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Decadal changes in South Pacific sea surface temperatures and the relationship to the Pacific decadal oscillation and upper ocean heat content

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Key Points:

- Relationship between South Pacific SST, ocean heat content, and PDO
- Improved constraints on Pacific decadal SST variability
- Inverse correlation between decadal SST in South Pacific and equator

Supporting Information:

- Data Set S1
- Text S1 and Figures S1–S5

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Abstract Decadal changes in Pacific sea surface temperatures (SSTs) and upper ocean heat content (OHC) remain poorly understood. We present an annual average composite coral Sr/Ca-derived SST time series extending back to 1791 from Fiji, Tonga, and Rarotonga (FTR) in the Pacific Decadal Oscillation (PDO) sensitive region of the southwest Pacific. Decadal SST maxima between 1805 and 1830 Common Era (C.E.) indicate unexplained elevated SSTs near the end of the Little Ice Age. The mean period of decadal SST variability in this region has a period near 25 years. Decades of warmer (cooler) FTR SST co-occur with PDO negative (positive) phases since at least ~1930 C.E. and positively correlate with South Pacific OHC (0–700 m). FTR SST is also inversely correlated with decadal changes in equatorial Pacific SST as measured by coral Sr/Ca. Collectively, these results support the fluctuating trade wind-shallow meridional overturning cell mechanism for decadal modulation of Pacific SSTs and OHC.

1. Introduction

Decadal-scale anomalies in surface temperatures, trade winds, sea level pressure, and rainfall in the Pacific basin that have developed since the start of the recent hiatus in Earth surface warming (~1999 Common Era (C.E.)) resemble the negative phase of the Pacific Decadal Oscillation (PDO) (see Figure 1). During this current negative phase of the PDO, the North and South Pacific central gyres and equatorial western Pacific are warmer than average while the eastern equatorial Pacific is cooler than average [*Mantua et al.*, 1997; *Balmaseda et al.*, 2013; *Meehl et al.*, 2013; *Trenberth and Fasullo*, 2013; *Trenberth et al.*, 2014]. Recent modeling efforts in conjunction with analysis of ARGO float data indicate elevated heat storage in the Pacific water column during this most recent negative phase of the PDO suggesting a relationship between the PDO and the hiatus [*Balmaseda et al.*, 2013; *Kosaka and Xie*, 2013; *Meehl et al.*, 2013; *Trenberth and Fasullo*, 2013; *England et al.*, 2014; *Trenberth et al.*, 2014; *Roemmich et al.*, 2015]. Decadal-scale changes in El Niño–Southern Oscillation (ENSO) since 1976 may also be associated with changes in global mean surface temperatures [*Kosaka and Xie*, 2013; *Trenberth et al.*, 2002] for, on average, El Niño events result in a net release of heat to the atmosphere and associated ~0.1 to 0.3°C increases in global mean temperature [*Trenberth et al.*, 2002; *Trenberth and Fasullo*, 2013; *Kosaka and Xie*, 2013; *Banholzer and Donner*, 2014]. While ENSO variations along the equator are considered well documented over the last century, decadal-scale variations in subtropical SST associated with the PDO are less well constrained before the 1960s due to the lack of instrumental data, particularly in the South Pacific, and the long recurrence interval of the PDO [*Deser et al.*, 2010; *Woodruff et al.*, 2011].

To evaluate regional decadal-scale SST changes in the sector of the South Pacific where SST variability has the highest correlation to the PDO, we generated a three-coral annually averaged Sr/Ca composite time series of reconstructed SST back to 1791 C.E. using subseasonal coral Sr/Ca data from the subtropical southwest Pacific islands of Fiji, Tonga, and Rarotonga (hereafter FTR; Figures 1 and 2 and see supporting information). These sites are arrayed NW-SE from 17°S, 180°E to 21°S, 160°W and are centrally located in the region where decadal changes in South Pacific SST appear to be best coordinated with the PDO. Coral Sr/Ca from these sites has been previously shown to accurately track seasonal and annual average SST over the last ~20 years [*Linsley et al.*, 2000, 2004; *Wu et al.*, 2013]. Here we discuss the decadal and lower frequency variability in this FTR coral Sr/Ca series.

2. The PDO and Upper Ocean Heat Storage Variability in the South Pacific

There is mounting evidence that the mechanisms driving the PDO are also sensitive to, and/or related to, Pacific ocean heat content (OHC) [*Balmaseda et al.*, 2013; *Meehl et al.*, 2013; *England et al.*, 2014; *Thompson et al.*, 2015;

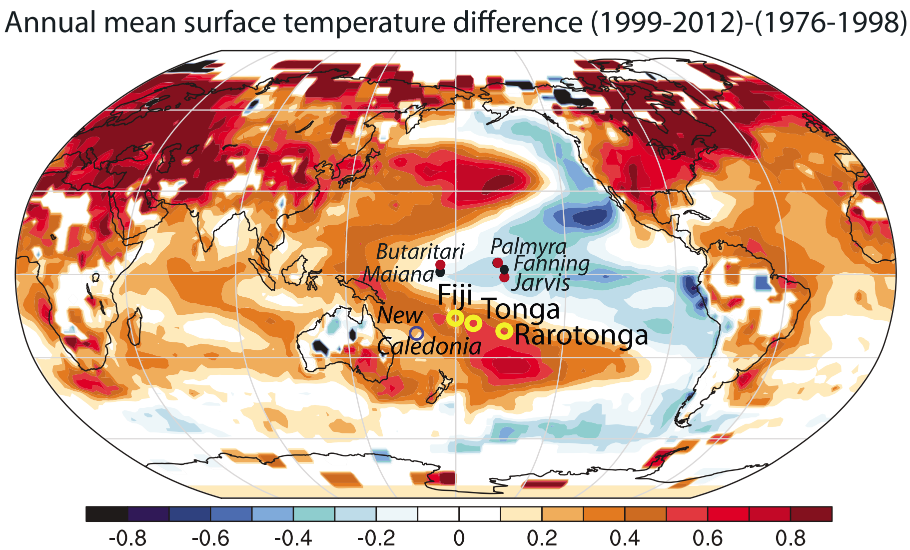

Figure 1. Mean annual surface temperature differences between the periods from 1999 to 2012 and 1976 to 1998 in °C. In the Pacific the spatial pattern strongly resembles the negative phase of the Pacific Decadal Oscillation (PDO) [*Trenberth and Fasullo*, 2013]. Our study sites at Fiji, Tonga, and Rarotonga (FTR) are indicated as is New Caledonia, Maiana, Jarvis, Fanning, and Palmyra (see text). Figure modified from *Trenberth and Fasullo* [2013].

Trenberth and Fasullo, 2013; *Trenberth et al.*, 2014]. The PDO has been identified with changes in sea level pressure in the Aleutian Low over the Gulf of Alaska (30°N–65°N, 160°E–140°W) [*Trenberth and Hurrell*, 1994] and is also defined as the pattern and time series of the first empirical orthogonal function of SST over the North Pacific north of 20°N [*Mantua et al.*, 1997; *Deser et al.*, 2004]. The PDO index, based on North Pacific SST, extends back to 1900 [*Mantua et al.*, 1997; *Zhang et al.*, 1997]. Including the sparse instrumental SST data from the South Pacific, the Pacific-wide decadal mode has been termed the Interdecadal Pacific Oscillation (IPO) [*Zhang et al.*, 1997; *Power et al.*, 1999; *Folland et al.*, 2002; *Shakun and Shaman*, 2010]. The PDO/IPO has a recurring pattern where on decadal timescales the central North and South Pacific gyres cool (during positive phases) at the same time as the eastern margin and equatorial sectors warm, and vice versa. The spatial structure of this decadal SST variability in the Pacific is similar to that of ENSO except with a wider latitudinal range in the eastern Pacific and greater amplitude in midlatitudes than in the tropics. Instrumental North Pacific SST data indicate that alternating phases of the PDO can last two to three decades with phase reversals centered on 1924/1925, 1946/1947, 1976/1977, and 1998/1999.

Recent studies indicate that intermediate and deep waters in the ocean are taking up ~90% of the expected energy imbalance associated with increasing greenhouse gases [e.g., *Balmaseda et al.*, 2013; *Levitus et al.*, 2012; *Meehl et al.*, 2013; *Trenberth and Fasullo*, 2013]. Changes in oceanic heat storage may also be related to the PDO and the most recent stall in rising Earth surface temperatures since ~1999 C.E. [*Kosaka and Xie*, 2013; *Trenberth and Fasullo*, 2013; *Trenberth et al.*, 2014; *England et al.*, 2014], in addition to possible forcing from atmospheric aerosols, tropospheric ozone, and stratospheric water vapor [*Solomon et al.*, 2010, 2011; *Lin et al.*, 2014]. It is thought that one important location for this heat exchange with the atmosphere is the tropical and midlatitude regions of the surface ocean, primarily in the Pacific [*Trenberth and Fasullo*, 2013; *Trenberth et al.*, 2014; *Meehl et al.*, 2014]. In the subtropics of the Pacific and Atlantic, surface waters can seasonally descend away from the surface along isopycnal surfaces as part of the shallow overturning cells that transmit water at subthermocline depths from the subtropical surface ocean toward the equator. Limited instrumental and modeling results indicate that in the Pacific, oceanic intermediate waters have recently been gaining heat coincident with the most recent stall in rising global temperatures that began in ~1999 [*Meehl et al.*, 2013; *Trenberth and Fasullo*, 2013]. An unprecedented strengthening of the Pacific Ocean shallow overturning cells has been suggested to be the primary cause of the oceanic heat gain [*Trenberth and Fasullo*, 2013; *Balmaseda et al.*, 2013; *England et al.*, 2014]. At the same time the stronger trade winds coupled with changes in ocean circulation and advection associated with the PDO phase switch in 1999–2000 have resulted in a cooling of the equatorial surface ocean over the last 15 years [*England et al.*, 2014; *Trenberth et al.*, 2014] (Figure 1).

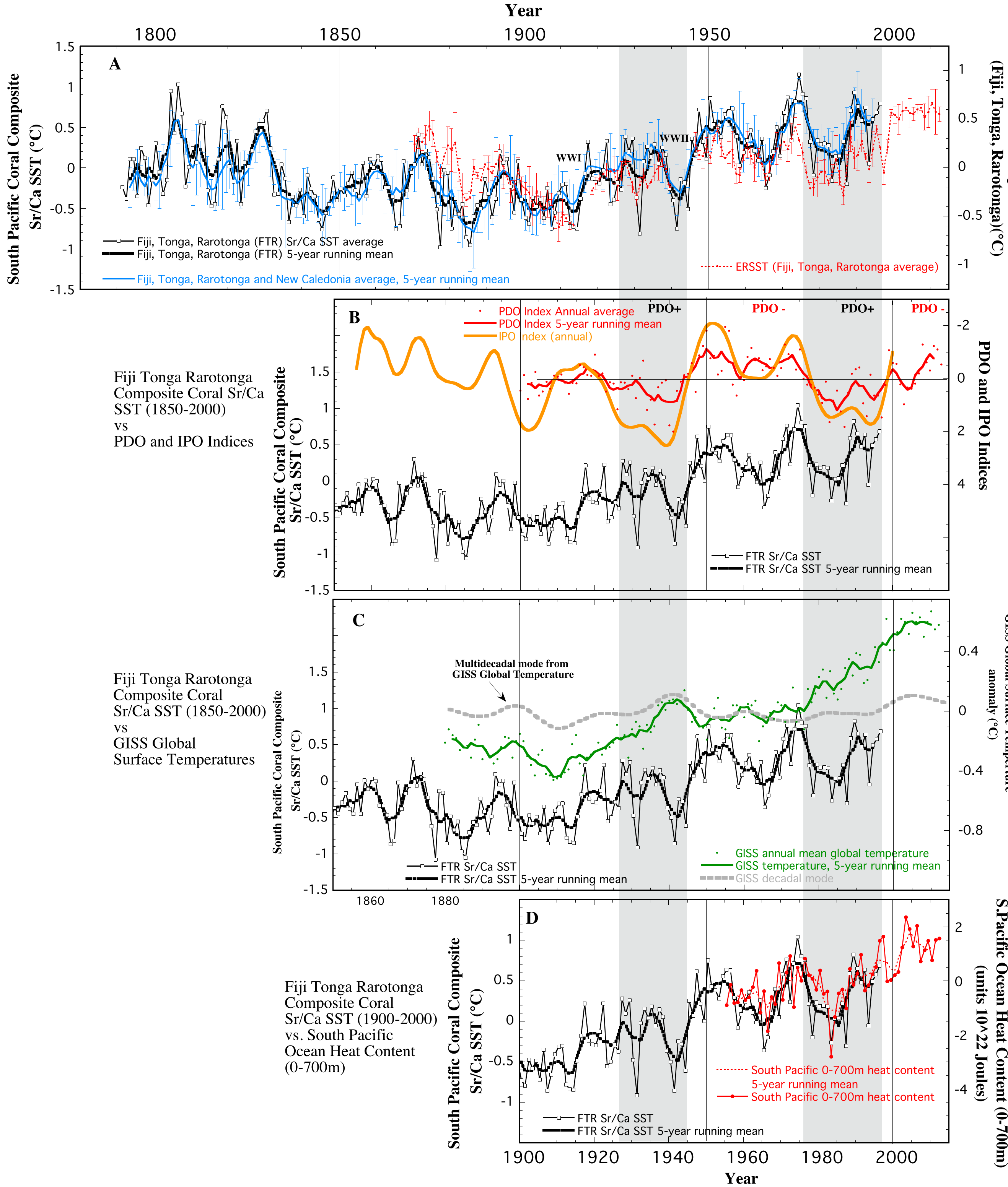

Figure 2. (a) Three-coral Sr/Ca SST average from Fiji, Tonga, and Rarotonga (in black) along with a 5 year running mean (dashed black line). The centered instrumental ERSST (version 3) (red) is from the grids that include these same FTR sites. Blue curve is the average of Fiji, Tonga, Rarotonga, and New Caledonia [from *Delong et al.*, 2012] Sr/Ca SST along with the standard error (SE). (b) The FTR Sr/Ca SST reconstruction compared to the PDO and IPO indices. Periods of positive PDO phases are demarcated in gray. (c) The FTR Sr/Ca SST reconstruction compared to the GISS Earth surface temperature record (green) [from *Hansen et al.*, 2010]. The decadal mode in the GISS record id in gray dots with the amplitude doubled. (d) 0–700 m heat content anomaly (red) [from *Levitus et al.*, 2012] relative to the 1955–2006 base period compared the FTR Sr/Ca SST reconstruction.

One of the main reasons for the limited understanding of decadal changes in surface ocean temperatures is the incomplete and patchy distribution of instrumental data in much of the ocean before ~1960. In addition, there are uncertainties in bias corrections that have been applied to the existing SST data to construct the various SST data products. Instrumental data are particularly sparse in the South Pacific but also for key intervals in the North Pacific [*Deser et al*., 2010; *Woodruff et al*., 2011; *Barton and Casey*, 2005; *Abraham and Baringer*, 2013] (see Figure S1 in the supporting information).

Despite sparse instrumental water temperature data to define the decadal changes at the sea surface and in the upper water column, the available data indicate a disproportionately large role of the Southwest Pacific in decadal-scale surface and subthermocline depth oceanographic variability in the Pacific [*Tsuchiya et al*., 1989; *Johnson and McPhaden*, 1999; *White and Cayan*, 1998]. For example, the South Pacific is currently the dominant (50%–75%) source region for isopycnal water transport to the equatorial thermocline and deeper [*Tsuchiya et al*., 1989; *Johnson and McPhaden*, 1999]. This is due in part to the partial blocking effect of the relatively buoyant surface ocean beneath the Intertropical Convergence Zone with a mean position located north of the equator and the weaker influence of the South Pacific Convergence Zone (SPCZ) on South Pacific isopycnal equatorward flow [*Johnson and McPhaden*, 1999; *White and Cayan*, 1998].

3. Results: FTR Sr/Ca SST Composite

The individual coral Sr/Ca time series at Fiji, Tonga, and Rarotonga (FTR) have calculated Sr/Ca versus SST slopes (sensitivities) that are very similar [*Linsley et al*., 2000, 2004; *Wu et al*., 2013]. At Rarotonga correlations to monthly SST indicate a coral Sr/Ca to SST sensitivity of −0.063 mmol/mol per 1°C [*Linsley et al*., 2000, 2004]. At Fiji and Tonga, correlations to monthly SST [*Linsley et al*., 2004; *Wu et al*., 2013] yield sensitivities of −0.058 and −0.062 mmol/mol per 1°C, respectively. We previously evaluated the biosmoothing-corrected sensitivity of −0.084 mmol/mol per 1°C proposed to account for the smoothing effect of calcification in the tissue layer of *Porites* sp. [*Gagan et al*., 2012]. The application of this larger slope only affects the amplitude of reconstructed coral Sr/Ca SST and does not affect the timing of the decadal changes in coral Sr/Ca reconstructed SST that is discussed here [*Wu et al*., 2013]. For this study, calendar year Sr/Ca SST averages were calculated for each core using the subseasonal Sr/Ca SST data (Figure S2). To calculate the three-coral core FTR Sr/Ca SST annual average composite, each individual Sr/Ca SST time series was first centered by removing the 1800–1997 mean Sr/Ca SST. The centering process corrected for differences in mean annual SST at each site. The FTR composite average was then calculated from the Fiji, Tonga, and Rarotonga S/Ca SST annual averages for the overlapped interval from 1791 to 1997 C.E. (Figure 2).

Although the three Sr/Ca time series are from different island groups separated by as much as 2245 km (Fiji to Rarotonga), all three records contain a common decadal SST signal that is clarified in the FTR Sr/Ca SST composite. The three-site FTR average has increased the decadal SST signal and minimized any interlocation differences due to mesoscale oceanographic variability or differences in island effects on the individual coral Sr/Ca records. This is demonstrated by comparison of the FTR composite to International Comprehensive Ocean-Atmosphere Data Set (ICOADS)-SST and Extended reconstructed sea surface temperature (ERSST) for the last 40 years, the interval of best instrumental data coverage. Correlations between annual FTR coral Sr/Ca SST and annual ICOADS and ERSST SST from the FTR grids back to 1960 are 0.71 ($p \leq 0.01$) and 0.75 ($p \leq 0.01$), respectively (see Figure S3). Correlations of individual Sr/Ca records to local Fiji, Tonga, and Rarotonga SST range from 0.5 to 0.58 ($p \leq 0.01$). This indicates that the composite average approach has increased the climatic signal-to-noise ratio resulting in a regionally representative reconstruction of South Pacific SST variability in a key IPO-PDO responsive area.

The FTR Sr/Ca SST series contains a significant long-term secular trend and a change in the dominant recurrence interval of the decadal-scale SST variability in the South Pacific. Wavelet analysis [*Torrence and Compo*, 1998] (using a Morlet mother wavelet) of the composite FTR Sr/Ca SST series indicates that there was a shift in the dominant recurrence interval from bimodal (~35 and ~ 20 years) in the 1790s up to ~1890 to variability with a period near 20 years after 1940, albeit the low number of repetitions (Figure S4). This result suggests that the periodicity of decadal-scale SST variability in the South Pacific changed to a higher frequency in the midtwentieth century. The long-term trend in the FTR composite Sr/Ca SST record also indicates that decadal maxima in South Pacific SST from 1805 to ~1830 were within error of late twentieth century decadal SST maxima in the most PDO sensitive region of the South Pacific (Figure 2). The coral Sr/Ca time series results from New Caledonia [*DeLong et al*., 2012] in the early 1800s supports this observation (see Figure 2a). This period of relatively warm SSTs in the South Pacific occurs during the end of the Little Ice Age, a time of cooler conditions in many regions globally. Warm conditions in the SPCZ region in the early 1800s indicates that there are under appreciated century-scale changes in South Pacific SST.

4. Discussion

To evaluate this South Pacific decadal SST mode in the context of larger-scale and lower frequency processes, we have compared our FTR SST reconstruction to (1) annual average ERSST from Fiji, Tonga, and Rarotonga, (2) to a multicentury length coral Sr/Ca record from New Caledonia [*DeLong et al*., 2012], (3) to the PDO and IPO indices, (4) to Global surface temperatures, and (5) to upper ocean (0–700 m) heat content data (see Figure 2). These comparisons reveal a number of interesting observations. Variability in the FTR Sr/Ca SST composite is generally coherent with variability in ERSST and with the PDO and IPO indices (Figure 2b). The correlation between our FTR Sr/Ca record (detrended), and the PDO index is 0.5 for annual average versions and 0.61 for 5 year running mean versions ($p < 0.001$ for both). The correlation between our FTR Sr/Ca record (detrended) and the IPO index is 0.4 for annual average versions and 0.56 for 5 year running mean versions ($p < 0.001$ for both). The correlations improve to 0.61 (FTR versus PDO) and 0.67 (FTR versus IPO) when 5 year running means of just the interval from 1935 to the present is used. The lower correlations when the interval prior to 1935 is included could be due to the greater uncertainties in the PDO and IPO indices during the early 1900s due to reduced data coverage at this time (see Figure S1).

We also compared the FTR Sr/Ca record to a subseasonal resolution coral Sr/Ca record from New Caledonia that overlaps the FTR record from 1791 to 1997 [*Delong et al*., 2012] (located at 22°28.8′S; 166°27.9E). Since New Caledonia is located outside of the region of strongest correlation between South Pacific SST and the PDO [*Delong et al*., 2012], when we included the New Caledonia Sr/Ca SST series into the composite average (see Figure 2a), the correlation to the PDO (annual average with 5 year running mean) did not increase. Based on this result we elected not to include the New Caledonia Sr/Ca record in the FTR composite. But the fact that the Fiji-Tonga-Rarotonga and Fiji-Tonga-Rarotonga-New Caledonia composite Sr/Ca SST reconstructions share 95% of total variance ($r^2 = 0.95$) supports our hypothesis that over the last ~200 years, decadal SST variability in the Southwest Pacific is coherent over a large region.

Decadal variability in FTR coral Sr/Ca SST is also positively correlated with changes in upper ocean heat content compiled for the South Pacific between 0.5°S–89.5°S and 63°W–147°E [*Levitus et al*., 2012] (available from NOAA at http://www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT/heat_global.html). Beginning in 1955 when the South Pacific upper ocean (0–700 m depth) heat content data start, decadal changes in FTR Sr/Ca SST are significantly correlated with oceanic heat storage [*Levitus et al*., 2012] (Figure 2d) ($R = 0.45$, $p < 0.01$ for annual averages and $R = 0.82$, $p < 0.001$ for 5 year running means). We note that this is equal to the correlation between ERSST from Fiji, Tonga, and Rarotonga and South Pacific 0–700 m OHC (both 5 year running means) ($R = 0.83$, $p < 0.001$). For comparison, New Caledonia Sr/Ca SST and South Pacific 0–700 m OHC have an $R = 0.52$ (correlation of 5 year running means) supporting the hypothesis that decadal changes in SST in the region of the South Pacific most strongly correlated to the PDO have the highest correlations to South Pacific 0–700 m OHC. The FTR region was also found to have positive correlations between monthly SST and local monthly OHC (0–380 m) ($R = \sim 0.3$) over the interval from 1980 to 1998 [*Trenberth et al*., 2002].

These observations indicate that the ~1°C higher South Pacific SSTs in the FTR region during decades of more negative PDO-IPO index correspond to ~1 to 2×10^{22} J of heat gain per year in the upper 700 m of the water column in the South Pacific, while cooler SST (more positive PDO-IPO index) coincides with net heat loss in the upper 700 m. Evaporative cooling effects in the Pacific on interannual timescales have been shown to be a key mechanism for releasing heat in the ocean to the atmosphere [*Trenberth et al*., 2002]. Today, the region of highest evaporation rates in the South Pacific occupies a broad ~20° latitudinal band that includes the FTR region and extends from 90°W, 20°S west across the South Pacific to the Australia continent at 150°E, 30°S (using data from *da Silva et al*. [1994]) (Figure S5). Our results of cooler decadal mean SSTs in the FTR region during positive phases of the PDO are suggestive of the importance of this evaporative cooling mechanism on decadal timescales.

Heat gain in the upper water column since 1999 has been attributed to a strengthening of the Pacific Ocean shallow overturning cells during this most recent negative phase of the PDO [*Trenberth and Fasullo*, 2013;

Balmaseda et al., 2013; *England et al*., 2014]. The importance of subtropical areas in the oceans is also reflected in deep ocean heat content increases since 1955, where the subtropical latitudes have gained 2 to 3 times more heat than the tropics or higher latitudes [*Levitus et al*., 2012]. Although the location of the main center for subduction in the South Pacific shallow overturning cell is most likely southeast of the FTR region due to presence of more buoyant surface water in the SPCZ region [*Johnson and McPhaden*, 1999; *McPhaden and Zhang*, 2004], the correlation of FTR Sr/Ca SST and South Pacific 0–700 m OHC suggests that the processes controlling decadal changes in SST and OHC in this region are related.

There is a growing body of evidence indicating that decadal changes in trade wind strength in the Pacific are, in some decades, correlated with changes in OHC and also with the rate of rising global temperatures. Recently, *Thompson et al*. [2015] presented Mn/Ca results in a Tarawa Atoll coral on the equator in the central equatorial Pacific suggesting that the rapid rise in Earth surface temperatures from 1910 to 1940 C.E. was, in part, related to reduced westerly flowing trade winds and heat release from the upper water column in the Pacific in addition to external forcings. Instrumental data suggest that the opposite occurred in the late twentieth century. Following the shift to the PDO negative phase that began in 1999–2000, stronger trade winds have resulted in more intense upwelling of cooler water along the equator in the eastern Pacific and at the same time increasing the subsidence of salty North and South Pacific subtropical gyre surface waters [*Meehl et al*., 2013; *Trenberth and Fasullo*, 2013; *England et al*., 2014; *Trenberth et al*., 2014].

To evaluate the relationship between decadal changes in South Pacific SST and global temperatures, we extracted the decadal mode (sum of 20 to 80 year reconstructed components) from the Goddard Institute for Space Studies (GISS) Earth surface temperature data set using Singular Spectrum Analysis (Figure 2c). The FTR coral-based SST reconstruction shows that the 1940s interval of cooler South Pacific SST occurred during a time of relatively warm global temperatures. Furthermore, the cool SSTs and PDO positive phase that began in ~1976 was a time of more rapidly rising temperatures. At other times there is no clear relationship between decadal changes in South Pacific SST and decadal changes in earth surface temperatures, highlighting the many controlling factors on global temperatures. However, the cooler SSTs in the FTR region in the decades centered on 1940 and 1980 during times of more rapidly warming surface temperatures is consistent with the accumulating evidence that in some decades, weaker Pacific trade winds coincide with more rapidly rising global surface temperatures as the rate of heat uptake by the oceans is reduced [*Trenberth et al*., 2014; *England et al*., 2014; *Thompson et al*., 2015].

Finally, we evaluate the relationship of decadal SST variability in the South Pacific to interannual and decadal equatorial Pacific surface ocean variability. For an index of interannual oceanographic variability in the central equatorial Pacific, we generated an equatorial coral δ^{18}O composite from three *Porites* coral δ^{18}O time series from Fanning Atoll (4°N, 159°W), Palmyra Atoll (6°N, 162°W), and Maiana Atoll (1°N, 173°E) [*Urban et al*., 2000; *Cobb et al*., 2013] (hereafter called FPM) (Figure 3, top). Interannual variability in these equatorial Pacific δ^{18}O records has been shown to be primarily associated with ENSO related changes in SST with more minor salinity influence [*Nurhati et al*., 2009; *Cobb et al*., 2013]. Moreover, the effects of sea surface salinity and SST on coral δ^{18}O is additive for ENSO events in this region. The strong agreement between these three δ^{18}O records in the western and central equatorial Pacific indicates that this FPM composite is a robust record of ENSO variability in this region. The 9 year smoothed FPM δ^{18}O composite (Figure 3) indicates a weak decadal mode with a more significant trend toward lower δ^{18}O after 1976. Wavelet analysis (not shown) demonstrates that equatorial FPM δ^{18}O and South Pacific FTR Sr/Ca are not coherent at decadal timescales with only the 1976 shift occurring at a PDO-IPO phase boundary. This 1976 shift has been shown to result from warming and freshening at Fanning and Palmyra [*Nurhati et al*., 2009] and primarily warming at Butaritari (near Maiana) [*Carilli et al*., 2014].

There are three published *Porites* coral Sr/Ca records from the equatorial Pacific that can be used to evaluate decadal changes in equatorial SST: Jarvis Atoll (0°22.3′S, 159°59.0′W [*Thompson et al*., 2015]), Palmyra (5°52′N, 162°04′W [*Nurhati et al*., 2011]), and Butaritari (3°09′N, 172°48′E [*Carilli et al*., 2014]). In Figure 3 (bottom) we compared detrended, decadally smoothed versions of each since the Jarvis Sr/Ca data were only released in a detrended, 10 year smoothed format. All three records are inversely correlated with our FTR record with Jarvis displaying the highest correlation (FTR-Jarvis, $R = -0.73$, $p \leq 0.001$: FTR-Palmyra, $R = -0.33$, $p < 0.002$; FTR-Butaritari, $R = -0.48$, $p < 0.02$). This inverse correlation is expected based on the PDO-IPO signatures in each region. But the different correlations to FTR suggest regional differences in decadal SST in the central

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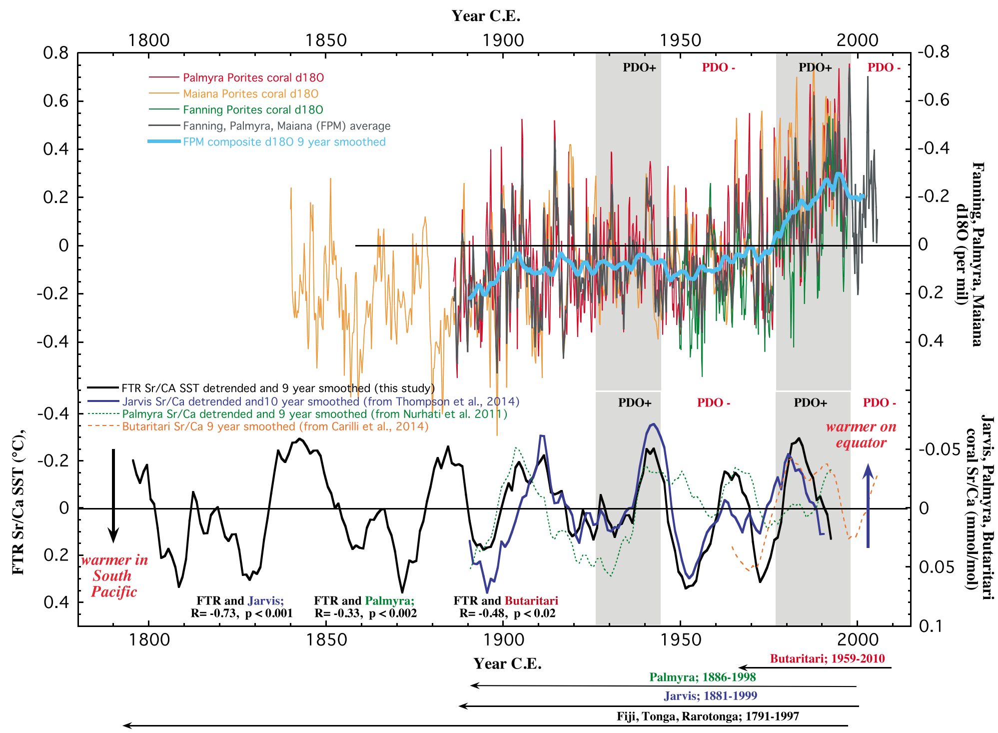

Figure 3. (top) Coral $\delta^{18}O$ records from the equatorial Pacific sites at Fanning [*Cobb et al.*, 2013], Palmyra [*Cobb et al.*, 2013], and Maiana [*Urban et al.*, 2000] along with the three-coral core $\delta^{18}O$ average (dark gray line) and the 9 year running average (blue line). (bottom) Fiji-Tonga-Rarotonga (FTR) coral Sr/Ca SST detrended and 9 year smoothed (black line) (note *y* axis is inverted) compared to decadal changes in coral Sr/Ca from Jarvis Atoll (in blue), Palmyra Atoll (in green), and Butaritari Atoll (in red). Jarvis coral Sr/Ca data (detrended and 10 year smoothed) from *Thompson et al.* [2015](blue line). Palmyra coral Sr/Ca (detrended and 9 year smoothed) from *Nurhati et al.* [2011]. Butaritari coral Sr/Ca (detrended and 9 year smoothed) from *Carilli et al.* [2014].

equatorial Pacific, perhaps related to spatial differences in equatorial upwelling with decadal changes in SST on the equator most highly (and inversely) correlated with the FTR region. The excellent correlation of Jarvis and FTR coral Sr/Ca SST, in particular, supports the use of coral Sr/Ca as a tracer of decadal SST changes at these open ocean sites. In addition, the FPM $\delta^{18}O$ and Jarvis, Palmyra, and Butaritari Sr/Ca records suggest that relatively large decadal signal in SST near the equator is muted in the coral $\delta^{18}O$ records perhaps due to the counteracting influences of SST and salinity.

A synthesis of these South Pacific and equatorial coral results in the context of recent findings on decadal climate change in the Pacific indicates that over the past century, decades of stronger trade winds during negative phases of the PDO result in elevated equatorial upwelling rates and cooler SST near the equator [e.g., *England et al.*, 2014; *Thompson et al.*, 2015]. At the same time, South Pacific SST warms as indicated by FTR Sr/Ca SST and upper ocean heat content in the South Pacific rises. Based on data from primarily the late twentieth century, *England et al.* [2014] proposed the link between increased trade winds, cool equatorial SSTs, intensified wind stress curl on either side of the equator, and a spin-up of the subtropical gyres to explain both the increase in subduction of warm subtropical water into the ventilated thermocline and also the increase in subsurface heat uptake in the Pacific. The coral-based SST results from FTR and the equatorial Pacific appear to document the importance of this process over the last 200 years.

In summary, our FTR results provide evidence that the decadal-scale changes in South Pacific SST have been a semiregular phenomenon since at least the 1790s with a mean period near 25 years. It appears likely that decadal SST changes in the North Pacific co-occur with those we observe in the South Pacific, but more paleorecords of the PDO will be needed to test this hypothesis. Decadal SST minima and maxima in the South Pacific are coincident with minima and maxima in South Pacific 0–700 m OHC suggesting that decadal changes in FTR Sr/Ca SST track decadal changes in heat storage in the upper water column. This relationship also provides support for the evaporative cooling mechanism for ocean-atmosphere heat exchange on decadal timescales. The longer visualization of decadal SST variability provided by our FTR record also has identified the early 1800s in the South Pacific as a time of unexplained elevated SST within error of SST in the late twentieth. The FTR and equatorial coral Sr/Ca SST records also suggests that when the PDO next reverses phase, South Pacific SSTs and OHC will decline and equatorial SSTs warm over approximately a decade as the net heat uptake from the atmosphere is reduced.

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Geophysical Research Letters

Supporting Information for

Decadal Changes in South Pacific Sea Surface Temperatures and the Relationship to the Pacific Decadal Oscillation and Upper Ocean Heat Content

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Introduction

The following is the site information and methods for the three coral Sr/Ca records from Fiji, Tonga and Rarotonga.

Site Information:

At Rarotonga, 3.5m of continuous coral core was collected from a massive colony of *Porites lutea* in 18.3m of water on the southwestern side of Rarotonga at 21°14'11"S, 159°49'59"W in April 1997 *(Linsley et al., 2000; 2004*). In Fiji, coral core (1F) was retrieved from a *P. lutea* colony growing at a depth of 10 m in the middle of Savusavu Bay on the south side of the island of Vanua Levu, Fiji in April 1997 (*Linsley et* *al., 2004*). At Ha'afera Tonga (19°56'S, 174°43'W), a large *P. lutea* colony with a dead flat top with live side surfaces was cored in November 2004 (*Wu et al, 2013; Linsley et al., 2008*). This colony was ~4 m high with ~1 m of water covering the top at low tide. Two coral cores TH1 Hole 4 (TH1-H4 hereafter) and TH1 Hole 5 (TH1-H5 hereafter) were collected from this colony. The 3.28m long core TH1-H4 was drilled from the dead top of the colony and the 67cm long core TH1-H5 was collected from the live side of the colony. Cores TH1-H4 and TH1-H5 were successfully spliced to form the Tonga core TH1 that was analyzed.

Analytical Methods:

All cores used for this study were cut into ~7mm thick slabs with a modified tile saw. The slabs were X-rayed with an HP cabinet X-ray system at 35kV for 90 seconds and the X-ray negatives were scanned to generate X-ray positives. X-ray collages of each core can be found in: Ren et al. (*2003*) for Rarotonga core 2R, in Linsley et al. (*2004*) for Fiji core 1F, and in Wu et al. (*2013*) for Tonga core TH1. Density bands and growth axes were visible on the X-ray positives allowing for the determination of sampling tracks and to look for signs of diagenesis. Prior to micro-sampling, the slabs were cleaned in deionized water in an ultrasonic bath for 30 minutes and then cleaned with a high-energy (500W, 20kHz) probe sonicator, also in a deionized water bath, for approximately 10 minutes on each slab face. The dried slabs were sampled using a low-speed microdrill with a 1mm round diamond drill bit along the maximum growth axis in tracks (U-shaped groves) parallel to corallite traces as identified in X-ray positives.

For core Fiji 1F and Rarotonga core 2R, 1mm increment samples were analyzed using a inductively coupled plasma atomic emission spectrophotometer (ICP-AES) at Harvard University to determine coral skeletal Sr/Ca (*Linsley et al., 2000; 2004; Schrag 1999*). The external precision is better than 0.15% (relative standard deviation, RSD) based on analyses of replicate samples (10% replicates). For Tonga core TH1, coral skeletal Sr/Ca measurements were made on samples collected at every-other 1 mm resolution (~5-7 samples per year)(see *Wu et al., 2013*). ~500 mg (±20 μg) of homogenized coral powder of each sample was dissolved in 2 mL Optima Grade HNO_3

in acid-cleaned microcentrifuge tubes to achieve 100 ppm of [Ca] per sample. These analyses were performed at Lamont-Doherty Earth Observatory using an inductively coupled plasma–optical emission spectrophotometer (ICP-OES) following a previously described technique (*Schrag 1999*) and optimized for the Lamont-Doherty ICP-OES (*Wu et al., 2013*). Long-term analysis of the JCp-1 coral standard (batch packaged October 2009) on this ICP-OES instrument has an RSD = 0.016%.

Chronology Development:

To develop an accurate chronology for Rarotonga core 2R and Fiji core 1F, we resolved the annual cycle with sub-seasonal Sr/Ca and $\delta^{18}O$ measurements taking great care to not miss any years at sampling track changes or at core breaks (*Linsley et al., 2000; 2004; 2008; Ren et al., 2003)*. The timing of known El Niño events was used to cross-check the chronology for each core. For Tonga core TH1 sub-seasonal $\delta^{18}O$ measurements were used to set the chronology back to 1944 C.E. (Linsley et al., 2008). The live top core was spliced onto to the top of the main core (with dead top) from the colonies central growth axis. Interannual variability in $\delta^{18}O$ indicated a clear match at 1982 between the bottom of the core with the live top and top of the central axis core as previously discussed (*Linsley et al., 2008*). This chronology was also cross-checked with Sr/Ca analyses on every-other 1mm samples and this sample resolution continued to the bottom of the core (*Wu et al., 2013*). The overlapped sections of all three corals extend back to 1791 C.E.

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Supplementary Figures:

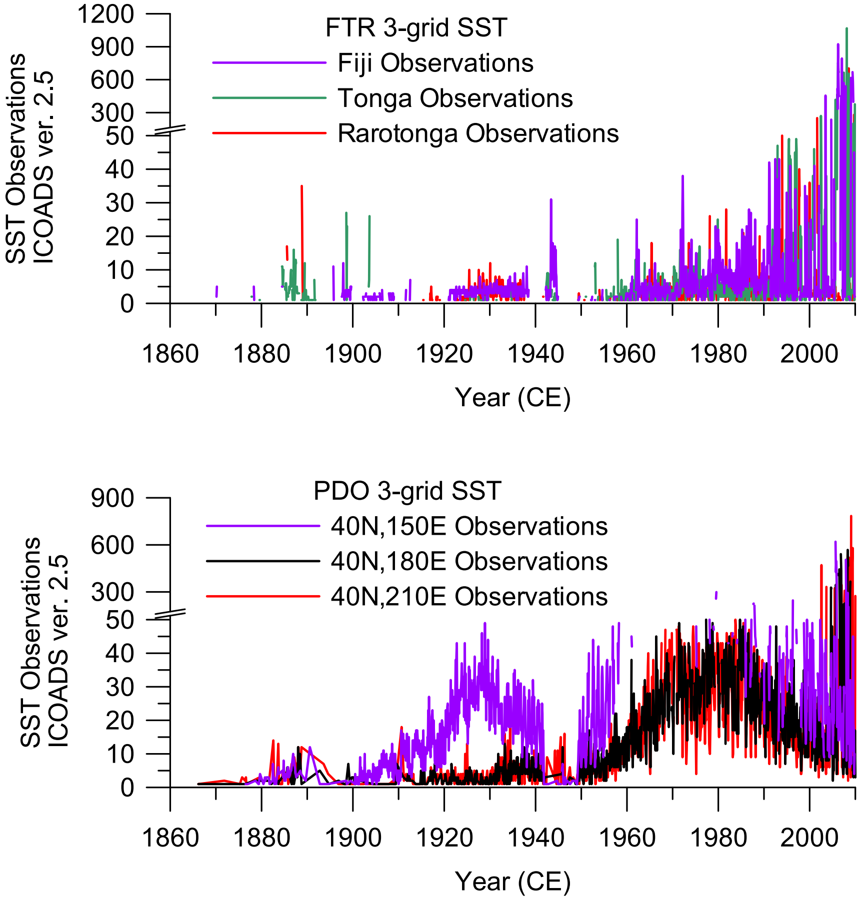

Figure S1: Number of total annual ICOADS SST measurements for the grids containing Fiji, Tonga and Rarotonga in the South Pacific (top) and three grids arrayed east to west along 40°N in the North Pacific (40°N, 210°E; 40°N, 180°E; 40°N, 150°E)(bottom). The North Pacific grid cells arrayed along 40°N are centrally located in the PDO sensitive region in the North Pacific. This highlights the overall lack of SST data to constrain key phase reversals of the PDO in 1924/25 and 1946/47.

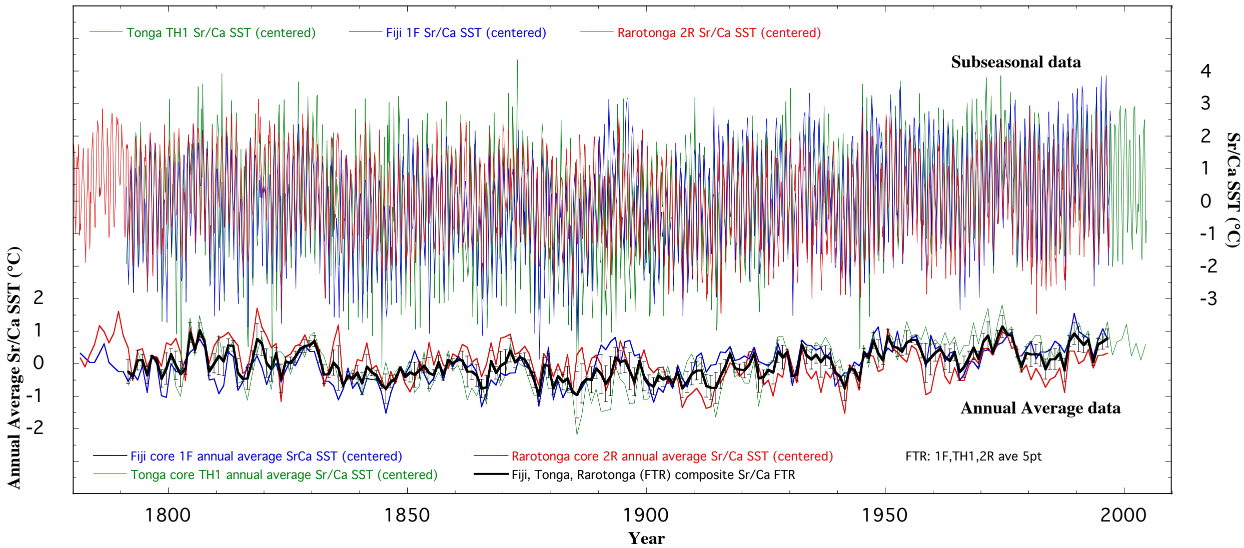

Figure S2: (top) Subseasonal Sr/Ca SST data from Fiji (blue), Tonga (green) and Rarotonga (red) based on sub-seasonal calibrations to SST. Data has been centered by removing the 1800-1997 C.E. average. (Bottom) Annually average Sr/Ca SST from the same three sites. Bold black line is the average with standard error (SE); where SE = (standard deviation of annual average / square root of n); where n = the number of cores in the FTR average for each year.

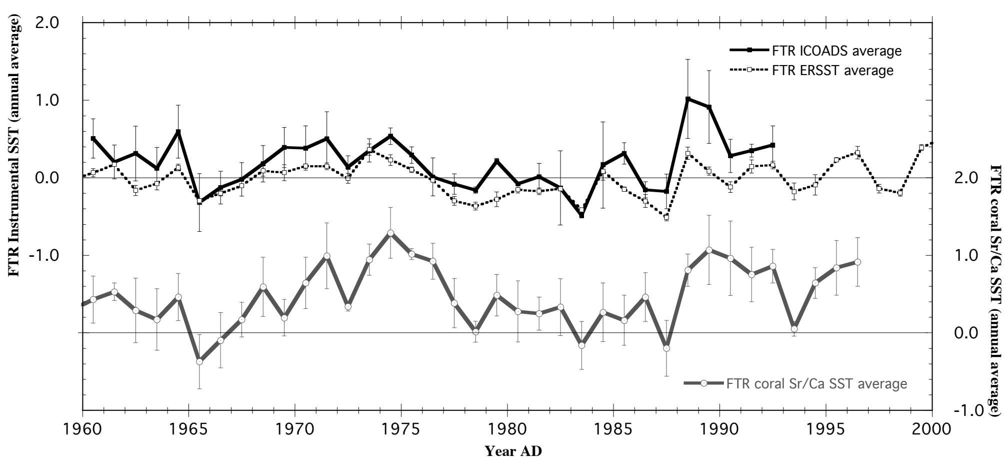

Figure S3: Comparison of annual average sea surface temperature (SST) data from ICOADS raw ship track data (bold solid line) and ERSST (*Rayner et al., 2003; Smith et al., 2008*) (dashed line) for the 2 x 2 grids including Fiji, Tonga, and Rarotonga to the annual average FTR coral Sr/Ca SST composite from the Fiji, Tonga and Rarotonga (bottom bold gray line). The standard error (SE) for each year is also shown. For the ICOADS data, only months with >3 SST measurements per month were used and only years with at least 4 months of data were used to make the annual averages.

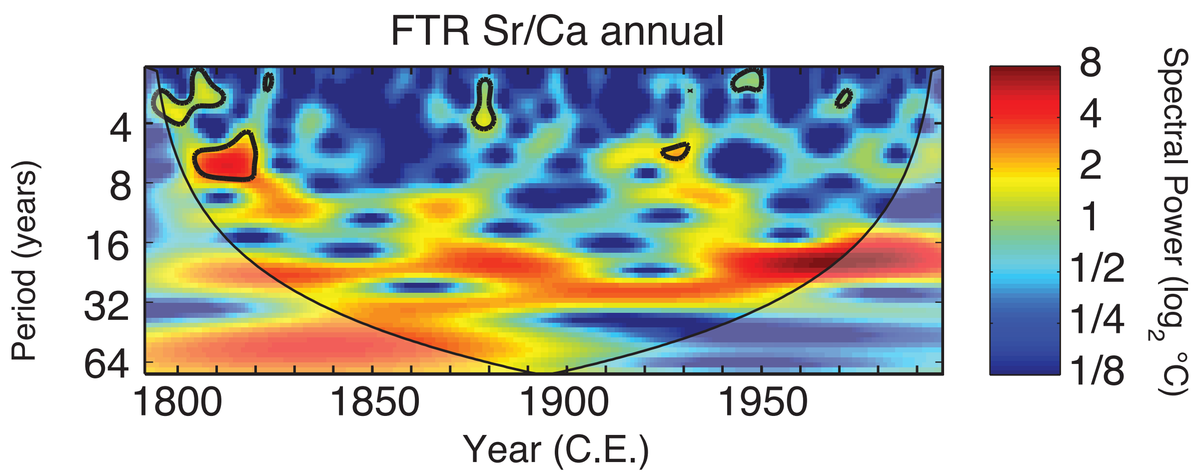

Figure S4: Wavelet spectra for the Fiji, Tonga and Rarotonga composite Sr/Ca SST time series. The thick black contours designate the 5% significance level against red noise. The cone of influence where edge effects might distort the periods and significance is shown as a lighter shade.

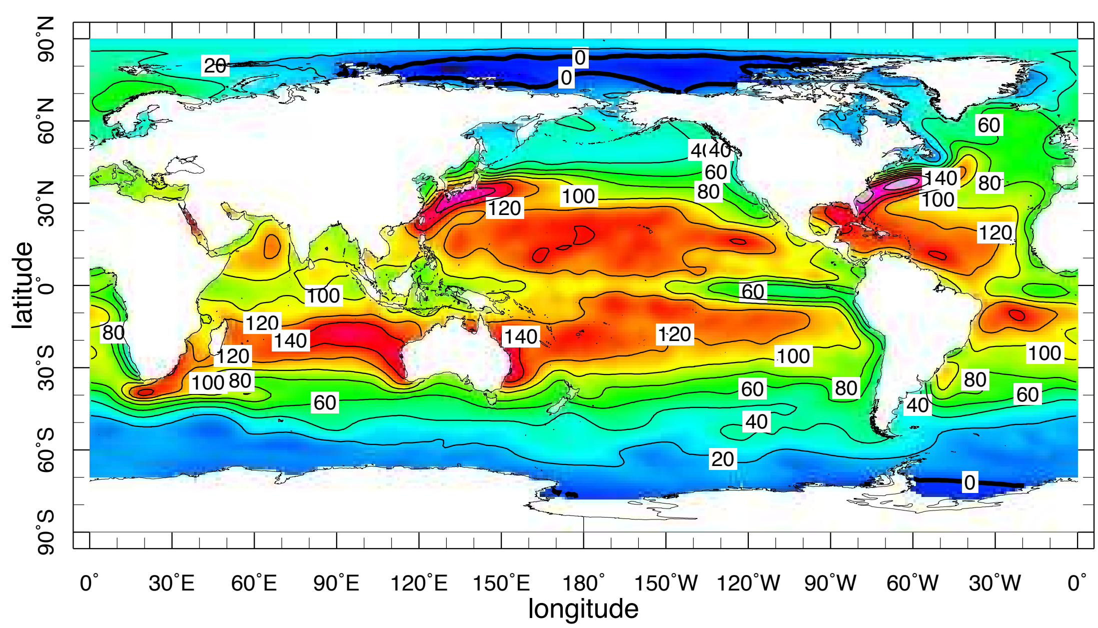

Figure S5: Climatology of latent heat flux (W/m^2) showing large regions of evaporative cooling indicated by elevated latent heat flux (red areas) in the subtropical South and North Pacific (from *daSilva et al., 1994*).

Supplemental Data ds01

ds01 Data File Name: Linsley et al., 2015 GRL data supplement.xls

Data File Description:
Coral Sr/Ca data used to make the Fiji. Tonga, Rarotonga (FTR) Sr/Ca SST composite is included in the supplement. The file includes the annually averaged Sr/Ca derived SST data as well as the seasonal scale (6 points per year) Sr/Ca mmol/mol data used to make the annual averages. The annual averaged data for each site was centered by subtracting the 200 year average SST. This corrected for small differences in mean annual temperature at each site. The FTR composite is the average of the annually resolved, centered Sr/Ca SST data from each site. The standard error of the FTR composite is also in the data file. The file also contains the coral $\delta^{18}O$ data from Fanning (*Cobb et al., 2013*), Palmyra (*Cobb et al., 2013*) and Maiana (*Urban et al., 2000*) used to make the three-coral core equatorial ENSO index shown in Figure 3.