An historical narrative on the Pacific Decadal Oscillation, interdecadal climate variability and ecosystem impacts

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Abstract

The term Pacific Decadal Oscillation (PDO) was coined in 1997 (Mantua et al. 1997) to describe a mode of north Pacific climate variability that varies on a multi-decadal time scale. A number of independent studies being conducted at the time contributed to the realization that the PDO had widespread climatic and ecosystem impacts. This brief report is our perspective on how the PDO was identified and named. We also provide summaries of more recent work characterizing the PDO and interdecadal climate variability, and give several examples of climate induced variability in the ecosystems of the North Pacific.

Introduction

In the past decade, there has been an explosion in the awareness of the effect of climate variability on marine and terrestrial populations. Much of the interest stems from the growing concern about the warming of the planet in response to increased concentration of greenhouse gases and deforestation, and the resultant impact on plant and animal life. A direct method of assessing the potential impacts of global warming is by examining how populations respond to natural climate variability.

In the Pacific Ocean, the natural climate phenomenon termed El Niño-Southern Oscillation (ENSO) has long been recognized. The two phases of ENSO are generally termed El Niño (or warm phase) and La Niña (cool phase). Studies of ENSO-related impacts on marine ecosystems are numerous (e.g., Wooster and Fluharty (1985), Mysak (1986), Glantz (1996)). After the seasonal cycle, ENSO is the largest climate signal over most of the Pacific Ocean. While termed an oscillation, the alternation between El Niño and La Niña events is quite irregular, though generally occurring every 3 to 7 years with individual events usually lasting 8 to 15 months.

The climatic and biotic impacts of ENSO events are largest near the equator and generally diminish towards the poles. The effects of ENSO are propagated to the extra-tropics via both oceanic and atmospheric pathways. No two ENSO events are exactly alike, differing in intensity, timing and spatial organization, and the extra-tropical climatological and ecological responses similarly vary from event to event. The five strongest El Nino events during the past 50 years occurred in 1982/83, 1997/98, 1957/58, 1986/87, 1972/73 (these episodes are listed in approximate decreasing order of intensity, as measured by equatorial sea surface temperatures in the Nino3 region) but regional variations in intensity can vary substantially). During La Niña events, atmospheric and oceanic conditions are essentially reversed from El Nino conditions. Recent strong La Niña events include 1998/99, 1967/68, 1971/72, 1974/75, 1988/89 and 1995/96.

While ENSO has dramatic impacts on the climate of the North Pacific, several investigators have noted that there is far from a one-to-one correspondence between the occurrence of ENSO events and ENSO-type climate responses. Most notably, over much of the past 25 years, the climate of the North Pacific has been in an almost continuous El Niño state despite the absence of tropical El Niño events in a majority of those years. This change, which originated with the strongly anomalous winter of 1976-1977 has been termed a regime shift. The first recognition that some important change has taken place in the climate of the north Pacific was Trenberth (1990) who described a step-like change in winter sea level pressure (SLP) in the North Pacific. The first detailed depiction of the climatic changes and the paper that dubbed the 1976/77 North Pacific event a regime shift was Miller et al. (1994).

At about the same time, perhaps even earlier, that climatologists were recognizing the apparent importance of climatic events in 1976/77, biologists were taking note of similar dramatic changes in much of the biota around the North Pacific. Ebbesmeyer et al. (1991) quantified the change in 40 “environmental” (climatic and biological) variables demonstrating a statistically significant 1977 step change in a composite of the time series. It was observations on salmon, however, specifically the catch history of salmon going back 70 years, that provided the most tantalizing evidence that a definite link existed between climate variability and biological production.

The remainder of this note deals with the recently identified and named Pacific Decadal Oscillation (PDO). Salmon play a pivotal role in the PDO story. In the next section, the sequence of events and publications leading to the characterization and naming of the PDO are recounted. A summary of PDO impacts around the North Pacific is then provided. In the last section, recent advances in PDO research are summarized.

Identification and naming of the PDO

In 1991, Robert Francis and Thomas Sibley of the University of Washington School of Fisheries published a relatively obscure paper (Francis and Sibley 1991) which contained two intriguing figures. The first figure compared smoothed Gulf of Alaska pink salmon catches from 1925-1985 with local air and sea temperatures over the same period of record. The synchronous rise and fall of the three time series (plotted as deviations from their respective means) – all mostly positive prior to the mid 1940s, mostly negative from the mid 1940s to mid 1970s and again mostly positive after the mid 1970s suggested some association between temperature and salmon. The second figure (reproduced and updated here in Figure 1) showed an apparent inverse relationship between catches of Gulf of Alaska pink salmon and U. S. west coast coho salmon. It was at this point in time that one of us (SRH) entered graduate studies at the Univ. of Washington with Dr. Francis as doctoral supervisor.

In a series of papers over the next several years (Francis and Hare (1994), Hare and Francis (1995), Francis and Hare 1997, Francis et al. 1998, Hare et al. 1999) Francis and Hare focused on Alaska salmon production and its link to climate. In these papers, they argued that Alaska salmon production was best characterized as alternating regimes, where the transition from one regime to another was abrupt. The regime shift of 1976-77 had the effect of boosting Alaska salmon productivity 1-3 years later depending on the species of salmon. In fitting time series models to the major pink and salmon sockeye stocks, they identified another regime shift – from a productive to unproductive regime – in the winter of 1946/47 (Figure 2). The earlier regime shift was identified from the salmon catch data. Alaska air and sea temperatures were then examined for shifts (interventions) in 1947 and 1977 and these were, in fact, found to be statistically significant.

At the same time as the work on salmon pointed towards climate, another research team at the University of Washington School of Atmospheric Sciences was also examining decadal scale climate variability. Yuan Zhang, and her advisor John (Mike) Wallace had assembled lengthy climate data sets and were researching Pacific climate variability after ENSO and global warming signals had been removed. The early results of their work (Wallace et al. 1996, Zhang et al. 1997) were published in the influential Journal of Climate.

In the fall of 1995, the University of Washington's Joint Institute for the Study of the Atmosphere and Oceans and School of Marine Affairs hired Mantua to fill a new position for a climate specialist to work on interdisciplinary studies of climate impacts on natural resources in the U.S. Pacific Northwest (PNW). Early in his work, Mantua found evidence that the regime shifts noted above had major impacts on PNW winter climate and related water resources. Opportunities for collaboration with Hare and Francis and Zhang and Wallace were clear.

The two research teams invited Mantua to serve as lead author on a synthesis paper that described the mode of interdecadal climate variability and its impacts on Pacific salmon production, climate and water resources in northwestern North America (Mantua et al. 1997). At the time, Hare and Zhang were finishing their Ph.D. dissertations (Hare 1996, and Zhang 1996, respectively), wherein they reported on their independent discoveries of the same mode of Pacific interdecadal climate variability.

The term Pacific Decadal Oscillation (PDO, coined by SRH) was adopted to identify this mode, and first appeared in the literature in Mantua et al. (1997). A third 20th century regime shift was first identified in the PDO paper, this one occurring in the winter of 1924/25. The PDO index is computed from gridded SSTs poleward of 20º N in the Pacific basin. The spatial signature of the PDO in other climatic fields (SLP winds, precipitation, 500 mb height, etc) is generally found by regressing those data against the PDO index.

The PDO has been described as a long-lived ENSO-like pattern of Pacific climate variability (Zhang et al. 1997). As seen with ENSO, extremes in the PDO pattern are marked by widespread variations in Pacific Basin and North American climate. Two main characteristics distinguish the PDO from ENSO. First, typical PDO "events" have shown remarkable persistence relative to that attributed to ENSO events - in this century, major PDO regimes have persisted for 20 to 30 years. It is the sudden switch from one polarity to the other that is termed a regime shift. There is both interannual and interdecadal variability in the PDO, but it is the interdecadal aspect of the signal that appears to most strongly influence Pacific ecosystems. Secondly, the climatic fingerprints of the PDO are most visible in the North Pacific/North American sector, while secondary signatures exist in the tropics - the opposite is true for ENSO. The spatial and temporal signatures of both ENSO and the PDO are illustrated in Figure 3.

Ecosystem Response to the PDO

The number of studies relating Pacific ecosystem response to interdecadal climate variability and the PDO has grown substantially the past few years. While it is not possible to mention all relevant publications, a brief summary of some of the more important contributions follows.

Salmon have continued to receive the greatest attention, essentially serving as the poster child of climate impacts on natural resources. Several papers linking Pacific basin-wide salmon catches to the Aleutian Low have been published by Beamish and co-workers (Beamish 1993, Beamish and Bouillon 1993, Beamish et al. 1999). Examination of the differing regional responses of salmon stocks along the west coast of North America has been conducted by Adkison et al. (1996) and Peterman et al. (1998). Their findings indicated that Alaskan stocks showed a strong uniform response to climate but British Columbia stocks were mixed. Hare et al. (1999) extended the geographic scope to include stocks from Washington, Oregon and California and analyzed catch records from the five major salmon species. They identified an “inverse production regime”, driven by the PDO, where the positive phase of the PDO is beneficial to Alaska stocks and detrimental to Washington, Oregon and California (WOC) stocks. The negative phase of the PDO has the opposite effect on Alaska and WOC stocks. The essence of their analysis is illustrated in Figure 4.

The response of groundfish stocks to the PDO has also been documented in several studies. A strong one year jump in recruitment in response to the 1976-77 regime shift was demonstrated for many commercially exploited stocks in the Northeast Pacific by Beamish (1993) and for sablefish in particular (McFarlane and Beamish 1992). Pacific halibut recruitment was shown by Clark et al. (1998) to have undergone interdecadal shifts closely matched to the phases of the PDO (Figure 5). Like Alaska salmon, halibut flourish during the PDO positive phase. Hollowed et al. (1998) assembled recruitment time series for the major exploited groundfish and pelagic species in Alaska and WOC. They found that while a large fraction of the species appeared to respond more to ENSO events, several flatfish species (arrowtooth flounder, Greenland turbot, Pacific halibut) exhibited PDO-like recruitment histories. In perhaps the most thorough documentation of the changes that have taken place in the groundfish complex, Anderson and Piatt

(1999) assembled 45 years of small mesh trawl survey records from the Gulf of Alaska. They show that the marine ecosystem underwent a transformation from one dominated by lower tropic level forage species (e.g., capelin, shrimp, sand lance) prior to the mid-1970s, to one dominated by higher trophic level groundfish (e.g., gadids and flatfish) since that time.

A number of other studies have shown impacts of the PDO on other components of the marine and terrestrial ecosystems of the North Pacific. At the plankton level, primary and secondary productivity responses to the climate shift of 1976-77 have been documented by Venrick et al. (1987), Brodeur and Ware (1992), Brodeur et al. (1996), Roemmich and McGowan (1995), and Mackas et al. (1998). At the higher, non-piscivore, trophic levels, Piatt and Anderson (1995) and Francis et al. (1998) discuss decadal changes in marine mammal and pisciverous bird populations, particularly in response to the climatic regime shift of 1976-77. More recently, Vandenbosch (2000) linked Hawaiian Island and Farallon Island population variability to phases of the PDO. Finally, Cayan et al. (2001) document a long term change in the onset of spring in the western United States – as measured by blooming times of lilac and honeysuckle bushes – which shows a high correlation to the springtime PDO. In perhaps the broadest examination to date of the widespread climatic impacts on the ecosystems of the North Pacific, Hare and Mantua (2000) conducted a principal component analysis on a matrix of 100 climatic and biological time series. The climatic time series were selected to represent the atmosphere and ocean across the North Pacific while the biological time series ranged across all trophic levels. The dominant principal component has the same time trajectory as the PDO. The ecosystem response to interdecadal climate variability in the California Current region was documented by McGowan et al. (1998).

Conceptual model

In attempting to understand the link between large scale climate variability and ecosystem change, a conceptual bottom-up model was outlined by Francis et al. (1998). In summary form, the model (illustrated in Figure 5) is:

1. The primary forcing function resulting from climate change is a change in surface wind stress. Changes in surface winds cause changes in the air-sea exchange of heat and momentum, which in turn alter important properties of the upper ocean (such as currents, temperatures, stratification, eddies, and fronts).
2. Upper ocean environmental changes lead to changes in primary production, the timing of blooms, mix of phytoplankton species, and their concentration and larger scale distributions.
3. These changes are reflected in the secondary (zooplankton) level and in transfer efficiencies between levels
4. Before and after a climate regime shift, forage and upper trophic levels will be selectively favored depending upon changes in habitat and feeding conditions
5. Growth and survival of upper trophic levels are affected by climate change primarily through direct effects on metabolic requirements of larvae and juveniles; availability of food; and distribution and abundance of predators.

6. Different components of the ecosystem track climate changes unequally due to lags and non-linearities, thus different trophic levels can be out of phase with each other and with environmental properties.
7. With different mixes of upper trophic level species, top down effects occur, with different pressures on stocks of forage of those predators and their prey.

This conceptual model was extended to the PDO-Alaska salmon connection by Hare (1996) and is illustrated in Figure 6. The positive phase of the PDO, which includes an enhanced Aleutian Low, is hypothesized to benefit Alaskan salmon through the following mechanisms:

1. The entire system is ultimately driven by variations in the Aleutian Low. In a productive regime, the Aleutian Low intensifies during winter (Nov.-March) months and is displaced to the southeast. This results in an increase in wind stress along the southern and eastern sides of the Alaska Gyre.
2. Geostrophic flow increases around the gyre's periphery, particularly along the Alaskan panhandle and the northern Gulf of Alaska.
3. The Alaska Gyre "spins up" in response to the Aleutian Low forcing. Enhanced Ekman pumping causes increased upwelling in the interior of the Alaska Gyre.
4. The mixed layer depth in the Subarctic Region becomes shallower.
5. Primary and secondary production is significantly enhanced along the Alaska coast and moderately so within the Gyre. The increased production is stimulated by vertical mixing in the water column and greater nutrient recycling, and is advected around the Alaska Gyre by the Alaskan Stream. Because phytoplankton production in the Subarctic Region is believed to be light-limited, the shallower mixed layer depth supports increased primary production.
6. The predominant zooplankton benefiting from increased primary production are copepods which peak in abundance in the spring.
7. Ocean survival rates increase for salmon smolts and juvenile salmon that feed predominantly on copepods. The improved feeding conditions result in increased early ocean growth which can benefit the young salmon in a number of ways, e.g., reduced vulnerability to predation. The early ocean life history stage is a period of high mortality believed to be the period when class size is established (Pearcy 1992), thus any reduction in mortality during this phase should result in an exceptional year class size.
8. Salmon are generally smaller upon return due to density dependent growth during their final year (or months) at sea.
9. Temperature likely plays an important role in several ways, including metabolic effects on growth, predator and prey distribution and limits on salmon foraging ranges.

An important contribution to the climate-salmon model was made by Gargett (1997) who used the concept of an “optimal stability window” to provide a possible mechanism underlying the inverse production regime between Alaska and WOC salmon.

Recent advances in PDO climate research

Understanding the nature of spatial modes of interdecadal climate variability in the North Pacific is an area of very active research. Some retrospective studies find evidence for distinct and independent lobes of North Pacific SST variability embedded within the canonical PDO pattern. Nakamura et al. (1997) examined SST data for the 1968-92 period of record and identified two independent centers of action, one encompassing the subtropical front north of Hawaii and the other encompassing the subarctic front that defines the Kuroshio/Oyashio Extension. Barlow et al. (2001) analyze Pacific SSTs for the 1945-93 period of record and identify a different pair of North Pacific SST modes, each spatially correlated with the canonical PDO pattern of Mantua et al. (1997). In contrast, Kaplan et al. (2000) applied an optimal interpolation scheme to available SST and SLP records for the 1854-1992 period of record, then recovered the PDO pattern as the second leading mode of covariability between the 5-year low-pass-filtered global fields (the leading mode of covariability was a trend mode). While these results paint somewhat different pictures of past North Pacific variability, there remains a wealth of evidence in support of interdecadal climate variations in the North Pacific that generally resemble, if not reproduce, the results obtained in Zhang and Hare's dissertations.
Evidence for PDO influences throughout the Pacific Hemisphere also continues to accumulate. Garreaud and Battisti (1999) extended the study of Zhang et al. (1997) to the Southern Hemisphere and identified a clear pattern of symmetric atmospheric circulation changes associated with the PDO. Dettinger et al. (2001) found evidence for a symmetric pattern of PDO-related precipitation anomalies in the Americas, wherein warm PDO (El Niño-like) periods tend to have anomalously wet subtropics but dry tropics and midlatitudes in both North and South America. Interdecadal changes in eastern Australia climate have also been correlated with the PDO; warm PDO periods are associated with anomalously warm-dry conditions, while cool PDO periods are associated with cool-wet conditions (Power et al. 1998).
There are other indications that the PDO may in fact be composed of two separate interdecadal scale oscillations, one with an approximately 20 year period, the other a 50-70 year period. The work is novel and not nearly definitive; the interested reader is referred to the following publications: Minobe (1997, 1999, 2000); Enfield and Mestas-Nuñez (1999), Mestas-Nuñez and Enfield (1999), Barnett et al. (1999), and Chao et al. (2000).

To better understand the long-term behavior of the PDO, several studies report on proxy environmental recorders of PDO-related climate change several hundred years back in time. Biondi et al. (2001) used ring-widths from moisture stressed trees in Southern California and Baja, Mexico; Gedalof and Smith (2001) used tree ring chronologies from a coastal transect from northern California to the Gulf of Alaska; the two research teams developed continuous records back to the 1600's. In each case, the most recent 100 years overlapped with the instrumental record and it was the PDO climate signal that best matched the dominant climate signal in the dendrochronologies. Gedalof and Smith (2001) identified 11 regime shifts in the PDO record since 1650 with the most recent occurring in 1976/77. With the average duration of a regime being 23 years, they suggest that another shift is due around the end of the century. Evans et al. (2000) examined 15 tree-ring chronologies from mid-latitude North and South America and also found that coherence in these records closely matched that in the PDO. Linsley et al. (2000) examined Sr/Ca variability in a long lived coral from Rarotonga and found a strong PDO signal in the extracted coral SST history that spans the period from 1726 to 1997. These last two proxy records are of special interest because they substantiate a robust PDO connection to tropical and southern hemisphere climate (Evans et al. (in press)).

Causes for, and the potential ability to predict, PDO variations are not currently known. Some climate simulation models produce PDO-like oscillations (e.g. Latif and Barnett 1994, Gu and Philander 1997), although often for different reasons (NRC 1998). The mechanisms giving rise to the PDO will determine whether skillful decades-long PDO climate predictions are possible. For example, if the PDO arises from air-sea interactions that require 10 year ocean adjustment times, then aspects of the phenomenon will (in theory) be predictable at lead times of up to 10 years. Even in the absence of a theoretical understanding, PDO climate information informs season-to-season and year-to-year climate forecasts for the Pacific, Australia and the Americas because of its strong tendency for multi-season and multi-year persistence. From a societal impacts perspective, recognition of PDO is important because it shows that "normal" climate conditions can vary over time periods comparable to the length of a human's lifetime.

Whether the PDO is actually two separate oscillations or one with two dominant frequencies, Hare and Mantua (2000) first noted that there has been a recent change in the commonly computed PDO index. In the fall of 1998, the index turned sharply negative and remained so until the beginning of 2001 when it returned to near zero. There are indications that the reversal in the PDO index in 1998 may mark the onset of a new regime. Coastal waters around the Gulf of Alaska and along the U.S. west coast have been anomalously cool. The planktonic community off the U.S. west coast has been dominated by subarctic species for the last three years (pers. comm., Bill Peterson, OSU), which bodes well for WOC salmon. Columbia River spring chinook had the highest return in over 50 years in 2001 (pers. comm., John Williams, NMFS). There are also indications that forage fish (eulachon, candlefish, etc.) are being seen in large numbers once again in the Gulf of Alaska (pers. comm. John Piatt, USGS). If there has indeed been a regime shift and a return to the negative phase of the PDO, a real world test of one of the central hypotheses of the climate-salmon model will be conducted over the next several years: Alaska salmon should experience a decline in production and – provided the freshwater habitat has not been overly destroyed – WOC salmon should experience a renaissance.

Conclusions

In this paper, we have attempted to provide a brief overview of the history of the Pacific Decadal Oscillation – from its initial description and naming to the ecosystem impacts attributed to it. While it is highly doubtful that the initial work in this area completely accurately and fully captured the dynamics and impacts of the PDO, more recent work has in large measure supported the early results. Like the early stage of ENSO research however, there remains much to be learned.

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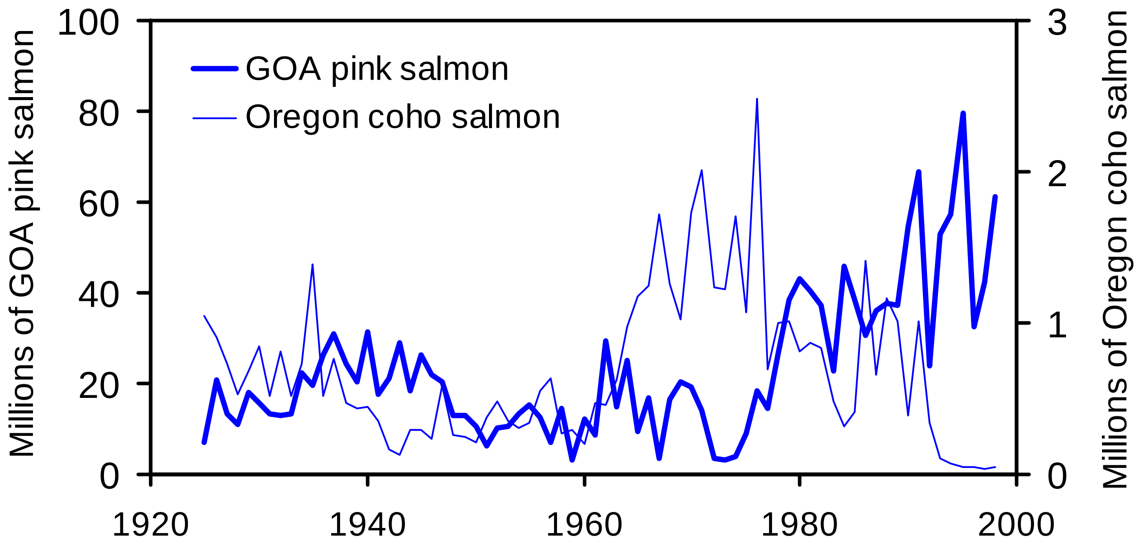

Figure 1. Catch histories for Gulf of Alaska (GOA) pink salmon and Oregon coho salmon. Figure is adapted and updated from Francis and Sibley (1991).

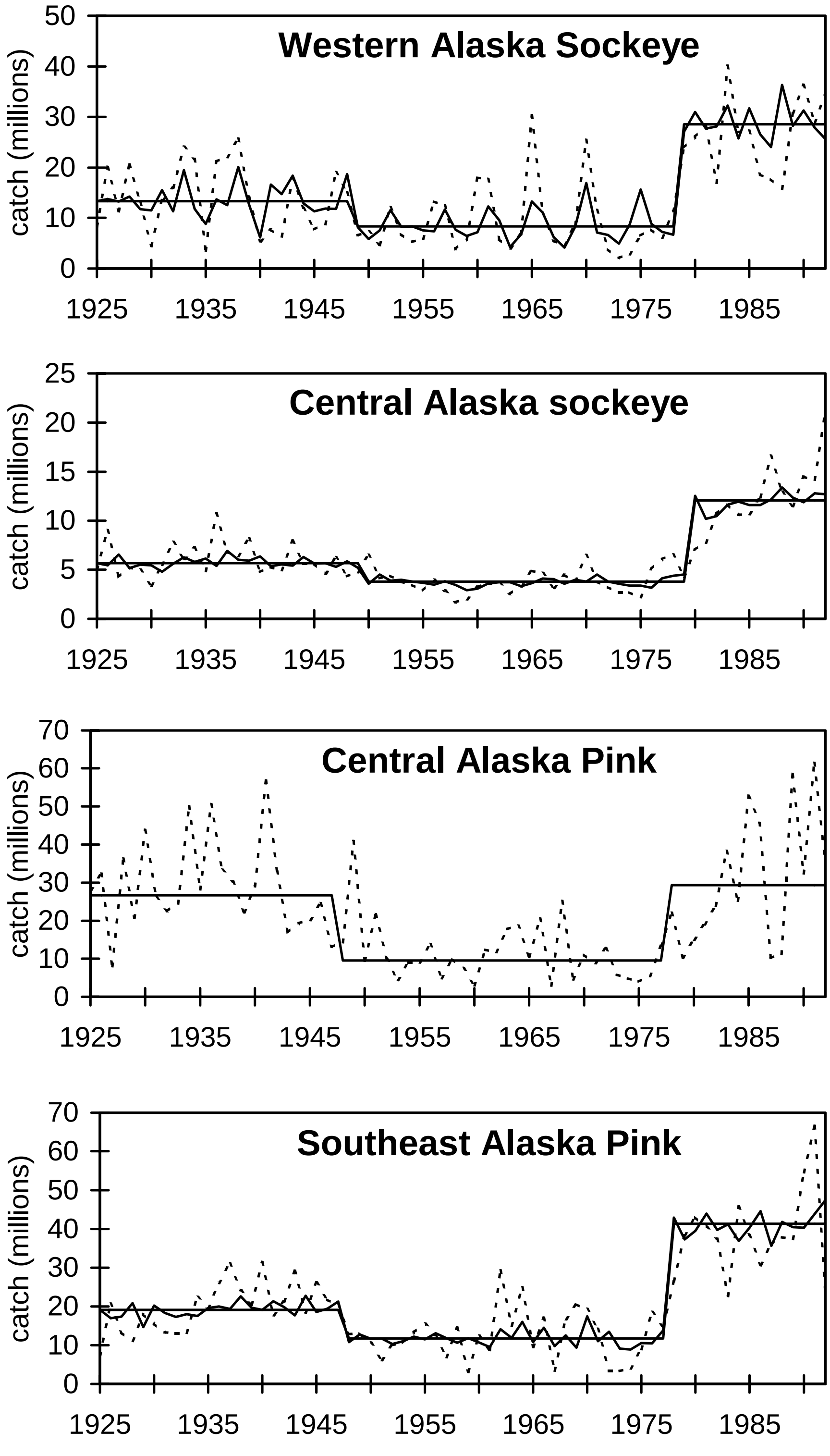

Figure 2. Time history (dashed lines), intervention model fits (thin solid lines) and estimated interventions (thick solid lines) for Alaska salmon time series (from Hare and Francis 1995).

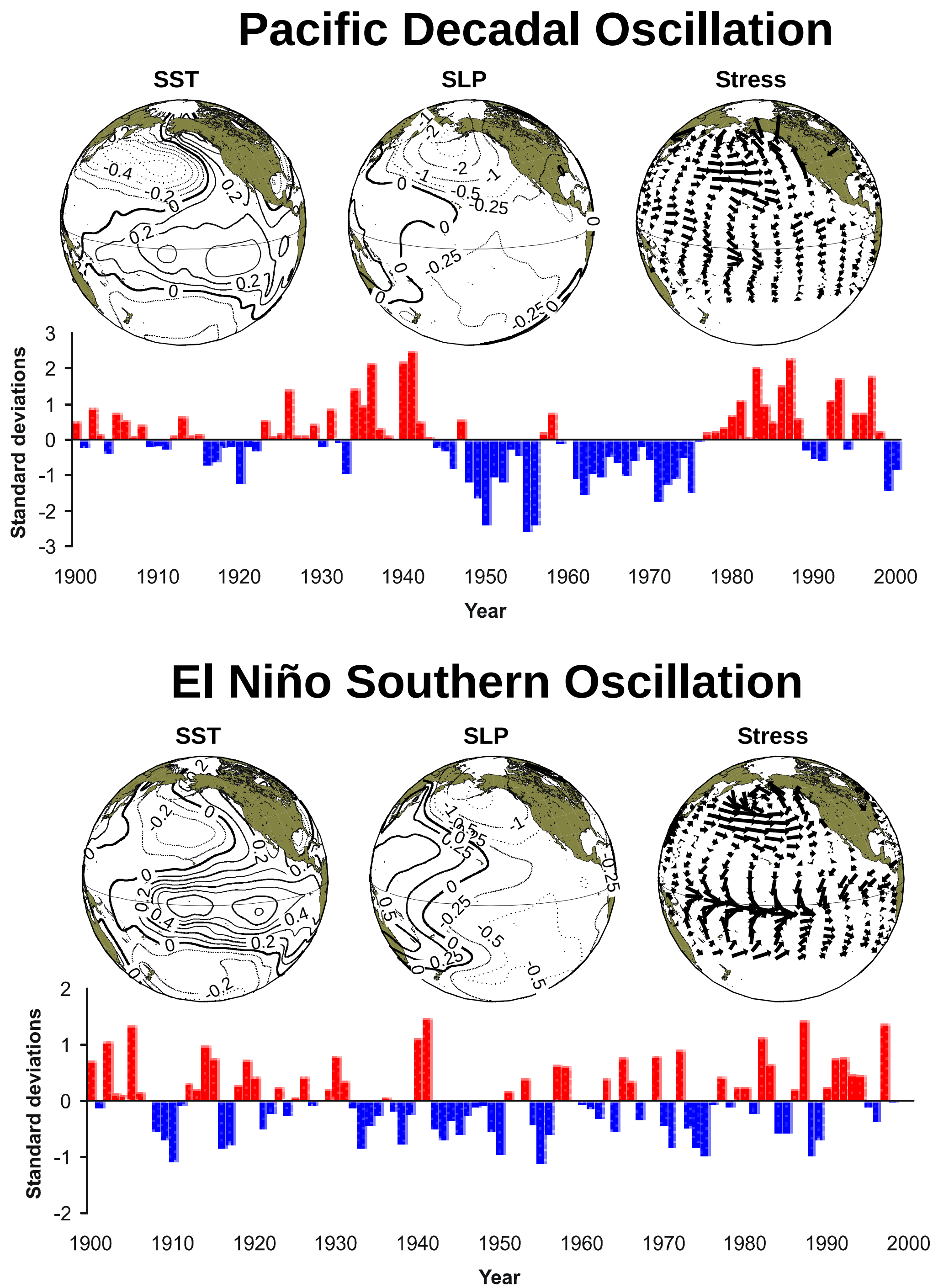

Figure 3. Anomalous climate conditions associated with the positive phases of the Pacific Decadal Oscillation (PDO) and El Niño-Southern Oscillation (ENSO), the PDO and ENSO temporal indices. Values shown are °C for sea surface temperature (SST), millibars for sea level pressure (SLP) and direction and 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 at a given location are obtained by multiply the climate anomaly by the associated index value. Adapted and updated from Mantua et al. (1997)

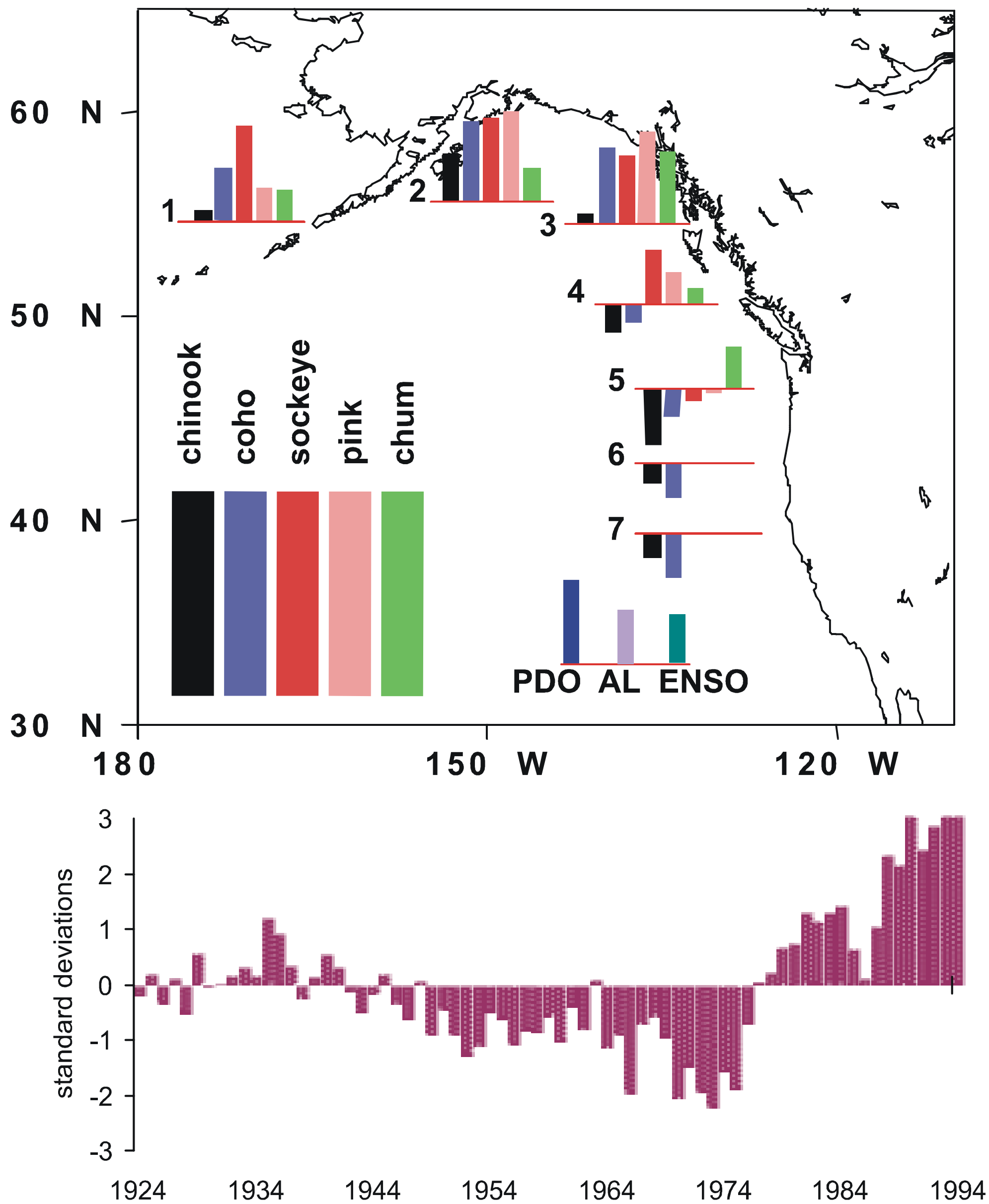

Figure 4. A graphical depiction of the "Inverse Production Regimes" of Hare et al. (1999). The bars represent loadings from a principal component analysis (PCA) of 30 salmon time series for the period 1925-1997. Regional definitions are as follows: 1 – Western Alaska, 2 – Central Alaska, 3 – Southeast Alaska, 4 – British Columbia, 5 – Washington, 6 – Oregon, 7 – California. Three climate indices were included in the PCA: Pacific Decadal Oscillation (PDO), Aleutian Low Pressure Index (AL) and the El Niño-Southern Oscillation (ENSO). The longest bar, Central Alaska pink salmon, has a value of 0.855, and represents the correlation between that time series and the illustrated temporal component (score) from the PCA.

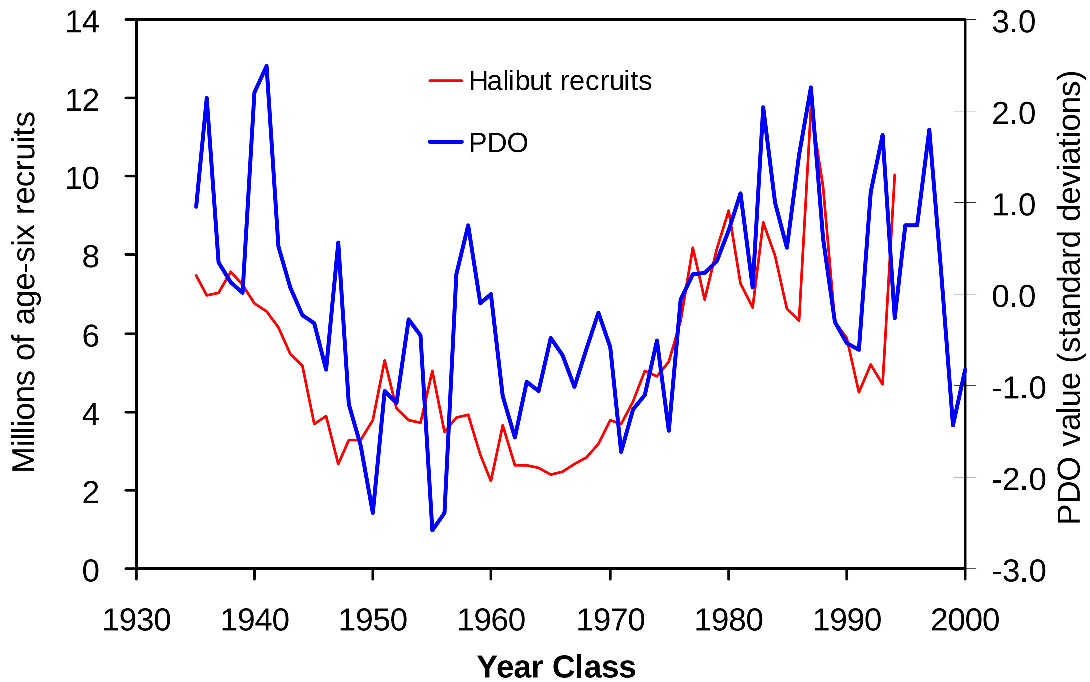

Figure 5. Recruitment of Pacific halibut in the Gulf of Alaska, year classes 1935-1994, plotted together with the winter PDO index aligned to year class.

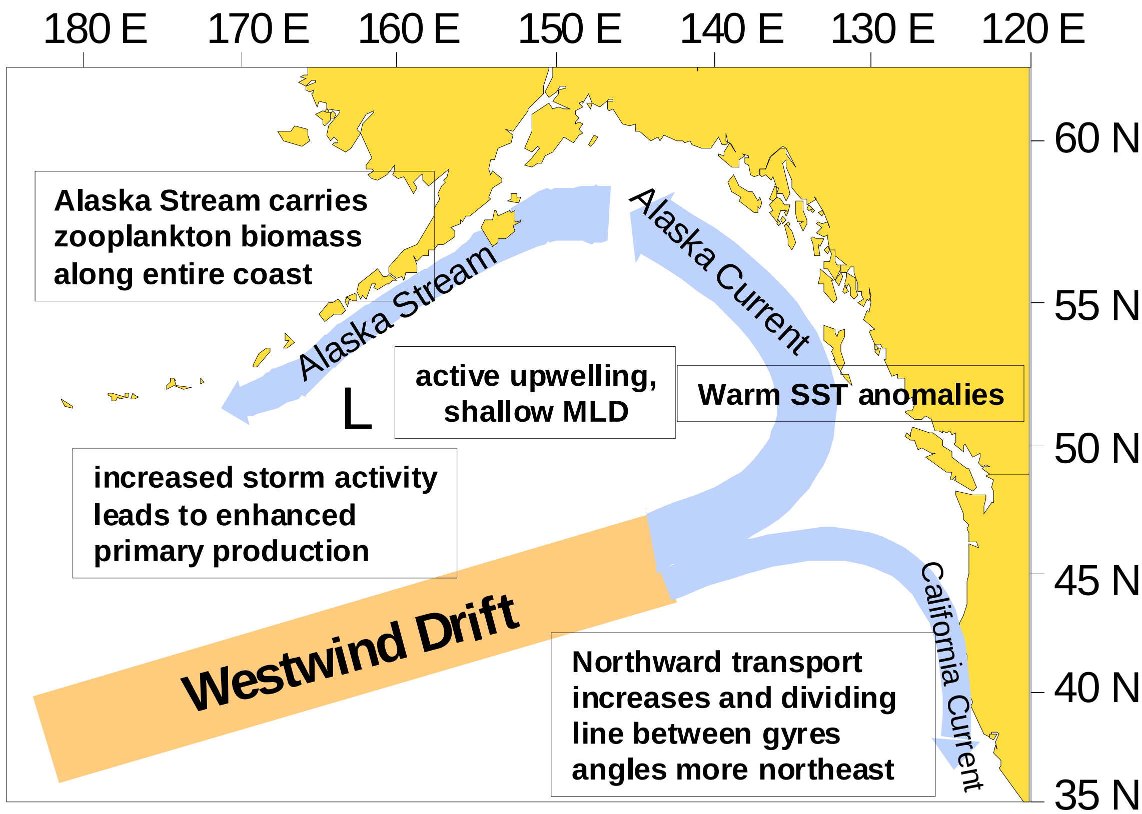

Figure 6. An illustration of the conceptual model linking decadal-scale climate regimes with variability in Alaskan salmon production (from Hare 1996).