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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 compara-