless of their absolute magnitude. Thus, relatively unimportant time

[1] The Nino3.4 data and documentation are available from http://nic.fb4.noaa.gov:80/data/cddb/

series such as Oregon chum or central Alaska chinook salmon have as much influence on the analysis as the major runs. Neither approach is ideal in this analysis, and we adopted a method that produces an analysis intermediate between a covariance and correlation PCA . We modified the data such that each of the seven regions had equal weight (unit variance) in the PCA but the relative variances among the five species within each region was preserved. To accomplish this weighting, we followed these steps:

(1) Sum the individual series variances within each region resulting in seven regional variance sums.

(2) For each series, compute the annual deviations from that series' long term mean.

(3) Divide each series by the square root of its regional variance sum.

We then conducted both PCAs using a covariance matrix with the modified data. In the catch-climate PCA each climate index had an input weight equal to each region since each been standardized to unit variance.

Results

Our results provide evidence of an inverse production relationship between Alaska and West Coast Pacific salmon stocks (Table 2). Loadings on the leading principal component for both the catch-only and catch-climate analyses were very similar, being almost uniformly of one sign for the northern stocks and almost uniformly of the opposite sign for the southern stocks. We interpret the leading loading vectors to mean that Alaska Pacific 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 also vary synchronously but opposite to the trend observed in Alaska Pacific salmon. The loadings on the British Columbia Pacific salmon catches suggest that those stocks occupy a transitional region, with chinook and coho salmon of the same sign as the southern stocks and the three other species of the same sign, but smaller magnitude, as the Alaska stocks. Washington chum salmon was the most notable exception to the inverse production pattern, having a loading of .404.

In the catch-climate PCA, all three climate indices had the same sign in the loading vector as the Alaska stocks, indicating a positive association with the Alaska Pacific salmon stocks and a negative association with the West Coast Pacific salmon stocks. Of the three indices, the PDO had the largest loading (0.728), compared to the AL loading of 0.553 and the ENSO index loading of 0.534. Inclusion of the climate indices had little impact on the salmon loadings and the same inverse relationship between the north and south stocks still emerged from the analysis.

The first principal component explained 34% of the variance in the catch-only PCA and 30% of the variance in the catch-climate PCA. To assess the significance of the principal components, we combined two eigenvalue tests - the scree plot (Cattell 1966) and “North’s rule of thumb” (North 1982). The scree plot gives a visual guide to the relative magnitude of the eigenvalues while North’s rule of thumb gives a quantitative estimate of the degree of separation between successive eigenvalues. Based on these two tests, we find that only the first PC is significant and interpretable (Fig. 4). In both PCAs, the sampling errors of all eigenvalues after the first one overlap indicating they are degenerate and non-interpretable. The scree plot also shows that the first eigenvalue lies well above a line drawn through the higher order eigenvalues and thus is a logical stopping point for PC retention and interpretation.

The time variability in both leading PC scores depicts an interdecadal oscillation with predominantly positive values from the mid-1920s to the mid-1940s, negative values from the late 1940's to about 1976, and then positive values from 1977 through 1994 (Fig. 5). Of the three climate indices, the PC score most closely resembles that for the PDO. The PC loadings in combination with the interdecadal PC score suggests the existence of interdecadal salmon production regimes with a clear inverse relationship between Alaska and West Coast stocks.

Discussion

We surmise that climatic influences are driving the alternating regimes of salmon production that we have identified in this analysis. The inverse production relationship between Alaska and West Coast Pacific salmon stocks was derived from an analysis of historical catch records. A second analysis that incorporated three Pacific climate indices confirmed the inverse relationship and suggested that decadal-scale production regimes in Pacific salmon are driven by the Pacific Decadal Oscillation, a North Pacific climate oscillation that alternates between positive and negative phases every 20-30 years.

Pacific salmon production also showed a strong relationship to indices for El Niño-Southern Oscillation (ENSO) and the Aleutian Low (AL). This is not surprising. The North Pacific impacts of the ENSO and PDO phenomena are largely determined through associated changes in the large-scale windstress field over the Pacific. Over the Northeast Pacific, ENSO and PDO windstress signatures are very similar, and much of this atmospheric variability is captured by the AL index. The AL and ENSO, however, both show more interannual variability than the PDO which operates under a preferentially interdecadal timescale. ENSO events typically occur every 2-7 years and last 12-18 months. El Niño events do tend to occur more frequently during positive phases of the PDO and less frequently during negative phases. Interannual variability in the AL is influenced by ENSO (Wallace and Gutzler 1981) while interdecadal variability in the AL is coherent with that of the PDO (Mantua et al. 1997).

The PDO has been primarily in its positive phase since the winter of 1976-77. Its reversal that winter has been well documented and often termed a “regime shift” (Graham 1994; Miller et al. 1994; Trenberth and Hurrell 1994). The current Alaska Pacific salmon production boom, and West Coast Pacific salmon production decline, began in the late 1970s. The last prolonged negative phase of the PDO lasted from 1947 to 1976 and the previous positive phase from 1925 to 1946. These periods match alternating production regimes for Alaska and West Coast Pacific salmon since 1925. We believe that much of the decadal-scale variability observed in Alaska and West Coast Pacific salmon stocks derives from a climatically driven bottom-up mechanism operating early in the oceanic phase of the salmon’s life history. Our conceptual model of climate driven salmon production originates with decadal-scale and basinwide climate variability over the North Pacific. Thus, in the two decades since the major climatic regime shift of 1976-1977, mixed layer depths (MLD) in the subarctic gyre decreased while those in the subtropical gyre increased (Polovina et al. 1995). Ocean surface layer temperatures warmed along the entire Pacific Coast of North America. This coastal warming has been well-simulated with an ocean model forced by observed surface wind and heat flux anomalies (Miller et al. 1994). The coastal warming was also associated with an increase in the stratification of the upper ocean along the Pacific coast from the Gulf of Alaska south to Southern California (Roemmich 1992, McGowan et al. 1998).

The ecological response to these large-scale changes in the physical environment was dramatic. At the base of the oceanic ecosystem(s) of the North Pacific, phytoplankton production increased in both gyres in response to the changes in MLD. Zooplankton biomass doubled in the Subarctic gyre (Brodeur and Ware 1992; Sugimoto and Tadokoro 1997) between the mid-1950s and mid-1980s and had a much broader distribution within the gyre and high abundance levels around the perimeter. In particular, calanoid copepods, a dominant prey of salmon, doubled at Ocean Station P concurrent with the climatic regime shift (McFarlane and Beamish 1992). On the other hand, zooplankton biomass in the southern California Current decreased by 70% between the mid-1960s and 1980s in response to warming and stratification of the upper surface layer (Roemmich and McGowan 1995). Brodeur et al. (1996) reported significant negative correlation between zooplankton biomasses at Ocean Station P (located near the southern periphery of the Subarctic gyre) and those measured in the California Current. A large number of higher trophic-level marine fish, bird, and mammal populations also showed abrupt increases or decreases coincident with the mid-1970s climate event (Francis et al. 1998; McGowan et al. 1998).

To summarize, according to our conceptual model, the Alaska and West Coast Pacific salmon populations are both responding to ocean climate conditions. For most of the past 20 years, conditions have favored Alaska Pacific salmon and have been unfavorable for West Coast Pacific salmon. A significant shift in zooplankton biomass as well as its distribution around the subarctic gyre has apparently provided favorable feeding conditions for migrant Alaska-origin smolts during a critical stage in their life history. Conversely, the dramatic decrease in zooplankton production off the West Coast due to stratification of California Current waters and decreased primary production has created a relatively barren ocean environment for West Coast smolts. As adults, many West Coast Pacific salmon migrate to and spend considerable time in the Subartic Gyre which they co-inhabit with adult Alaska-origin Pacific salmon. However, because it is during the early ocean near shore phase of their life history that we hypothesize the oceanic influence occurs, we would expect these two populations to show inverse trends in production.

Gargett (1997) recently advanced a conceptual extension to this model. The key notion of this extension is the possible existence of an “optimum window” for coastal water column stability, driven by large-scale fluctuations in Pacific basin climate, that affects both light levels and nutrient supply for phytoplankton growth. Assuming that the stability of the coastal Northeast Pacific varies “in phase” in response to decadal-scale variation in the Aleutian Low/PDO process, she hypothesizes that northern (Gulf of Alaska/Bering Sea) and southern (California Current) phytoplankton populations occupy opposite ends of this “window” producing variations in primary (and secondary) production in the two regions that are out of phase.

Our analysis does not account for the dramatic regionally-specific changes in freshwater habitat, hatchery practices, and harvest strategies that have taken place over the past 70 years. It is also possible that some of the fisheries (such as those in western

Alaska) were not yet fully exploited by the early 1920s resulting in an underestimate of actual production. In spite of these limitations, we find that a large fraction of the observed variations in Pacific salmon landings are coherent with large scale patterns of Pacific climate variability.

The salmon species showing the strongest association with the inverse production pattern were pink, coho and sockeye while chinook and chum showed a much less consistent association. Chum and chinook salmon generally have less uniform life histories than coho or pink salmon. Chinook salmon, in particular, "appear to have evolved a variety of juvenile and adult behavior patterns in order to spread the risk of mortality across years and across habitats." (Healey 1991). One could speculate that chinook and chum are better adapted to maintaining population levels during poor ocean regimes in comparison to the species where all members of a year class enter and exit the ocean simultaneously. Conversely, pink, coho and certain stocks of sockeye, can better exploit productive regimes. While this is only speculation, the tendencies are borne out by the catch histories – interannual variability appears to be more pronounced, in relation to interdecadal variability, in chinook and chum.

There are significant management implications if the observed pattern of salmon catch fluctuations is tied to the Pacific Decadal Oscillation (PDO). The phases of the PDO have lasted 20-30 years this century with the current phase in place since 1977. Therefore, the current phase (or regime) should be expected to reverse within a decade, at which time favorable ocean conditions should return for West Coast salmon.

Does this mean that restoration efforts on the freshwater and estuarine habitat end of the salmon's world are pointless? Absolutely not; highly productive wild salmon populations are indicative of high-quality environmental conditions at every stage of the salmon's life cycle. The only common denominator in regions of the Northeast Pacific (e.g., Pacific Northwest) where a number of salmon stocks are in serious jeopardy of extinction is the profound influence of man on altering and destroying freshwater habitat, either directly through reengineering of watersheds or indirectly through the widespread use of hatcheries (Flagg et al. 1995; Waples 1995). We believe that Pacific salmon have evolved their metapopulation structures over millennia to deal with variations in ocean conditions of the kind we have reported in this paper. Although mechanisms are not absolutely clear, it is our feeling that the physical template provided by naturally functioning watersheds is the ultimate source of "climate insurance" necessary for wild salmon populations to persist.

Our results support Lawson's (1993) argument that management actions cannot be expected to control all aspects of salmon ecology. We caution that a lack of immediate increases in production following restoration efforts may be misconstrued as management failures in periods of poor ocean conditions. Instead, we believe that management actions to carefully limit harvest, improve hatchery practices, and restore freshwater and estuarine habitats should be viewed as necessary long-term investments whose overall returns are strongly influenced by variations in the ocean environment.

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

species	years	range (years)
sockeye	2	1-3
pink	1	1
chum	3	2-4
coho[1]	1	1-3
chinook	3	1-5

[1] Coho spend approximately 1.5 years in fresh water and 1.5 years in the marine environment. Most commonly, the year of return is the calendar year following the year of seaward migration.

Table 2. CATCH Component loadings from two principal component (PC) analyses on 30 Pacific salmon catch time series and three climate indices. Loadings are on the first PC from a catch data only analysis and a catch plus climate data analysis

Region	Species	Catch data only	Catch and climate data
Western Alaska	Sockeye	0.831	0.799
	Pink	0.177	0.228
	Chum	0.122	0.148
	Coho	0.441	0.394
	Chinook	0.036	0.010
Central Alaska	Sockeye	0.831	0.716
	Pink	0.855	0.744
	Chum	0.415	0.411
	Coho	0.797	0.774
	Chinook	0.603	0.519
Southeast Alaska	Sockeye	0.702	0.616
	Pink	0.805	0.667
	Chum	0.716	0.620
	Coho	0.717	0.580
	Chinook	0.011	-0.026
British Columbia	Sockeye	0.437	0.340
	Pink	0.269	0.117
	Chum	0.093	0.067
	Coho	-0.044	-0.103
	Chinook	-0.477	-0.495
Washington	Sockeye	-0.149	-0.152
	Pink	-0.033	-0.056
	Chum	0.404	0.341
	Coho	-0.337	-0.358
	Chinook	-0.734	-0.692
Oregon	Chum	0.009	0.032
	Coho	-0.382	-0.359
	Chinook	-0.161	-0.090
California	Coho	-0.489	-0.484
	Chinook	-0.245	-0.164
PDO			0.728
AL			0.553
ENSO			0.534

Figure 1. Catch histories for five species of Pacific salmon from seven regions in the U. S. and Canada. All numbers are in millions of fish and represent the combined commercial, recreational and subsistence catches. The western Alaska and central Alaska catches have been adjusted for high seas interceptions between 1952 and 1992.

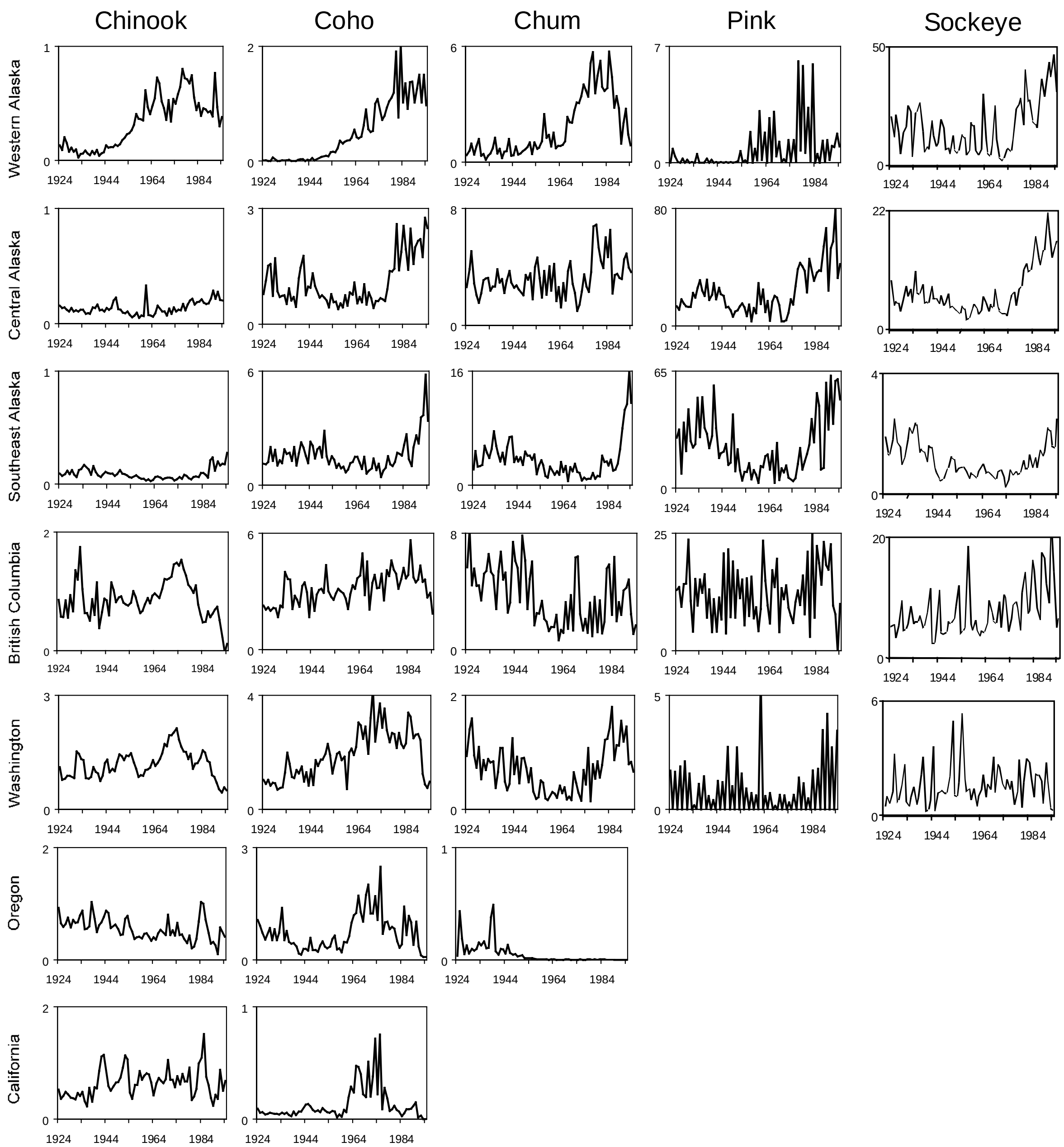

Figure 2. A comparison of anomalous climate conditions associated with the positive phases of the Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO). The values show °C for sea surface temperature (SST), millibars for sea level pressure (SLP) and direction and intensity of surface wind stress. The longest wind vectors represent a stress of 10 m^2/s^2. Actual anomaly values for a given year associated with the PDO and ENSO are computed by multiplying the climate anomaly with the associated temporal index (Fig. 3). Adapted from Mantua et al. (1997).

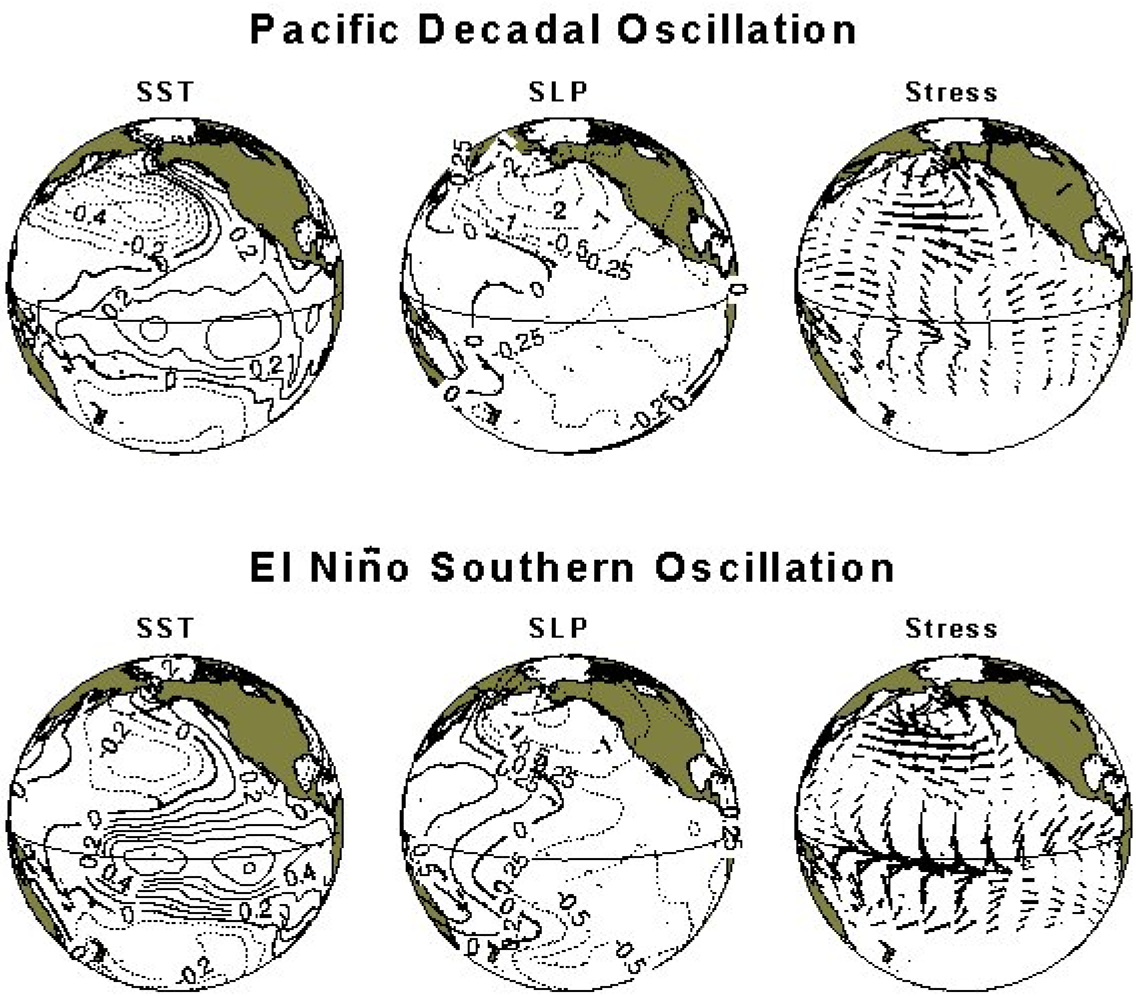

Figure 3. Annual mean NINO3.4, PDO, and Dec. - Mar. mean AL climate indices. Positive values are shaded in black, negative in gray. For NINO3.4 and the PDO, positive values indicate a positive, or warm, phase of the cycle. For the AL, a positive value indicates an enhanced Aleutian Low, i. e., lower surface pressure. All time series have been standardized with respect to the 1900-1997 period of record. See text for definition of each index.

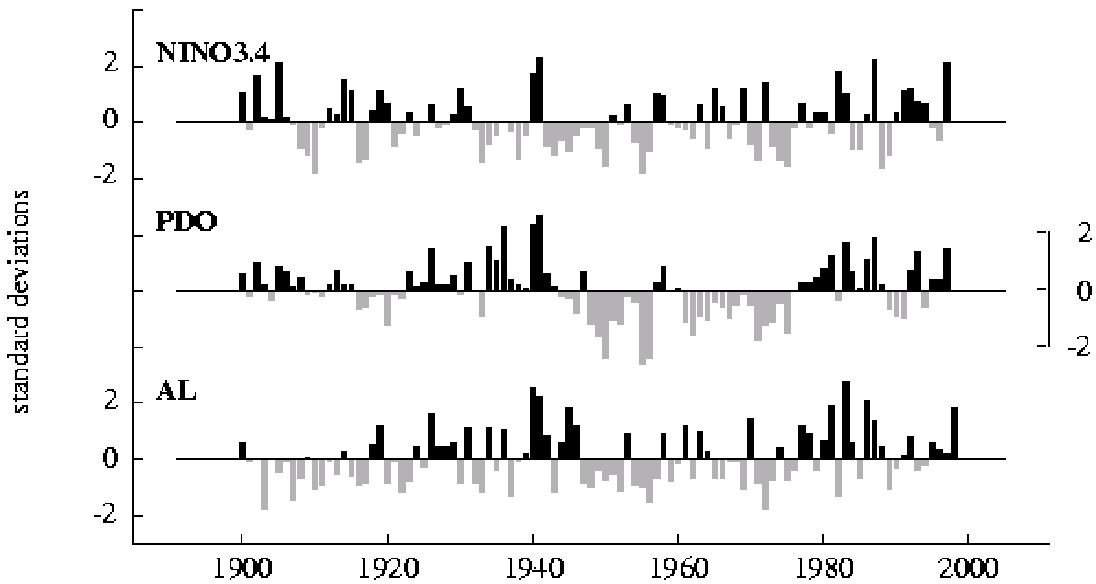

Figure 4. Eigenvalue scree plots from the catch-only and catch-climate principal component analyses. Error bars were computed by the formula of North et al. (1982).

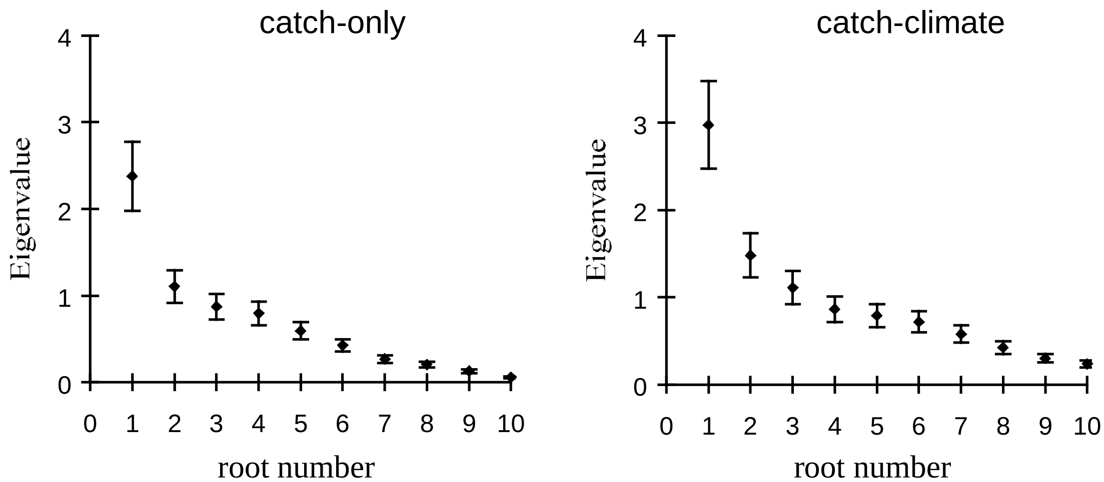

Figure 5. The principal component (PC) scores for the analysis of the catch-only (top) and catch-climate (middle) data covariance matrices. The PDO index, as shown in Figure 1, is repeated at the bottom for comparison. PC values are standard deviations and give the temporal strength of the associated loading vector (Table 1).