Late 20th century warming and freshening in the central tropical Pacific

Intan S. Nurhati,[1] Kim M. Cobb,[1] Christopher D. Charles,[2] and Robert B. Dunbar[3]

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[1] Global climate models and analyses of instrumental datasets provide a wide range of scenarios for future tropical Pacific climate change, limiting the accuracy of regional climate projections. Coral records provide continuous reconstructions of tropical Pacific climate trends that are difficult to quantify using the short, sparse instrumental datasets available from the tropical Pacific. Here, we present coral-based reconstructions of late 20th century sea-surface temperature and salinity trends from several islands in the central tropical Pacific. The coral data reveal warming trends that increase towards the equator, implying a decrease in equatorial upwelling in the last decades. Seawater freshening trends on the southern edge of the Inter-Tropical Convergence Zone suggest a strengthening and/or an equatorward shift of the convergence zone. Together, the new coral records support a late 20th century trend towards "El Niño-like" conditions in the tropical Pacific, in line with the majority of coupled global climate model projections. **Citation:** Nurhati, I. S., K. M. Cobb, C. D. Charles, and R. B. Dunbar (2009), Late 20th century warming and freshening in the central tropical Pacific, *Geophys. Res. Lett.*, *36*, L21606, doi:10.1029/2009GL040270.

1. Introduction

[2] A comprehensive understanding of how tropical Pacific climate might evolve under global warming is critical in formulating adaptation strategies for future climate change. Tropical Pacific climate variability is responsible for a significant fraction of global temperature and precipitation variability via atmospheric teleconnections. However, climate models provide opposing views on the evolution of tropical Pacific climate under global warming [*Knutson and Manabe*, 1995; *Meehl and Washington*, 1996; *Vecchi et al.*, 2006; *Clement et al.*, 1996; *Cane et al.*, 1997]. A majority of atmosphere-ocean coupled general circulation models (GCMs) project a weakening of the tropical Pacific zonal sea-surface temperature (SST) gradient (often referred to as "El Niño-like" conditions) under increasing atmospheric CO_2 concentrations [*Intergovernmental Panel on Climate Change* (*IPCC*), 2007]. On the other hand, some models suggest that the zonal SST gradient may increase (akin to "La Niña-like" conditions) in response to anthropogenic warming [*Clement et al.*, 1996; *Cane et al.*, 1997].

[3] Large uncertainties associated with instrumental climate datasets obscure tropical Pacific trends over the 20th century. For example, it has been shown that instrumental SST datasets contain tropical Pacific trends of different signs over the late 20th century [*Vecchi et al.*, 2008]. Further, biases in satellite-derived SST products that are larger early in these datasets and non-uniform in space and time are now widely recognized [*Reynolds et al.*, 2007]. Precipitation trends derived from satellites, which require extensive calibrations, are prone to even larger uncertainties [e.g., *New et al.*, 2001].

[4] Coral skeletal geochemistry provides continuous, monthly-resolved tropical climate proxy records to reconstruct climate trends over the last decades to centuries. While the coral-based timeseries are derived from discrete locations, the fact that the recording process within coral skeletons does not change through time allows for the estimation of climate trends that complement those derived from the instrumental climate record. Furthermore, the regional-scale significance of coral-based climate trends can be assessed through replication of the coral geochemical records among multiple sites [*Hendy et al.*, 2002]. Most coral reconstructions are based on the oxygen isotopic ratio ($\delta^{18}O$) of the coral skeleton that reflects changes in SST and the $\delta^{18}O$ of seawater ($\delta^{18}O_{SW}$), with the latter linearly correlated to sea-surface salinity (SSS) changes [*Fairbanks et al.*, 1997]. In the case of the central tropical Pacific (CTP), warm SSTs and positive precipitation anomalies that occur during El Niño events (Figure 1b) both contribute to negative coral $\delta^{18}O$ anomalies, making CTP corals valuable archives for the reconstruction of the El Niño/Southern Oscillation (ENSO) [*Evans et al.*, 1999; *Cobb et al.*, 2001]. Several CTP corals exhibit prominent trends towards depleted coral $\delta^{18}O$ values over the late 20th century [*Evans et al.*, 1999; *Urban et al.*, 2000; *Cobb et al.*, 2001], suggesting that some combination of warming and freshening has occurred in this region. That such trends are very likely unprecedented in the last millennium [*Cobb et al.*, 2003] strongly suggests that they are related to anthropogenic forcing.

[5] It is important to quantify both the SST and SSS contributions to the unprecedented CTP coral $\delta^{18}O$ trends in order to resolve the character of late 20th century tropical Pacific climate change. Coral Sr/Ca ratio can be used to quantify SST changes [*Beck et al.*, 1992; *Alibert and McCulloch*, 1997] that can in turn be removed from the coral $\delta^{18}O$ records to yield reconstructions of $\delta^{18}O_{SW}$ [*McCulloch et al.*, 1994; *Gagan et al.*, 1998]. In the context of the debate surrounding late 20th century tropical Pacific climate trends, an "El Niño-like" trend would imply positive SST and freshening trends in the CTP, and vice versa for a "La Niña-like" trend. In reconstructing both

[1]School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia, USA.
[2]Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California, USA.
[3]School of Earth Sciences, Stanford University, Stanford, California, USA.

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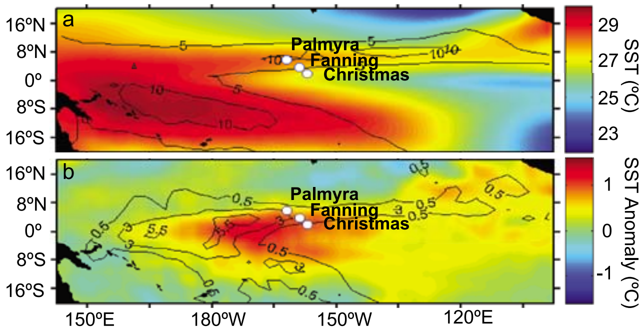

Figure 1. Map of the study islands in the central tropical Pacific. (a) Climatological Dec-Jan-Feb (DJF) SST shown in color [*Reynolds et al.*, 2002] and precipitation shown by the solid lines [*Xie and Arkin*, 1997] (in units of mm/day) averaged over 1982–1998. (b) DJF SST and precipitation anomalies for composite 1987 and 1994 moderate El Niño events (NINO3.4 SST anomalies between 1–2°C).

SST and hydrology in multiple long coral records from the CTP, we provide data that can be used to directly address the nature of CTP climate trends.

[6] Here, we generate coral δ^{18}O, Sr/Ca and $\delta^{18}O_{SW}$ records from multiple coral cores from Palmyra, Fanning, and Christmas Islands (2°N–6°N, 157°W–162°W) during the late 20th century (1972–1998). The three islands span large gradients in annually-averaged SST and SSS (Figure 1a). Palmyra, as the northernmost island at 6°N, lies in the path of the eastward flowing North Equatorial Counter Current that delivers warm (∼28.5°C) waters from the West Pacific Warm Pool to the CTP [*Reynolds et al.*, 2002]. Palmyra receives substantial rainfall associated with the Inter-Tropical Convergence Zone (ITCZ), as reflected by average SSS values of ∼34.8 psu [*Levitus et al.*, 1994]. At 2°N, Christmas is bathed by cooler (∼27.5°C) waters that highlight the influence of equatorial upwelling on climate in this region. During non-El Niño years, Christmas receives less than 2 mm/year of rainfall [*Xie and Arkin*, 1997], leading to relatively high average SSS values of ∼35.1 psu. Fanning lies between Palmyra and Christmas Islands, and as such is characterized by intermediate climatological SST (∼28°C) and SSS (∼34.9 psu). During moderate El Niño events, Christmas exhibits the strongest warming due to the reduction in upwelling, while Palmyra experiences high rainfall associated with an equatorward movement of the ITCZ (Figure 1b). The north–south alignment of these CTP islands allows us to isolate the relative importance of ocean circulation versus ITCZ-related trends in this region by quantifying the relative differences in SST (via coral Sr/Ca) and SSS (via $\delta^{18}O_{SW}$) trends across these three islands.

2. Methods

[7] Coral δ^{18}O and Sr/Ca analyses were conducted on *Porites sp.* coral cores from Palmyra, Fanning, and Christmas with sub-monthly resolution, following standard procedures (see auxiliary material).[1] The Palmyra coral δ^{18}O record is previously published [*Cobb et al.*, 2001], while the coral δ^{18}O records from both Fanning and Christmas are presented here for the first time, as are all the coral Sr/Ca records. Coral δ^{18}O and Sr/Ca reproducibility studies were carried out with multiple cores from the three islands (see auxiliary material). It is important to note that the final Fanning coral δ^{18}O and Sr/Ca timeseries were constructed by splicing together records from two separate Fanning cores in order to avoid sampling secondary aragonite in one of the cores (see auxiliary material). We reconstruct changes in δ^{18}O of seawater ($\delta^{18}O_{SW}$) as a proxy for SSS by subtracting the Sr/Ca-derived SST contribution to the coral δ^{18}O records following *Ren et al.* [2003] (see auxiliary material). We limit our analysis to the 1972–1998 period, when we have coral records from all three islands, noting that the unprecedented coral δ^{18}O trend occurs in this interval.

3. Results and Discussion

[8] Over the 1972–1998 period, all three coral δ^{18}O records exhibit significant trends towards depleted coral δ^{18}O values, confirming that warming and/or freshening has occurred in the region (Figure 3b). Coral δ^{18}O trends over the 26-year period are -0.52 ± 0.09‰ (1σ) at Palmyra, -0.40 ± 0.09‰ (1σ) at Fanning, and -0.32 ± 0.10‰ (1σ) at Christmas. The errors indicated for these coral δ^{18}O trends account for uncertainties in both analytical precision and the coral δ^{18}O trend estimation (see auxiliary material).

[9] Strong correlations between the coral Sr/Ca and instrumental SST records confirm the fidelity of the Sr/Ca-derived SST proxy at these CTP sites (Figure 2). The coral-based SST reconstructions are generated by calibrating the coral Sr/Ca timeseries against SST using 1° × 1° blended ship and satellite IGOSS SST data from each island [*Reynolds et al.*, 2002], as the IGOSS SST data are most

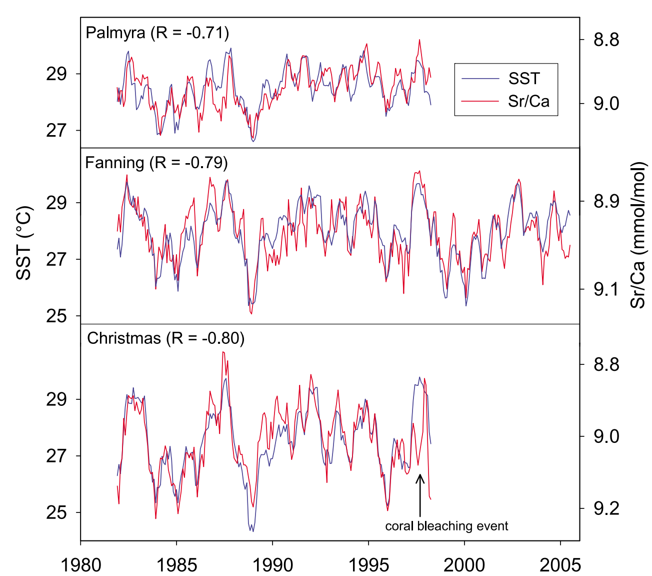

Figure 2. Comparison of coral Sr/Ca records with instrumental SST. Coral Sr/Ca is calibrated with monthly 1° × 1° grid IGOSS SST dataset at each island [*Reynolds et al.*, 2002]. Coral bleaching witnessed by K. M. Cobb at Christmas Island during the 1997/98 El Niño.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL040270.

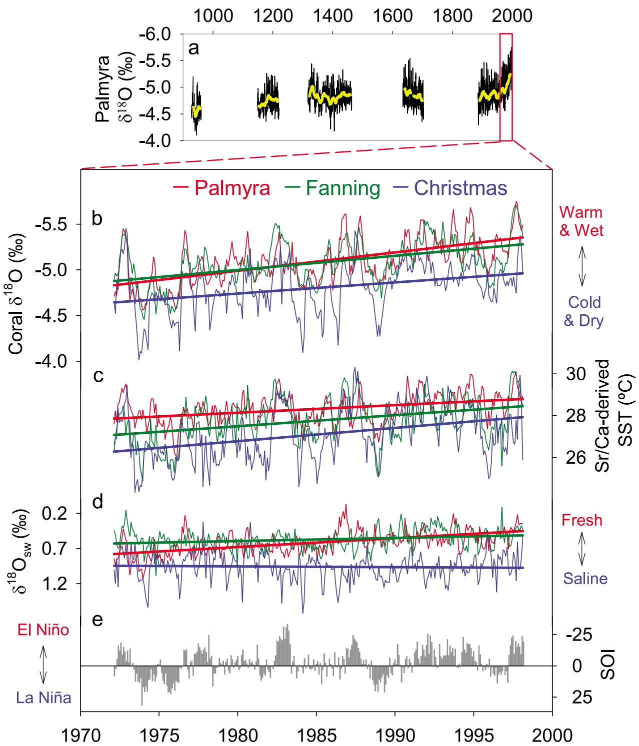

Figure 3. Central tropical Pacific coral climate proxy records. (a) A millennium-long coral δ^{18}O reconstruction from Palmyra Island [*Cobb et al.*, 2003] showing the unprecedented late 20th century trend towards lower coral δ^{18}O values (warmer, wetter conditions; note inverted y-axis). (b) Coral δ^{18}O records from Palmyra [*Cobb et al.*, 2001] (red), Fanning (green), and Christmas (blue) islands (note inverted y-axis). (c) Sr/Ca-derived SST reconstructions from Palmyra, Fanning, and Christmas. (d) $\delta^{18}O_{SW}$ (SSS proxy) reconstructions from Palmyra, Fanning, and Christmas. (e) The Southern Oscillation Index (SOI).

consistent with *in situ* SST data available from Palmyra (see auxiliary material). We apply reduced major axis regression analysis to calculate the Sr/Ca-SST relationship, a technique which minimizes residuals in two variables that have nonzero uncertainties [*Solow and Huppert*, 2004]. The coral Sr/Ca (reported in mmol/mol) is highly correlated to instrumental SST at all three islands:

$$SST_{PALMYRA} = 130.43 - 11.39 \times Sr/Ca_{PALM} \cdot (\text{Nov 1981} - \text{Mar 1998}, R = -0.71, CI > 99\%)$$

$$SST_{FANNING} = 166.81 - 15.47 \times Sr/Ca_{FANN} \cdot (\text{Nov 1981} - \text{Jun 2005}, R = -0.79, CI > 99\%)$$

$$SST_{CHRISTMAS} = 141.57 - 12.66 \times Sr/Ca_{CHRS} \cdot (\text{Nov 1981} - \text{Mar 1998}, R = -0.80, CI > 99\%)$$

The Sr/Ca-SST slopes shown here are not sensitive to the choice of calibration period, and fall within the range of existing Sr/Ca-SST calibration slopes calculated for *Porites sp.* corals [*Corrège*, 2006]. High reproducibility of intra- and inter-coral colony Sr/Ca records from our corals further illustrates the fidelity of coral Sr/Ca-based SST reconstructions from these sites (see auxiliary material).

[10] Over the 1972–1998 period, the coral Sr/Ca-derived SST reconstructions reveal warming trends at all three islands, ranging from 0.94 ± 5.81°C (1σ) at Palmyra, to 1.37 ± 6.57°C (1σ) at Fanning, to 1.65 ± 5.73°C (1σ) at Christmas (Figure 3c). The coral-based warming trends are in relatively good agreement with gridded instrumental SST data from each island (see auxiliary material). The error estimates for the coral-based SST trends, while relatively large, are conservative estimates that combine uncertainties in analytical measurement, trend estimation, and the slope of the Sr/Ca-SST calibration from each island (see auxiliary material). Choosing slightly different intervals for trend estimation does not change the result that all three islands have warmed since 1972, with Christmas Island warming the most (see auxiliary material).

[11] The relatively large late 20th century CTP warming trends, and specifically the evidence for enhanced equatorial warming, are consistent with a recent shift towards “El Niño-like” conditions in the tropical Pacific [*Vecchi et al.*, 2006]. Stronger equatorial warming is in line with instrumental observations of reduced equatorial upwelling over the late 20th century [*McPhaden and Zhang*, 2002], and is a robust feature of CO_2-doubling GCM simulations [*DiNezio et al.*, 2009].

[12] We investigate the impact of the late 20th century enhanced equatorial warming on hydrology in the central tropical Pacific. Over the period 1972–1998, the $\delta^{18}O_{SW}$ records from Palmyra and Fanning exhibit freshening trends of −0.32 ± 0.08‰ (1σ) and −0.12 ± 0.08‰ (1σ) respectively, while the $\delta^{18}O_{SW}$ record from Christmas exhibits no statistically significant trend (0.03 ± 0.11‰ at 1σ; Figure 3d). The error bars for these trends include uncertainties in the slopes of the Sr/Ca-SST calibration at each island and the δ^{18}O-SST regression from *Ren et al.* [2003], as well as analytical uncertainty of Sr/Ca, and uncertainty in the $\delta^{18}O_{SW}$ trend (see auxiliary material). The largest freshening trend is observed at Palmyra, the island closest to the ITCZ, suggesting that warmer equatorial SSTs may have caused a strengthening and/or an equatorward migration of the ITCZ. Freshening trends at Palmyra and Fanning, as well as a minimal or lack of freshening trend at Christmas, follow a pattern that mimics weak to moderate El Niño conditions (Figure 1b).

[13] Freshening trends observed in the CTP corals are in line with analyses of instrumental data documenting enhanced precipitation [*Morrissey and Graham*, 1996] and decreased SSS [*Delcroix et al.*, 2007] in the CTP over the late 20th century. The coral-based $\delta^{18}O_{SW}$ trends are also in line with projections for an enhancement of the hydrological cycle, based on theoretical and GCM results [*Held and Soden*, 2006].

[14] Taken together, the pattern of warming and freshening evident in the CTP corals is reminiscent of weak El Niño conditions, characterized by enhanced equatorial warming and convection in the central tropical Pacific. Significant late 20th century warming in the central equatorial Pacific emerges from recent efforts to reconstruct instrumental SSTs in this region [*Bunge and Clarke*, 2009]. Likewise, a late 20th century reduction in the Walker circulation has been inferred from analyses of available wind stress [*Clarke and Lebedev*, 1996] and sea-level pressure data [*Vecchi et al.*, 2006; *Bunge and Clarke*, 2009].

[15] The enhanced equatorial Pacific warming and strengthened ITCZ are consistent with an "El Niño-like" shift in tropical Pacific climate, but this analogy likely oversimplifies the complexity of tropical Pacific anthropogenic climate change. Indeed, any of a number of large-scale climate changes that are likely to occur in a greenhouse world might overwhelm or at the very least fundamentally reshape the expected impacts of an "El Niño-like" trend. For example, a projected enhancement of global precipitation minus evaporation patterns may dominate regional hydrological responses to global warming [*Held and Soden*, 2006; *IPCC*, 2007]. In this regard, the prominent warming and freshening trends uncovered in the coral reconstructions undoubtedly represent a combination of dynamics that are fundamentally different than those associated with the ENSO phenomenon. Nonetheless, this study demonstrates the utility of generating well-reproduced 20th century paleoclimate reconstructions to compare with model simulations of greenhouse climate changes – an approach that is particularly important for constraining future hydrological changes.

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C. D. Charles, Scripps Institution of Oceanography, University of California, San Diego, 8615 Discovery Way, La Jolla, CA 92093, USA.

K. M. Cobb and I. S. Nurhati, School of Earth and Atmospheric Sciences, Georgia Institute of Technology, 311 Ferst Dr., Atlanta, GA 30332-0340, USA. (intan@gatech.edu)

R. B. Dunbar, School of Earth Sciences, Stanford University, 320 Bruan Hall, Stanford, CA 94305, USA.