

## Systematic ENSO-driven nutrient variability recorded by central equatorial Pacific corals

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[1] Variations in ocean productivity are driven largely by nutrient supply to the photic zone, but temporal records of nutrient variability are sparse. Here we show scleractinian coral P/Ca proxy records of variations in phosphate concentrations during El Niño Southern Oscillation (ENSO) cycles in the central equatorial Pacific. Covarying P/Ca records in *Porites* corals from Christmas and Fanning Islands show a regional ~40% decrease during the upwelling relaxation of the 1997–1998 El Niño, consistent with less frequent nutrient measurements from this area. Similar ~35–45% skeletal P/Ca decreases occur during the 1982–1983 and 1986–1987 El Niño events, which predate satellite color and regional nutrient measurements. After each El Niño event, nutrient increases lag temperature recovery by 4–12 months, likely reflecting uptake by massive phytoplankton blooms that followed resumption of upwelling. The results support the utility of coral P/Ca to probe the mechanisms linking ENSO, equatorial upwelling, and carbon cycling in the past. **Citation:** LaVigne, M., I. S. Nurhati, K. M. Cobb, H. V. McGregor, D. Sinclair, and R. M. Sherrell (2013), Systematic ENSO-driven nutrient variability recorded by central equatorial Pacific corals, *Geophys. Res. Lett.*, 40, doi:10.1002/grl.50765.

### 1. Introduction

[2] Equatorial Pacific upwelling supports one quarter of global new production and constitutes the largest natural oceanic source of carbon dioxide (CO<sub>2</sub>) to the atmosphere [Tans *et al.*, 1990; Park *et al.*, 2010]. Equatorial Pacific upwelling, biological activity, and CO<sub>2</sub> outgassing vary

interannually in response to changes in trade wind strength, equatorial wave activity [Evans *et al.*, 2009], thermocline depth [Guilderson and Schrag, 1998; Ryan *et al.*, 2006], and micronutrient and macronutrient supply to the photic zone, associated with the El Niño Southern Oscillation (ENSO) [Feely *et al.*, 1999; Strutton and Chavez, 2000; Chavez *et al.*, 2011]. The Tropical Ocean–Global Atmosphere (TOGA)–Tropical Atmosphere Ocean (TAO) buoy array (now TAO/Triangle Trans-Ocean Buoy Network) stretching across the equatorial Pacific has furthered our understanding of ENSO dynamics since the late 1990s, but the impact of climate variability on nutrient distributions in this region prior to TOGA-TAO is relatively unknown [Strutton and Chavez, 2000; Chavez *et al.*, 2003; Strutton *et al.*, 2008]. Recent surface seawater measurements at locations in the TAO array confirm that this region is characterized by a highly variable nutrient regime with >50% changes in seawater phosphate concentration (PO<sub>4SW</sub>), occurring on subweekly time scales and on small spatial scales of <100 km (Figure S1 in the supporting information). Long-term continuous time series measurements at fixed locations, such as those carried out in the subtropical gyres of the North Pacific and North Atlantic, are required to resolve the linkages between climate, nutrient variability, and primary productivity on subseasonal to decadal time scales [Karl, 2010; Lomas *et al.*, 2013].

[3] The 1997–1998 El Niño was, by some measures, the strongest ENSO cycle ever recorded [McPhaden, 1999]. This event was also the first of its kind to be captured by instrumental chlorophyll, nutrient, temperature, and mixed layer depth time series measurements with the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite and the TOGA-TAO mooring array. These robust data sets have led to a detailed understanding of the spatial and temporal evolution and biogeochemical implications of the strong 1997–1998 event and subsequent ENSO cycles [Chavez *et al.*, 1999; McPhaden, 1999]. In 1997, the regional weakening of trade winds, increased stratification, and suppression of equatorial upwelling resulted in a ~50% reduction in mixed layer nutrient concentrations, phytoplankton biomass, and primary productivity, as well as a reduction in phytoplankton cell size in the normally highly productive central equatorial Pacific [Chavez *et al.*, 1999; McPhaden, 1999; Strutton and Chavez, 2000; Strutton *et al.*, 2008]. In May of 1998, the warm phase ended abruptly and a strong La Niña (strong upwelling, cool sea surface temperatures) phase brought macronutrients and micronutrients to the central and eastern equatorial Pacific euphotic zone by way of the Equatorial Undercurrent, driving unusually intense chlorophyll blooms and an approximately twofold increase in primary productivity along the equator relative

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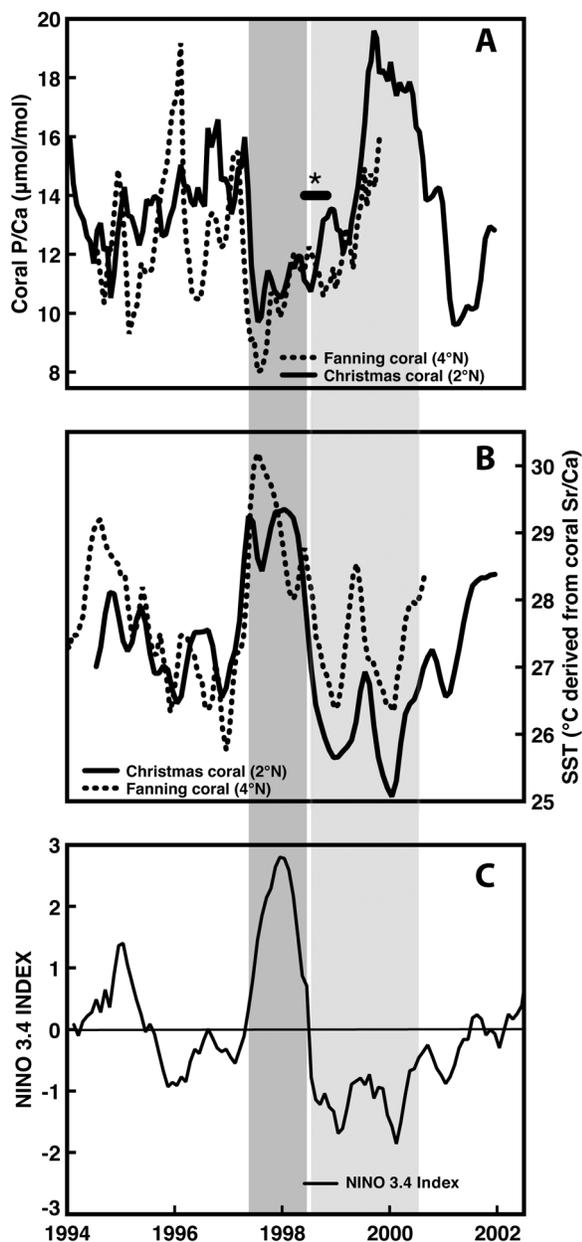
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**Figure 1.** Line Island coral proxy records of central equatorial Pacific  $\text{PO}_{4\text{SW}}$  through the 1997–1998 ENSO cycle compared against SST and Niño 3.4 Index. (a) Three- to four-point ( $\sim 3$  month) moving average of P/Ca data from Fanning Island coral (dotted line) and Christmas Island coral 1 (solid line). P/Ca analytical uncertainty =  $\pm 5$ –6%. (b) Monthly resolution SST records for Fanning (dotted line) and Christmas Island (solid line) from coral Sr/Ca records [Nurhati et al., 2009] [McGregor et al., 2013]. (c) Niño 3.4 Index plotted at monthly resolution ([http://www.cpc.nrao.gov/products/analysis\\_monitoring/ensostuff/ensoyears.shtml](http://www.cpc.nrao.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml)). Dark and light grey shaded bars represent the 1997–1998 warm El Niño and 1998–2000 cool La Niña phases of the ENSO cycle, respectively (warm/cool episodes defined by the Oceanic Niño Index  $> \pm 0.5^\circ\text{C}$  for more than five consecutive months). Duration of the 1998 phytoplankton bloom indicated by the length of the black bar is marked with an asterisk (June–September 1998; “Bloom #2” as described in Ryan et al. [2002]; see text).

to the climatological mean [Chavez et al., 1999; Strutton and Chavez, 2000; Ryan et al., 2002; Ryan et al., 2006; Slemons et al., 2010].

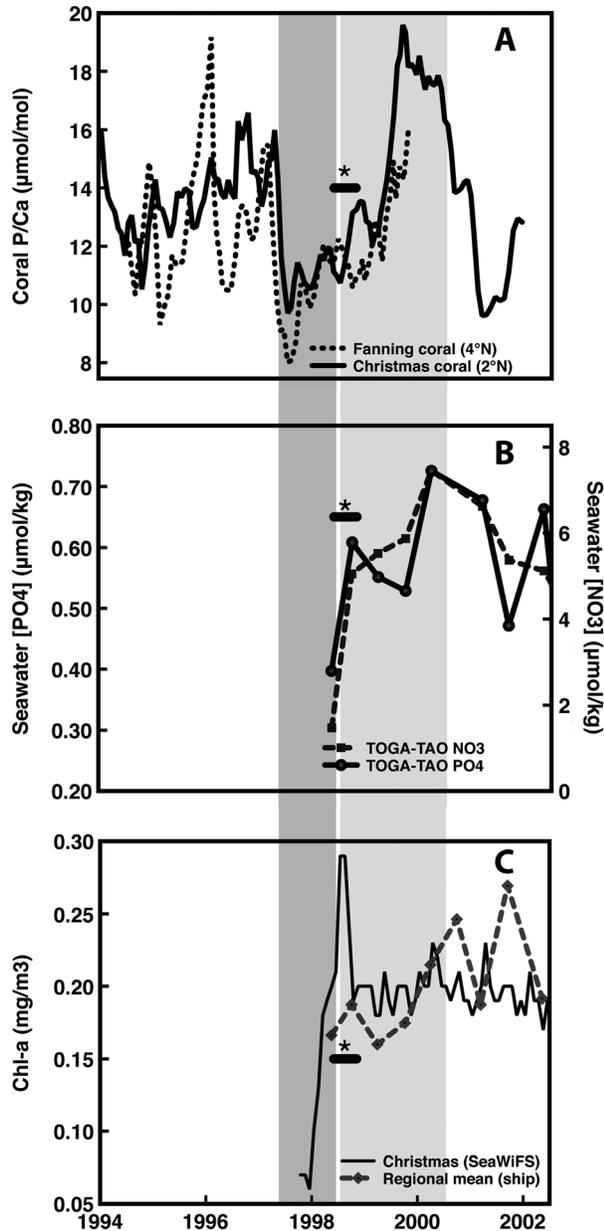
[4] Although broad geographic averages of nutrient data suggest that the reduction of upwelled nutrients at the onset of the 1997–1998 event was the primary driver of these observed biological shifts, the temporal resolution of ship-board bottle sampling was insufficient to characterize the precise timing of nutrient change at the specific locations of the phytoplankton blooms [Chavez et al., 1999; Strutton et al., 2008; Ryan et al., 2002; Strutton and Chavez, 2000]. Thus, interpretations of nutrient variability through this event are limited to either (1) high-spatial-resolution maps coarsely resolved in time (e.g., broad seasonal ENSO versus non-ENSO comparisons; [Chavez et al., 1999; Strutton et al., 2008]) or (2) high-resolution (monthly) nutrient time series integrated over large, sparsely sampled swaths of the ocean mixed layer [e.g., Strutton et al., 2008]. While these data sets and analyses have provided the first direct measurements of nutrient changes through ENSO cycles, the interpretation of long-term sparsely sampled nutrient time series is complicated by the high degree of spatial and temporal biogeochemical variability in this region (Figure S1).

[5] The power of coral skeletal archives to act as continuous recorders of seawater chemistry at a single location allows reconstruction of long-term records of nutrient chemistry for remote areas of the equatorial Pacific where instrumental data have been sparse. Nutrient proxies in surface-dwelling corals can, therefore, be used to reveal how equatorial nutrient dynamics and upwelling have responded to rapid variations in global climate in the past.

[6] In order to assess the relationship between equatorial Pacific surface ocean nutrient availability and ENSO, we applied a new paleoceanographic nutrient proxy, the phosphorus content of coral aragonite (or P/Ca), in corals from Christmas (Kiritimati) and Fanning (Tabuaeran) Islands, located in the Central Equatorial Pacific (CEP) Line Islands (Figure S2). The continuity and time-averaging qualities of these coral skeletal archives offer distinct advantages over discrete, sparse in situ  $\text{PO}_{4\text{SW}}$  measurements for quantifying long-term variations and trends in surface nutrient concentrations.

## 2. Coral Samples

[7] P/Ca ratios were analyzed at subseasonal resolution through three of the strongest ENSO events on record (1997–1998, 1986–1987, 1982–1983) in two *Porites* corals from Christmas Island and one from Fanning Island, located at  $2^\circ\text{N}$  and  $4^\circ\text{N}$  in the central equatorial Pacific (Figure S2; Table S1). Geochemical proxy sea surface temperature (SST) reconstructions from these and other Line Island corals are highly correlated with the Niño 3.4 Index, suggesting that cores from these locations capture regional-scale climatic variability [Evans et al., 1999; Woodroffe and Gagan, 2000; Woodroffe et al., 2003; Nurhati et al., 2009; McGregor et al., 2011]. In this study, coral P/Ca was measured along tracks immediately adjacent to (Fanning coral and Christmas coral 2) or in line with (Christmas coral 1) sampling tracks used for coral Sr/Ca in the studies referenced above. In the case of Christmas coral 1, samples were taken along the major growth axis [McGregor et al., 2011], with odd-numbered samples analyzed for Sr/Ca [McGregor et al., 2013] and even-numbered samples analyzed for P/Ca.



**Figure 2.** Line Island coral proxy records of central equatorial Pacific  $\text{PO}_{4\text{SW}}$  through the 1997–1998 ENSO cycle compared against central equatorial Pacific in situ nutrient and chlorophyll measurements. (a) Same as Figure 1a. (b) Regional mean mixed layer in situ phosphate ( $\text{PO}_4$ ,  $\mu\text{mol/kg}$ ; circles, solid line) and nitrate ( $\text{NO}_3$ ;  $\mu\text{mol/kg}$ ; squares, dashed line) concentrations measured along central Pacific  $5^\circ\text{N}$  to  $5^\circ\text{S}$ ,  $125^\circ\text{W}$ ,  $140^\circ\text{W}$ , and  $155^\circ\text{W}$  TAO lines (data from *Strutton et al.* [2008]). (c) Regional mean mixed layer in situ chlorophyll *a* concentrations ( $\text{mg/m}^3$ ) measured from ship samples along central Pacific  $5^\circ\text{N}$  to  $5^\circ\text{S}$ ,  $125^\circ\text{W}$ ,  $140^\circ\text{W}$ , and  $155^\circ\text{W}$  TAO lines (grey diamonds, dashed line; data from *Strutton et al.* [2008]) and a local chlorophyll *a* record for Christmas Island from SeaWiFS.R5.2 (solid line;  $\text{mg/m}^3$ ;  $0.75^\circ \times 0.5^\circ$  grid centered at  $157.375^\circ\text{W}$ ,  $1.85^\circ\text{N}$ ; analyses produced with the Giovanni online data system, developed and maintained by the NASA Goddard Earth Sciences Data and Information Services Center). Dark and light grey shaded bars represent ENSO cycles as defined in Figure 1. The 1998 phytoplankton bloom is indicated by an asterisk as in Figure 1.

Thege models used for the P/Ca records were derived by matching coral Sr/Ca to the corresponding grid box from the Integrated Global Ocean Services System SST data set [*Reynolds et al.*, 2002]. The uncertainty in relative age differences between the coral P/Ca records and Sr/Ca age models is  $\pm \sim 1$ –2 weeks in all corals. This uncertainty was estimated from the even-odd sampling interval in Christmas coral 1 and the  $\pm \sim 0.5$  mm uncertainty in along-axis sample locations between tracks in Fanning and Christmas coral 2 slabs (see Sample Preparation and Analysis in the supporting information).

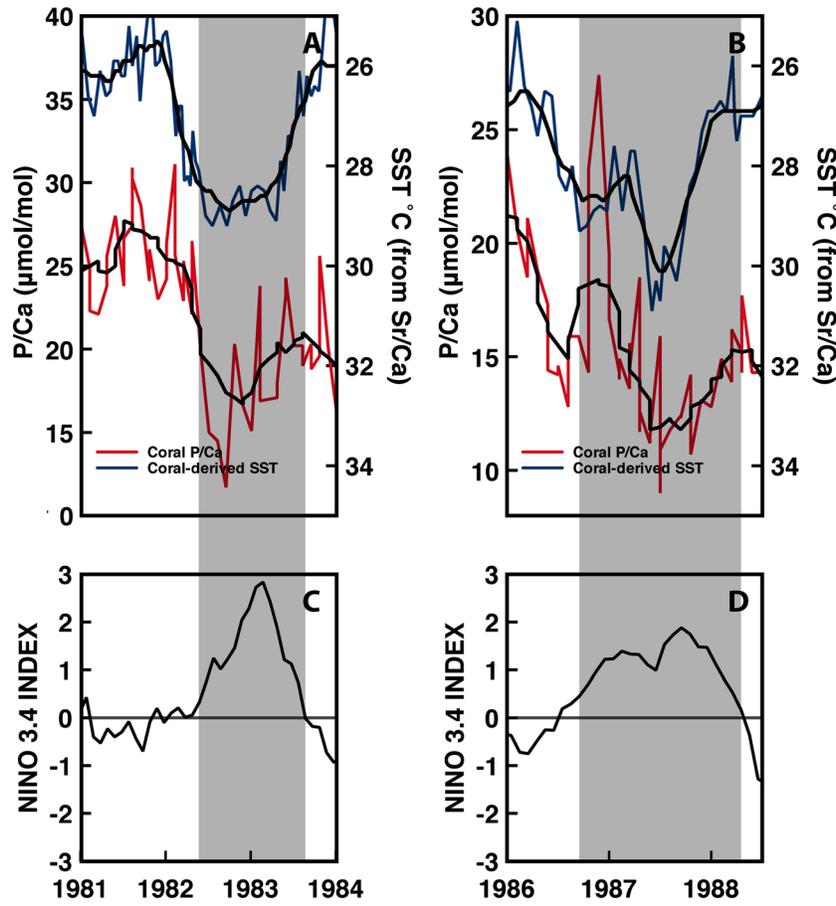
### 3. The Coral P/Ca Proxy

[8] Recent calibration work has shown that high-resolution records of coral skeleton P/Ca are strongly correlated with in situ  $\text{PO}_{4\text{SW}}$  time series measurements, with good intercolony agreement in P/Ca response to  $\text{PO}_{4\text{SW}}$  variations among colocated corals [*LaVigne et al.*, 2008, 2010]. While evidence suggests that this new P/Ca proxy is broadly applicable across genera and in distinct nutrient regimes [*LaVigne et al.*, 2010], site- and species-specific calibrations are necessary to quantify absolute  $\text{PO}_{4\text{SW}}$  from surface coral P/Ca. Our coral P/Ca record thus reflects relative changes in regional  $\text{PO}_{4\text{SW}}$  concentration through ENSO cycles.

## 4. Results and Discussion

### 4.1. Coral P/Ca Through the 1997–1998 El Niño Event

[9] The coral P/Ca records agree with and extend the ship-board nutrient measurements for the 1997–1998 El Niño event (Figures 1 and 2). The  $\sim 50\%$  decrease in central equatorial Pacific surface mixed layer nutrient concentrations was just barely captured by the timing of bottle sampling during the warm phase of the 1997–1998 El Niño event (Figure 2) [*Chavez et al.*, 1999; *Strutton and Chavez*, 2000; *Strutton et al.*, 2008]. This broad-scale reduction in nutrients is replicated in the Fanning and Christmas Island coral records as  $37 \pm 6\%$  and  $37 \pm 8\%$  decreases in P/Ca in June–August 1997 relative to mean P/Ca over 1 year prior to the El Niño event, respectively (Figures 1 and 2). The 6–8% uncertainty on the P/Ca reduction calculated using within-run precision of P/Ca measurements (5–6%) is within the intercolony uncertainty found previously for *Porites* corals (5–12%) [*LaVigne et al.*, 2010]. The trends in these two coral records are highly correlated ( $r=0.82$ ; 1997.4–1999.8), and the P/Ca dips correspond to the timing of the  $\sim 3^\circ\text{C}$  warming during the 1997–1998 warm phase (Figure 1). The agreement between these coral P/Ca data and broad in situ nutrient trends demonstrates that P/Ca in central equatorial Pacific *Porites* corals constitutes a record of regional-scale nutrient variability rather than local-scale nutrient heterogeneities (Figure 2) [*Strutton et al.*, 2008]. The P/Ca trends cannot be explained by an indirect or secondary sensitivity of P/Ca to SST; evidence from other regions suggests that SST variations have no direct effect on coral P/Ca (supporting information) [*LaVigne*, 2010]. Also, the so-called “vital effects” likely have a minimal influence on coral P/Ca, based on an absence of correlation between P/Ca and skeletal extension rate in these coral samples (supporting information). Therefore, the agreement between broad-scale variations in water sample nutrient measurements and data from two corals collected from distinct locations in the central equatorial Pacific confirms that equatorial Pacific



**Figure 3.** Coral proxy records of central equatorial Pacific  $\text{PO}_{4\text{SW}}$  and SST through the 1982–1983 and 1986–1987 ENSO cycles compared against the Niño 3.4 Index. Four-point moving average (black) of raw P/Ca data (red) and SST record derived from coral Sr/Ca (blue; note inverted y axis) in Christmas coral 2 [Nurhati *et al.*, 2009] through the (a) 1982–1983 and (b) 1986–1987 ENSO cycles. Moving averages in Figures 3a and 3b (solid line) represent  $\sim 6$  and  $\sim 5$  month resolution smoothing of raw P/Ca and SST data, respectively. P/Ca analytical uncertainty =  $\pm 6\%$ . Niño 3.4 Index plotted at monthly resolution through the (c) 1982–1983 and (d) 1986–1987 events. Grey shaded bars represent the duration of warm El Niño phases as defined in Figure 1.

*Porites* P/Ca records reflect the regional-scale changes in upwelling and seawater nutrients associated with the 1997–1998 ENSO event.

[10] The P/Ca decrease is observed in the Christmas and Fanning Island corals at the onset of the 1997–1998 El Niño warm phase with no leads or lags among P/Ca, coral Sr/Ca-derived SST, and the Niño 3.4 Index (dark grey shading Figure 1). However, the P/Ca and SST records decouple during the subsequent La Niña cool phase, indicating that surface phosphate concentrations did not return immediately to pre-ENSO levels once upwelling recovered (light grey shading Figure 1). This delayed recovery of surface nutrient concentration at the start of the La Niña phase from approximately mid-1998 to mid-1999 is longer than the  $\pm 1$ – $2$  week coral age model uncertainty and is likely a direct result of nutrient uptake by large phytoplankton blooms that occurred during the strong 1998–2000 La Niña [Ryan *et al.* 2002; Ryan *et al.* 2006]. The period of SST and P/Ca divergence in the Christmas and Fanning coral records corresponds to the timing of this vast bloom as well as to measured shifts in central equatorial Pacific nutricline depth (June–September of 1998; asterisk symbol in Figures 1 and 2) [Ryan *et al.*, 2002]. The 1998 central equatorial Pacific bloom would have consumed macronutrients supplied by the recently restored

equatorial upwelling and prevented  $\text{PO}_{4\text{SW}}$  from returning immediately to pre-El Niño concentrations [Ryan *et al.*, 2002; Ryan *et al.*, 2006]. Once the bloom dissipated in September of 1998, P/Ca increased; exceeding pre-El Niño levels by mid-2000. The trends evident in these coral data agree with shipboard measurements of broad nutrient concentrations integrated across the entire CEP mixed layer, which also show that nitrate, phosphate, and silicate increased steadily following oligotrophic conditions at the height of the warm phase, through the subsequent 1998 La Niña, peaking in  $\sim 2000$  (Figures 1 and 2) [Chavez *et al.*, 1999; Strutton *et al.*, 2008]. This agreement further validates the application of the P/Ca proxy to equatorial Pacific *Porites* and demonstrates the utility of coral archives for high-resolution biogeochemical reconstructions in surface waters. Furthermore, the duration of the  $\text{PO}_{4\text{SW}}$  “hold back” (or  $\text{PO}_{4\text{SW}}$  and SST decoupling) during the resumption of upwelling in La Niña could provide insight into the duration of phytoplankton blooms for ENSO cycles that predate the satellite chlorophyll record.

#### 4.2. Past ENSO Events

[11] Instrumental and satellite data sets from 1997 to 2000 demonstrate the broad-scale impacts that a strong ENSO cycle has on equatorial hydrography, biogeochemistry,

and productivity. The 1997–1998 El Niño and 1998–2000 La Niña events, however, are known to have been unusually strong with respect to subsequent ENSO cycles recorded by the TAO buoy and SeaWiFS data [McPhaden, 1999]. In situ data that would be required to put the 1997–1998 event in a longer-term biogeochemical context, however, are lacking. Therefore, we produced P/Ca records through two strong preinstrumental ENSO cycles (1982–1983 and 1986–1987) from a second Christmas Island coral (Christmas coral 2) to determine whether the phosphate decreases during El Niño warming and the biologically driven nutrient hold back during La Niña cooling were unique to the 1997–1998 cycle, or not. The results are consistent; the 1982–1983 and 1986–1987 coral records show distinct decreases in P/Ca during ENSO warming in response to regional weakening of trade winds, resultant suppression of upwelling, increased stratification, and decreased  $\text{PO}_{4\text{SW}}$  (Figure 3) [Nurhati et al., 2009]. As during the 1997–1998 ENSO, P/Ca and SST in the 1982–1983 and 1986–1987 ENSO events covary during the onset of warming (approximately early 1982 and early 1986) but decouple following peak warming (e.g., approximately early 1983 and approximately early 1988; Figure 3). These trends resemble that of the 1997–1998 cycle, suggesting that regional productivity blooms delayed surface nutrient recovery in 1982–1983 and 1986–1987, by at least ~3–4 months (Figure 3). Detailed satellite chlorophyll mapping of blooms would be required to confirm this hypothesis. Although the 1997–1998 ENSO cycle is the strongest recorded in recent years by the TOGA-TAO array, the 1982–1983 and 1986–1987 events resulted in a similar degree of warming in the central equatorial Pacific (~3–4°C; Niño 3.4 Index ~2–3; Figures 1 and 3). The new proxy data support the similarity, as the strong El Niño events of 1982–1983, 1987–1988, and 1997–1998 all corresponded to rapid (3–7 month)  $\text{PO}_{4\text{SW}}$  depletions of similar magnitude, suggesting that the degree of upwelling suppression and the reduction of macronutrient availability in surface waters was similar during these three events ( $47 \pm 7\%$ ,  $35 \pm 7\%$ , and  $37 \pm 8\%$  decrease in P/Ca relative to a mean of 1 year prior to the El Niño events, respectively).

[12] While the relative degree of short-term P/Ca decrease was similar for all three ENSO events, a longer-term decrease of ~26 to ~15  $\mu\text{mol mol}^{-1}$  in absolute coral P/Ca (pre-El Niño mean, Figures 1–3) is also apparent in the 1982–1997 time slices. This trend in P/Ca values could indicate that a longer-term change in mean  $\text{PO}_{4\text{SW}}$  background concentration may have also occurred in the CEP through this period. Hydrographic measurements of equatorial Pacific nutrient concentrations over the past few decades, however, are too sparse and variable to confirm or refute this trend (supporting information) [McPhaden and Zhang, 2002; Martinez et al., 2009]. Surface ocean warming over the past several decades has been linked, however, to a decline in trade wind strength [Clarke and Lebedev, 1996], weaker atmospheric Walker circulation [Vecchi et al., 2006], a shift in east equatorial Pacific vertical thermal structure [Guilderson and Schrag, 1998], and a slowdown of wind-driven upper ocean meridional overturning accompanied by reduced equatorial upwelling [McPhaden and Zhang, 2002, 2004; Tokinaga et al., 2012] which would have had a substantial influence on nutrient availability, primary production, and carbon cycling [Martinez et al., 2009; Boyce et al., 2010]. The records shown here are too short to confirm a long-term trend in mean  $\text{PO}_{4\text{SW}}$  concentration;

however, this could be explored further with the analysis of additional coral records spanning this time period.

[13] These data constitute the first direct paleoceanographic records of ENSO-driven changes in surface nutrient availability in the tropical Pacific Ocean. The high-resolution coral records from Christmas and Fanning Island corals are consistent with regional-scale trends in instrumental measurements and support the use of the P/Ca proxy to reconstruct nutrient time series from other remote areas of the equatorial ocean where instrumental data have been sparse until recent years. High-resolution coral proxy records spanning three distinct ENSO cycles demonstrate similar climate-driven patterns in seawater nutrient concentration. Thus, ENSO appears to have a systematic impact on upwelling and primary productivity in the central equatorial Pacific. Furthermore, the processes controlling equatorial nutrient concentrations and SST can be decoupled, underscoring the importance of long-term nutrient time series measurements and paleoceanographic reconstructions. These findings illustrate the power of combining coral-derived SST and nutrient proxy records to probe the mechanisms that link rapid climate change, nutrient availability, primary productivity, and carbon cycling in this key region of the ocean.

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