A central tropical Pacific coral demonstrates Pacific, Indian, and Atlantic decadal climate connections

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Abstract. While instrumental and proxy-based climate records describe significant decadal-scale climate variability throughout the tropical Pacific, Indian, and Atlantic Oceans, the processes responsible for these variations and their interactions are not readily apparent from the observations. A new 112-yr coral-based sea surface temperature (SST) reconstruction from Palmyra Island in the central tropical Pacific (CTP) exhibits strong decadal variability with an amplitude of roughly 0.3°C. A 12-13yr-period signal in this coral record is highly coherent with long equatorial Atlantic and Indian Ocean climate records, implying a unified phenomenon. The Atlantic pattern suggests that it may fall under direct influence of anomalous SST in the CTP, as it does over interannual timescales, while the Indian Ocean pattern exhibits maximum response during the switch between warm/cold states in the tropical Pacific. The results demonstrate that the CTP has played a significant role in determining the expression of global decadal climate variability over the twentieth century.

Introduction

Climate model experiments outline several different mechanisms of regional decadal- scale variability [*Latif and Barnett,* 1994; *Gu and Philander,* 1997; *Chang et al,* 1997; *Xie and Tanimoto,* 1998; *Grotzner et al,* 1998], each with their own important consequences for long-range forecasting. Generally, in these models, air-sea interaction in either the high latitude or tropical ocean produces anomalies that then propagate by either ocean or atmospheric processes. Yet the actual instrumental record of such mechanisms is much less clear, because significant gaps in the record occur prior to 1950 for critical regions of the ocean, particularly in the tropics. However, recent analyses of the available instrumental data suggest that the expression of global decadal variability loosely resembles that of ENSO [*Zhang et al,* 1997; *White and Cayan,* 1998; *Garreaud and Battisti,* 1999].

Several important implications arise from such analyses, including the possibility that interannual and decadal variability share a common set of processes, and that much of the observed global climate variability on decadal time scales simply reflects a response to changing conditions in the central tropical Pacific Ocean.

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Defining the frequency characteristics of the decadal variability and the sequence of events in the different ocean basins – especially with respect to the central tropical Pacific – represents a critical component of pursuing the implications of an "ENSO-like" decadal variability. For this purpose, it is essential to have sufficient realizations of decadal oscillations from those regions of the tropical Pacific experiencing the strongest decadal climate variability. As instrumental results suggest that decadal variability is maximized in a region stretching from $\sim$ 100°W to the international dateline, and from 10°N to 10°S [*Mantua et al,* 1997; *Garreaud and Battisti,* 1999], a long proxy record from this region would fill a critical data gap.

Here we present a new 112-yr coral-based SST reconstruction from Palmyra Island (6°N, 162°W), in the heart of the CTP. We compare a strong decadal signal found in the Palmyra coral with long, high-resolution climate records from Indian and Atlantic locations. Analyses of the three independent records define a fairly specific mode of climate variability with a characteristic time scale and evolution throughout the 20^{th} century. Projecting this well- defined mode onto the instrumental record in turn allows a description of the spatial pattern of global SST that occurs over the course of an average decadal oscillation.

Results

The coral used for the CTP climate reconstruction was drilled from a 3m tall *Porites lutea* colony growing in 10m of water near the middle of a 1km^2 submerged reef flat lying off the western side of Palmyra Island. A relatively high growth rate of 20mm/yr afforded sub-monthly resolution for the oxygen isotopic measurements (δ^{18}O) that constitute the climate proxy record. Although the annual growth bands in the coral are sometimes ill-defined in the core, a strong annual cycle in δ^{18}O made the construction of a chronology straightforward. As a result, we estimate that the time scale has a maximum error of $\sim$ 4 months at any given point in the record.

The Palmyra monthly oxygen isotopic anomalies (after trend removal) and the NIÑO3.4 SST index [*Kaplan et al,* 1998] are highly correlated (R=0.62), demonstrating that the coral-based reconstruction accurately reflects regional temperature variability (Figure 1b). The oxygen isotopic record is dominated by ENSO and decadal-scale variability, superimposed on a prominent warming trend beginning in the mid-1970's (Figure 1). Because the oxygen isotopic signal records both SST and the isotopic composition of the seawater (linearly related to salinity), it is likely that precip-

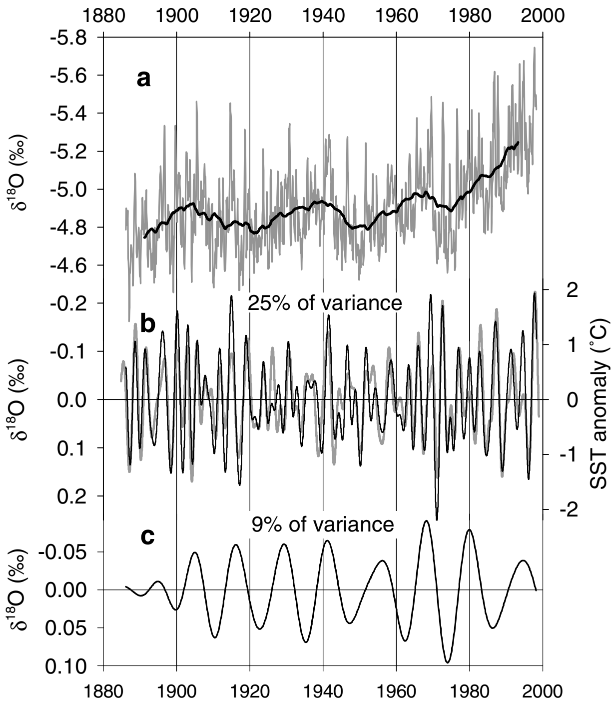

Figure 1. (a). Palmyra coral oxygen isotopic record (grey line) shown with 10-yr running mean (black line). (b). Comparison of ENSO variability at Palmyra (black line), with ENSO variability in the NIÑO3.4 SST index, the average of available SSTs from the region 120-170°W and 5°N-5°S, (grey line), isolated by applying 2-7y band-pass filters. (c). Decadal variability at Palmyra from a 9-16y band-pass filter.

itation anomalies from increased convection associated with warming contribute to the observed variability in the coral geochemical record [*Urban et al,* 2000].

Using a conversion factor of -0.23 per mil (‰) per 1°C obtained from a regression performed on raw oxygen isotopic and satellite-based SST data [*Reynolds and Smith,* 1984] for the period 1981-1998 (R=0.83), the 112-yr warming trend is $\sim$ 1.5°C. Comparisons with the instrumental SST record from the Palmyra region suggest that approximately half of this coral-based trend is attributable to increased precipitation over the last century. On interannual time scales, however, the -0.23 ‰ /°C calibration implies 0.5-1°C SST anomalies at Palmyra during El Niño events, indistinguishable from ENSO amplitudes in the instrumental record of SST at Palmyra. If this same calibration is applied to the coral's decadal signal, the isotopic anomalies convert to $\sim$ 0.3°C, comparable to a weak El Niño event.

Comparison of the decadal signal at Palmyra with those found in other analogous climate records from the Atlantic and Indian Oceans yields significantly high coherence among all regions. For the purposes of illustration, we include two continuous archives of climate over the last 120 years: the record of oxygen isotopes in a Seychelles coral which represents monsoonal variability in the tropical Indian Ocean [*Charles et al,* 1997], and the record of Nordeste rainfall – taken as an index of tropical Atlantic Ocean Inter-tropical Convergent Zone (ITCZ) variability [*Moura and Shukla,* 1981]. Both of these records carry a strong ENSO signature: anomalous warming associated with a weakened Indian monsoon in the tropical West Indian and drought conditions in Brazil typically occur 2-6 months after peak El Niño conditions in the Pacific [*Enfield,* 1990; *Webster et al,* 1998]. However, spectral analyses of the Palmyra coral with the Seychelles coral and Nordeste rainfall (Figure 2) reveal significant variance not only at ENSO periods, ranging from 2-7 years, but also at decadal periods centered at 12-13 years [*Mann and Lees,* 1996]. More importantly, the decadal variability in all three records is highly coherent, suggesting that an interrelated set of processes and conditions contributes to substantial climate variability in all three ocean basins. In this respect, decadal shifts in Pacific tropical SST, Indian monsoon strength, and the ITCZ migration over the Atlantic Ocean are likely acting in concert.

The high coherence among the three basins' decadal signals allows for a meaningful analysis of the Pacific-Indian-Atlantic phase relationships of the decadal cycle. Contrary to the sequence of events observed over the ENSO band, CTP warming occurs 2-3yrs after (or 9-10yrs prior to) warming in the tropical Western Indian Ocean. The Pacific-Atlantic decadal phase relationship is such that Nordeste drought lags peak CTP warming by $\sim$ 1 year, a sequence that also occurs on interannual time scales. Filtered versions of these records (Figure 3) illustrate the temporal consistency of the frequency and phase of the decadal variability across the tropics.

Building on the statistical confidence obtained from the correlation between three long proxy records, we apply the proxy-based time scale to the instrumental record to resolve the global SST pattern associated with the decadal signal. We construct global SST composites using the 9-16yr filtered Palmyra record as an index of the decadal variability (Figure 4). The pattern that emerges demonstrates that a broad region of the central Pacific fluctuates with at least $\pm$0.2°C anomalies on the imposed time scale. The Indian Ocean SST anomalies are considerably lower than those of the Pacific, but, in this ocean basin characterized by high absolute surface temperatures, small SST anomalies can generate substantial shifts in convective patterns associated with the Asian monsoon system. A strong Atlantic SST response stretches across the entire basin, where five regions of alternating SST's exhibit consistently reversed signs during opposite extremes of the decadal oscillation, reminiscent of the Pan-Atlantic Decadal Oscillation observed in previous instrumental and modeling analyses [*Xie and Tanimoto,* 1998]. North Pacific SST anomalies are inversely related to tropical Pacific SST as observed with the ENSO and the Pacific Decadal Oscillation [*Halpert and Ropelewski,* 1992; *Mantua et al,* 1997].

Discussion

The SST composite analysis indicates that the Palmyra coral lies near the center of a decadal climate oscillation with a near-global footprint, and confirms the sense of inter-basin relationships uncovered in the Pacific-Indian-Atlantic proxy comparisons. The spatial pattern of global decadal variability resolved by multi-proxy analysis bears strong resemblance to that arising from independent analyses of the instrumental record [*Zhang et al,* 1997; *Garreaud and Battisti,* 1999]. Both analyses conclude that a large region of the CTP fluctuates with $\sim$ 0.3°C anomalies on decadal time scales, but the relationships among adjoining tropical oceans is resolved only through the analysis of the longer proxy

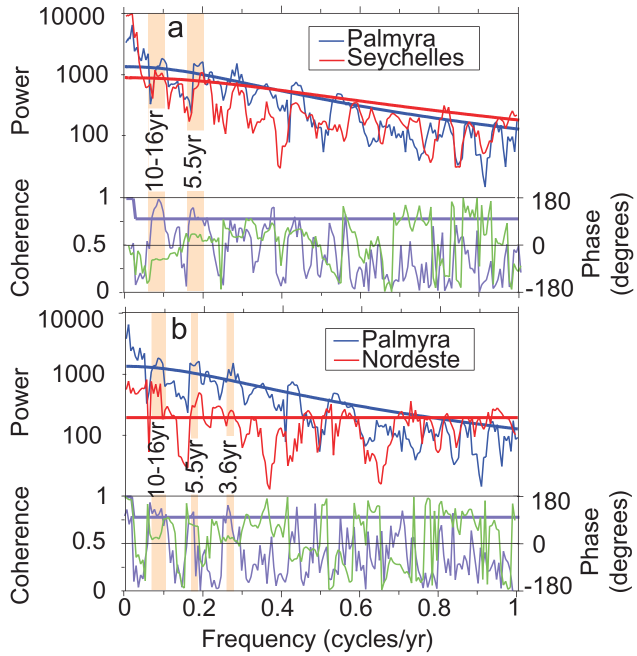

Figure 2. (a). Multi-taper cross-spectral analysis of the Palmyra (blue) and Seychelles (red) coral-based deseasoned proxy records for the period 1886-1995 [*Mann and Lees,* 1996], plotted with red-noise 95% significance levels. Coherence and phase (purple and green lines respectively) are plotted in the lower portion of the figure with a 95% significance level for coherence (thick purple line) [*Mann and Park,* 1993]. (b). Same as in (a) but computed for the Palmyra coral and Nordeste rainfall.

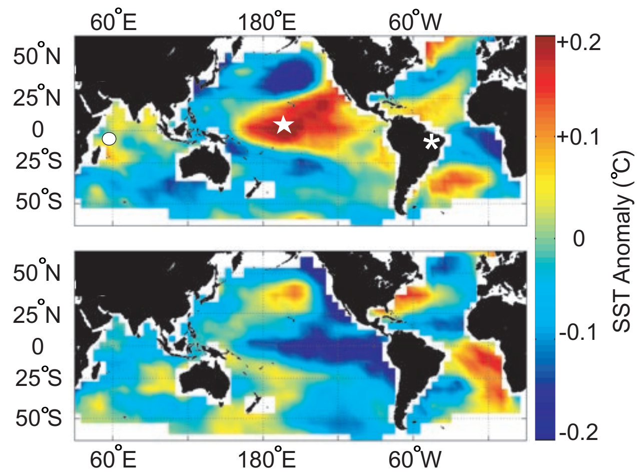

Figure 4. (top). 6yr averages of global SST anomalies (GISST 2.2 data) were computed centered on the following 7 realizations of the decadal warming: 1905, 1916, 1929, 1941, 1956, 1968, and 1980, and these were in turn averaged together to reflect the composite SST response. The locations of Palmyra (⋆), Seychelles (●), and Nordeste (∗) are also shown. (bottom). Same as top panel but the averaging periods were shifted by 6.5 years to reflect the opposite phase of the proposed 12-13yr oscillation.

records. For instance, using the proxy-based time-scale, a strong link between the tropical Pacific and pan- Atlantic decadal signals emerges, implying that the Atlantic decadal variability may be forced from the tropical Pacific, probably through teleconnections similar to those operating on interannual time scales [*Saravanan and Chang,* 2000]. Modeling efforts explain the well-documented Atlantic decadal signal as being the result of ocean-atmosphere feedbacks internal to the Atlantic basin [*Xie and Tanimoto,* 1998; *Chang et al,* 1997; *Grotzner et al,* 1998]. However, our results clearly demand consideration of the external influence of tropical Pacific variability.

The dynamical connection between the three proxy records must involve the large-scale Walker circulation, because CTP warming destabilizes both the descending and ascending branches of the cell which influences the tropical Atlantic and Indian basins, respectively. Observations and climate models show that enhanced convection in the Eastern Pacific affects trade winds in the tropical Atlantic, serving to warm the north tropical Atlantic and shift the Atlantic ITCZ northward, causing Nordeste drought [*Saravanan and Chang,* 2000; *Chiang et al,* 2000]. Indian anomalies that consistently peak 2-3yrs prior to those in the CTP point to a Pacific-Indian decadal relationship that involves more than a passive response to CTP warming. The fact that maximum Indian Ocean anomalies occur at a time when the external "forcing" from tropical Pacific SST is minimal may provide a clue. One might expect that, under these conditions, monsoonal processes should exert considerable influence over the climate variability of both the tropics and mid-latitudes, imposing their characteristic time scales and spatial structure.

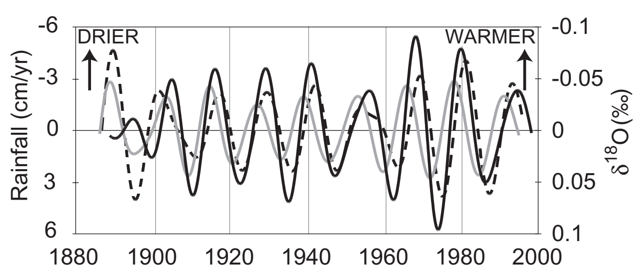

Figure 3. 9-16yr band-passed Gaussian filter products. The Palmyra coral (black), Seychelles coral (grey), and Nordeste rainfall (dashed) are closely linked on decadal time scales such that when Palmyra is warm, Seychelles is warm and the Nordeste region experiences drought.

To be plausible, any mechanistic model for the origins of global decadal-scale variability must operate within the relatively strict frequency constraints outlined by the proxy records. The regularity of the decadal oscillations in these records implies a frequency distribution distinct from the broad-band signature expected from both "ENSO-like" [*Zhang et al,* 1997; *Garreaud and Battisti,* 1999] and extratropically-forced models [*Latif and Barnett,* 1994; *Gu and Philander,* 1997] of decadal variability that incorporate stochastic forcing. A recent 800yr sedimentary record of tropical Atlantic climate variability, when combined with the Palmyra, Seychelles, and Nordeste spectral analyses presented here, provides compelling evidence that tropical decadal variability occurs with a narrowly defined period of 12-13yrs [*Black et al,* 1999]. Thus, while the decadal variability expressed in these proxy records shares some similarities with ENSO–for example, geographic pattern and, most likely, certain teleconnections–it can be described as a separate mode as opposed to an extension or modulation of ENSO.

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