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Tropical origins of North and South Pacific decadal variability

Jeremy D. Shakun[1] and Jeffrey Shaman[2]

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[1] The origin of the Pacific Decadal Oscillation (PDO), the leading mode of sea surface temperature variability for the North Pacific, is a matter of considerable debate. One paradigm views the PDO as an independent mode centered in the North Pacific, while another regards it as a largely reddened response to El Niño-Southern Oscillation (ENSO) forcing from the tropics. We calculate the Southern Hemisphere equivalent of the PDO index based on the leading mode of sea surface temperature variability for the South Pacific and find that it adequately explains the spatial structure of the PDO in the North Pacific. A first-order autoregressive model forced by ENSO is used to reproduce the observed PDO indices in the North and South Pacific. These results highlight the strong similarity in Pacific decadal variability on either side of the equator and suggest it may best be viewed as a reddened response to ENSO.

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1. Introduction and Approach

[2] The origin of Pacific decadal variability (PDV) remains an outstanding question in climate dynamics. This issue has received considerable attention over the past 15 years and numerous hypotheses have been advanced concerning the mechanisms responsible for generating PDV. These hypotheses lie along a spectrum based on the geographic region held accountable for driving PDV. At one end of the spectrum, emphasis is placed on the tropical Pacific; on the other, the extratropical North Pacific is seen as the driver, and in between tropical-extratropical interactions are called upon. In reality, these hypotheses should be seen as representing a continuum of possibilities, with perhaps several processes in play.

[3] Much evidence favors a tropical source for PDV. *Newman et al.* [2003] developed a simple statistical model to show that North Pacific decadal variability can be well represented as a reddened response to the El Niño-Southern Oscillation (ENSO). *Deser et al.* [2004] showed that the North Pacific Index (NPI; a measure of the strength of the Aleutian Low) was coherent with numerous climate variables in the tropical Indo-Pacific on decadal timescales over the 20th century. *Kidson and Renwick* [2002] found that large scale South Pacific sea surface temperature SST variability from 1981–1999 is almost entirely related to ENSO and coherent extratropical modes do not appear to be significant. Observations and modeling indicate that El Niño anomalies can persist for over a decade in the extratropical ocean as they propagate westward as Rossby waves [*Jacobs et al.*, 1994]. The regime shift in 1976/77 from a negative to a positive phase of PDV was concurrent with a deepening of the eastern tropical Pacific thermocline recorded in Galapagos corals [*Guilderson and Schrag*, 1998], while modeling suggests this thermocline shift can be explained solely by equatorial wind forcing and does not require a link to the extratropics [*Karspeck and Cane*, 2002].

[4] At the same time, there is notable support for a North Pacific driver of PDV, particularly from modeling. One hypothesis is that ocean-atmosphere coupling involving the subtropical gyre and the Aleutian Low gives rise to a decadal oscillation in the North Pacific, with the timescale of the oscillation set by the spin-up time of the gyre [*Latif and Barnett*, 1994; *White and Cayan*, 1998; *Barnett et al.*, 1999]. In essence, the meridional gradient of SST is amplified by atmospheric feedbacks, but as SST anomalies propagate around the gyre, wind stress curl anomalies reverse and the opposite phase of the oscillation is reached. Also, observations indicate that North Pacific wintertime ocean-atmosphere variability may be largely independent of ENSO on both interannual and interdecadal timescales [*Zhang et al.*, 1996]. While these results suggest North Pacific decadal variability is not driven from the tropics, several studies argue that the North Pacific instead modulates ENSO variability. For example, the seasonal footprinting mechanism posits that North Pacific SST anomalies generated by winter atmospheric variability can influence tropical and subtropical atmospheric circulation the following summer, including the zonal wind stress anomalies along the equator important for driving ENSO variability [*Vimont et al.*, 2001, 2003a, 2003b].

[5] Tropical-extratropical interactions have also received considerable attention. A well-known example is the conceptual and numerical work of *Gu and Philander* [1997], which modeled PDV as a self-sustaining oscillation involving exchanges between the tropical and extratropical oceans. In their model, a tropical warming, for example, strengthens the mid-latitude westerlies causing cooling there. An extratropical cold SST anomaly then subducts in the subtropical gyre along isopycnals and upwells at the equator approximately a decade later reversing the phase of the oscillation. *Zhang et al.* [1998] suggested such a process triggered the 1976/77 climate shift. *Schneider et al.* [1999], on the other hand, found extratropical thermal anomalies do not propagate equatorward of 18°N.

[6] In addition to this debate over the geographic origin of PDV, a related question concerns the nature of PDV itself. Some paradigms view PDV as a true oscillatory mode, while others suggest it manifests from the superposition of several quasi-independent processes acting at

[1]Department of Geosciences, Oregon State University, Corvallis, Oregon, USA.
[2]College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon, USA.

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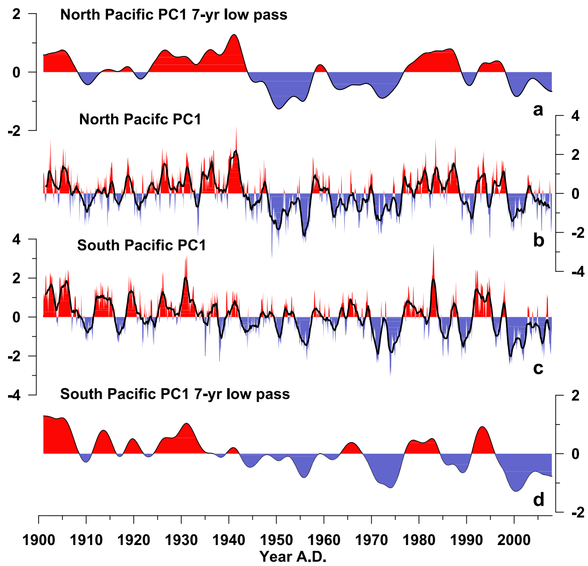

Figure 1. The leading PCs of (b) North and (c) South Pacific monthly SST anomalies, each poleward of 20° latitude. Both account for 23% of the variance in their respective domains. The time series have been standardized to unit variance. Also shown are the PCs after low pass filtering with a 7 year cutoff to remove ENSO-band variability for the (a) North and (d) South Pacific PCs.

various spatial and temporal scales. Examples of an oscillator include those involving the isopycnal subduction mechanism of *Gu and Philander* [1997] as well as the delayed gyre-atmosphere coupling first proposed by *Latif and Barnett* [1994]. In contrast, several statistical approaches have decomposed PDV into a number of distinct phenomena. *Schneider and Cornuelle* [2005] were able to reconstruct North Pacific decadal variability over the latter half of the 20th century using a first-order autoregressive model forced by ENSO, the NPI, and zonal advection anomalies in the Kuroshio-Oyashio extension (KOE) region. The contribution of these processes to PDV was found to be frequency dependent with subannual timescales dominated by the NPI, interannual timescales by the NPI and ENSO, and decadal timescales by all three. *Newman* [2007] arrived at a similar conclusion in reconstructing PDV from a multivariate empirical model, which suggested PDV arises from several red noise processes each with their own decay timescale and spatial pattern. Lastly, *Vimont* [2005] showed that the SST pattern of PDV can be recovered using only interannual information, specifically, three leading patterns of variability corresponding to ENSO precursors, peak ENSO conditions, and ENSO 'leftovers'. He concluded, therefore, that PDV may simply represent the long-term average of ENSO cycle variations.

[7] A fundamental characteristic of PDV is its spatial signature, which is often described as "ENSO-like" with

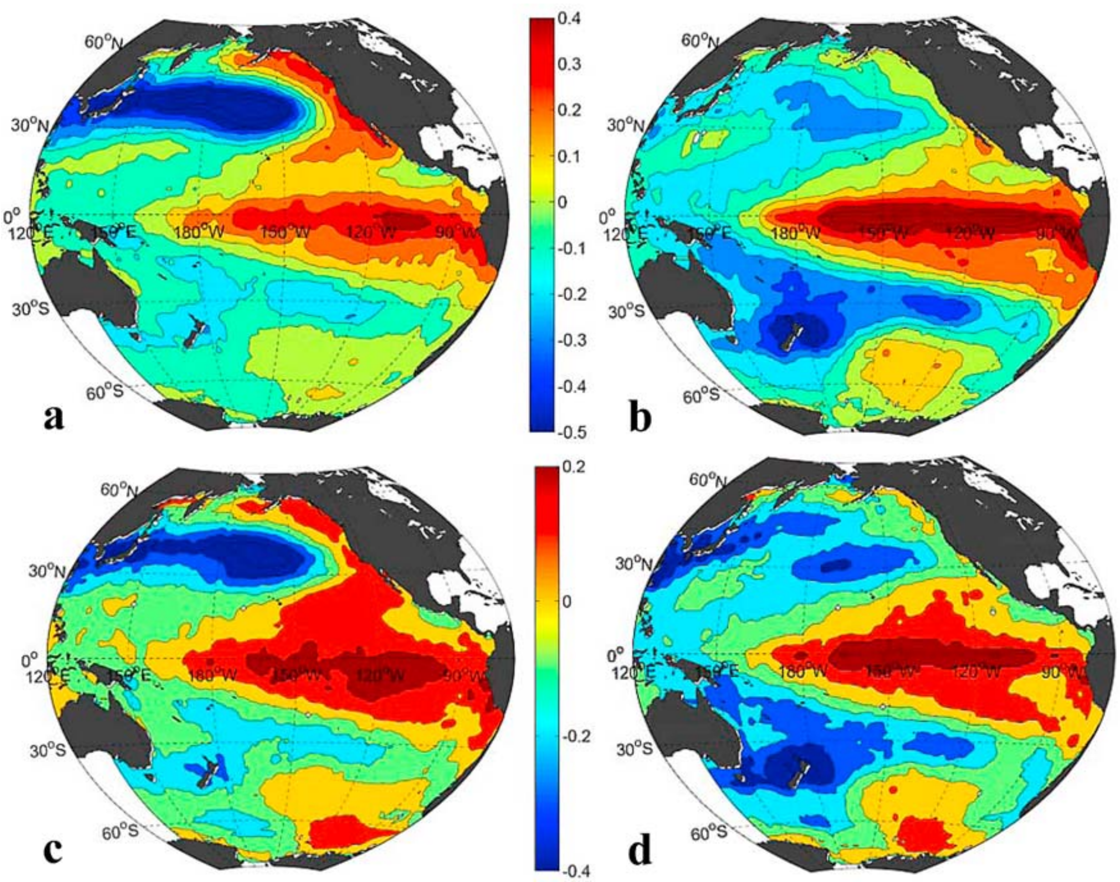

Figure 2. Basin-wide monthly SST anomalies regressed onto PC1 for the (a) North and (b) South Pacific. Regression parameters have been standardized such that they show the °C change per standard deviation of the PC. SST regressions onto the low pass filtered (c) North and (d) South Pacific are also shown. Contour intervals are 0.1°C.

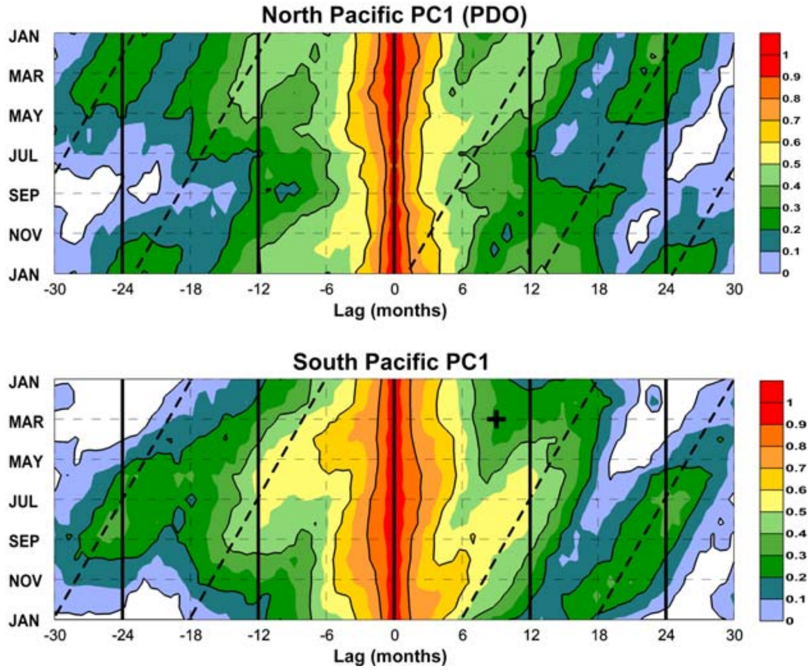

Figure 3. Plots of monthly lag autocorrelation for (top) North and (bottom) South Pacific PC1. Lag in months is given on the abscissa, and month of the year is given on the ordinate. Correlations are represented by the color bar on the right and are contoured in intervals of 0.2. Lags of 0, 1, and 2 years are demarcated by the vertical black bars. The diagonal dashed lines highlight the seasonal cycle of lag autocorrelation, which is centered on February for North Pacific PC1 and July for South Pacific PC1. The black cross shows the correlation between South Pacific PC1 during March and the following December, as an example.

(SST) anomalies of one sign in the central to eastern tropical Pacific and along eastern boundaries surrounded by a horseshoe of oppositely signed anomalies extending into the central North and South Pacific from the western tropical Pacific [*Zhang et al.*, 1997; *Garreaud and Battisti*, 1999]. This interhemispheric symmetry and similarity to ENSO has been taken as evidence that PDV is driven from the tropics [*Garreaud and Battisti*, 1999; *Linsley et al.*, 2000]. However, while ENSO anomalies are largest in the tropics and rather narrowly confined about the equator, tropical anomalies associated with PDV are broader and similar in magnitude to those in the extratropics, particularly the North Pacific [*Vimont*, 2005]. Thus, the North Pacific is often seen as the center of action. Accordingly, a commonly used metric of PDV is the Pacific Decadal Oscillation (PDO) index, which is the leading mode of SST variability in the North Pacific. More specifically, the PDO is defined as the leading principal component (PC) of residual monthly SST anomalies in the North Pacific poleward of 20°N after removing global mean SST anomalies [*Mantua et al.*, 1997]. While the domain of the PDO and the term itself implicitly suggest PDV arises from an oscillation centered in the North Pacific, the pan-Pacific nature and apparent symmetry about the equator of PDV argue against this more regionalized perspective.

[8] A simple approach is taken here to address the geographic extent of the PDO and quantify the interhemispheric symmetry of PDV. We calculate the Southern Hemisphere equivalent of the PDO index for 1901–2007 AD based on the leading PC of residual monthly SST anomalies in the South Pacific poleward of 20°S using the HadISST1 dataset [*Rayner et al.*, 2003]. This "Southern Hemisphere PDO" is strongly correlated with its Northern Hemisphere counterpart strengthening the case for tropically-driven PDV.

2. Results

[9] The leading PCs of monthly SST anomalies in the North and South Pacific are shown in Figure 1. Both account for 23% of the variance in their respective domains. The timing of positive and negative phases in the PCs are broadly similar; indeed, the two time series are significantly correlated at $r = 0.38$ ($p < 0.0001$, using Student's t-test, the 1284 monthly data points, and a conservative estimate of 128 df). In addition, the prominent regime shifts in North Pacific PC1 (i.e., the PDO index) appear to generally have South Pacific counterparts, particularly those in 1976/77 and 1998/99. These leading PCs were low-pass filtered with a 7-year cutoff to remove interannual variability associated with ENSO that is almost certainly in common in the North and South Pacific [*Karoly*, 1989]. This increases their correlation to $r = 0.59$. One modest difference between the PCs worth noting is that North Pacific PC1 is somewhat redder than South Pacific PC1 and exhibits slightly greater variability at decadal periods. *Schneider and Cornuelle* [2005] found that decadal variability in the North Pacific was due in approximately equal part to ENSO, NPI, and KOE zonal advection anomalies. While ENSO also directly affects the South Pacific, the latter two phenomena are confined to the North Pacific, which may explain the weaker low frequency variability in the South Pacific.

[10] Regressing basinwide monthly SST anomalies onto the leading PCs from the North and South Pacific produces

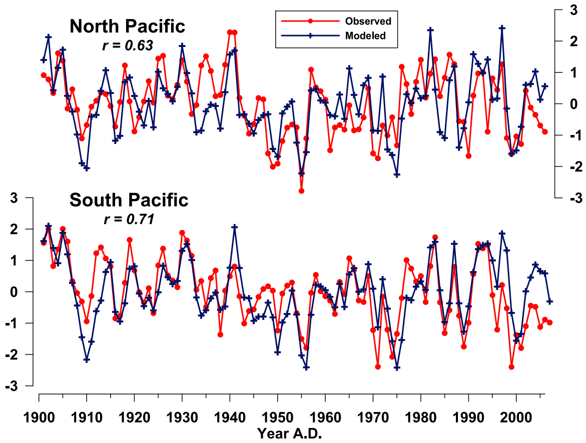

Figure 4. Observed (red line with circles) and modeled (blue line with slashes) PC1s for the (top) North and (bottom) South Pacific. The model is of an AR-1 process forced by ENSO; see text for more details.

fields with high pattern correlation (r = 0.75) (Figure 2). The correlation within the PDO domain (i.e., poleward of 20°N) is r = 0.83. Repeating this regression onto the low pass filtered PCs increases the basinwide spatial correlation to r = 0.87 (Figure 2). These observations indicate the spatial structure of the PDO in the North Pacific can be well explained by the leading mode of variability for the South Pacific. This result is particularly striking in light of the various fundamental differences between the North and South Pacific, such as basin geometry, a much stronger western boundary current (Kuroshio-Oyashio) and an isolated subpolar low pressure center (Aleutian Low) in the North Pacific, a subtropical atmospheric convergence zone in the South Pacific, and the equatorial asymmetry of ENSO SST anomalies in the eastern tropical Pacific. We also explored whether the reduced space optimal interpolation used to create the HadISST1 dataset may have corrupted this finding of interhemispheric symmetry, but found this unlikely (see auxiliary material).[1] It thus appears PDV is very similar on both sides of the equator implicating the tropics as the common forcing.

[11] Plots of monthly lag autocorrelation for the North and South Pacific PC1s reveal an interesting similarity. In both cases, the annual cycle of lag autocorrelation exhibits considerable seasonality with maximum autocorrelation in the winter and minimum autocorrelation in the summer of each respective hemisphere (Figure 3). This reflects the interannual persistence of winter SST anomalies despite the lack of a relationship between SST anomalies from one summer to the next. This phenomenon has received considerable attention in the North Pacific and has been theorized to be a product of the reemergence mechanism in which winter SST anomalies are sequestered beneath a thin summer mixed layer only to reemerge the following winter as mixing increases and the mixed layer thickens [*Alexander et al.*, 1999; *Deser et al.*, 2003].

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL040313.

[12] Based on the two observations made above, namely that tropical forcing and reemergence both appear to play important roles in Pacific SST variability, we model PDV as a first-order autoregressive process driven by ENSO as done by *Newman et al.* [2003]. This AR-1 model is applied to the North and South Pacific separately.

$$\mathrm{PDO_n} = \alpha \mathrm{PDO_{n-1}} + \beta \mathrm{ENSO_n} + \eta_\mathrm{n}$$

The modeled PDO index at year n is a function of the modeled PDO index at $n - 1$ and the observed ENSO index (Niño 3.4) at n. These annually-averaged indices are centered on boreal winter (Jul–Jun) for the North Pacific and austral winter (Jan–Dec) for the South Pacific. Per *Newman et al.* [2003], the coefficients β and α are parameters derived, respectively, by regression of the PDO index on the ENSO index, then autoregression of the residual time series with a lag of one year. η is an uncorrelated noise term not used in our analysis but shown for completeness. α and β are 0.51 and 0.56 for North Pacific PC1 and 0.62 and 0.71 for South Pacific PC1. While *Newman et al.* [2003] found this simple model did a remarkable job reproducing the observed 20th century PDO index in the North Pacific (r = 0.63 in our study), it yields an even stronger fit to our Southern Hemisphere PDO index (r = 0.71) (Figure 4). The greater success of the model in the South Pacific may be a function of its larger α and β terms, which indicate that the persistence of SST anomalies and ENSO forcing are more important. The stronger ENSO signal in the South Pacific may derive from the equatorial asymmetry of ENSO SST anomalies in the eastern tropical Pacific, which extend considerably farther to the south than to the north. One implication of this finding is that the South Pacific may be a better place to develop paleo-ENSO records as it appears to contain a 'cleaner' ENSO signal.

3. Conclusions

[13] Deriving a Southern Hemisphere equivalent of the PDO index shows that the spatial signature of the PDO can be well explained by the leading mode of SST variability for the South Pacific. Thus, PDV appears to be a basin-wide phenomenon most likely driven from the tropics. Moreover, while it was already known PDV north of the equator could be adequately modeled as a reddened response to ENSO, our results indicate this is true to an even greater extent in the South Pacific.

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J. D. Shakun, Department of Geosciences, Oregon State University, Corvallis, OR 97331, USA. (shakunj@geo.oregonstate.edu)

J. Shaman, College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331, USA.