

Support for tropically-driven Pacific decadal variability based on paleoproxy evidence

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Abstract. Two independent proxy reconstructions of sea surface temperature reflect a common pattern of Pacific decadal sea surface temperature variability over the past two centuries. Since the pattern extends to both the northern and southern hemispheres, this result supports the idea that Pacific decadal variability is a basin-wide phenomenon originating in the tropics.

The causes of Pacific decadal climate variability (here termed PDV) are the subject of much debate. Most work describing PDV has focused on the North Pacific, where the leading EOF of low-pass filtered sea surface temperature (SST) poleward of 20°S was labelled the Pacific Decadal Oscillation (PDO) [Zhang *et al.*, 1997; Mantua *et al.*, 1997]. But is PDV generated in the North Pacific? Or is PDV a basin-wide pattern of variability? If so, then it is most likely to originate in the tropics [Garreaud and Battisti, 1999]. Resolving the processes controlling PDV is important for predicting socially important downstream effects on Pacific fisheries and water resources in the arid western United States [Mantua *et al.*, 1997; Dettinger *et al.*, 2001]. Paleoclimatologists are extending observations of PDV into the past using proxy observations to help address such questions [Minobe, 1997; Wiles *et al.*, 1998; Linsley *et al.*, 2000a; Biondi *et al.*, 2001; Gedalof and Smith, 2001]. These studies have identified large variations in the frequency of and interval between reconstructed PDO regime shifts prior to the observational period. However, the physical mechanism for PDV remains unknown.

Two recent sets of proxy observations support the contention that PDV is a tropically-driven basin-scale phenomenon. One is a time series of Strontium:Calcium (Sr/Ca) ratio measurements on a reef coral growing offshore of Rarotonga (21°S, 160°W) [Linsley *et al.*, 2000b]. On centennial time scales, sea water Sr/Ca ratio is approximately constant, and coral aragonite Sr/Ca composition varies linearly with temperature [Beck *et al.*, 1992]. The Sr/Ca data resolve the seasonal cycle and cover the period from 1726 to 1997; resolution of the seasonal SST cycle at Rarotonga keeps proxy

data age model error to a few months. Linsley *et al.* [2000b] argued that their time series resembles the PDO index. As illustrated in Figure 1a, the pattern of SST variability associated with Rarotonga Sr/Ca on decadal time scales is similar to that observed by Garreaud and Battisti [1999] in 1958–1996 reanalysis data [Kalnay *et al.*, 1996]. Citing symmetry arguments [Garreaud and Battisti, 1999], Linsley *et al.* [2000b] suggested a tropical source for basin-scale PDV.

Recent independently-derived dendroclimatological estimates of PDV support this idea. Evans *et al.* [2001] used a set of 15 tree ring indicators from Pacific-influenced regions of extratropical North and South America to reconstruct the Pacific basin SST field (70°W - 110°E, 70°N-60°S). The tree ring indicators are sensitive to air temperature, precipitation or drought [Villalba *et al.*, 2001]; each indicator is itself based on cross-correlation and standardization of many individual tree-ring data series from each site. Evans *et al.* [2001] found that these 15 tree-ring indicators could verifiably resolve one SST pattern, through presumed downstream influences on tree-ring site precipitation and/or temperature. This pattern is illustrated in Figure 1b; again, the pattern is similar to that illustrated by Garreaud and Battisti [1999].

We now compare these two paleo-PDV estimates (here called “Sr/Ca” and “TrSSTa”) to examine their consistency. We defer analysis of the earliest part of the Sr/Ca record (1727–1768) until the large observed shift in this interval can be replicated. Coherency between records (Figure 2) varies over time and frequency (Figure 3). To illustrate this we used singular spectral analysis (SSA; Vautard and Ghil [1989]) to divide each time series into decadal, interannual and biennial frequency components (Table 1). Coherence significance was determined by Monte Carlo simulations of correlations between time series having the red noise characteristics of the actual paleoproxy frequency components (Table 1). Coherence between decadal frequency components is significant at the 90% level in the 20th century, but varies between 70-90% for the 18th century (Figure 3a,d,e). Coherence between interannual components is $\geq 95\%$ significant over the entire comparison interval (Figure 3b,d,e), while coherence significance of biennial components is low throughout the record (Figure 3c,d,e).

The temporal similarity of these proxies corroborates recent modeling and observational studies linking tropical and basin-scale phenomena in the Pacific. The approximate symmetry of the spatial pattern about the equator and the simultaneous coherence between northern and southern Hemisphere proxy observations suggest a tropically mediated mechanism. Garreaud and Battisti [1999] suggested that basin-wide PDV originates in the tropical Pacific. Kar-speck and Cane [2000] showed that a wind-driven tropical ocean model can reproduce a well-known feature of PDV, the 1976–77 decadal shift in thermocline depth anomaly. In a coupled atmosphere-ocean general circulation model

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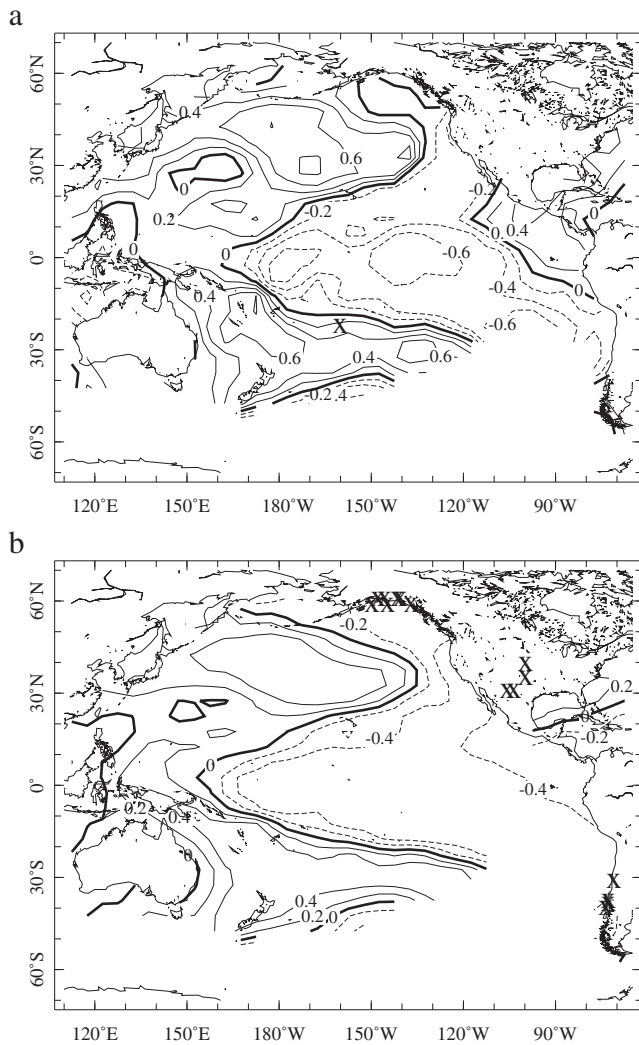


Figure 1. (a): Correlation between 11-year averages of Rarotonga Sr/Ca [Linsley et al., 2000b] and Pacific Basin SST, 1856–1990. Contours are at 0.2 correlation unit; correlation of ± 0.5 are significant at the 90% level assuming 10 degrees of freedom. Location of Rarotonga marked by “x”. (b): Spatial pattern reconstructed by Evans et al. [2001], as illustrated by the correlation of the reconstructed time series with Pacific SST, 1856–1990. Correlations of ± 0.3 are significant at the 90% level. Locations of dendroclimatic indicators used marked as in (a).

study, Pierce et al. [2000] observed simultaneous decadal time scale anomalies in the tropical and extratropical Pacific. They argued that a rapid atmospheric teleconnection may be more important than ocean propagation (e.g. via ventilated thermocline [Deser et al., 1996; Gu and Philander, 1997]) or Rossby wave propagation, as these latter two mechanisms require at least 7–10 years. Other studies have argued against a leading role for extratropical forcing of PDV. Hazeleger et al. [2001] observed in model simulations that although the North Pacific subtropical gyre advects upper ocean heating anomalies [Latif and Barnett, 1994], these do not reach the equatorial ocean; Schneider et al. [1999] found they appear to, but the tropical signal nevertheless is a response to local winds.

The climatic links argued here are essentially those of Garreaud and Battisti [1999]: An ENSO-like pattern of SST anomalies, symmetric about the equator, explains the si-

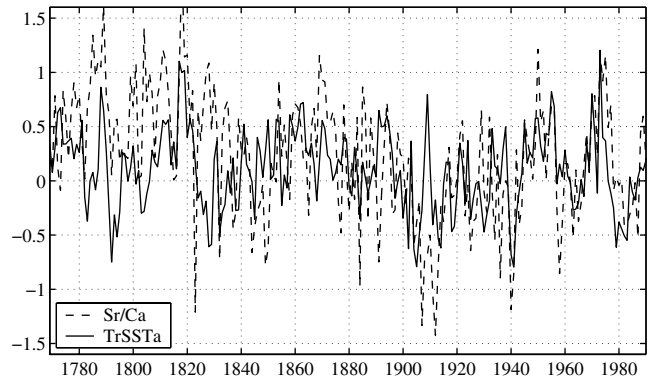


Figure 2. ((a): Time series plots of the Rarotonga Sr/Ca and TrSSTa (tree-ring-based Pacific Basin SSTa) records, the latter scaled as NINO3.4 SST, over the interval 1769–1990. Units are $^{\circ}\text{C}$. Correlation between annual series is 0.39.

multaneous coherency of the proxy data. Chao et al. [2000] analyzed 20th century SSTs to reach similar conclusions. A number of model studies have shown that the tropical SST anomalies can be generated by tropical wind anomalies, which in turn may be generated in the extratropics

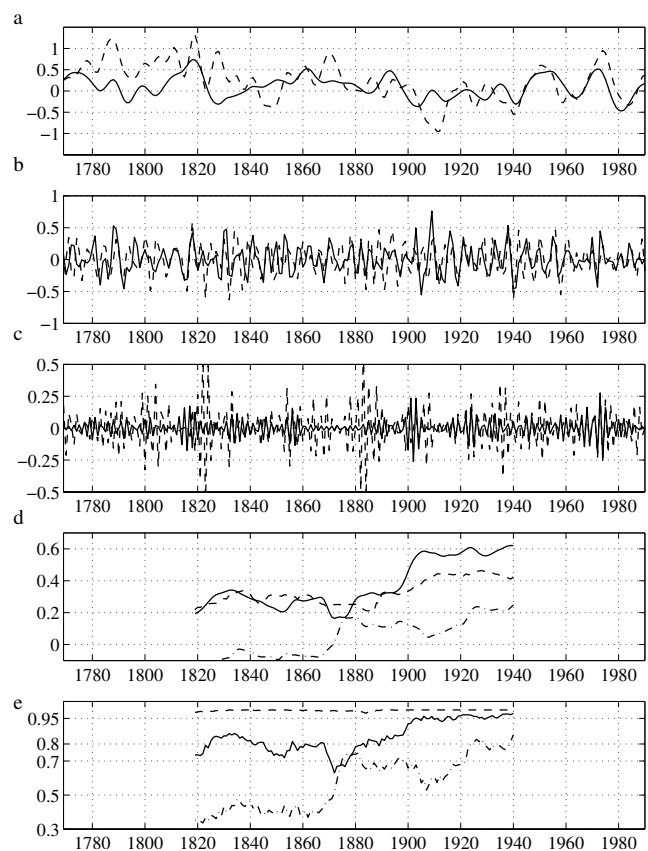


Figure 3. (a): Time series plot of decadal frequency components of the two time series. Units are $^{\circ}\text{C}$. Legend as in Figure 2. (b): As in (a), except for interannual frequency components. (c): As in (a), except for biennial frequency components (see text and Table 1 for details). (d): Running coherence between 101-year intervals of the frequency components in (a,b,c). Solid line: decadal coherence. Dashed line: interannual coherence. Dot-dashed line: biennial coherence. (e) Running Monte-Carlo significance tests of correlations plotted in (d). Legend as in (d).

Table 1. SSA analysis of Sr/Ca and TrSSTa time series, 1769–1990

RCs	% variance	Periods	$\phi \pm$ S.D.
Sr/Ca 1–3	68	≤ 7 yr	0.93 ± 0.02
TrSSTa 1–2	55	≤ 8 yr	0.96 ± 0.01
Sr/Ca 4–7	21	2.5–7 yr	0.06 ± 0.04
TrSSTa 3–8	39	3–8 yr	0.22 ± 0.04
Sr/Ca 8–10	11	2–2.5 yr	-0.84 ± 0.01
TrSSTa 9–10	6	2–2.5 yr	-0.93 ± 0.01

RCs, reconstructed components [Vautard and Ghil, 1989]. SSA analysis performed with embedding dimension 10; sum of RCs 1–10 is identical to the input data set. ϕ , mean first-order autoregression coefficient calculated for 101 year intervals used to calculate Monte-Carlo correlation significances (see Figure 3.) S.D., standard deviation.

(e.g. Pierce et al. [2000]). Alternatively, they may result from coupled interactions in the tropics, as in the many intermediate ENSO models showing power at decadal periods as one feature of their irregular behavior (e.g. Cane et al. [1995]). We note that the mechanism supported here requires no well-defined time scale. This is consistent with modern observations (Pierce [2001]) and the variety of time scales identified by other PDO paleo-reconstruction efforts. Temporal changes in coherency over time could be due to proxy data quality issues. Small shifts in pattern position could also influence cross-site coherency because Rarotonga is located near a pattern node. Alternatively, the increase in coherency since the early 20th century [Figure 3; Biondi et al. (2001); Villalba et al. (2001)] may be consistent with PDV as the residual of an energetic ENSO and a historically-observed global trend in SST over the 20th century [Bottomley et al., 1990; Cane et al., 1997; Hoerling et al., 2001]. Overall, the coral and tree-ring records are evidence for basin wide PDV extending back 200 years, and perhaps intensifying in the 20th century. By employing two independent paleoproxy estimates of the basin-scale phenomenon, one oceanographic and from the south Pacific, the other terrestrial and from both hemispheres, we put the hypothesis that PDV is generated in the tropics on a firmer footing. Confidence in these conclusions could be greatly improved by a network of paleo-estimates of large-scale SST variability in the Pacific Basin.

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