LETTERS

North Pacific Decadal Climate Variability since 1661

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ABSTRACT

Climate in the North Pacific and North American sectors has experienced interdecadal shifts during the twentieth century. A network of recently developed tree-ring chronologies for Southern and Baja California extends the instrumental record and reveals decadal-scale variability back to 1661. The Pacific decadal oscillation (PDO) is closely matched by the dominant mode of tree-ring variability that provides a preliminary view of multiannual climate fluctuations spanning the past four centuries. The reconstructed PDO index features a prominent bidecadal oscillation, whose amplitude weakened in the late l700s to mid-1800s. A comparison with proxy records of ENSO suggests that the greatest decadal-scale oscillations in Pacific climate between 1706 and 1977 occurred around 1750, 1905, and 1947.

1. Introduction

Ice-free waters of the Pacific Ocean cover about one-third of earth's surface, an area larger than all land masses combined. The global impact of Pacific-wide interannual anomalies has been clearly demonstrated by the far-reaching effects of El Niño–Southern Oscillation (ENSO; Glantz 1996). It is now clear that Pacific climate also undergoes decadal-scale shifts (Trenberth and Hurrell 1994) as part of a coherent interdecadal mode of variability (Latif and Barnett 1994; Enfield and Mestas-Nuñez 1999) with strong influences upon weather patterns over North America. Such a decadal-scale mode, named North Pacific oscillation when it was first recognized,[1] has recently been represented by the Pacific decadal oscillation (PDO), that is, the leading mode of October–March sea surface temperature variability poleward of 20° (Mantua et al. 1997). PDO has been shown to modulate ENSO teleconnections to North America, and the skill of ENSO-based long-range climate forecasting can be improved by incorporating PDO information (Gershunov and Barnett 1998; McCabe and Dettinger 1999). However, the timescale and long-term dynamics of the PDO are not well understood. Knowledge of internally driven decadal-scale climate processes may also contribute to assessing how large-scale features of climate respond to external forcings with similar periodicities, such as solar radiation (Hoyt and Schatten 1997) and lunar cycles (Cook et al. 1997).

Instrumental sea surface temperature records are mostly limited to the past century and therefore are too short to adequately describe natural variability at decadal timescales and to unravel changes in low-frequency connections between midlatitudinal and tropical conditions. As an alternative, proxy climatic records from tree rings have provided high-resolution, accurately dated information on North Pacific climate at scales much longer than those attained by instrumental records (D'Arrigo et al. 1999; Cook et al. 2000). Here we use a network of newly developed chronologies for Southern and Baja California to recover the timing, amplitude, and frequency of decadal-scale climate oscillations in the Pacific basin, and address fundamental

[1] The same term was used by Gershunov and Barnett (1998), but it was originally mentioned in the 1930s by Walker and Bliss (T. P. Barnett 2000, personal communication).

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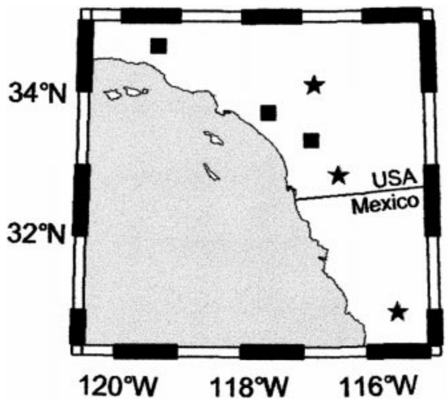

FIG. 1. Location of pine (★) and big-cone Douglas fir (■) tree-ring collections in Southern and in Baja California.

questions about the PDO timescale, dominant periodicity, and long-term evolution.

2. Materials and methods

Tree-ring sites were located in a direction roughly parallel to the coastline, from the Transverse Mountains of Southern California to Sierra San Pedro Martir in northern Baja California (Fig. 1; Table 1). This region was targeted after noticing that tree-ring records from this area are better correlated with PDO than with ENSO (Biondi et al. 1999). Tree-ring records from Jeffrey pine (*Pinus jeffreyi*) and big-cone Douglas fir (*Pseudotsuga macrocarpa*) were gathered and processed according to standard dendrochronological procedures for paleoclimatic reconstruction (Cook and Kairiukstis 1990). Xylem growth rates of these Southern California species are mostly influenced by cool-season precipitation variability (Biondi and Cayan 1999; Michaelsen et al. 1987). Measured ring-width series (''segments'') were combined by site and species to produce tree-ring chronologies. Mean segment length (Cook et al. 1995) ranged between 164 and 355 yr, with 21–56 segments in each chronology (Table 1). Tree-ring indices were computed as ratios between cross-dated ring widths and their expected value based on the age/size trend, modeled by either a modified negative exponential or a straight line with slope ≤ 0. Time series autocorrelation (Box and Jenkins 1976) was not removed in order to preserve multiannual variability. Interdecadal patterns were estimated using a 10-yr cubic smoothing spline (Cook and Peters 1981).

Climatic persistence and lagged tree response mediated by soil moisture and species physiology (Fritts 1976) were modeled by including previous, current, and next year's tree growth in a multivariate analysis. Three potential predictors of the raw instrumental PDO at year t were the lag 1, concurrent, and lead 1 values of the first EOF, or principal component (Jolliffe 1986), of the six unsmoothed tree-ring chronologies. This procedure was aimed at exploiting low-frequency climate signals in annual tree-ring records that are considered a function of climate. Objective model selection criteria repeatedly chose all three predictors over either one or two of them. The reconstruction was performed after a double calibration–validation test. First, the regression model was estimated using only the last three decades (1962–91), and model predictions were evaluated against the actual measurements for the first three decades (1925–54). Then, the periods used for calibration and validation were interchanged, and the model rechecked. Time-dependent changes in the PDO proxy series were identified using singular spectrum analysis (Vautard et al. 1992) and evolutive spectra. Maximum entropy spectra (Penland et al. 1991) of 100-yr intervals lagged 5 yr from each other were used to obtain the evolutive spectrum. Correlations between PDO and Wolf sunspot numbers, group sunspot numbers, or solar irradiance since AD 1610 (data courtesy of J. Lean 2000, personal communication) were computed using both annual and decadally filtered values.

3. Results and discussion

Interannual and interdecadal variability of tree-ring chronologies show remarkable similarities among sites. In the twentieth century, the major PDO reversals of 1947 and 1977 are matched by reversals in tree growth time series (Fig. 2). The first EOF of the six annual tree-ring chronologies accounts for 58.4% of variance from 1660 to 1992. The second (12.2% of variance) and third (9.3% of variance) EOFs did not significantly enhance our analysis and/or reconstruction. Tree growth and PDO patterns are in close relationship from the 1990s back to about 1925. Prior to 1920–30, when PDO values

TABLE 1. Summary of tree-ring chronologies, listed by species in decreasing order of latitude.

Species	Lat (°N)	Long (°W)	Elev (m)	C (T)	First–Last	SD	MS	A_1	MSL
PSMA	34.65	119.37	1500	29 (13)	1470–1993	0.363	0.358	0.426	355
PSMA	33.73	117.55	1200	56 (33)	1660–1995	0.382	0.335	0.467	164
PSMA	33.35	116.85	1524	21 (10)	1640–1992	0.291	0.230	0.493	210
PIJE	34.12	116.80	2890	25 (12)	1560–1995	0.290	0.199	0.647	237
PIJE	32.87	116.42	1800	29 (14)	1660–1995	0.403	0.286	0.680	208
PIJE	30.97	115.50	2400	29 (17)	1560–1995	0.212	0.173	0.524	332

PMSA = *Pseudotsuga macrocarpa*; PIJE = *Pinus jeffreyi*; C (T) = number of cores (trees); First–Last = chronology interval; SD = std dev; MS = mean sensitivity; A_1 = lag-1 autocorrelation; MSL = mean segment length.

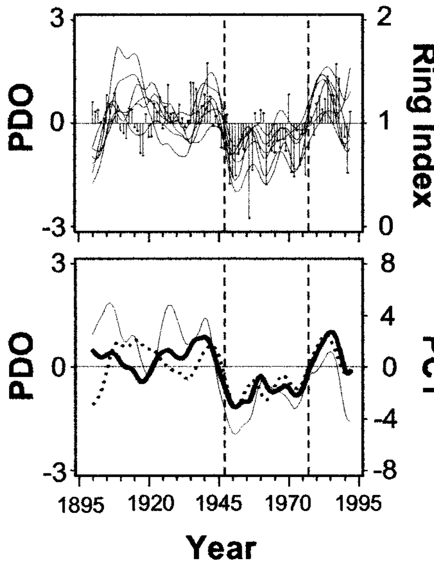

FIG. 2. (Upper) Interdecadal variability of tree-ring chronologies (Ring Index, smooth lines) closely matches the PDO (needles) since about 1925, especially with regard to the major reversals of 1947 and 1977 (dashed vertical lines). (Lower) At decadal scales, the leading mode of tree-ring variability (PC1, dotted line) well represents PDO patterns (solid heavy line). The disagreement in the early 1900s between the instrumental and proxy PDO series is also found between PDO patterns computed from different instrumental datasets [Mantua et al. (1997): solid heavy line; GISST 2.2 data: solid thin line].

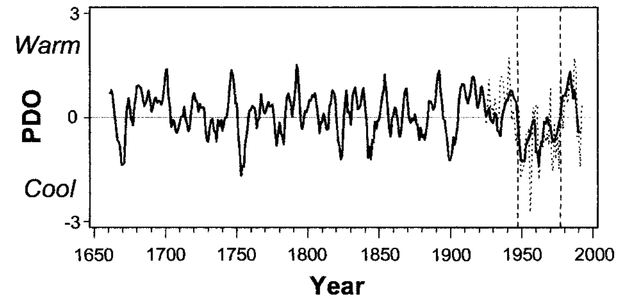

FIG. 3. Reconstructed PDO since 1660. Correlation between instrumental (dashed line) and reconstructed PDO is 0.64 from 1925 to 1991. During warm periods, the eastern North Pacific is warmer than usual, and the central North Pacific is cooler (vice versa during cool periods). Warm and cool PDO phases are qualitatively similar to warm and cool ENSO events, but different because of slower temporal dynamics and stronger midlatitudinal responses.

frequently change sign, there is less agreement with tree-ring records. Sea surface temperature fields in the early 1900s were based on a much smaller number of data points than in recent decades (Slutz et al. 1985). The PDO index being reconstructed (Mantua et al. 1997) and one we derived from a different dataset (Rayner et al. 1996) also diverge in the early 1900s, while they are in close agreement during the more recent decades (Fig. 2). Based on that comparison, we argue that the discrepancy between the instrumental and proxy PDO records in the early portion of the twentieth century is likely to depend on undersampling of the sea surface temperature fields.

Statistical comparisons indicate enough skill in the model to warrant its use for climate hindcasting (Table 2). The tree-ring proxy record has a 0.6–0.7 correlation with validation data, and it captures the low-frequency features of the instrumental record (Fig. 3). The broad coherency peak at bidecadal periods between the instrumental and proxy PDO records (Fig. 4a) confirms the reliability of the reconstruction for this frequency range. The instrumental PDO record used for calibration is characterized by significant (at the 95% level, estimated using methodology proposed by Mitchell et al. 1966) power at 22.7 yr. The reconstructed PDO series shows a ''spreading out'' of significant peaks in the raw periodogram to periods between 17 and 28 yr. The first two eigenelements of the proxy PDO time series from 1661 to 1991 define a ~23-yr oscillatory mode that accounts for 28.5% of the variance (Fig. 4b). Smaller amplitude in the middle section of the time series suggests a reduced strength of the PDO, especially in the early to mid-1800s. Weakening of the bidecadal oscillation in the late 1700s and early 1800s is also revealed by the evolutive spectrum (Fig. 4c). While the bidecadal mode remains present throughout the length of the record, lower frequencies (from multidecadal to centennial and longer) are restricted to the twentieth century. Such patterns of the 1900s are anomalous when compared to the previous three centuries, and could be linked either to an unfolding trend or to an increasing amount of time spent by the system in one phase before reversing to the opposite phase.

The 1800s transition to a more energetic PDO regime also coincides with a nineteenth- to twentieth-century increase in the interannual variability of ENSO

TABLE 2. Calibration (CAL) and validation (VAL) statistics* for the tree-ring reconstruction of PDO.

	CAL	VAL	CAL	VAL
Time period	1962–91	1925–54	1925–54	1962–91
Variance explained (R^2_a)	0.60	0.38	0.49	0.43
Cross-product *t* test	4.23	2.37	2.85	2.69
Linear correlation test	0.78	0.64	0.71	0.67
Sign-product test	4	10	8	6
Reduction of error test	0.61	0.27	0.50	0.35

* Two 30-yr periods were alternatively used for calibration and validation. All tests are significant at the 95% confidence level (Holmes 1994).

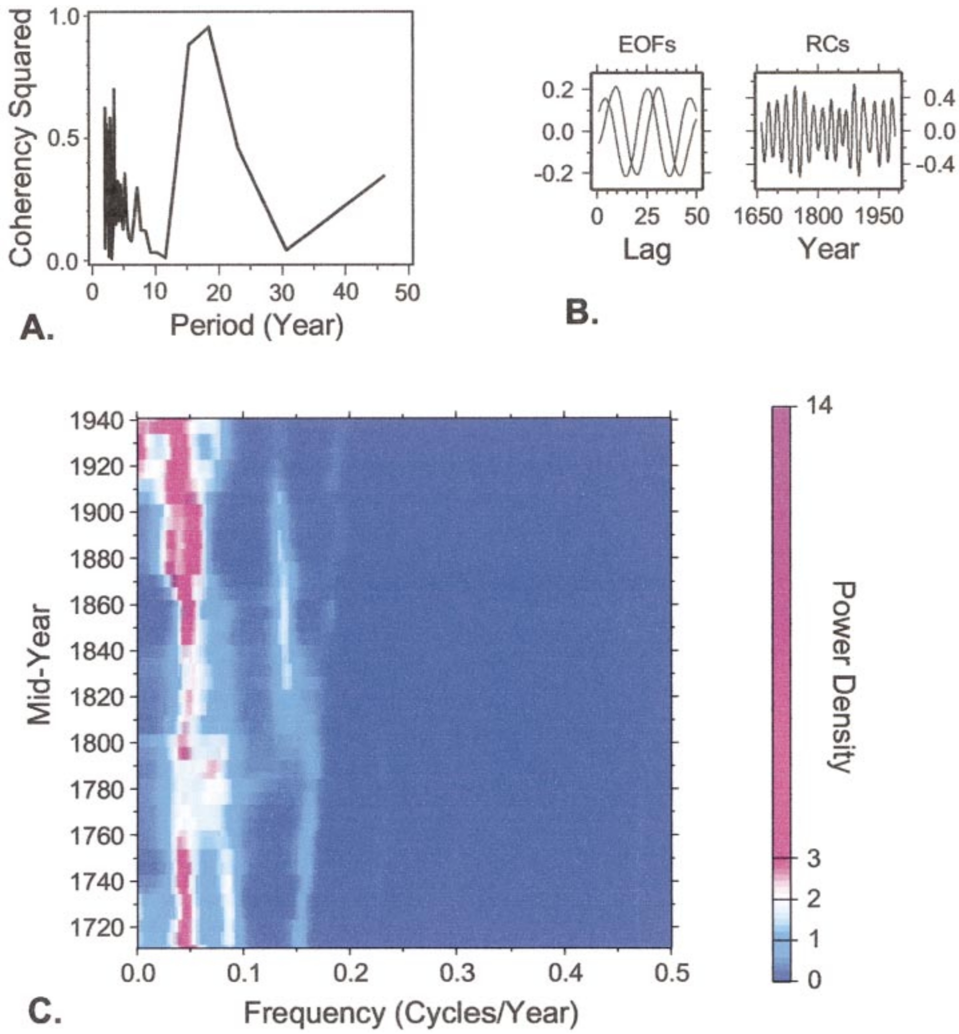

FIG. 4. (a) In the common period 1900–91, the instrumental and reconstructed PDO are spectrally coherent in the bidecadal band. (b) The two leading eigenfunctions (EOFs) of reconstructed PDO form an oscillatory pair that accounts for 28.5% of the variance. The combined amplitude of those two components (RCs) has a ~23-yr period, and represents the time-varying strength of the bidecadal oscillation. (c) Evolutive spectrum of reconstructed PDO, showing a prominent bidecadal mode whose strength was less intense from the late 1700s to the mid-1800s. Lower frequencies (from multidecadal to centennial and longer) in the PDO time series are restricted to the twentieth century.

identified over the 1706–1977 period (Stahle et al. 1998). That proxy record of winter Southern Oscillation index (SOI) provides a basis to highlight preinstrumental periods of constructive and destructive PDO–ENSO interference. Stahle et al.'s reconstruction and our PDO record show little correlation ($r = 0.17$), as well as nonoverlapping spectral properties. While interdecadal timescales prevail in our PDO series, Stahle et al.'s SOI record is dominated by interannual periodicities. The PDO modulation of ENSO teleconnections identified by Gershunov and Barnett (1998) is based on a stronger (weaker) climate response to tropical conditions when those modes of variability are in phase (out of phase). The most drastic climate transition is then associated with a transition from El Niño to La Niña (or vice versa) that coincides with a PDO reversal from a warm to a cool phase (or vice versa). From 1706 to 1977, the largest PDO–ENSO swings are centered around 1750, 1905, and 1947 (Fig. 5). Both the 1750 and 1947 warm-to-cool transitions happened rapidly, as the interval between extremely high and extremely low values covers about 10 years. It should be noted, however, that the 1750 oscillation might be an isolated excursion, rather than a true climate reversal, because preceding and following values fluctuate widely. The 1905 cool-to-warm transition was less abrupt, with the interval from low to high peaks spanning about 15 years. Considering that the record shown in Fig. 5 stops before the very strong and rapid 1977 cool-to-warm transition, the twentieth century

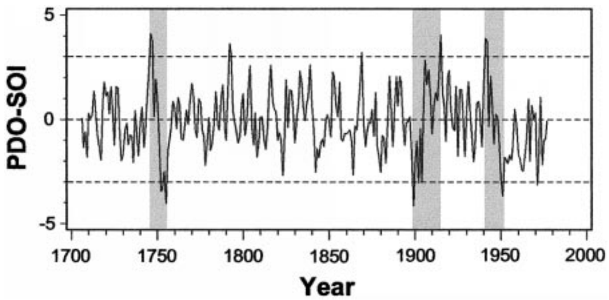

FIG. 5. PDO–ENSO patterns from 1706 to 1977, obtained by adding the proxy PDO record (Fig. 3) with a proxy record of winter SOI (Stahle et al. 1998). Both series were first converted to standard deviation units, and the sign of SOI was reversed to make El Niño years positive. Absolute values are higher (lower) during constructive (destructive) interference between PDO and ENSO.

experienced three of the four most significant decadal-scale climate episodes of the past 330 years.

The PDO–tree ring association provides evidence for decadal-scale modulation of forest growth by North Pacific climate. A 22-yr periodicity is also shown by solar activity (Lean and Rind 1998), but the PDO proxy record shows no correlation with the Sun's radiative forcing at either annual or decadal timescales. Hence, internal dynamics of the coupled ocean–atmosphere system have greater dendroclimatic significance than solar cycles at our study areas. Although ecological mechanisms underpinning the relationship between tree-ring chronologies and PDO are likely to be complex, Southern California chronologies are exposed to a homogeneous climatic regime. Tree-ring sites are either within or next to the boundary of California Climate Division 6 (South Coast Drainage; Guttman and Quayle 1996). Northern Baja California experiences a similar climate, as indicated by small differences in floristic and vegetational features on both the U.S. and the Mexican sides of the Peninsular Ranges (Minnich and Vizcaíno 1998). Based on dendroclimatic response functions, precipitation is the dominant climatic signal in the six tree-ring chronologies at interannual scales. Winter and spring precipitation are commonly significant in response functions (Guiot 1991) computed using monthly precipitation and temperature records for California Climate Division 6 from 1895 to 1992. Among seasonal or annual precipitation totals, October–March precipitation has the highest correlation ($r = 0.6$) with the first EOF of the six chronologies, and the synoptic pattern shows a pronounced southwest-to-northeast gradient over the western United States (Biondi et al. 1999). While temperature effects may play a synergistic role at longer timescales (Swetnam and Betancourt 1998), the expression of PDO in tree-ring records is likely to be a combination of tree growth response to precipitation amounts as well as frequency (Woodhouse and Meko 1997), which are both influenced by the PDO directly (Latif and Barnett 1996) and through its interference with ENSO (Gershunov et al. 1999).

4. Conclusions

Overall, this reconstruction indicates that decadal-scale reversals of Pacific climate have occurred throughout the last four centuries. Significant interdecadal climate changes have been reported for the joint ocean–atmosphere system in the Northern Hemisphere (Mann and Park 1996) and for the whole globe (Mann et al. 1995). We uncovered a dominant bidecadal mode of PDO that is consistent with circulation time of the Pacific gyre suggested by simulation models (Barnett et al. 1999). The drift toward lower PDO frequencies observed in the 1900s could then reconcile model physics with previous observations of 50–70-yr recurrence intervals in PDO-like climate variability (Minobe 1997). At the same time, the appearance of longer periodicities combined with a greater number of large PDO–ENSO climate swings reveal anomalous conditions in the 1900s. This has significant implications for global change research. Anthropogenic greenhouse warming may be either manifested in or confounded by alterations of natural, large-scale modes of climate variability. It is conceivable that the severity of PDO–ENSO regime shifts during the twentieth century was enhanced by the emerging lower frequencies of PDO. An expansion of the present analysis using different networks, perhaps containing multiple proxies, should then be conducted to verify and extend our findings. The very strong 1997/98 El Niño episode was followed by La Niña conditions, and the state of North Pacific climate suggests a possible reversal to a cool PDO stage from the warm PDO phase that began in 1977. Regime shifts of PDO and ENSO happening in phase or out of phase have far-reaching societal impacts, and to recognize them will require the longer historical perspective that multicentury, annually resolved records of Pacific climate can provide.

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