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Variations in the Pacific Decadal Oscillation over the past millennium

Glen M. MacDonald and Roslyn A. Case

Department of Geography, University of California, Los Angeles, California, USA

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[1] Hydrologically sensitive tree-ring chronologies from *Pinus flexilis* in California and Alberta were used to produce an AD 993–1996 reconstruction of the Pacific Decadal Oscillation (PDO) and to assess long-term variability in the PDO's strength and periodicity. The reconstruction indicates that a ~50 to 70 year periodicity in the PDO is typical for the past 200 years but, was only intermittently a strong mode of variability prior to that. Between AD 1600 and 1800 there is a general absence of significant variability within the 50 to 100 year frequency range. Significant variability within in the frequency range of 50 to 100 years reemerges between AD 1500 and 1300 and AD 1200 to 1000. A prolonged period of strongly negative PDO values between AD 993 and 1300 is contemporaneous with a severe medieval megadrought that is apparent in many proxy hydrologic records for the western United States and Canada. **Citation:** MacDonald, G. M., and R. A. Case (2005), Variations in the Pacific Decadal Oscillation over the past millennium, *Geophys. Res. Lett.*, *32*, L08703, doi:10.1029/2005GL022478.

1. Introduction

[2] The Pacific Decadal Oscillation (PDO) is a leading mode of multi-decadal variability in sea surface temperatures (SST's) in the extratropical North Pacific [*Mantua et al.*, 1997; *Nigam et al.*, 1999; *Minobe*, 2000; *Mantua and Hare*, 2002]. The PDO index is derived from an EOF analysis of SST's and positive phases of the PDO are typified by warm SST's in the northeastern Pacific (Figure 1). The climatic and environmental impacts of positive and negative PDO phases are of major importance to fisheries and water resources [*Latif and Barnett*, 1993; *Cayan et al.*, 1998; *Nigam et al.*, 1999; *Minobe*, 2000; *Barlow et al.*, 2001; *Mantua and Hare*, 2002; *Chavez et al.*, 2003]. In western North America, positive phases of the PDO are associated with climatic conditions similar to El Niño – although weaker in expression. These conditions include decreased winter precipitation, snowpack and streamflow in the northwest and higher precipitation in the southwest. Conditions reverse during negative PDO phases. The PDO has been shown to modulate climatic teleconnections between North American climate and the equatorial Pacific during El Niño and La Niña events [*Gershunov and Barnett*, 1998; *Brown and Comrie*, 2004].

[3] A positive PDO regime existed between 1977 and 1997. The index now appears to be moving toward a negative or more variable state. The causes of shifts in the PDO remain uncertain [*Mantua and Hare*, 2002], but possibly lie in the tropical Pacific [*Latif and Barnett*, 1993; *Zhang et al.*, 1998; *Cane and Evans*, 2000; *Linsley et al.*, 2000; *Evans et al.*, 2001]. Shifts between states of the PDO may reflect non-linear dynamics of the ocean-atmosphere system [*Overland et al.*, 2000] and/or be forced by factors such as strong El Niño and La Niña events [*Biondi et al.*, 2001; *Newman et al.*, 2003]. Fluctuations in the strength of both positive and negative PDO phases occur in the El Niño/Southern Oscillation (ENSO) frequency bands of 2 to 7 years [*Minobe*, 2000].

[4] Dominant periodicities in the 50 to 70 year and bidecadal year bands have been proposed for the PDO [*Minobe*, 1999]. Testing the persistence of dominant periodicities in the PDO is of key concern in predicting future climate variations in western North America. Unfortunately, instrumental records of SST's are too short in duration to confidently gauge the long-term persistence and multi-decadal variability of the PDO. Instrumental records of North Pacific SST's are relatively sparse prior to the 1940's [*Woodruff et al.*, 1987] and calculations of the PDO can be inconsistent with one another prior to that time [*Biondi et al.*, 2001]. Here we present a >1000-year reconstruction of the PDO derived from tree-ring records and examine the long-term multi-decadal variability of the PDO. We also demonstrate that a prolonged depression in the PDO correlates with an episode of aridity apparent throughout much of western North America between AD 900 and 1300.

2. Study Sites and Methods

[5] Southern California and western Canada lie at opposite ends of the PDO precipitation dipole (Figure 1) and hydrological variations related to the PDO should be of opposite sign in the two regions. Both regions support *Pinus flexilis* (James) trees that are useful in producing dendroclimtological records of precipitation and streamflow [*Case and MacDonald*, 1995, 2003; *Hidalgo et al.*, 2001]. Chronologies from trees growing at the two ends of the PDO precipitation dipole should maximize the probability of producing a robust representative reconstruction of the PDO. Chronologies were developed from living and dead *Pinus flexilis* trees occurring in open groves on rocky substrates. The California site is located near Mount San Gorgonio (34°04′ 116°29′) while the Alberta site lies on the flanks of the Rocky Mountains at Whirlpool Point near Nordegg, Alberta (52°00′N 116°27′W). We used standard techniques [*Stokes and Smiley*, 1968; *Fritts*, 1976; *Cook and Kairiukstis*, 1990] to develop millennial length tree-ring chronologies for both sites. Minimum sample depth was six radii and mean sensitivity ranged from 0.168 at San Gorgonio to 0.397 at Whirlpool Point. Both chronologies displayed significant correlations ($p \leq 0.05$) with monthly precipitation records and selected monthly PDO index values. Using standard chronologies and the 1940–1998 PDO index from Mantua (http//:jisao.washington.edu/pdo/

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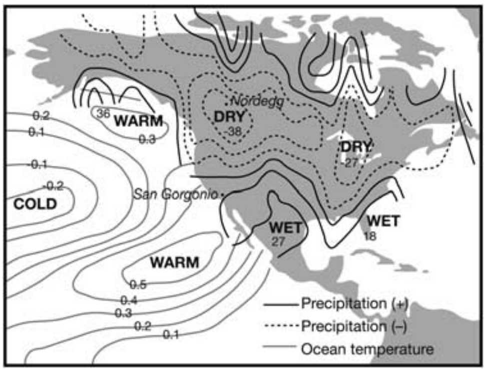

Figure 1. Location of the San Gorgonio, California and Nordegg, Alberta tree-ring sampling sites. PDO index loading vectors (1945–1993) for Pacific SST's and correlations between North American winter precipitation and the PDO index are shown [from *Mantua et al.*, 1997; *Nigam et al.*, 1999].

Table 1. Calibration and Verification Statistics for PDO Reconstruction Model[a]

Model and Calibration Period	R^b	$R^{2\,c}_{adj}$	r^d	Verification Period	r^e	RE^f	CE^g
Full[h]	0.69	0.45	0.66				
Early[i]	0.72	0.46	0.67	Late	0.57	0.50	0.22
Late[j]	0.61	0.30	0.66	Early	0.69	0.44	0.10

[a]All testable statistics significant at $p \leq 0.05$.
[b]R, multiple correlation coefficient.
[c]R^2_{adj}, multiple correlation coefficient adjusted for degrees of freedom.
[d, e]r, correlation coefficient between model and observational data.
[f]RE, Reduction of error (values > 0 considered acceptable).
[g]CE, Coefficient of efficiency (values > 0 considered acceptable).
[h]Full Model (PDO = −3.502 + ((2.698 × SanG) − 0.606 × Nordegg) + (1.318 × SanGprioryear)) calibration period extends 1940–1996.
[i]Early Model (PDO = −3.532 + ((2.876 × SanG) − 0.766 × Nordegg) + (1.458 × SanGprioryear)) calibration period extends 1940–1967; verification period extends 1968–1996.
[j]Late Model (PDO = −5.458 + ((3.385 × SanG) − 0.386 × Nordegg) + (2.083 × SanGprioryear)) calibration period extends 1968–1996; verification period extends 1940–1967.

pdo.latest) for calibration and verification purposes [*Fritts*, 1976; *Cook and Kairiukstis*, 1990] we produced a multiple regression based reconstruction of annual PDO (Jan–Dec) that extends from AD 993 to 1996 (Figure 2 and Table 1). The 1940 to 1996 PDO record was used for calibration because there is a high density of SST measurements and a good correspondence between different PDO indices over this period. Verification (Figure 2 and Table 1) was done using sequence splitting (1940–1967 and 1968–1996). As expected, the regression coefficients for the Alberta chronology were consistently opposite in sign to the coefficients for the California chronology (Table 1).

[6] To further examine veracity of the PDO model, the resulting reconstruction was statistically compared with earlier PDO reconstructions produced using tree-rings from Mexico and the southwestern United States and from the Pacific Northwest [*Biondi et al.*, 2001; *Gedalof and Smith*, 2001]. In both cases our reconstruction was significantly positively correlated ($p \leq 0.05$) with the earlier independent reconstructions over their common intervals. The three reconstructions are most coherent at the low frequencies (Figure 3). The correlation between our reconstruction and the *Biondi et al.* [2001] reconstruction (r = 0.57) is higher than with the *Gedalof and Smith* [2001] reconstruction (r = 0.19).

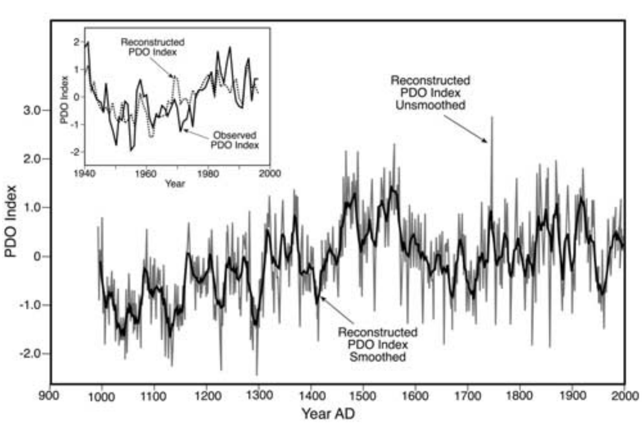

Figure 2. Reconstructed annual PDO compared to observed annual PDO [*Mantua et al.*, 1997] (insert) and reconstructed annual PDO index from AD 993 to 1996. The heavy line is the index smoothed using an 11 year moving average.

3. Results

[7] The most salient feature of the PDO reconstruction (Figure 2) is a prolonged and pronounced negative PDO state between approximately AD 993 and 1300. The mean PDO value during this time (−0.752) is more than one standard deviation below the overall mean for AD 1301 to 1996 (0.155) and the 20th century mean (0.198). Additional, major features of the reconstruction include generally elevated positive values between AD 1450 and 1550 and generally low values between AD 1600 and 1800.

[8] In order to examine the variability in the PDO within multidecadal spectral bands, the lowest frequency variability was removed using a quadratic polynomial model (Figure 4) and the detrended reconstruction was subjected to wavelet analysis [*Torrence and Compo*, 1998]. The significance of peaks in the wavelet power spectrum was tested against an autoregressive red noise background spectrum. Wavelet analysis indicates that overall there is significant power in the ~50 to 70 year band consistent with lower frequency variability present in observed PDO behavior. Throughout the record there is also weakly significant power in the 4 to 7 year band typical of ENSO. The wavelet spectrum sug-

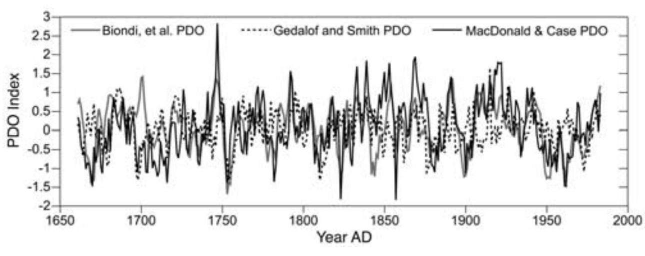

Figure 3. Comparison of our PDO reconstruction with the *Biondi et al.* [2001] and *Gedalof and Smith* [2001] reconstructions for the common period of AD 1661–1983.

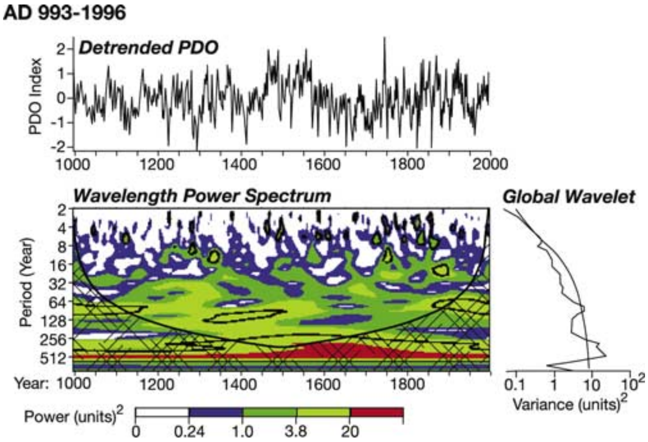

Figure 4. Wavelet analysis of the detrended PDO reconstruction. Significant periodicities (p $\leq$ 0.05) are outlined in black on the wavelet power spectrum and extend to or beyond the dashed curve on the global wavelet profile. The cone of influence where edge effects may be important is indicated by crosshatching.

gests that while the $\sim$50 year pattern of variability is a significant mode of variability over the past millennium, it is not consistently present, with notable weakening from approximately AD 1200 to 1300 and from AD 1500 to the early 1800's. Finally, there is also possible variation at the very low frequencies of 250 to 500 years related to the low to negative states of the PDO in the medieval period and the 15th and 16th centuries.

4. Discussion

[9] In the context of climate variability and resources planning the reconstruction of the PDO possesses two particularly important features. First, the reconstruction provides evidence for the persistence of a strongly negative PDO state, suggesting a cool northeastern Pacific, during the medieval period ($\sim$ AD 900 to 1300). This prolonged episode of negative PDO values corresponds to a period of severe and prolonged dry conditions evident throughout western and central North America [*Cook et al.*, 2004]. There is also additional evidence for cooler northeastern Pacific SSTs, higher rates of upwelling and increased marine productivity along coast during this general time period [*Ingram*, 1998; *Finney et al.*, 2002; *Kim et al.*, 2004]. The aridity extended across the current PDO dipole. The PDO reconstruction together with the other evidence for pronounced cooling in the northeastern Pacific and geographically extensive prolonged drought suggest a pattern of medieval aridity in western North America which reflects the persistence of a different mean state of the ocean-atmosphere system than that typical today or anticipatable from the instrumental period. The causes of such a state, or the associated 250 to 500 year variability observed in the PDO, are unknown at this point.

[10] Second, the 50 to 70 year mode of PDO variability inferred from instrumental observations of SST's has been generally persistent and significant over the past $\sim$200 years and intermittently significant prior to that.. Previous tree-ring based reconstructions of the PDO also provide evidence of decadal variability, but often with greater strength in the 12 to 28 year frequencies [*Biondi et al.*, 2001; *D'Arrigo et al.*, 2001; *Gedalof and Smith*, 2001; *Gedalof et al.*, 2002]. These records also indicate changes in the strength of decadal to multidecadal modes of variability over time [*Gedalof et al.*, 2002]. The reason for the greater propensity of our reconstruction to capture the longer >50 year frequency signal is not clear, but may be related to the geographic location of the sites or the relative sensitivity of different tree species to persistent drought [*Hidalgo et al.*, 2001]. Our reconstruction and the other available records indicate that unlike the persistent ENSO signal, the multidecadal variability typical of the PDO for the past two hundred years has not been stable. For extended periods in the 13th century and in the 17th through 18th centuries the 50 to 70 year PDO signal weakened or disappeared. The causes of the apparent flickering in the multidecadal PDO variability are uncertain, but could be a result of non-linear dynamics in the ocean-atmosphere system that impacted the northeastern Pacific or broader ocean-atmosphere linkages [*Overland et al.*, 2000]. Although the factors controlling the periodicity and strength of the PDO remain to be resolved, it is clear that this mode of variability has changed several times in the past 1000 years and may be expected to do so again in the future. These results suggest caution should be exercised when using the multidecadal behavior of the PDO observed in 20th century instrumental records as a basis for anticipating or planning for long-term variability in water resources beyond the immediate future.

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R. A. Case and G. M. MacDonald, Department of Geography, University of California, Los Angeles, Los Angeles, CA 90095, USA. (macdonal@geog.ucla.edu)