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Interdecadal climate variability and regime-scale shifts in Pacific North America

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Abstract. A transect of climate sensitive tree ring-width chronologies from coastal western North America provides a useful proxy index of North Pacific ocean-atmosphere variability since 1600 AD. Here we use this high-resolution record to identify intervals of an enhanced interdecadal climate signal in the North Pacific, and to assess the timing and magnitude of abrupt shifts in this system. In the context of this record, the step-like climate shift that occurred in 1976-1977 is not a unique event, with similar events having occurred frequently during the past 400 years. Furthermore, most of the pre-instrumental portion of this record is characterized by pronounced interdecadal variability, while the secular portion is more strongly interannual in nature. If the 1976-1977 event marks a return to this mode of variability there may be significant consequences for natural resources management in the North Pacific Sector.

Introduction

Interdecadal variability in Pacific North America has been identified in a number of climatological [*Ghil and Vautard*, 1991; *Cayan et al.*, 1998] and environmental studies [*Cayan*, 1989; *Francis et al.*, 1998]. This variability is accepted to be a response to North Pacific climate forcing, generally termed the Pacific Decadal Oscillation (PDO) [*Mantua et al.*, 1997]. The PDO may be distinct from other forms of climate variability in that it does not appear to be truly oscillatory, but rather may shift abruptly between relatively warmer and cooler states. These shifts have only occurred three times over the instrumental record, however, making it difficult to determine how robust this model of PDO variability is. In this paper we provide some evidence to support this step-shift model, based on a dendroclimatic analysis.

We have compiled a transect of six tree ring-width chronologies from stands of mountain hemlock (*Tsuga mertensiana* [Bong.] Carr.) growing near treeline that extends from southern Oregon to the Kenai Peninsula, Alaska. The chronologies were compiled from existing sources [*Wiles et al.*, 1996; *Grissino-Mayer and Fritts*, 1997; *Frank*, 1998] and newly collected tree-ring series Table 1. Our analysis of these chronologies focuses on variability in the time-domain, which allows us to directly relate changes in radial growth to annual variations in the North Pacific ocean-atmosphere system.

Analysis of the Tree-Ring Record

Chronology development

Each ring-width series was transformed into dimensionless indices to remove growth-trends related to tree age and stand dynamics [*Cook et al.*, 1990]. Detrending was undertaken using a negative exponential curve, followed by a spline curve with a 50 percent frequency cutoff of 95 years [*Gedalof and Smith, in press*]. These individual series were then combined into site chronologies using a robust mean [*Cook et al.*, 1990]. The minimum segment length used in this analysis was 85 years, with 90 percent of the segments greater than 143 years in length [*Cook et al.*, 1995]. The growth-climate relationship at each site was determined using a response function analysis [*Fritts*, 1976] to ensure that the series were providing a consistent climate signal. These analyses indicate that while summer temperature is the dominant factor influencing the annual radial growth of mountain hemlock, winter precipitation is also an important factor at lower latitudes [*Gedalof and Smith, in press*].

Following this assessment, the individual site chronologies were compiled into a single series using a Factor Analysis (FA). The goal of FA in a dendroclimatological context is to extract the variance that is common between sites, thereby enhancing the common climate signal and suppressing any local climate or disturbance related components. Only the leading eigenvector was retained (F1 hereafter), which explained 44 percent of the variability in ring-width index along the transect (Figure 1). A limitation of this method is that the resulting chronology is restricted to the interval common to all input series; in our analysis from 1599 to 1983.

Chronology interpretation

The extracted eigenvector was compared to four indices of ocean- atmosphere variability. The Cold-Tongue Index (CTI) [*Deser and Wallace*, 1990] and the Southern Oscillation Index (SOI) are used to represent the oceanic and atmospheric components of the El Niño / Southern Oscillation

Table 1. Ring width chronologies used in analysis

Site Name	Lat.(N)	Lon.(W)	Elev.[1]	Years
Crater Lk.[2]	42.6	122.1	2200	1564-1983
Strathcona Park[3]	49.5	125.5	1500	1412-1995
Queen Charlotte Is.[3]	53.0	132.1	615	1585-1998
Hemlock Knob[4]	59.5	139.1	30	1599-1995
Eyak Mountain[5]	60.6	145.7	430	1365-1992
Ellsworth Glacier[5]	60.1	149.0	480	1543-1991

[1] meters above sea level.

[2] International Tree-Ring Data Bank see also *Briffa et al.* [1992].

[3] [*Gedalof and Smith, in press*]

[4] [*Frank*, 1998]

[5] [*Wiles et al.*, 1998]

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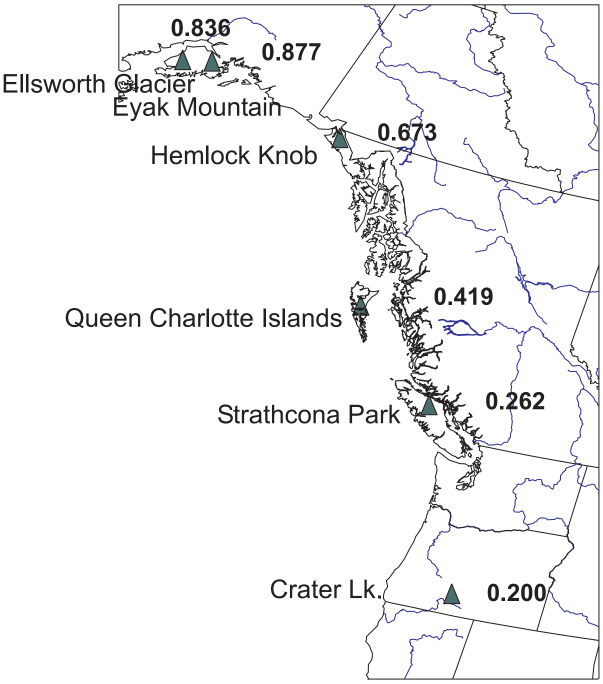

Figure 1. The locations and factor loadings of the mountain hemlock chronologies used in the analysis.

(ENSO) system, while the PDO index and the North Pacific Pressure Index (NPPI) [*Mantua et al.*, 1997] are similarly used to represent variability in the North Pacific. For this analysis, mean winter (Dec-Feb), spring (Mar-May) and annual index values were considered. While F1 is most strongly correlated with the spring PDO index (r = 0.52, p = 0.000), it is also well correlated with the remaining indices (e.g. annual NPPI, -0.44; spring CTI, 0.34; annual SOI, -0.27). The higher correlations to oceanic versus atmospheric indices probably reflects the fact that sea surface temperature (SST) represents a synthesis of many climate variables, having strong links to atmospheric pressure, heat fluxes, and resulting temperature and precipitation patterns.

A partial correlation analysis, controlling for the variability in F1 which is explained by the spring PDO index, indicates that the remaining indices contribute no additional information regarding F1 ($\mathrm{pr} < 0.03, p > 0.8$ for all other indices). This result implies ENSO does not contribute any unique information about F1 that is not also expressed in the PDO index. Consequently, we interpret F1 as representing an extratropical North Pacific climate signal, rather than a tropical ENSO signal, or a combination of (unique) tropical and extratropical signals.

It is worth noting, too, that eight identically specified models, using mean seasonal temperature and total seasonal precipitation values from proximal meteorological stations produced only marginally better correlation coefficients with the climate indices. The strongest relationship identified in this analysis was between the leading mode of variability in winter temperature and the spring PDO index (r=0.61, p=0.000). This finding suggests that the regional mountain hemlock tree-ring record provides almost as good a record of spring PDO variability as a comparable network of meteorological stations.

Pre-Instrumental North Pacific Climate Variability

F1 was used in a simple linear regression to construct a proxy mean-spring PDO index since 1600 AD (Figure 2). A number of salient features are recognizable, including the abrupt shift that occurred in 1976-77, as well as earlier documented shifts in the 1920s and 1940s. In all three of these examples, however, the reconstructed series exhibits reduced variance over the observed series, suggesting that the tree-ring record gives a conservative estimate of the year-to-year change associated with these regime changes.

Verification of our reconstruction was undertaken using the "leave-one-out" method [*Blasing et al.*, 1981], where each year of the instrumental record is estimated using the remaining years of data as predictors. This method of cross validation is intended to avoid bias which might be introduced by the arbitrary division of a time-series into segments which may have experienced different climatic conditions, such as would have occurred during different phases of the PDO. The verified series is well correlated with the PDO index (r=0.52, p=0.000) and exhibits the same sign as the original series 70 percent of the time. A product means test

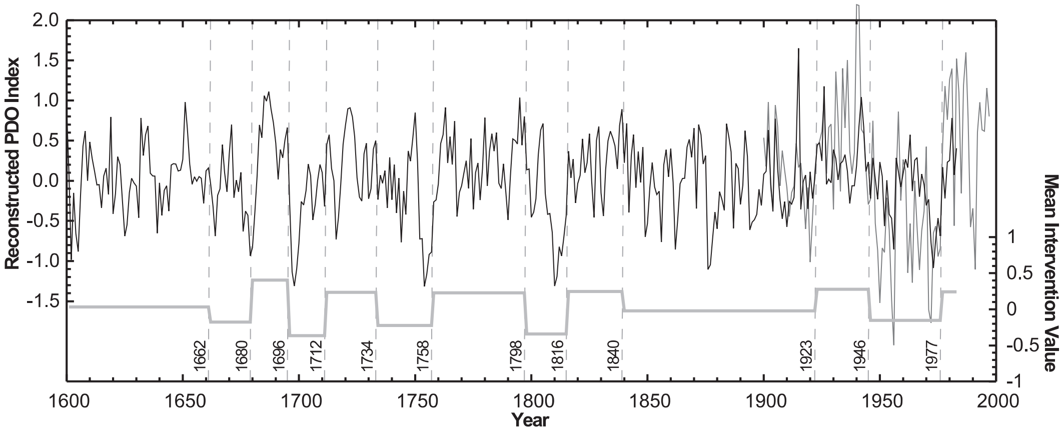

Figure 2. The observed (grey) and reconstructed (black) mean spring (March - May) PDO index. The low frequency component has been emphasized using a spline fit with a 50 percent frequency cutoff of 25 years. Shown at the bottom is the intervention model fit to the reconstructed series.

Table 2. The years and directions of interventions detected using the two-samples t-test.

Year of Intervention	$\Delta F1$[1]	Intervention coefficient	Intervention p-value
Prior to 1662	N/A	+0.033	0.558
1662	-0.20	-0.168	0.072
1680	+0.10	+0.448	0.000
1696	-0.96	-0.364	0.001
1712	+0.77	+0.236	0.013
1734	-0.73	-0.223	0.014
1758	+0.63	+0.226	0.001
1798	-0.66	-0.342	0.001
1816	+0.80	+0.247	0.007
1840 [2]	-0.66	+0.026	0.761
1923	+0.43	+0.257	0.005
1946	-0.46	-0.151	0.061
1977 [3]	+0.86	+0.242	0.149

[1] Indicates the change in the mean springtime PDO index between the year indicated in column 1 and the preceding year.

[2] 1840 begins an interval where the mean springtime PDO index is not statistically different from zero.

[3] The 1977 regime shift is not significant in the tree-ring series due to the incomplete record; the intervention in the instrumental record for the same interval is not significant, either. If the reconstructed series is padded with observed values of the PDO index from 1984 to 1999 the coefficient and p-value are 0.63 and 0.082 respectively.

[*Fritts*, 1976] supports the observation that in most cases where the signs of the observed and estimated series are different the two series have values near zero. The Reduction in Error statistic is 0.10 and, while this statistic is very sensitive to even a single poor estimate, any value greater than zero is encouraging [*Fritts*, 1976].

The reconstructed series was interpreted in both the time and frequency domains. In order to assess the uniqueness of the 1976-77 step-shift in the North Pacific, an intervention detection algorithm was applied to the series. This algorithm uses a 30-year moving window that uses a two-samples t-test to identify whether the mean of the first 15 years is significantly different from the last 15 years within the window. In most cases where a shift was found, more than a single consecutive year was identified as representing the transition point between the two intervals. A random walk through the window was used to identify the most probable year at which the shift occurs. The significance and magnitude of each identified shift was tested using an intervention model [*Box and Tiao*, 1975] (Table 2, Figure 2). This analysis identified the three shifts in mean SST which are known to have occurred in the Twentieth Century ($p < 0.10$), as well as eight earlier shifts between 1650 and 1850.

The eleven PDO shifts separate intervals over which the mean PDO index is significantly different from the long-term mean of the series. Throughout the record there are only two intervals for which the mean is not significantly different from zero: the portion prior to 1662, and the portion between 1840 and 1923. The first of these intervals is interpreted with some caution because of poor sample replication prior to ca. 1650. The 1840 to 1923 interval is well-replicated and clearly represents an interval when regime-shifts were not occurring in the North Pacific. These results suggest that much of the pre-instrumental record in the Pacific Northwest region of North America is characterized by alternating regimes of relatively warmer and cooler SST in the North Pacific, punctuated by abrupt shifts in the mean background state.

A wavelet analysis was undertaken on the reconstructed series in order to assess the dominant frequencies of variability, as well as how those modes vary over the period of record [*Torrence and Compo*, 1998]. The wavelet spectrum was tested for significance at a 90 percent confidence level against a red-noise process Figure 3. This analysis shows that there is variability at approximately decadal scales (10-20 yrs.) throughout the period of record. However, virtually

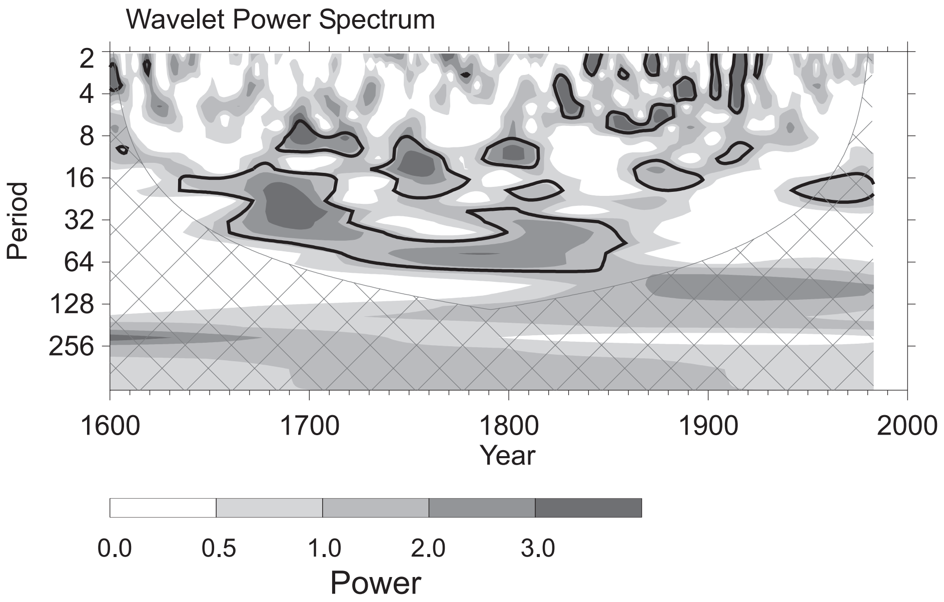

Figure 3. The local wavelet power spectrum of the tree-ring reconstruction. The thick contour encloses regions significant at 90 percent confidence, relative to red-noise. The cross-hatched region indicates where edge effects caused by zero-padding become significant (Wavelet software provided by C. Torrence and G. Compo, and is available at http://paos.colorado.edu/research/wavelets).

all of the interdecadal energy (30-70 yrs.) is confined to the pre- ca. 1840 portion of the series. In contrast, nearly all of the interannual energy (< 8 yrs.) occurs between ca. 1840 and 1930. The dominant spectra identified in this analysis are consistent with other studies of both instrumental data [*Ghil and Vautard*, 1991; *Ware*, 1995] and proxy records [*Minobe*, 1997; *Wiles et al.*, 1998; *Kadonaga et al.*, 1999]. The anomalous interval from ca. 1840 to 1930, identified in both the time-domain and frequency domain analyses, has been identified as interesting in other analyses, suggesting a period of unusual activity in the North Pacific sector [*Villalba et al.*, 1999; *Finney et al.*, 2000].

Conclusions

Interpreted together, our time-domain and frequency-domain analyses suggest that the historical instrumental record may not be indicative of the long-term importance of interdecadal climate variability in Pacific North America, and that abrupt shifts in this system have been relatively common occurrences. An important corollary to these findings is that the inter-regime fluctuations represent a substantial portion of the total variability in the PDO index, and any global warming signal present in the North Pacific will be complicated by the presence of a PDO signal. Our findings also suggest that it may be inappropriate to identify a single average North Pacific climate state, given that this system may vary between at least two mean states.

Our analyses have shown that regime shifts in the North Pacific have occurred 11 times since 1650 and are therefore unlikely to be either artifacts of either SST data [*Guilderson and Schrag*, 1998] or an effect of beat harmonics in low-frequency oscillations [*Ware*, 1995]. The average duration of a single phase is 23 years. Given this understanding, and accepting that the paleo-record is a reliable analogue for current variability, then another regime-scale shift in the North Pacific is almost certainly imminent [*Ingraham et al.*, 1998; *Hare et al.*, 1999].

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