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ON THE ASIAN EXPRESSION OF THE PDO

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ABSTRACT

The causes and mechanisms of Pacific Decadal Variability (PDV) are still being investigated. One reason that such variability is not better understood is the scarcity of high-resolution paleoclimatic records from the Asian side of the North Pacific. Here we present a reconstruction of the boreal spring (March–May) Pacific Decadal Oscillation (PDO) index, spanning A.D. 1565–1988, that is the first to represent the large-scale Asian expression of this phenomenon using tree-ring data. Intervention analysis reveals significant (95% level) regime shifts corresponding to those in the instrumental PDO during the mid-1920s, mid-1940s and mid-1970s, the latter period associated with the famed 1976 shift in Pacific climate. Shifts in the preinstrumental period show varying correspondence with those of a North American-based tree-ring reconstruction of the North Pacific index (NPI), another indicator of Pacific decadal climate variability. Differences between these two time series hint at modulation of local climate from Asian monsoon, El Niño-Southern Oscillation (ENSO) and volcanic forcing, which could be partly masked by combining data from these sensitive regions in future PDO reconstructions. Overall, however, comparison of the reconstructions from both Asia and North America (NA) is useful for evaluating the distinct expressions of the PDO on both sides of the North Pacific and their interactions with the tropics. Copyright © 2006 Royal Meteorological Society.

KEY WORDS: PDO; Asia; tree rings; reconstruction; dendrochronology; monsoon; North Pacific; ENSO

1. INTRODUCTION

The search continues for the causes and mechanisms of Pacific Decadal Variability (PDV) and its linkages to tropical climate (Minobe, 1997; Trenberth and Hurrell, 1994; Deser *et al*., 2004). Instrumental records of PDV are of insufficient length to adequately assess the long-term behavior and complexity of this phenomenon. To fulfill the need for longer records, a suite of reconstructions of the Pacific Decadal Oscillation (PDO; the dominant mode of North Pacific sea-surface temperature (SST); Mantua *et al*., 1997) has been produced using tree-ring records from western North America (NA; Biondi *et al*., 2001; D'Arrigo *et al*., 2001; Gedalof and Smith, 2001; Cook, 2003; MacDonald and Case, 2005). Although these records generally agree well with each other during the twentieth century, there is relatively little agreement before this time. This may partly result from the varying spatial coverage of NA tree-ring data used for these PDO reconstructions, as well as the fact that the models are all calibrated during the recent period using teleconnected relationships that may not be time-stable. However, the early lack of agreement may also reflect a real pattern of less coherency in the Pacific atmosphere–ocean system prior to the twentieth century.

One missing piece of the puzzle is that none of the above-mentioned tree-ring reconstructions of the PDO include data from the Asian (upstream) side of the North Pacific. Yet, there is increasing evidence that Asian climate plays a critical role in PDV and its tropical teleconnections. North Pacific SST anomalies have been correlated with climate extremes across eastern Asia, and can interact with the Asian monsoon (Nakamura

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et al., 2002; Chongyin *et al*., 2004; Lau *et al*., 2004; Chan and Zhou, 2005). Japanese coastal air temperatures demonstrate PDO-related regime shifts (Minobe, 1997), and Asia's atmospheric circulation has been shown to interact with Pacific anomalies on decadal time scales (Frauenfeld and Davis, 2002). Compared to western NA, the climate of eastern Asia will respond differently to fluctuations in the Kuroshio–Oyashio Extension, east of Japan (Figure 1), an important factor influencing PDO variability (Schneider and Cornuelle, 2005), or to Atlantic forcing (Schwing *et al*., 2003). It has also been suggested that a key to the famed 1976 regime shift and related PDV may lie in the upstream circulation and recent warming of the Asian landmass, and that decadal Pacific SST variability could be forced by the atmosphere over Eurasia (Frauenfeld and Davis, 2002). These observations suggest that the climate of Asia plays an active role in determining PDO variability, and that an extended record of the Asian expression of the PDO could contribute to our understanding of the long-term variability of Pacific climate and its teleconnections.

A reconstruction of the spring PDO index, developed solely from Asian tree-ring data, is presented herein. We demonstrate that this reconstruction is distinct from a reconstructed index of North Pacific climate variability, the North Pacific index (NPI), partly developed from NA tree-ring data previously used to reconstruct the PDO. We also compare the Asian PDO reconstruction to climate records for the tropical Indo-Pacific region, as previous studies have found evidence for a North Pacific-tropical climate connection (Trenberth and Hurrell, 1994; Deser *et al*., 2004). The 1976 regime shift, for example, is evident in both North Pacific and tropical climate indices (e.g. Deser *et al*., 2004), and common decadal fluctuations exist between North Pacific and tropical Indian Ocean SSTs (Minobe, 1997; Chelliah and Bell, 2004). Indices of PDV and Indian monsoon rainfall correlate significantly on decadal time scales, and positive PDO phases can amplify the impact of El

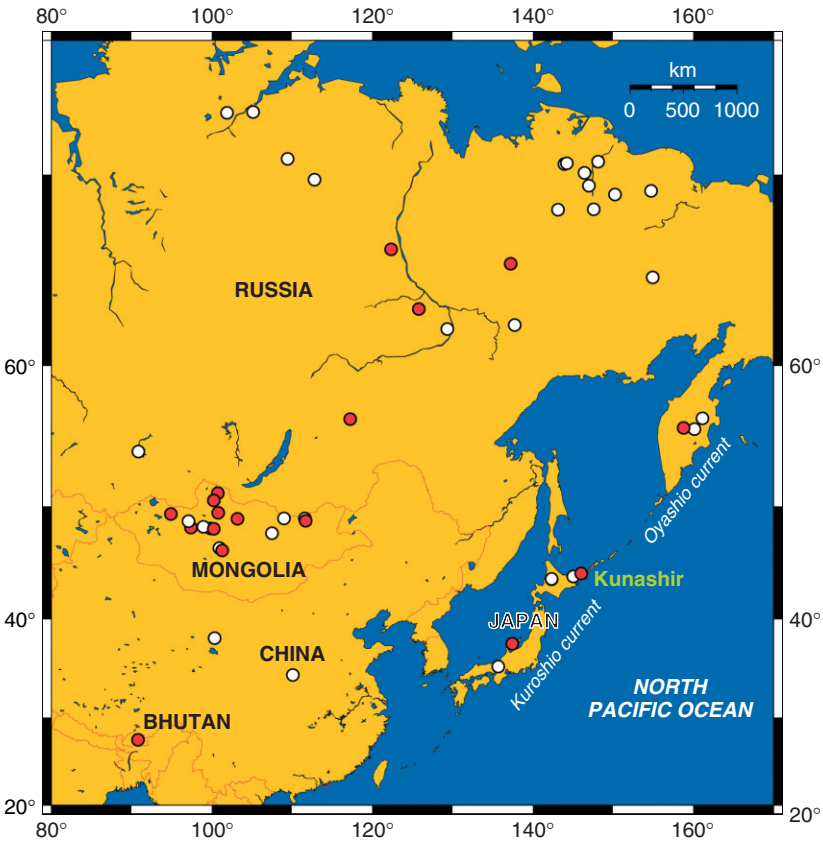


Figure 1. Map of east Asia showing locations of tree-ring sites (white dots) used as candidate predictors of the Asian PDO (some dots represent more than one site). Sites in red are those included in the regression model used to reconstruct the PDO for the most replicated (1720–1988) nest

Niño-Southern Oscillation (ENSO) warm events, resulting in failure of the Indian monsoon (Krishnan and Sugi, 2003; Sen Roy and Balling, 2003). The PDO thus appears to have a tropical Indo-Pacific component, and may be an important factor contributing to decadal monsoon variability (Krishnan and Sugi, 2003).

2. DATA

A data set of 70 tree-ring chronologies from eastern Asia was assembled for this analysis (Figure 1). Some of these records were previously shown to be sensitive to local or regional climate (temperature and/or precipitation) variability (e.g. Pederson *et al*., 2001; Davi *et al*., 2002; Jacoby *et al*., 2004; Davi *et al*., 2005). One of the records, from Kunashir, Kurile Islands, was previously found to correlate (negatively) with the summer PDO (Jacoby *et al*., 2004). Additional chronologies were obtained from the NOAA Paleoclimatology International Tree-Ring Data Bank (ITRDB; http://www.ncdc.noaa.gov/paleo/paleo.html) and other sources. These records were evaluated for possible inclusion in the Asian PDO reconstruction.

The monthly PDO index of Mantua *et al*. (1997) was used to calibrate the Asian PDO reconstruction. The reconstruction is compared to several instrumental climate data sets and indices, including: the global SST data set of Kaplan *et al*. (1998), Hadley CRU2 global land/marine temperature data set (Jones *et al*., 1999), CRU precipitation data set (Hulme *et al*., 1998), HADSLP1 sea-level pressure (SLP) data set (Basnett and Parker, 1997), Indian Ocean SSTs, an Indian monsoon rainfall index (Parthasarathy *et al*., 1995) and an East Asian winter monsoon index (EAWMI, D'Arrigo *et al*., 2005a).

We also compare the Asian PDO reconstruction to a reconstruction of the NPI, an atmospheric index of Aleutian low intensity (Trenberth and Hurrell, 1994) that is significantly correlated with the PDO. These two indices show parallel regime shifts in the twentieth century (correlation between the two indices in winter is 0.5 over 1900–1992; Mantua *et al*., 1997). Together, the atmosphere–ocean covariability reflected in these two modes is considered to be the essence of the PDO signature (Mantua *et al*., 1997), although there is still considerable variance that is not common between them. The NPI reconstruction was used in this study because it is based only on tree-ring data from the Gulf of Alaska and Pacific Northwest (D'Arrigo *et al*., 2005b). As a result it has a purer emphasis on North Pacific climate variations than NA-based PDO reconstructions (based partly on the same northwestern tree-ring data), that also include chronologies from the southwestern USA. These latter chronologies tend to correlate more strongly with ENSO (e.g. Biondi *et al*., 2001; D'Arrigo *et al*., 2001). Additional comparison is made with a coral δ^{18}O SST record, Malindi, for the far western Indian Ocean (Cole *et al*., 2000).

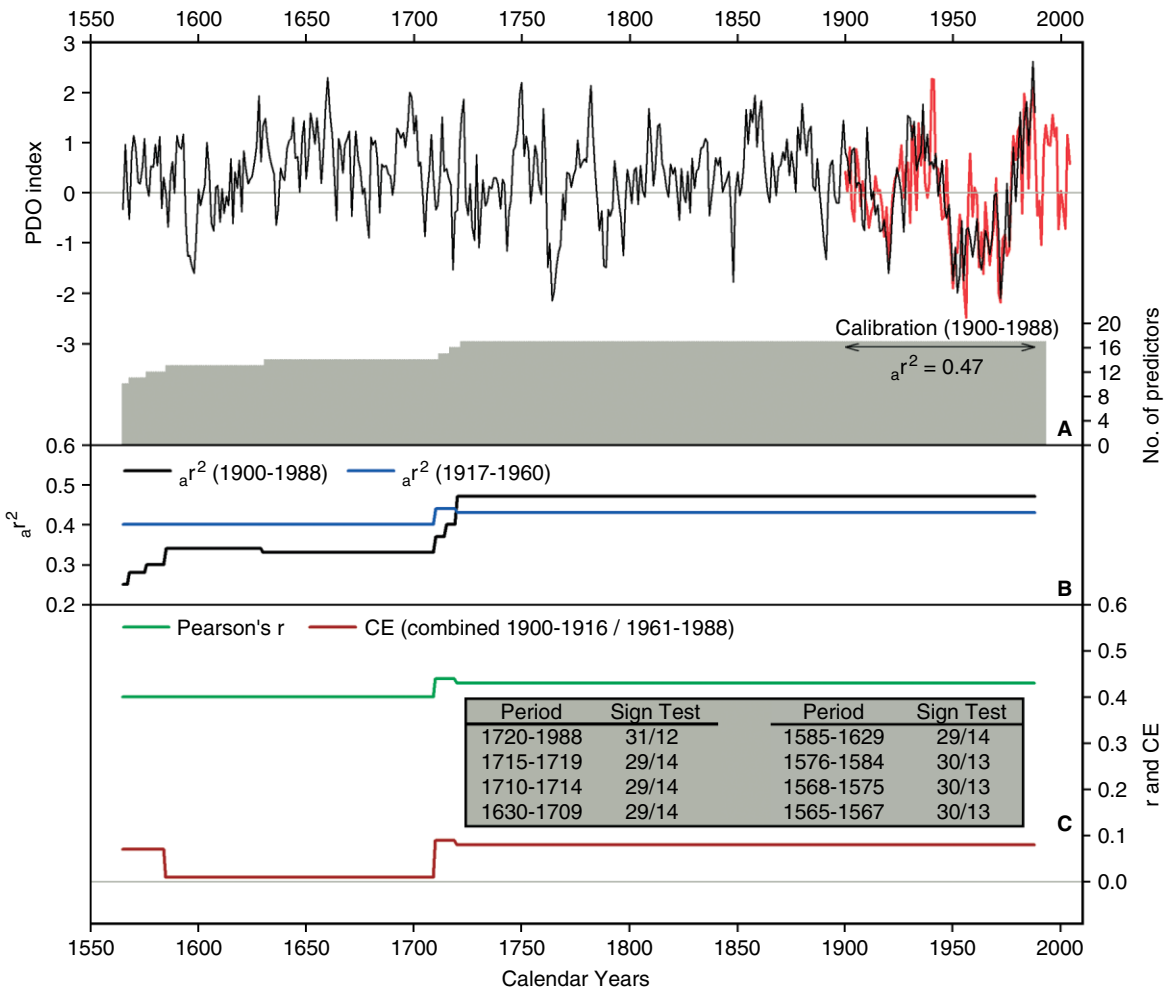
3. THE ASIAN PDO RECONSTRUCTION

The Asian tree-ring data were screened against the monthly PDO index for the 1900–1988 common period. Of the original 70 chronologies, 17 (shown as red dots in Figure 1) correlated significantly at the 90% significance level or above for the spring months (MAM) just prior to the growing season, and were retained for further analysis. This spring season, which coincides with the onset of tree growth in many locations, represents the strongest calibrated PDO signal in the combined Asian proxies. The trees at the sites from which the original 70 chronologies were derived likely respond to a range of seasons and climate variables (e.g. temperature, precipitation) with varying degrees of sensitivity at their respective locations.

A nested approach, which takes into account the decreasing number of chronologies back in time, was employed to develop the longest possible reconstruction. A principal components regression model (Cook *et al*., 1999) was first developed using all available data, resulting in the most robust reconstructed series. A second nest was based on the next common period of all series with the shortest series removed, and so on. For each nested subset, a reconstruction was developed and separate statistics computed for both a calibration period (1917–1960) and two combined verification periods (1900–1916 and 1961–1988). This procedure allowed for an assessment of the loss in signal fidelity in the reconstruction over time. To create the final reconstruction, the relevant segments from each full period (1900–1988) calibrated nested model were

spliced together. This was done after the mean and variance of each nested time series were adjusted to that of the most replicated nest, to avoid artificial changes in variance due to weakening of the modeled signal. Eight nested subsets were used to generate the reconstruction, starting in 1565 (10 chronologies) and ending in 1720 (17 chronologies). The instrumental PDO was spliced onto the reconstruction after 1988, following adjustment of mean and variance based on the most replicated (1720) nest to extend the reconstruction to the present. The best model, found for the spring (March–May) season, accounts for 47% of the variance in the instrumental PDO for the most replicated nest (1720–1988) (Figure 2). The full Asian PDO reconstruction, dating from A.D. 1565–1988, is presented in Figure 2(A).

Calibration and verification tests (Cook and Kairiukstis, 1990) indicate that the final reconstruction model provides valid estimates of past PDO variability over its length (Figure 2(B) and (C)). Statistical results include positive values of the CE, a rigorous test of predictive skill. Significant ST values indicate year-to-year agreement between the actual and estimated PDO data. We should caution that the earlier parts of the



Period	Sign Test	Period	Sign Test
1720-1988	31/12	1585-1629	29/14
1715-1719	29/14	1576-1584	30/13
1710-1714	29/14	1568-1575	30/13
1630-1709	29/14	1565-1567	30/13

Figure 2. Tree-ring based Asian PDO reconstruction. (A) Reconstruction of the March–May PDO from A.D. 1565–1988 based on Asian tree-ring data. Gray shading represents changing number of chronologies over time included in the nested models. (B) Nested calibration and verification $_ar^2$; the $_ar^2$ is the level of explained variance after adjustment for degrees of freedom. (C) The coefficient of efficiency (CE) is a measure of the common variance between the actual series and the tree-ring estimates, for which a positive value indicates skill in the regression. The sign test (ST) measures how well the reconstructed estimates track the year-to-year variations in the instrumental data (Fritts, 1976; Cook and Kairiukstis, 1990). These results demonstrate that the reconstruction provides useful information about the Asian expression of the PDO at both interannual and decadal time scales

reconstruction, due to less data prior to ~1720 and lower levels of explained variance, should be viewed with less certainty. There is, however, reasonable verification for all eight nested models over the length of the reconstruction. These tests indicate that the tree-ring estimates reasonably capture the interannual to Decadal Variability in the PDO.

Multitaper method (MTM, Mann and Lees, 1996) spectral analysis reveals significant (above 99% level) peaks at ~2–3 and 26 years, and a broad range of lower (multidecadal-centennial) frequencies over the 1565–1988 period. Singular spectrum analysis (SSA; Vautard, 1995) similarly revealed dominant modes at ~2–3, 26, and 63 years. The 63-year mode falls within the range of the 50–70 year oscillatory mode identified by Minobe (1997) for the North Pacific. These results are difficult to compare to the North American reconstructions, which are primarily for the colder season months and for different time intervals (correlation between the spring (MAM) and winter (DJF) PDO is 0.75 over 1901–2002). However, some common modes of variation are found on decadal to multidecadal time scales (e.g. 25–50 years for D'Arrigo *et al*. (2001) and 17–28 years for Biondi *et al*. (2001).

Spatial correlation fields computed between the reconstructed Asian and instrumental PDO and global SSTs (Kaplan *et al*., 1998) show similar patterns, indicating that the Asian PDO reconstruction captures the dominant spatial features of the North Pacific-tropical climate relationship during the calibration period, albeit more weakly than the instrumental PDO (Figure 3(A) and (B)). The correlation fields display the characteristic PDO-type pattern of SSTs over the Pacific (Mantua *et al*., 1997). The PDO has been shown to have a robust Indian Ocean component (Krishnan and Sugi, 2003), and we observe positive correlations over much of the Indian Ocean (see also correlations with averaged Indian Ocean SSTs in Table I, which compares the Asian PDO reconstruction with several climate indices). Note that correlations with ENSO are relatively weak on the interannual time scale (Table I), that may reflect the observed weakness of ENSO in the boreal spring season (the 'predictability barrier'; e.g. Allan, 2000).

Figure 3(C)–(E) show correlations between the 9-point filtered PDO index and global land/marine temperature (Jones *et al*., 1999), precipitation (Hulme *et al*., 1998) and SLP (HADSLP, Basnett and Parker, 1997) fields for 1900–1988. These comparisons provide further indication of the interrelationship between the PDO and Asian climate documented in prior studies (e.g. Mantua and Hare, 2002; Zhu and Yang, 2003; and see references in Section 1).

Table I. Correlations between the Asian (March–May) PDO and other climate indices over the 1900–1988 period. **A** = unfiltered, **B** = 1st differenced and **C** = 9 pt. binomial filter. Correlations are provided using both the March–May season of the PDO instrumental data (**inst**) and the Asian PDO reconstruction (**rec**). Indian SSTs are for Jan–Dec. Other seasons utilized are those that were generated in original papers: NPI = Dec–May (D'Arrigo *et al*., 2005a), EAWMI = Dec–Feb East Asian winter monsoon index (D'Arrigo *et al*., 2005b), NINO3 SST = Dec–Feb (Kaplan *et al*., 1998). * = denotes correlations significant at the 95% confidence limit. Autocorrelation was not taken into account when calculating these significance levels

A Unfiltered	NPI Dec–May	EAWM	All India	Indian J-D SSTs	NINO3 DJF
March–May PDO inst	−0.70*	0.34*	−0.02	0.48*	0.46*
Asia PDO rec	−0.42*	0.37*	−0.03	0.32*	0.20
B 1st differenced	NPI Dec–May	EAWM	All India	Indian J-D SSTs	NINO3 DJF
March–May PDO inst	−0.76*	0.28*	0.11	0.28*	0.45*
Asia PDO rec	−0.31*	0.21*	0.14	−0.02	0.10
C 9 pt. binomial filter	NPI Dec–May	EAWM	All India	Indian J-D SSTs	NINO3 DJF
March–May PDO inst	−0.71	0.53	−0.08	0.47	0.55
Asia PDO rec	−0.61	0.56	−0.16	0.42	0.45

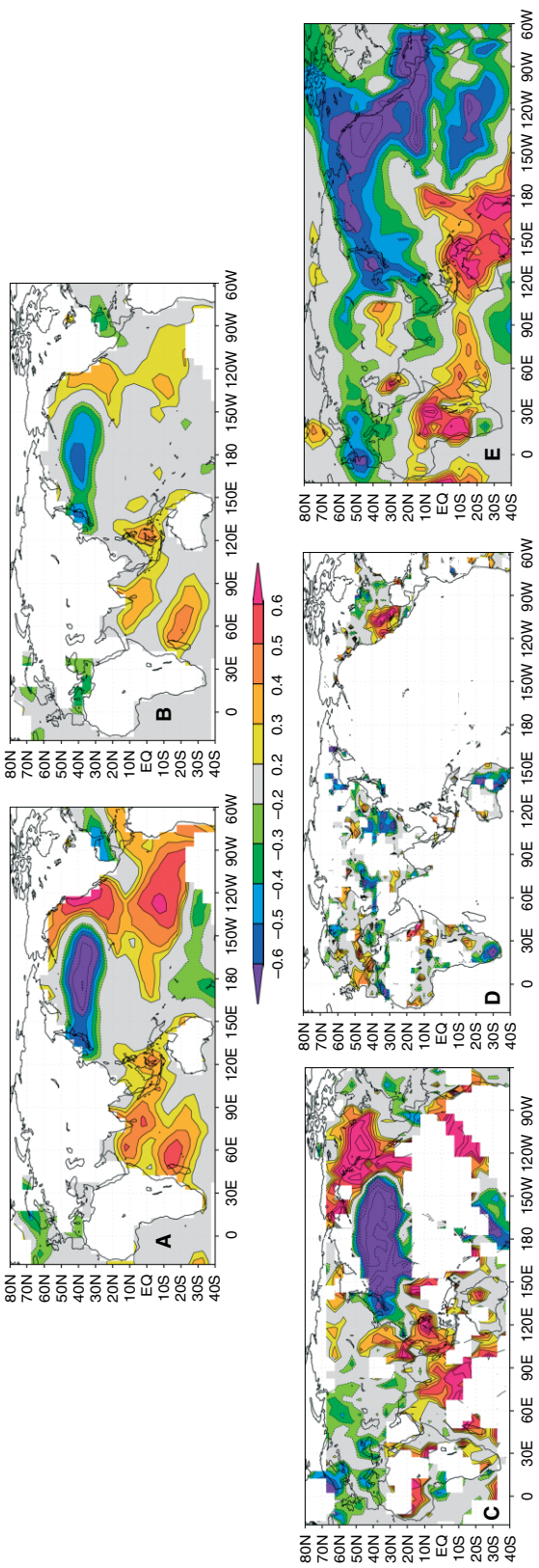


Figure 3. Comparison of actual (A) and reconstructed (B) Asian March–May PDO index with global March–May SSTs for 1900–1988 (Kaplan *et al.*, 1998). Also shown are comparisons between the smoothed (9-point filter) PDO index and (C) CRU land/marine temperatures, v2, variance stabilized, Jones *et al.*, 1999; (D) CRU gridded land precipitation (Hulme *et al.*, 1998; and (E) Hadley Centre SLP data (HadSLP1, Basnett and Parker, 1997). As might be expected, the Asian land signal is stronger at decadal time scales, as shown here, rather than interannual time scales

The teleconnected link with Indian Ocean SSTs is further highlighted by comparing the Asian PDO reconstruction with the Malindi $\delta^{18}O$ coral record for the far western Indian Ocean (Figure 4). Correlations with this SST proxy are significant over the 1870–1988 period ($r = -0.47$), although there is no coherence between the records prior to this time. The earlier, low correlation period may reflect decoupling in decadal-scale coherence between the tropics and extratropics (D'Arrigo *et al*., 2005b), or between the Asian proxies and the PDO.

The Asian PDO reconstruction shows linkages to several aspects of the broader Asian monsoon system. For example, significant correlations are observed with the EAWMI, particularly at decadal time scales (Table I(C); D'Arrigo *et al*., 2005a). This finding implies an important interaction between North PDV and the monsoon, at least during the twentieth century. This is supported by the significant relationships observed between the PDO, EAWM and NPI (Jhun and Lee, 2004), and between the PDO and climate anomalies over Asia (e.g. Krishnan and Sugi, 2003). However, no apparent coherence exists with the all India monsoon rainfall index (Parthasarathy *et al*., 1995). This latter observation does not agree with analysis by Krishnan and Sugi (2003), who showed a significant relationship between the PDO and Indian summer monsoon rainfall. This inconsistency may be due to the differently defined spatial grids and methods used by Krishnan and Sugi (2003) to generate their PDO index compared to that used herein (Mantua *et al*., 1997). We do, however, observe some connection between the PDO and episodes of monsoon failure over India (see Table II below).

Intervention analysis (Rodionov, 2004) was applied to the Asian PDO reconstruction to identify significant shifts (at the 95% confidence limit) in this series (Figure 5(A)). For this analysis, mean values of 15-year periods were compared on either side of each year throughout the reconstruction. The Asian PDO reconstruction reasonably tracks regime shifts seen in the instrumental PDO in the mid-1920s, mid-1940s and mid-1970s (Mantua *et al*., 1997) (Figure 5(A)). Although, as noted above, the quality of the PDO reconstruction decreases somewhat back in time, there are decadal-scale variations prior to the instrumental period that may also represent regime shifts: in 1594, 1617, 1724, 1746, 1762, 1771, 1785, 1799, 1854 and 1885. The mean period between shifts is broadly consistent with that observed by Minobe (1997).

A similar intervention analysis undertaken on the NPI reconstruction also identifies the three main twentieth century shifts (Figure 5(B)). When compared to the results for the Asian PDO reconstruction prior to the twentieth century, quite different phase shifts are identified. However, there are some pre-twentieth century shifts that appear to be common between the Asian and NA data sets, although their 'local' postshift responses can differ. For example, similar shifts are identified around 1723/1724, 1771, 1785/1787 and 1854. Some of the differences between the PDO and NPI reconstructions might be related to inherent differences in behavior between these two indices, as well as the different seasons used for reconstruction.

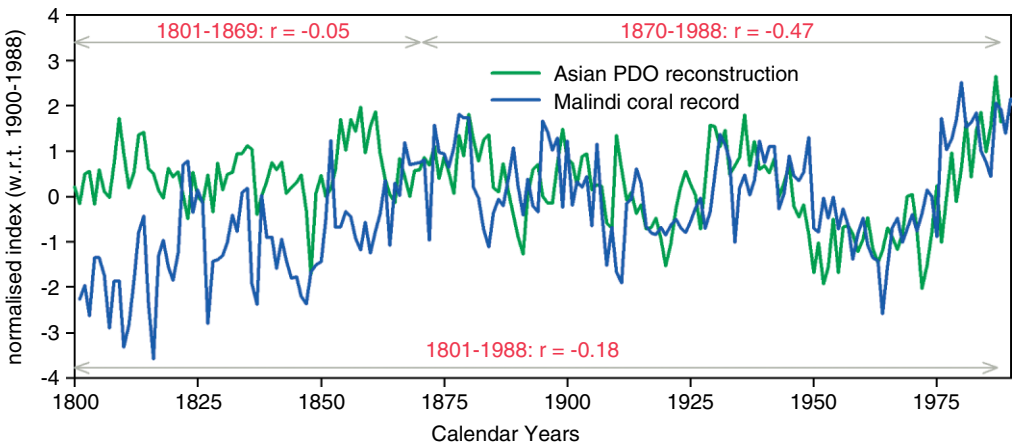


Figure 4. Comparison of the Asian PDO reconstruction with the coral O_{18} record of Indian Ocean SST for Malindi (Cole *et al*., 2000). Both records were normalized to the 1900–1988 period and the sign of the Malindi record inverted for visual comparison

Table II. Extreme (>3 standard deviations) difference years between the Asian PDO and NA NPI reconstructions after they were normalized to the 1900–1988 period (Figure 5(C)). Difference = difference value in standard deviations between annual or averaged multiple values. QEV = Quinn (1992) defined ENSO events. Number is magnitude value, while year of event is in parentheses. Monsoon droughts: EA = East Asian; IN = Indian; AU = Australian (sources in Nicholls, 1992 for 1788–1886, Quinn, 1992 since 1824). ASS = Ammann sulfate signature (Ammann and Naveau, 2003) of tropical volcanic events. Sources for candidate volcanic event information are Simkin and Siebert (1994), Briffa *et al.* (1998) and http://www.volcano.si.edu/world/

Year/ Period	Difference	QEV	Monsoon drought	ASS	Candidate volcanic events
Values above					
1601	3.1	4 (1600)	–	1600	1600: Huayaputina
1621	5.4	3 (1621)	–	1619	–
1698/1699	3.5	3 (1697)	–		Unknown multiple eruptions (Briffa *et al.*, 1998)
1723	3.3	3 (1723)	–	1721	1721: Katla
1749/1750	3.6	–	–	1749	–
1753	3.6		–	1752	–
1756	3.1	2 (1754/55)	–		1755: Katla
1809/1810	3.5	3 (1810)	AU (1808–1815)	1808	Unknown 1808 eruption
1813/1814	3.7	3 (1812)/4 (1814)	IN (1812–1813)	1813	1812: Awu/1813: Suwanose–Jima/ 1814: Mayon
1855–1858	3.3	2 (1854)/2 (1857/1858)	EA and IN (1855)	–	1854: Shiveluch 1856: Komaga–Take/ 1857: Fuego
1860–1863	3.3	2 (1860)	IN (1860)	1861	1861: Makian
1876–1878	3.8	6 (1877/1878)	EA, IN and AU (1876–1878)	–	1875: Askja/1877: Suwanose–Jima and Cotopaxi
1880–1883	4.3	2 (1880)	EA, IN and AU (1880/1881)	1881/1883	1880: Fuego/1883: Krakatau and Augustine
Values below					
1765	−3.3	2 (1765)	–	–	1764: Michoacan–Guanajuato

The variations in the reconstructions over time are compared in Figure 5(C), which highlights those periods when they deviate from each other. We interpret these intervals as representing periods of varying coherency between climate on opposite sides of the North Pacific. After taking the difference between the normalized reconstructed time series (Figure 5(C)), we have listed the extreme (>3 standard deviations) difference years in Table II. Intriguingly, for many of these cases, there is a corresponding moderate to strong ENSO event (Nicholls, 1992; Quinn, 1992) and/or volcanic event within 1–2 years (Ammann and Naveau, 2003), with many of these episodes also being linked with monsoon failure over India, Indonesia and/or Australia (Quinn, 1992). For example, the very strong ENSO of 1877–1878, associated with monsoon failure over much of Asia, has a differential value of 3.8 standard deviations between the two reconstructions (Table II). These observations suggest that the large-scale coherence between Decadal Variability in the North Pacific Ocean and its interactions with both Asian and North American climate may be modulated/affected by both ENSO and volcanic events (Adams *et al.*, 2003). Overall, the correlation between the Asian PDO and NA NPI

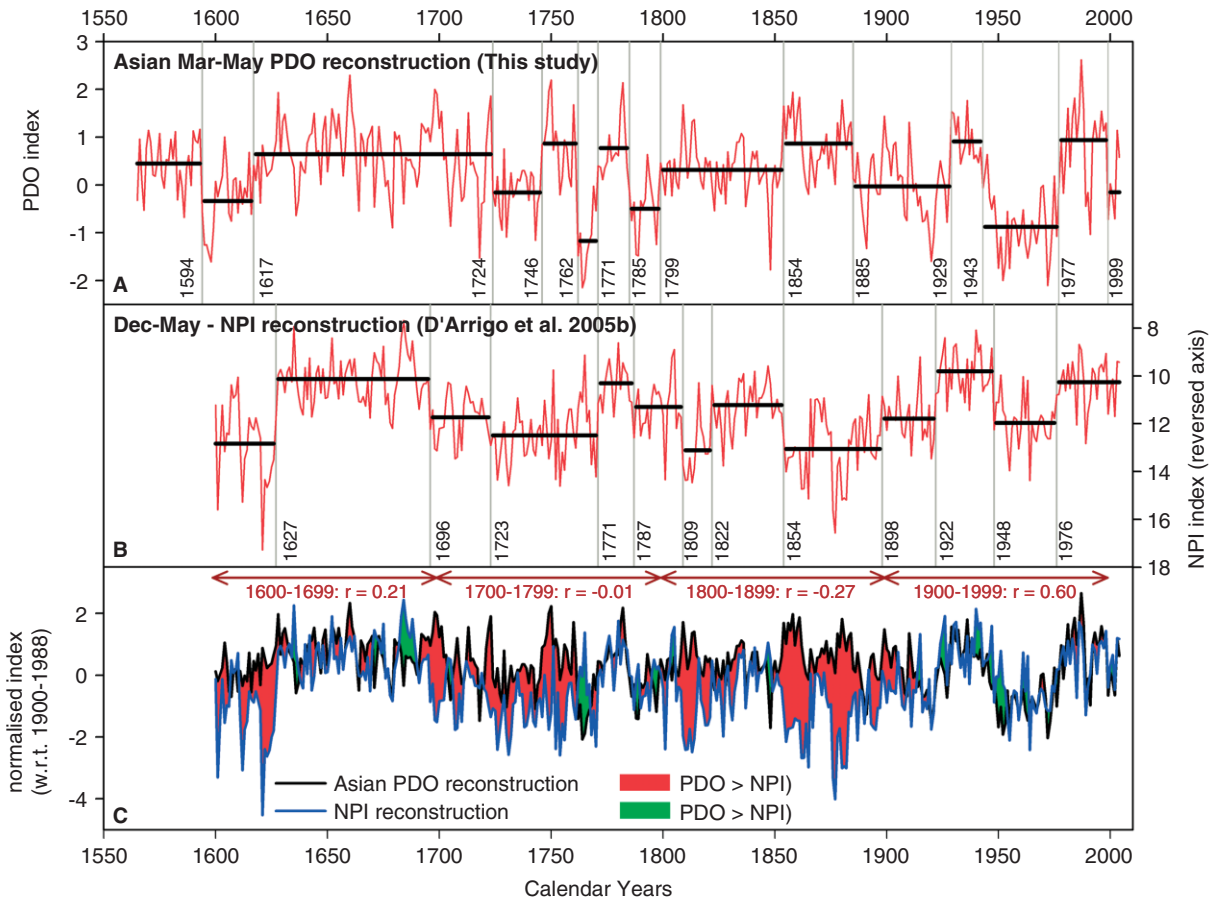


Figure 5. Highlighted phase shifts identified using intervention analysis based on the Rodionov (2004) method. Shifts are significant at the 95% confidence limit. (A) Asian PDO reconstruction. (B) NPI reconstruction (D'Arrigo *et al*., 2005b). (C) Comparison of the two reconstructions (normalized to the 1900–1988 period) and correlation over time; differences are highlighted. The sign of the normalized NPI series has been reversed

reconstructions is extremely weak (1600–1983: $r = 0.09$, $p = 0.08$). However, if the extreme difference years noted in Table II are removed from the time series, the correlation value increases to 0.29 ($p = 0.00$). These findings imply, therefore, that one reason that the suite of NA PDO reconstructions do not correlate well prior to the twentieth century calibration period is because of the differential local response of the different proxy series to ENSO episodes, volcanic eruptions and other extreme events. This may be a result of the overall greater spatial coherency during this recent period. However, this hypothesis requires further investigation.

4. SUMMARY

We have presented the first large-scale tree-ring reconstruction of the Asian expression of the PDO, spanning four centuries. This record extends previous instrumental analyses (e.g. Frauenfeld and Davis, 2002) in which it was found that Eurasian climate interacts with PDV on annual to decadal time scales. The Asian PDO reconstruction accounts for 47% of the variance for its most replicated nest and is well verified over its length. Comparative analysis with the NA NPI reconstruction shows that valid, independent reconstructions of PDV can be developed using Asian and NA tree-ring data. However, differences between these time series hint at

modulation of local climate from ENSO, monsoon failure or volcanic events. To minimize these effects, which can 'muddy' the PDV signal, future attempts at reconstructing the PDO may be optimized by including both Asian and NA data. Overall, however, comparison of the reconstructions from both Asia and NA is useful for evaluating the distinct expressions of the PDO on both sides of the North Pacific and their interactions with tropical climate, and could be of value in future predictive efforts.

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