

A multi-century perspective of variability in the Pacific Decadal Oscillation: new insights from tree rings and coral

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[1] Annual growth increments from trees and coral heads provide an opportunity to develop proxy records of climatic variability that extend back in time well beyond the earliest instrumental records, and in regions where records have not been kept. Here we combine five published proxy records of North Pacific climatic variability in order to identify the extent to which these records provide a coherent picture of Pacific Basin climatic variability. This composite chronology is well correlated with the Pacific Decadal Oscillation (PDO) index, and provides a better record of PDO variability than any of the constituent chronologies back to 1840. A comparison of these records suggests that the PDO may not have been an important organizing structure in the North Pacific climate system over much of the 19th century, possibly indicating changes in the spatial pattern of sea-level pressure and consequent surface climate patterns of variability over the Americas. *INDEX TERMS*: 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 4221 Oceanography: General: Dendrochronology; 4267 Oceanography: General: Paleooceanography; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620). **Citation**: Gedalof, Z., N. J. Mantua, and D. L. Peterson, A multi-century perspective of variability in the Pacific Decadal Oscillation: new insights from tree rings and coral, *Geophys. Res. Lett.*, 29(24), 2204, doi:10.1029/2002GL015824, 2002.

1. Introduction

[2] Instrumental climate records provide strong evidence that the North Pacific Basin experiences coherent modes of variability at interannual to interdecadal scales, generally termed the Pacific Decadal Oscillation (PDO) [Mantua *et al.*, 1997; Zhang *et al.*, 1997]. The spatial structure of this variability is very similar to that of El Niño/Southern Oscillation (ENSO), but with greater amplitude at high-latitudes and a reduced tropical expression. During warm PDO regimes the western and central North Pacific Ocean typically exhibits cold surface temperature anomalies while the eastern Pacific exhibits above average temperatures. The opposite condition exists during cool regimes. The temporal variability of the PDO is characterized by much longer persistence than ENSO, on the order of 20 to 30 years. The PDO also appears to shift abruptly between warm and cool states, with observed shifts occurring in 1925, 1947 and 1977 [Hare, 1996; Minobe, 1997] and some evidence that it may have

exhibited many such shifts prior to instrumental observations [D'Arrigo *et al.*, 2001; Gedalof and Smith, 2001]. The cool-season Aleutian Low pressure system is generally more intense during warm PDO regimes and less intense during cool PDO regimes, with significant impacts on climate throughout North America [Wallace and Gutzler, 1981].

[3] In spite of the rapid developments in our understanding of the PDO, several key issues remain unresolved: (1) Is the PDO a robust feature of North Pacific climate variability, or is it a 20th century phenomenon? (2) Does the PDO have a preferred time scale? (3) Are the observed regime shifts typical characteristics of the PDO? and (4) Does PDO forcing originate in the tropics or in the extratropics? Each of these issues has implications for the predictability of the North Pacific climate system and attendant resource management concerns. Given the long time scale of the PDO and the short length of the instrumental record there are some non-trivial limitations to analyses. Proxy records provide the opportunity to extend these records. A number of proxy reconstructions have recently become available, incorporating tree rings [Minobe, 1997; Evans *et al.*, 2000; Biondi *et al.*, 2001; D'Arrigo *et al.*, 2001; Gedalof and Smith, 2001] and coral skeletal chemistry [Linsley *et al.*, 2000; Urban *et al.*, 2000; Cobb *et al.*, 2001].

2. Data Description and Analytical Methods

[4] To address the four questions outlined above we compiled five published climate reconstructions from around the Pacific Basin that all report a link to extratropical interdecadal variability (Table 1). Gedalof and Smith [2001] used six high-elevation mountain hemlock (*Tsuga mertensiana*) chronologies from a transect extending from Oregon to Southeast Alaska to reconstruct the mean spring PDO index since 1600. This record has been extended from its original termination date in 1983 to 1990 using several of the constituent chronologies as predictors in a simple linear regression. Biondi *et al.* [2001] used chronologies from Jeffrey pine (*Pinus jeffreyi*) and bigcone Douglas-fir (*Pseudotsuga macrocarpa*) from six sites in California and northwestern Mexico to reconstruct the mean winter half-year PDO index back to 1661. Evans *et al.* [2000] used 15 tree-ring chronologies from various species located in Pacific influenced regions of extratropical North and South America to reconstruct one pattern in sea surface temperature (SST) that is structurally very similar to the PDO. Urban *et al.* [2000] used a $\delta^{18}\text{O}$ chronology derived from a coral in Maiana to reconstruct regional SST variability back to 1840. This record exhibits good correspondence to drought in the

Table 1. Summary of Proxy Chronologies

Principal Author	Data Type	Period of Record	Geographic Region
Gedalof	Tree rings	1600–1990	Pacific Northwest, Gulf of Alaska
Biondi	Tree rings	1661–1991	American southwest, Mexico
Evans	Tree rings	1001–1990	Extratropical N. and S. America
Urban	Coral	1840–1994	Maiana, central tropical Pacific
Linsley	Coral	1726–1997	Rarotonga, eastern subtropical S. Pacific

American Southwest [Cole *et al.*, 2002], and is well correlated to indices of North Pacific decadal variability. Linsley *et al.* [2000] developed a SST chronology based on Sr/Ca measurements from a coral in Rarotonga, located in the eastern subtropical South Pacific. This record extends back to 1726, and also exhibits interdecadal variability that is coherent with North Pacific records. Hereafter these studies and the chronologies they produced will be identified by their principal investigator.

[5] There are several important differences between coral and trees that have implications for proxy climate reconstructions. In particular, tree rings represent a terrestrial, mid-latitude response to climate, whereas coral records provide a marine, low-latitude response. Tree-ring time series typically provide an annually resolved record of growing season conditions, whereas coral continuously integrate their immediate environment, and the resolution is limited by sampling frequency and dating control. At present, tree-ring chronologies are well-replicated and based on large sample sizes, whereas coral records are relatively sparse and reconstructions are often based on a single core. In order to directly compare these reconstructions the coral chronologies were resampled to a calendar-year timestep. While there may be more appropriate methods of resampling these time series, this approach is simple and objective, and suggests that the results presented here are a conservative estimate of the strength of the common signal between the tree-ring and coral chronologies.

[6] In order to compare the five chronologies we used a principal components analysis (PCA) to extract common modes of variance from the chronologies. This analysis is restricted to the interval 1840 to 1990, the interval common to all of the proxy records. The resulting eigenvectors were scaled to have zero mean and unit variance, and were then regressed onto the mean Oct. to March NCEP/NCAR reanalysis SST fields for the 1950–1960 period of record [Kalnay *et al.*, 1996]. Pearson's product moment correlation

Table 2. The Intercorrelations Between the Five Proxy Chronologies^a

	Gedalof	Biondi	Evans	Urban	Linsley	PC1
Gedalof	–	0.001	0.000	0.133	0.032	0.435
Biondi	0.184	–	0.000	0.365	0.033	0.406
Evans	–0.461	–0.223	–	0.000	0.000	–0.545
Urban	–0.126	–0.074	0.370	–	0.102	–0.342
Linsley	–0.134	–0.131	0.349	0.132	–	–0.483

^aThe correlation coefficient is shown in the lower portion of the grid, and the p-values in the upper portion. Correlations that are significant at 95 percent confidence are indicated in bold script. The correlation between the proxy chronology and the leading PC is shown in the last column.

was used to assess the strength of the association between the eigenvectors and two indices of Pacific climate variability: the Cold Tongue Index (CTI) is an ENSO index based on SST in the eastern equatorial Pacific [Zhang *et al.*, 1997]; and the PDO Index is derived from the leading mode of variability in Pacific Ocean SST polewards of 20°N [Mantua *et al.*, 1997].

3. Results and Discussion

[7] Only the first eigenvector was well resolved [North *et al.*, 1982], and was therefore retained from the PCA for further investigation. This leading mode of variability explains 41 percent of the total variance, and loads moderately strongly on all five proxy records (Table 2). The principal component time series associated with this mode (PC1 hereafter) is well correlated with the PDO Index ($r = 0.64$, $p < 0.001$; Figure 1). A partial correlation analysis indicates that this time series does not contain any information on the state of the CTI that is not intrinsically expressed in the PDO, suggesting that this record represents primarily a North Pacific climate signal, and not a tropical (i.e. ENSO) signal. It is worth noting that the observed correlation with the PDO index is higher than the correlation observed for any of the individual input series, indicating that the combined chronology is capturing more of the variability than any of its constituent components.

[8] A distinct characteristic of the instrumental record of the PDO is the regime shifts that occurred in 1925, 1947 and 1977 [Hare, 1996; Mantua *et al.*, 1997]. An intervention model [Box and Tiao, 1975] applied to PC1 identified the 1947 and 1977 shifts as being significant, but failed to identify the 1925 shift. An intervention detection algorithm [see Gedalof and Smith, 2001] identified a significant shift from cool to warm states in 1905, consistent with the findings of Biondi, but no earlier shifts.

[9] Regressing the SST field onto PC1 produces a spatial pattern that is similar in structure and magnitude to the PDO, with warm SST anomalies occurring in the eastern equatorial Pacific and along coastal western North America, and cool anomalies in the Aleutian Low region of the North Pacific (Figure 2). There is a similar cool water anomaly in the South Pacific. This symmetrical structure in SST suggests a tropical forcing mechanism for the PDO [Garreaud and Battisti, 1999; Evans *et al.*, 2001].

[10] The fact that a PDO-like structure emerged as the leading eigenvector among these geographically dispersed proxies suggests that the PDO is a robust feature of Pacific

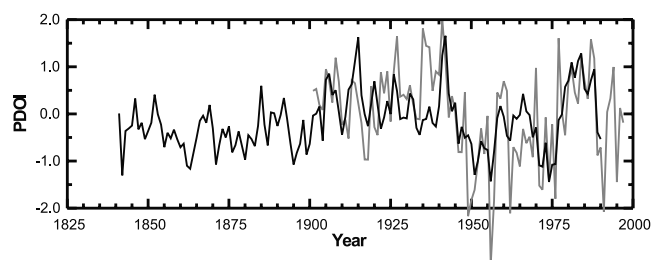


Figure 1. The time series of the leading principal component (PC1), scaled to match the mean October to March PDO index (shown in gray).

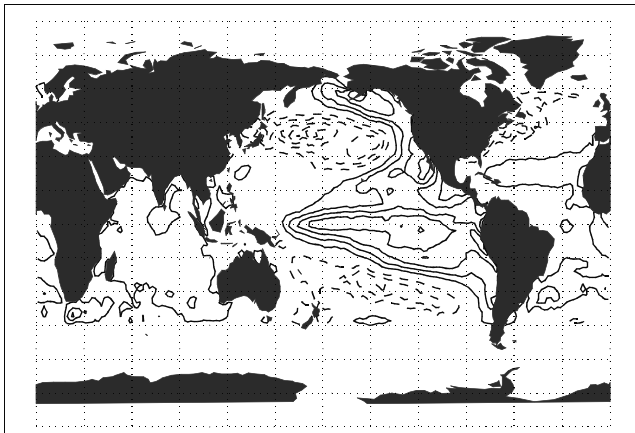


Figure 2. The sea surface temperature field regressed onto the reconstructed PDO index. Contour interval is 0.1°C per standard deviation. Positive anomalies are indicated by solid contours, negative anomalies by dashed contours, and the zero contour is not shown.

climate variability, because it represents the dominant mode of variability over the last 160 years. But an examination of the intercorrelation between the five proxy chronologies reveals a more complex situation (Figure 3). Eigenvector techniques are designed to find simple structure in data matrices and consequently will be biased towards regions or intervals with simple structure. Over the interval considered in this analysis there is a conspicuously stronger intercorrelation between the five proxies over the 20th century, and in particular since ca. 1975. This observation suggests that, while it may be the dominant mode of variability represented by these proxies, the PDO has not been a coherent structure over time. Also intriguing is the observation that the sign and strength of the correlations between the longest proxies prior to ca. 1825 suggest that a mode of variability with similar SST structure and downstream teleconnections to the PDO *was* operating over this time. Interpreted together, these findings suggest that the PDO has probably been operating at least since 1600 but that it was not an important mode of variability over much of the 19th century. This interval is consistent with a period of poor correspondence between tree rings at high latitudes in North

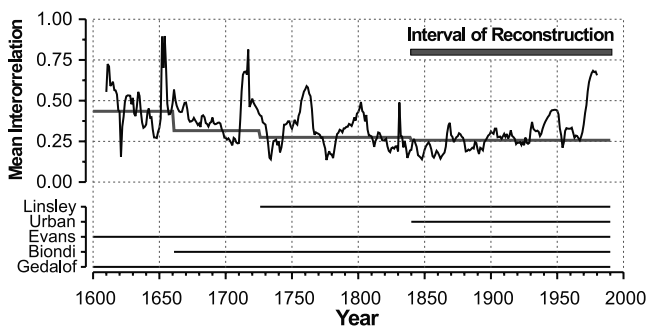


Figure 3. (upper panel) The mean intercorrelation between all proxies that have data, calculated over a 21-year moving window. The 95 percent confidence level for the appropriate number of intercorrelations is shown in gray. (lower panel) The interval for which each proxy reports data. The shaded overbar indicates the interval used in the PCA, over which all proxies provide data.

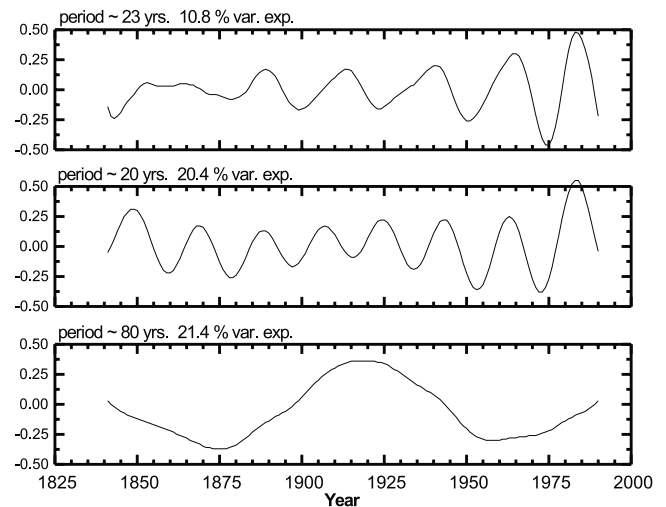


Figure 4. Weighted sums of the three leading pairs of eigenvectors extracted using singular spectrum analysis. The oscillatory modes have periods of ca. 85, 20, and 23 years (lower, middle and upper panels respectively).

and South America [Villalba *et al.*, 1999], and in proxy records of salmon abundance and SST in the Gulf of Alaska [Finney *et al.*, 2000]. Alternatively, this poor inter-correspondence could indicate non-stationarities in the climate-growth relationships developed for paleoproxy analyses.

[11] These interpretations of PDO variability suggest that, over the interval considered in the PCA, we should not expect to see a well-defined peak in variability at low frequencies. Indeed, a spectral analysis of PC1 reveals a predominantly red spectrum (results not shown). Nonetheless, several studies have characterized the PDO as emerging from a phase-locked interaction between oscillations with ca. 20 and 50 year periods [Nakamura *et al.*, 1997; Minobe, 1999; Minobe, 2000]. The Aleutian Low is believed to be the keystone that connects these two processes. Regime shifts occur when the oscillations change phase simultaneously. Minobe, [1999] noted that the synchrony of the oscillations was not strong in the early portion of the 20th century. We applied a singular spectrum analysis (SSA) [Vautard, 1992] to the reconstructed PDO index in order to evaluate this characterization (Figure 4). Three dominant waveforms were identified in this analysis, with characteristic periods of approximately 85, 23 and 20 years. These three waveforms explain 53 percent of the variance in mean winter PDO index, and capture the observed regime shifts of the 20th century. An interesting feature of this analysis is the distinctly weak energy in the ~ 23 year mode prior to ca. 1875 - the interval when the proxies exhibit poor intercorrelation. SSA of the individual proxies supports this interpretation: the Gedalof, Evans and Linsley chronologies exhibit similar weak energy from ca. 1825 to 1875 in oscillatory modes with approximately bi-decadal periods. These findings suggest that the poor correspondence between the proxy records over most of the 19th century may be a consequence of the small energy in this mode of variability. Interestingly, this mode appears to have been increasing in amplitude over the 20th century when the intercorrelation has been strongest. It is unclear from the current analysis whether the 20 and 23 year oscillatory modes are actually distinct, or if they are artifacts of differ-

ences in biological processes or the analytical approaches adopted by the original authors.

[12] This analysis demonstrates that proxy chronologies from tree rings and coral may be directly incorporated into investigations of very large-scale ocean-atmosphere interactions. Reconstructions derived from these paleoproxy networks may capture these large-scale processes better than the spatially restricted networks necessitated by single-proxy analyses. In light of this observation further energy expended in extending the length of coral records will provide substantial and immediate returns in terms of an improved understanding of low-frequency variability in the ocean-atmosphere system.

4. Conclusions

[13] Our results provide insight into the long-term behavior of the PDO, and support the inference that North Pacific climate variability at decadal and longer frequencies may be a consequence of the complex interaction of several modes of variability. In the context of the four questions outlined in the introduction, this analysis supports the following interpretation: (1) The PDO does not appear to be a 20th century phenomenon, but it also does not appear to have always been a robust feature of North Pacific climate variability. Instead, it seems to have fluctuated in importance, with a notable interval of reduced influence over much of the 19th century. (2) Given this finding, and restricting the analysis to the period common to all five proxies, it was not possible to assess the extent to which the PDO exhibits a preferred time-scale in this analysis. However, there is some evidence to support the hypothesis of Minobe [1999] and others that the PDO is composed of phase-locked oscillations with periods of ca. 20 and 50 to 70 years. Consistent with Minobe we found poor synchrony between these modes in the early portion of the reconstructed PDO index. This interval is coeval with a period of poor intercorrelation between the individual paleoproxy records considered in the analysis. An examination of the longer proxy records suggests that this pattern of poor coherence occurred over much of the 19th century. (3) Given the uncertain nature of the PDO over the 19th century this analysis was unable to determine whether the observed regime shifts are characteristic features of the PDO. (4) The significant and consistent correlation structure between the tropical and extratropical proxies, including several from the Southern Hemisphere, all point to a tropical forcing mechanism for the PDO.

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