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Review

The Pacific Decadal Oscillation

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The *Pacific Decadal Oscillation* (PDO) has been described by some as a long-lived El Niño-like pattern of Pacific climate variability, and by others as a blend of two sometimes independent modes having distinct spatial and temporal characteristics of North Pacific sea surface temperature (SST) variability. A growing body of evidence highlights a strong tendency for PDO impacts in the Southern Hemisphere, with important surface climate anomalies over the mid-latitude South Pacific Ocean, Australia and South America. Several independent studies find evidence for just two full PDO cycles in the past century: "cool" PDO regimes prevailed from 1890–1924 and again from 1947–1976, while "warm" PDO regimes dominated from 1925–1946 and from 1977 through (at least) the mid-1990's. Interdecadal changes in Pacific climate have widespread impacts on natural systems, including water resources in the Americas and many marine fisheries in the North Pacific. Tree-ring and Pacific coral based climate reconstructions suggest that PDO variations—at a range of varying time scales—can be traced back to at least 1600, although there are important differences between different proxy reconstructions. While 20th Century PDO fluctuations were most energetic in two general periodicities—one from 15-to-25 years, and the other from 50-to-70 years—the mechanisms causing PDO variability remain unclear. To date, there is little in the way of observational evidence to support a mid-latitude coupled air-sea interaction for PDO, though there are several well-understood mechanisms that promote multi-year persistence in North Pacific upper ocean temperature anomalies.

Keywords:
· Regime shift,
· climate impacts,
· PDO,
· IPO,
· NPO,
· fishery oceanography.

1. Introduction

Climate records from around the Pacific Basin contain evidence for strong interannual to interdecadal variability, in special cases with remarkably large-scales (O(10^4 km)) of spatial coherence (NRC, 1998). El Niño/Southern Oscillation (ENSO) has long been known to be the prominent source for hemispheric-scale interannual climate variations for the Pacific and the global tropics (Rasmussen and Wallace, 1983). In the last two decades of the 20th Century, the extratropical Pacific Ocean was in an almost continuous El Niño-like state despite the absence of tropical El Niño events in a majority of those years. This situation, which originated with a strongly anomalous winter in 1976–1977, has been termed a "climatic regime", following a regime shift in 1977. The 1977 change in Pacific climate was first reported by Nitta and Yamada (1989) and Trenberth (1990), who described a step-like shift in the mean state of winter sea level pressure (SLP) in the North Pacific. Miller *et al.* (1994) provided the first detailed depiction of the climatic changes and dubbed the 1976/77 North Pacific event a regime shift.

Biologists noted dramatic late-1970's 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 step between 1976 and 1977 in a composite of the time series. It was observations on Pacific salmon, however, specifically the catch history of Pacific salmon going back 70 years, that provided the most

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tantalizing evidence that a definite link existed between interdecadal changes in North Pacific climate and North Pacific fisheries. In a series of papers, Francis and Hare focused on Alaska salmon production and its link to climate (Francis and Hare, 1994; Hare and Francis, 1995; Francis and Hare, 1997), arguing that Alaska salmon production was best characterized as alternating regimes, where the transition from one regime to another was abrupt.

The race to describe and understand interdecadal changes in the Pacific accelerated through the 1990's. Latif and Barnett (1996) provided a comparison of the low-frequency variability in observations with that in the output from a coupled ocean/atmosphere model simulation, and proposed a mechanism for Pacific Decadal Variability (PDV) with a near-20 year periodicity. Zhang *et al*. (1997) offered a series of analyses teasing apart subtle spatial differences between Pacific climate variability at interannual versus interdecadal time scales. Mantua *et al*. (1997) capitalized on the maturity of the rapidly evolving research, synthesizing and extending research results from fishery, climate and hydroclimate studies, and labeled the dominant pattern of PDV the *Pacific (inter)Decadal Oscillation* (PDO). Other studies have used other names for what we call the PDO, for example: the Interdecadal Pacific Oscillation (IPO) of Power *et al*. (1997, 1999a), and the North Pacific Oscillation (NPO) of Gershunov and Barnett (1998).

The collective body of research suggested that three main characteristics distinguished PDO from ENSO: first, 20th century PDO "events" persisted for 20-to-30 years, while typical ENSO events persisted for 6 to 18 months; second, the climatic fingerprints of the PDO were most visible in the extratropics, especially the North Pacific/North American sector, while secondary signatures existed in the tropics, and the opposite was true for ENSO; and third, the mechanisms causing PDO variability were not known, while causes for ENSO variability were relatively well-understood (Zhang *et al*., 1997; Mantua *et al*., 1997; NRC, 1998).

A PDO index developed by Hare (1996) and Zhang (1996), also used by Mantua *et al*. (1997), is the leading PC from an un-rotated EOF analysis of monthly, "residual" North Pacific sea surface temperature (SST) anomalies, poleward of 20°N for the 1900–1993 period of record (see lower panel of Fig. 1). "Residuals" are here defined as the difference between observed anomalies and the monthly mean global average SST anomaly (see Zhang *et al*., 1997). A remarkable characteristic of this index is its tendency for multiyear and multidecadal persistence, with a few instances of abrupt sign changes. Based on a variety of studies, sign changes beginning in 1925, 1947, and 1977 have been labeled regime shifts (Hare and Francis, 1995; Zhang *et al*., 1997; Mantua *et al*., 1997; Minobe, 1997). These and other studies also provided evidence that PDO variations had considerable influence on climate-sensitive natural resources in the Pacific and over parts of North America in the 20th Century.

Subsequent study has revealed several new and important wrinkles to a rapidly growing literature on the general topic of PDV and on the nature of the PDO. Accumulating evidence suggests that the PDO mode of variability exhibits a robust symmetry in interdecadal climate variations of the Northern and Southern Hemispheres (e.g. White and Cayan, 1998; Garreaud and Battisti, 1999; Dettinger *et al*., 2000), with signature responses in East Asia, North, South and Central America, and Australia. Historical records tracking aspects of Pacific marine ecosystems suggest a strong association between PDO variability and Pacific salmon production (Beamish and Bouillon, 1993; Beamish *et al*., 1999; Hare *et al*., 1999), Pacific sea birds (Vandenbosch, 2000), Alaska ground fish and zooplankton production in the central and eastern North Pacific (Hollowed *et al*., 1998; Francis *et al*., 1998), and Gulf of Alaska marine species assemblages (Anderson and Piatt, 1999), to name just a few. Careful reconstructions of instrumental data have extended the PDO record back to 1854 (Kaplan *et al*., 2000), and paleoclimate reconstructions now provide an extended, albeit sometimes contradictory, view of PDV and PDO behavior back to 1600 (cf. Minobe, 1997; Evans *et al*., 2000; Linsley *et al*., 2000; Biondi *et al*., 2001; Gedalof and Smith, 2001).

Research into the dynamics of PDV has also produced numerous publications, yet at this time mechanisms for PDO behavior remain mysterious (see Miller and Schneider (2000) for a comprehensive review). In spite of the remaining mysteries, a number of insights into mechanisms favoring multi-year persistence of North Pacific climate anomalies have recently come to light (Schneider and Miller, 2001; Seager *et al*., 2001; Deser (Clara Deser, NCAR, Boulder Colorado, personal communication); and Barsugli and Battisti, 1998), indicating promising prospects for PDV predictability at lead times of one to a few years.

Mantua *et al*. (1997) proposed that the PDO represents a special class of PDV defined by a preferred spatial pattern with a range of interdecadal time scales of variability. We argue here that the case for a robust PDO mode of PDV is, on balance, strengthened by the results of recent studies, although many critical questions about the PDO await answers. Whether there is a preferred PDO time scale is critical for several reasons, including the issue of mechanisms and how understanding those mechanisms should aid the development of a PDO monitoring and prediction system. Regardless of PDO predictability, we also believe that recognition of PDO variability is important because it clearly demonstrates that "normal" climate conditions can vary over time periods comparable to the length of a human's lifetime, and climate anomalies that persist for one to a few decades can cause especially large impacts on ecosystems and societies.

For brevity, we will provide only a select review of PDO research in the remainder of this article, and in doing so will omit many valuable research results. We apologize here for those omissions, but hope that our survey offers readers a solid foundation for the present state of PDO research.

2. PDO Characteristics

2.1 Spatial patterns

Typical sea surface temperature, surface wind, and sea level pressure anomaly patterns for warm phases of the PDO are shown in the top panels of Fig. 1. During warm PDO phases sea surface temperatures (SSTs) tend to be anomalously cool in the central North Pacific coincident with anomalously warm SSTs along the west coast of the Americas. For November-to-March averages, warm PDO sea level pressure (SLP) anomalies have low pressures over the North Pacific which cause enhanced counterclockwise winds, and high SLP over the northern subtropical Pacific which cause enhanced clockwise winds. Anomalously high SLP in the western tropical Pacific and low SLP in the eastern tropical Pacific depict a relatively weak negative phase of the Southern Oscillation (see Trenberth and Shea, 1987). PDO circulation anomalies in the Northern Hemisphere extend through the depth of the troposphere, and are well-expressed as persistence in the Pacific North America (PNA) teleconnection pattern described by Wallace and Gutzler (1981) (not shown). Because all these patterns were derived from linear analyses, climate anomalies associated with cool phases of the PDO are simply opposites of those for warm PDO phases (not shown).

Although the PDO mode of variability has been discussed widely in the literature, the more general quest for understanding PDV is an area of very active research. One important lesson is clear from the published literature: different analyses yield different descriptions of 20th Century PDV. Some studies find evidence for distinct and independent lobes of North Pacific SST variability embedded within the canonical PDO pattern shown in Fig. 1. Nakamura *et al.* (1997) examined low-pass filtered North Pacific SST data for the 1968–1992 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) analyzed Pacific SSTs for the 1945–1993 period of record and identified 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 co-variability between the five-year low-pass-filtered global fields (the leading mode of co-variability was a trend mode). While these results yield somewhat different pic-

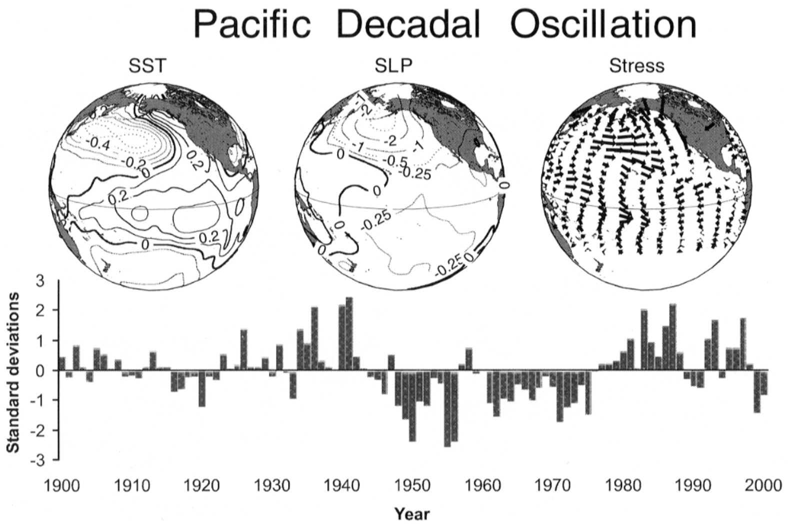


Fig. 1. (top) Anomalous climate conditions associated with warm phases of the Pacific Decadal Oscillation (PDO), and (bottom) November–March average values of the PDO index. Values shown are °C for sea surface temperature (SST), millibars for sea level pressure (SLP) and direction and intensity of surface wind stress. The longest wind vectors represent a pseudostress of 10 m^2/s^2. Actual anomaly values for a given year at a given location are obtained by multiplying the climate anomaly by the associated index value. Adapted and updated from Mantua *et al.* (1997).

tures of past PDV, there remains a wealth of evidence in support of spatial modes that generally resemble, if not reproduce, the canonical PDO pattern (cf. Tanimoto *et al.*, 1993; Graham, 1994; Trenberth and Hurrell, 1994; Latif and Barnett, 1994, 1996; Zhang, 1996; Hare, 1996; Mantua *et al.*, 1997; Minobe, 1997; Nakamura *et al.*, 1997; Enfield and Mestas-Nuñez, 1999; Folland *et al.*, 1999; Kaplan *et al.*, 2000; Barlow *et al.*, 2001; Tourre *et al.*, 2001).

2.2 Temporal scales of variability

Research aimed at identifying temporal scales of PDV also yield a variety of results, again based on the data examined and the analysis techniques employed. In a pair of closely related studies, Minobe (1999, 2000) applied Wavelet analysis to indices for boreal winter and spring North Pacific SST and SLP and found PDO fluctuations were most energetic at periodicities in the 15-to-25 year and 50-to-70 year bands. Chao *et al.* (2000) applied Singular Spectrum Analysis to a persistence index for North Pacific SST variations, and they found evidence for oscillatory variations at 15-to-20 and near 70 year periodicities. Tourre *et al.* (2001) used a Multi-Taper-Method/Singular Value Decomposition (MTM/SVD) technique to identify coherent patterns of low-frequency 20th Century Pacific SST and SLP variations from 30°S to 60°N. The canonical PDO SST pattern shown in Fig. 1 is clearly reproduced by the spatial patterns of Tourre's *et al.* (2001) Interdecadal mode (which has peak variance at 12-to-25 year periods), and somewhat similar to that of their Decadal mode (which has peak variance at 9-to-12 year periods) (see Tourre's *et al.* (2001); figure 2).

2.3 Paleoclimate reconstructions

To better understand the long-term behavior of the PDO, several studies report on proxy environmental recorders of PDO-related climate changes several hundred years back in time. Minobe (1997) used Fritts' (1991) tree-ring based temperature reconstructions to project North American air temperatures back to 1600. The leading EOF had the same 50–70 peak periodicity as the instrumental record from which the PDO was identified. Biondi *et al.* (2001) used ring-widths from moisture stressed trees in Southern California and Baja, Mexico, to create a paleo-PDO time series to 1661; Gedalof and Smith (2001) used tree-ring chronologies from a coastal transect spanning northern California to the Gulf of Alaska to reconstruct a PDO index to 1600. The PDO index was positively correlated with the dominant climate signal in the 20th Century sections of these two dendrochronologies (Fig. 2, see Table 1). Gedalof and Smith (2001) identified 11 regime shifts in the PDO record since 1650 with the most recent occurring in 1976/77. With average duration of a regime being 23 years, they suggest that another shift is due around the end of the century. While the two dendrochronologies capture much of the interdecadal variability in the instrumental PDO indices of Mantua *et al.* (1997) and Kaplan *et al.* (2000) (Fig. 2), they also exhibit periods in which they show little, if any correspondence with each other. This situation warrants further investigation, and highlights opportunities to narrow the uncertainty of pre-instrumental PDV, perhaps through multi-proxy reconstructions.

Table 1. Correlation coefficients between the time series displayed in Fig. 2. Correlations were computed on the common period of record (1903–1981). Note that these time series are 5-year running averages of the raw data series.

	PDO Index	Gedalof	Biondi	Kaplan
Gedalof	0.55			
Biondi	0.58	0.31		
Kaplan	0.77	0.58	0.31	

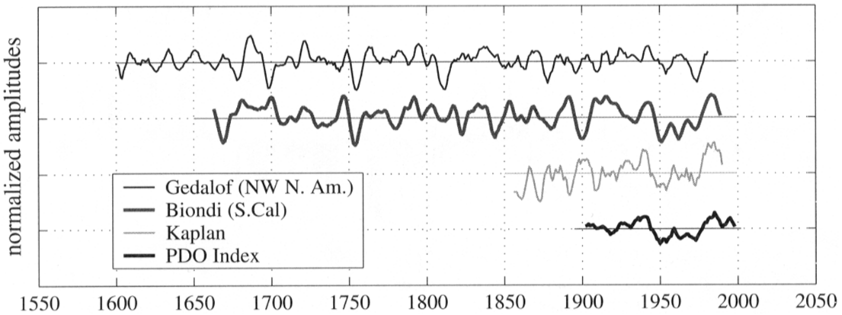


Fig. 2. 5-year running average plots of tree-ring based PDO reconstructions of Gedalof and Smith (2001) and Biondi *et al.* (2001), along with Kaplan *et al.*'s (2000) COADS SST index for 1854–1992 and Mantua *et al.*'s (1997) SST-based PDO index. Each time series has been normalized with respect to the available period of record, and they are plotted with an offset for clarity.

Results of PDO index reconstructions from outside North America have also been published. Evans *et al*. (2000) examined 15 tree-ring chronologies from mid-latitude North and South America and found 20th Century coherence in these records closely matched that in the PDO index. 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*., 2001).

3. PDO Impacts

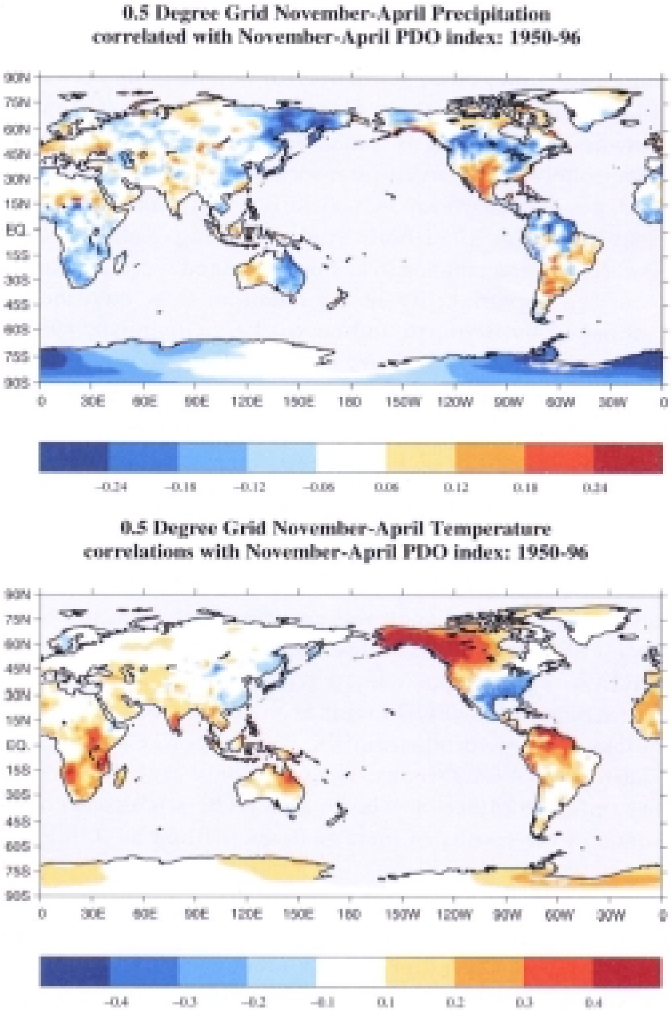
3.1 Surface climate

Many of the climate anomalies associated with PDO are broadly similar to those connected with ENSO variations (El Niño and La Niña), though generally not as extreme (Latif and Barnett, 1996; Mantua *et al*., 1997; Minobe, 1997). Correlations between the November–April PDO index and the 0.5 degree gridded surface temperature and precipitation data of Willmott and Matsuura (2000) (see also Willmott and Robeson, 1995) are shown in Fig. 3.

The correlations suggest the following patterns of PDO precipitation anomalies: warm phases of the PDO coincide with anomalously dry periods in eastern Australia, Korea, Japan, the Russian Far East, interior Alaska, in a zonally elongated belt from the Pacific Northwest to the Great Lakes, the Ohio Valley, and in much of Central America and northern South America; warm PDO phases also tend to coincide with anomalously wet periods in the coastal Gulf of Alaska, the southwest US and Mexico, southeast Brazil, south central South America, and western Australia.

The correlations suggest the following patterns of November–April PDO temperature anomalies: warm phases of the PDO tend to coincide with anomalously warm temperatures in northwestern North America, northern South America, and northwestern Australia, and anomalously cool temperatures in eastern China, Korea, Japan, Kamchatka, and the southeast US and Mexico. It is notable that Minobe (2000) and Cayan *et al*. (2001) find that the most prominent PDO temperature signal in North America is in the boreal spring, rather than winter season.

Independent studies have confirmed PDO signals in the Southern Hemisphere. 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*. (2000) found evidence for a symmetric pattern of PDO-related precipitation and water year (October-to-September) streamflow 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. Power *et al*. (1997, 1999a, 1999b) examined interdecadal changes in eastern Australian climate, finding warm PDO periods to be associated with anomalously warm-dry conditions, while cool PDO periods are associated with cool-wet conditions, consistent with the correlation fields displayed in Fig. 3.


0.5 Degree Grid November-April Precipitation correlated with November-April PDO index: 1950-96

0.5 Degree Grid November-April Temperature correlations with November-April PDO index: 1950-96

Fig. 3. Correlations between November–April mean precipitation (top) and temperature (bottom) and the November–April mean PDO index shown in Fig. 1. Precipitation and temperature data are the 0.5 degree grid climatologically aided interpolation (CAI) fields produced at the University of Delaware by Cort Willmott and collaborators (available via the internet at http://climate.geog.udel.edu/, also see Willmott and Robeson, 1995). Negative correlation coefficients are shaded in blues, positive correlation coefficients are shaded in reds and yellows.

4. Marine Ecosystems

In the past few decades a number of studies have identified compelling evidence for connections between PDV and variations in Pacific marine ecosystems. Kawasaki (1991) has documented a remarkable 20th Century coherence between interdecadal fluctuations in sardine population off Japan, California, Chile and Peru (see also Yasuda *et al*., 1999). Studies linking 20th Century Pacific salmon catches in eastern Asia and western North America to variability in the Aleutian Low have been published by Beamish and co-workers (Beamish, 1993; Beamish and Bouillon, 1993; Beamish *et al*., 1999).

The differing regional responses of salmon stocks along the west coast of North America have been examined 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", associated with the PDO, where the warm phase of the PDO favors high production for Alaska stocks and low production for Washington, Oregon and California (WOC) stocks. The cool phase of the PDO has the opposite effect on Alaska and WOC stocks. The essence of the results of their analysis is illustrated in Fig. 4.

The response of groundfish stocks to the PDO has also been documented in several studies. A strong one year jump in recruitment coincident with 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*. (1999) to have undergone interdecadal shifts closely matched to the phases of the PDO (Fig. 4). Like Alaska salmon, halibut flourish during warm phases of the PDO. 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 one of the most thorough documentations 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 trophic 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.

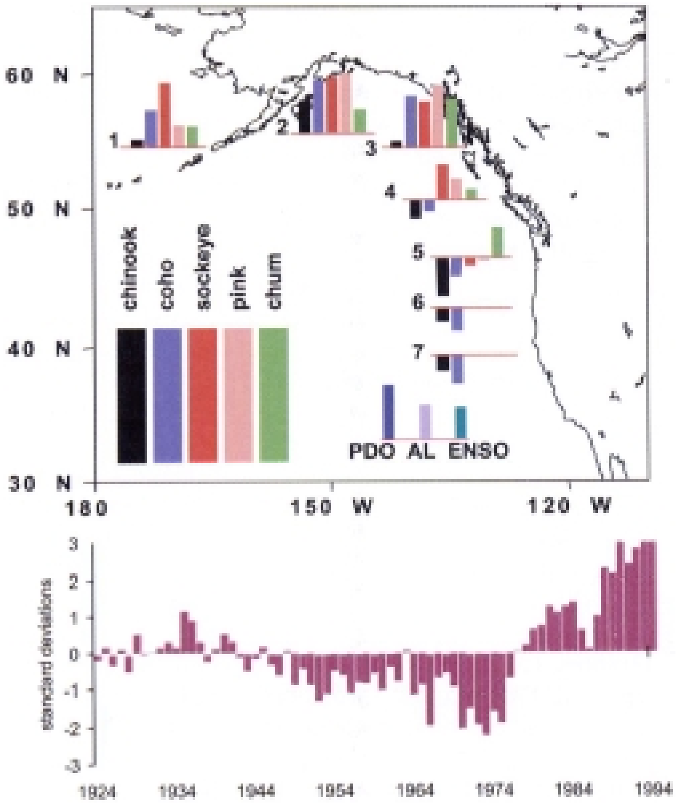


Fig. 4. A graphical depiction of the "Inverse Production Regimes" of Hare *et al*. (1999). The bars represent loadings from a principal component analysis (PCA) of 30 salmon time series for the period 1925–1997. Regional definitions are as follows: 1 - Western Alaska, 2 - Central Alaska, 3 - Southeast 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, represents a correlation coefficient with a value of 0.855, and represents the correlation between that time series and the illustrated temporal component (score) from the PCA.

A number of other studies have shown impacts of the PDO on other components of the marine and terrestrial ecosystems of the North Pacific and North America. 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), McGowan *et al*. (1998), 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 seabird population variability to phases of the PDO. Finally, Cayan *et al*. (2001) document a long term change to an earlier onset of spring in the western United States—as measured by blooming times of lilac and honeysuckle bushes—and variability in this timing also shows a high correlation with the springtime PDO index. In perhaps the broadest examinations 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.

5. Dynamics and Predictability

The physical mechanism(s) behind the PDO are not currently known. Some climate simulation models produce PDO-like oscillations (e.g. Latif and Barnett, 1994), although often for different reasons (NRC, 1998). The mechanisms giving rise to PDO will determine whether skillful PDO climate predictions for up to one or more decades into the future are possible. Even in the absence of a theoretical understanding, PDO climate information improves season-to-season and year-to-year climate forecasts for North America because of its strong tendency for multi-season and multi-year persistence.

While causes for the PDO remain unclear, several mechanisms promoting persistence in extratropical climate have been identified. Alexander *et al*. (1999, 2001) detail simple mixed layer mechanisms that give rise to the reemergence of subsurface thermal anomalies from one winter to the next. Deser (Clara Deser, NCAR, personal communication) reports on the ability to reproduce the observed multiyear autocorrelation structure of North Pacific and North Atlantic SSTs with a simple entraining mixed-layer model. Barsugli and Battisti (1998) use a simple model to demonstrate that local air-sea interactions yield “differential thermal damping” on atmospheric anomalies that redden the spectrum of variability and increase the overall variance over that which would occur in the absence of feedback.

The complimentary results of Seager *et al*. (in review) and Schneider and Miller (2001 (in press)) offer strong support for multi-year predictability for important aspects of mid-latitude ocean variability. Both studies report on the dynamic response of the thermocline in the Kuroshio/Oyashio Extension (KOE) region to the integrated wind-stress curl over the previous few years. Their hypothesis suggests the following: in a situation with enhanced westerly surface winds over the central North Pacific, for instance due to an anomalously deep Aleutian Low, the local intensification of the westerlies cool the interior North Pacific via enhanced surface heat fluxes and anomalous Ekman advection of the mean meridional temperature field; this wind field also displaces the zero windstress curl line to lower latitudes, thereby generating anomalous upwelling Rossby Waves at the latitude of zero-windstress curl that slowly propagate to the west; these upwelling Rossby waves eventually raise the thermocline in the KOE region one to several years hence; subsequent deep winter mixing in the KOE region transmits the thermocline anomalies to the surface where they eventually cool the SST. The end result is that the same wind anomalies that generate negative SST anomalies in the interior North Pacific eventually generate SST anomalies of the same sign in the KOE region one to a few years later. Any persistence in those winds will therefore result in an amplified persistence in the North Pacific SST field.

6. Discussion and Conclusions

We have provided a review of late 20th Century studies of Pacific Decadal Variability (PDV), with particular attention to a special case of PDV known as the Pacific Decadal Oscillation (PDO). Much controversy now exists over how PDO works, and how it might best be monitored, modeled and predicted. The stakes in PDO science are high, as an improved PDO understanding offers even sharper views of future climate and its attendant impacts on resources than those now provided by ENSO science alone.

We believe that the case for a robust PDO mode of PDV is, on balance, strengthened by the results of recent studies, while acknowledging the fact that many critical questions about the PDO remain unanswered. Regardless of PDO predictability, we also believe that recognition of PDO variability is important because it clearly demonstrates that “normal” climate conditions can vary over time periods comparable to the length of a human’s lifetime, and climate anomalies that persist for one to a few decades can cause especially large impacts on ecosystems and societies.

Recent advances in understanding mechanisms for persistence and slow changes in extratropical SST anomalies offer improved confidence for PDV predictability at lead times of one to a few years. Accurate PDO monitoring and prediction may have practical benefits in both seasonal and longer term climate forecasts for select regions. Gershunov and Barnett (1998), for example, argued that combining PDO and ENSO information may enhance the skill of empirical North American climate forecasts.

The potential for skillful PDV predictions at lead times beyond a few years hinges on the premise that unstable coupled ocean-atmosphere interactions and delayed negative feedbacks contribute to PDV. Direct observational evidence for these types of interactions, at least outside the tropical Pacific, is tantalizing yet equivocal (see NRC, 1998; Miller and Schneider, 2000). Proxy and instrumental evidence for robust PDO impacts within and around the Pacific Rim, both in the tropics and mid-latitudes of the Northern and Southern Hemisphere, supports the idea that causes for PDO variability originate in the tropics (Evans *et al*., 2001).

The present day skill in PDO-related forecasts comes from persistence. This skill disappears when there is an unforeseen sign change in the PDO pattern. Such a change—a flip from warm to cool PDO phases—may have taken place in 1998, coincident with the demise of the 1997/98 El Niño and the beginning of the subsequent La Niña episode (Hare and Mantua, 2000; Schwing and Moore, 2000). However, because no one is certain how the PDO works, it is not possible to say with confidence that the 1998 changes in Pacific climate mark the beginning of a 20-to-30 year long cool phase of the PDO.

The lack of PDO understanding presents a barrier to both real-time monitoring and forecasting PDO regime shifts. The research community's experience with ENSO demonstrated that improved understanding and predictions came with the synergy of observational, theoretical, and modeling studies (NRC, 1996). Each of these lines of PDO research have been identified as high priorities by the ongoing International CLIVAR program (see http://www.clivar.org/). PDO science is relatively new compared to ENSO science, but insights into the PDO came at a furious pace in the last decade of the 20th Century. More insights into how PDO works, and how to predict PDO variations, are sure to follow throughout the first decade of the 21st Century.

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