Geochemistry Geophysics Geosystems G3

Article
Volume 14, Number 5
17 May 2013
doi:10.1029/2012GC004293
ISSN: 1525-2027

Published by AGU and the Geochemical Society

Oceanographic variability in the South Pacific Convergence Zone region over the last 210 years from multi-site coral Sr/Ca records

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[1] In the South Pacific Convergence Zone (SPCZ), the variability in a sub-seasonally resolved microatoll *Porites* colony Sr/Ca record from Tonga and a previously published high-resolution record from Fiji are strongly influenced by sea surface temperature (SST) over the calibration period from 1981 to 2004 ($R^2 = 0.67$–0.68). However, the Sr/Ca-derived SST correlation to instrumental SST decreases back in time. The lower frequency secular trend (~1°C) and decadal-scale (~2–3°C) modes in Sr/Ca-derived SST are almost two times larger than that observed in instrumental SST. The coral Sr/Ca records suggest that local effects on SST generate larger amplitude variability than gridded SST products indicate. Reconstructed $\delta^{18}O$ of seawater ($\delta^{18}O_{sw}$) at these sites correlate with instrumental sea surface salinity (SSS; $r = 0.64$–0.67) but not local precipitation ($r = -0.10$ to -0.22) demonstrating that the advection and mixing of different salinity water masses may be the predominant control on $\delta^{18}O_{sw}$ in this region. The Sr/Ca records indicate SST warming over the last 100 years and appears to be related to the expansion of the western Pacific warm pool (WPWP) including an increasing rate of expansion in the last ~20 years. The reconstructed $\delta^{18}O_{sw}$ over the last 100 years also shows surface water freshening across the SPCZ. The warming and freshening of the surface ocean in our study area suggests that the SPCZ has been shifting (expanding) southeast, possibly related to the southward shift and intensification of the South Pacific gyre over the last 50 years in response to strengthened westerly winds.

Components: 12,748 words, 10 figures, 3 tables.

Keywords: *Porites* coral; Sr/Ca; sea surface temperature; South Pacific Convergence Zone.

Index Terms: 0473 Biogeosciences: Paleoclimatology and paleoceanography (3344, 4900); 4954 Paleoceanography: Sea surface temperature; 4220 Oceanography: General: Coral reef systems (4916).

Received 20 June 2012; **Revised** 1 November 2012; **Accepted** 20 November 2012; **Published** 17 May 2013.

Wu, H. C., B. K. Linsley, E. P. Dassié, B. Schiraldi Jr., and P. B. deMenocal (2013), Oceanographic variability in the South Pacific Convergence Zone region over the last 210 years from multi-site coral Sr/Ca records, *Geochem. Geophys. Geosyst.*, *14*, 1435–1453, doi:10.1029/2012GC004293.

1. Introduction

[2] Tropical sea surface temperature (SST) is an important parameter influencing the global moisture budget through its impact on the position of the convective Intertropical Convergence Zone (ITCZ) and its effect on ocean atmosphere interactions. In the southwestern Pacific basin, the South Pacific Convergence Zone (SPCZ) is the largest spur of the main ITCZ extending from the equator southeast from ~160°E to 140°W in the southwestern Pacific [*Kiladis et al.*, 1989; *Vincent*, 1994]. The SPCZ is also the only permanent ITCZ feature in the Southern Hemisphere. Seasonally, the SPCZ rainfall maximum shifts north during winter and south during austral summer [*Vincent*, 1994] (Figures 1A and 1B). Located at the southeastern edge of the SPCZ, the waters of the Republic of Fiji and Kingdom of Tonga (~15°S to ~21°S and ~174°W to ~177°E) are not only influenced by changes in the position of the SPCZ but also affected by the seasonally shifting surface ocean salinity front (Figures 1C and 1D) that separates the warm/fresher waters in the northwest from the cool/saline waters in the southeast and east [*Halpert and Ropelewski*, 1992; *Yan et al.*, 1992; *Delcroix and McPhaden*, 2002].

[3] Interannual changes in the western Pacific warm pool (WPWP) position are directly tied to the phase of El Niño/Southern Oscillation (ENSO) [*Trenberth*, 1976; *Folland et al.*, 2002]. In the SPCZ region, the axis of maximum rainfall is known to shift northeast during El Niño (EN) events and southwest during La Niña (LN) events [*Salinger et al.*, 2001; *Folland et al.*, 2002; *Gouriou and Delcroix*, 2002; *Cravatte et al.*, 2009; *Vincent et al.*, 2009; *Cai et al.*, 2012]. Depending on the phase of ENSO, the position of the surface ocean salinity front on the southeastern edge of the SPCZ generally changes; during an EN event, it will shift to the west, while during a LN event, it will shift back to the east. The southeastern edge of the SPCZ is also subjected to large-scale decadal-interdecadal variability [*Trenberth and Hurrell*, 1994; *McPhaden and Zhang*, 2002; *Linsley et al.*, 2000, 2004, 2008; *Cai et al.*, 2012]. The Interdecadal Pacific Oscillation (IPO) is the Pacific-wide recurring pattern of ocean-atmospheric variability in which the central gyres of the Pacific cool (warm) and the eastern margin warms (cools), during the positive (negative) phases [*Folland et al.*, 2002; *Delcroix et al.*, 2007]. The alternating phases of the IPO can last for multiple decades with IPO positive (negative) phases often coinciding with an increase in the relative frequency of EN (LN) events [*Salinger et al.*, 2001].

[4] One of the least well-understood modes of oceanographic variability is centennial-scale change in SST, sea surface salinity (SSS), and ocean circulation. Massive hermatypic *Porites* sp. corals are uniquely suited to potentially evaluate these secular trends in the tropics and subtropics over the last several hundred years. *Porites* sp. corals offer precise sub-seasonal scale chronologic age control and well-calibrated tracers of temperature and salinity in their skeletons [e.g., *Druffel*, 1997; *Gagan et al.*, 2000; *Corrège*, 2006]. In particular, *Porites* sp. coral skeletal Sr/Ca has been shown to correlate well with SST in many oceanic settings [e.g., *Smith et al.*, 1979; *Beck et al.*, 1992; *Linsley et al.*, 2000; *Nurhati et al.*, 2009; and many others].

[5] However, various issues and effects such as the seasonal variability of seawater Sr/Ca [*Shen et al.*, 1996] and coral growth-related effects on Sr/Ca have been reported [*de Villiers et al.*, 1994; 1995; *Cohen et al.*, 2001; *Alibert and Kinsley*, 2008]. Recently described temperature dependencies and variations of Sr/Ca in coral skeleton over daily, seasonal, and interannual timescales [*Gaetani et al.*, 2011] further explain why calibration equations to SST are highly variable among individual corals. In addition, *Gagan et al.* [2012] reported significant bio-smoothing of geochemical tracers in *Porites* that lead to underestimates of the true amplitude of water temperature and/or salinity variability over time. This effect could explain reported issues of muted regression slopes between monthly SST and near-monthly Sr/Ca over the modern calibration interval. These lower Sr/Ca-SST slopes result in unrealistically large SST secular trends [*Linsley et al.*, 2006; *Alibert and Kinsley*, 2008]. Furthermore, post depositional skeletal changes such as the formation of secondary aragonite and skeletal micro-dissolution can affect Sr/Ca records [*Enmar et al.*, 2000; *Mueller et al.*, 2001; *McGregor and Gagan*, 2003; *Quinn and Taylor*, 2006; *Allison et al.*, 2007; *Hendy et al.*, 2007; *Nothdurft et al.*, 2007; *McGregor and Abram*, 2008]. To further complicate inter-colony

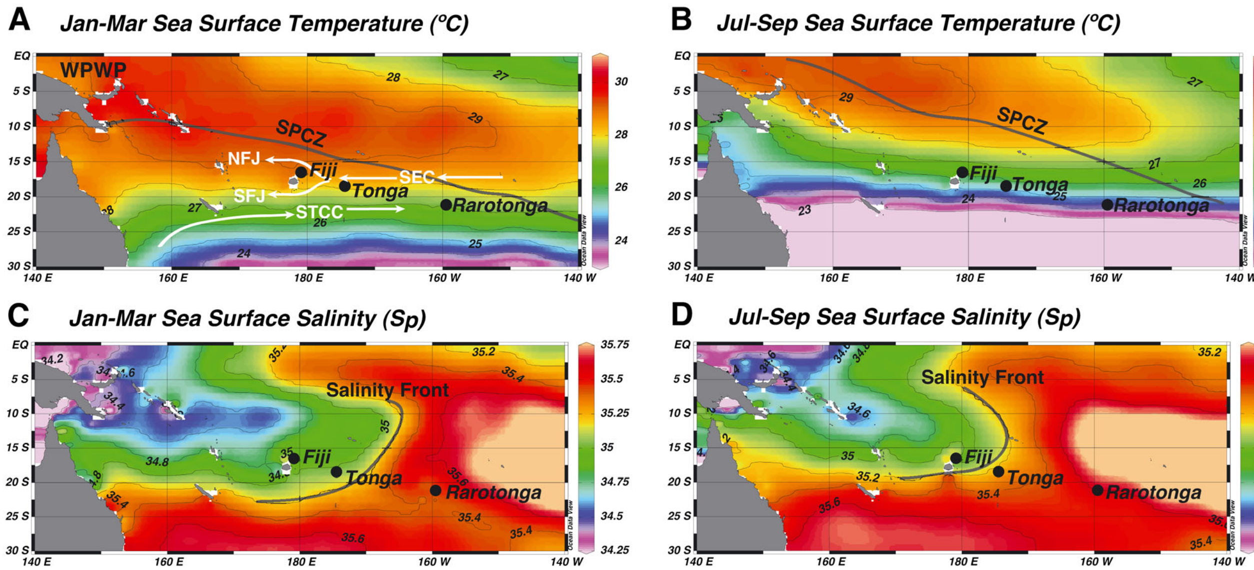

Figure 1. The microatoll *Porites lutea* coral sampling location (Kingdom of Tonga; 19.5°S, 174.4°W) of this study in the South Pacific Convergence Zone (SPCZ) in relation to previously published SPCZ *Porites* sp. coral Sr/Ca records (Republic of Fiji core 1 F (16.5°S, 179.14°E) [*Linsley et al*., 2006] and Rarotonga core 2R (21.14°S, 159.47°W) [*Linsley et al*., 2000, 2004]). The top panels (A and B) depict sea surface temperature (°C), and the bottom panels (C and D) are sea surface salinity (S_p) from the World Ocean Atlas 2009 [*Antonov et al*., 2010; *Locarnini et al*., 2010]. The mean surface conditions of austral summer (January–March) are the left panels, and the mean surface conditions of austral winter (July–September) are the right panels. The major currents and jets affecting the region (South Equatorial Current, SEC; Subtropical Counter Current, STCC; North Fiji Jet, NFJ; and South Fiji Jet, SFJ) are depicted in panel A as well as the position of the seasonally shifting salinity front between Fiji and Tonga marked on panels C and D.

Sr/Ca comparisons across sites and regions, interlaboratory differences due to differences in instrumentation, internal calibration, and methodology have also been described [*Corrège*, 2006].

[6] To document past lower frequency oceanographic variability in the western South Pacific, we have been analyzing cores from massive corals with the goal of replicating the down-core geochemical variability. In this contribution, we present a bimonthly resolved Sr/Ca record of a *Porites lutea* microatoll colony from Tonga (1792–2004) as part of a unique regional network of coral Sr/Ca time series arrayed along a northwest-southeast transect at the edge of the SPCZ. In this region, the South Equatorial Current (SEC) is broken up into a series of westward flowing jets as it passes through the archipelagos of Tonga and Fiji (Figure 1A). Our goals are as follows: (a) to assess the utility and reproducibility of *Porites* Sr/Ca in a relatively small region of the southwestern Pacific including a microatoll as proxy of SST, (b) to compare these Sr/Ca time series to other *Porites* Sr/Ca records from the SPCZ, (c) to use gridded instrumental sea surface salinity (SSS) time series from the SPCZ [*Delcroix et al*., 2011] to evaluate how well δ^{18}O of seawater ($\delta^{18}O_{sw}$) calculated from coral skeletal δ^{18}O and Sr/Ca correlates with SSS and rainfall, and finally (d) to evaluate the significance of longer-term lower frequency variability (decadal-scale patterns) and secular trends in reconstructed SST and $\delta^{18}O_{sw}$ in this region over the last two centuries.

2. Materials and Methods

[7] Sequential coral skeletal samples were microdrilled from two cores collected in November 2004 from a single *P. lutea* microatoll colony (TH1) growing near the island of Ha'afera in central Tonga (19°56′S, 174°43′W; Figure 1). The colony was 4 m high and growing at ~1 m below the surface at low tide. The morphology of this colony makes it a microatoll due to its discoid-shaped outward growth resulting from the shallow water depth that restricts its vertical extension [*Stoddart and Scoffin*, 1979]. A 3.28 m long core extending from the dead top surface along the central growth axis and a 67 cm long core from the live lateral surface of the colony were collected [*Linsley et al*., 2008]. *Linsley et al*. [2008] spliced together a continuous skeletal δ^{18}O ($\delta^{18}O_c$) record of the TH1 cores using the timing of known EN events that both confirmed the methodology and agreed with other studies' usage of *Porites* microatolls [*Woodroffe and Gagan*, 2000; *McGregor et al*., 2011].

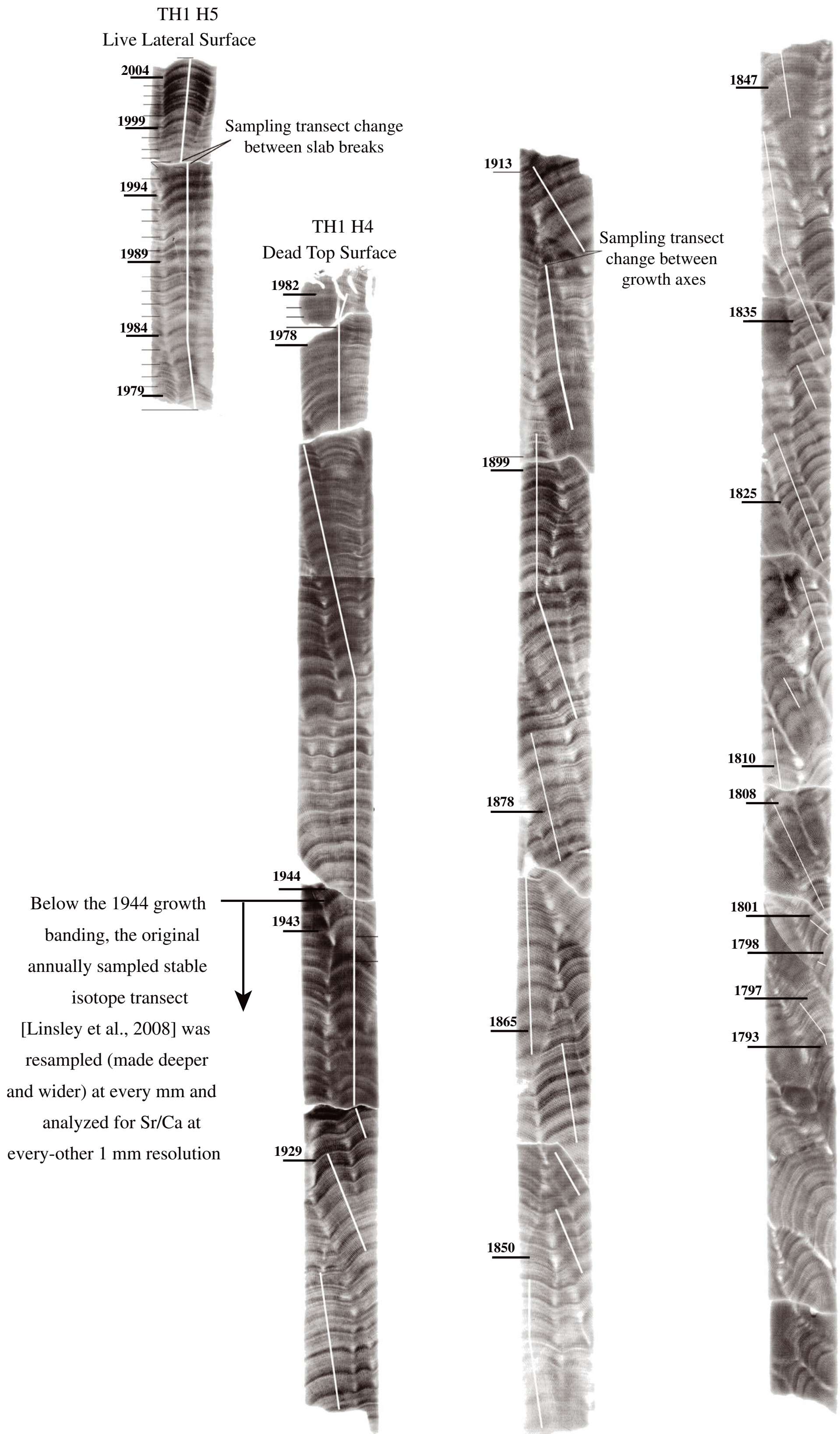
TH1 H5
Live Lateral Surface
2004
1999
1994
1989
1984
1979
Sampling transect change between slab breaks
TH1 H4
Dead Top Surface
1982
1978
1944
1943
1929
Below the 1944 growth banding, the original annually sampled stable isotope transect [Linsley et al., 2008] was resampled (made deeper and wider) at every mm and analyzed for Sr/Ca at every-other 1 mm resolution
1913
Sampling transect change between growth axes
1899
1878
1865
1850
1847
1835
1825
1810
1808
1801
1798
1797
1793

Figure 2

[8] TH1 coral cores were cut into ~7 mm thick slabs along the major growth axis using a tile saw, cleaned in deionized water in an ultrasonic bath (15 min) and with a probe sonicator (500 W, 20 kHz) for 6 min per side, and air-dried at room temperature. X-radiographs of the slabs reveal the density banding and growth geometry (Figure 2). Sampling tracks along the maximum growth axes were determined using the X-radiograph images, and powder sub-samples were taken at 1-mm intervals for the entire core using a micro-drill with a 1-mm round diamond drill bit (Figure 2).

[9] Coral skeletal Sr/Ca ratios were measured on samples at every other 1 mm resolution or ~5–7 samples per year based on a mean annual extension rate of 15.29 ± 2.78 mm year^{-1}. Sr/Ca measurements from 1944 to 2004 were determined on the same sample powders analyzed by *Linsley et al.* [2008] for $\delta^{18}O_c$. Sr/Ca measurements before 1944 are from new coral powder samples collected by re-drilling the same sampling transects used in *Linsley et al.* [2008] for annual $\delta^{18}O_c$ samples. The transects were made slightly deeper and wider to collect enough powder for replicate analysis (Figure 2). Approximately, 500 ± 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 concentration. The analyses were performed at Lamont-Doherty Earth Observatory using an inductively coupled plasma-optical emission spectrometer (ICP-OES), following the technique described in detail by *Schrag* [1999] and modified for the Lamont-Doherty ICP-OES [*Wu*, 2010]. Replicate coral sample measurements ($n = 115$) indicate precision better than ± 0.041 mmol/mol (relative standard deviation of 0.45%). Repeat measurements of laboratory consistency standards ($n = 193$) demonstrated analytical precision better than ± 0.047 mmol/mol (relative standard deviation of 0.48%).

[10] The TH1 coral chronology was completed in two parts. For post-1970 samples, the chronology was based on the depths of annual skeletal density bands (high-density banding secreted in the warmest times of each year (February/March) coinciding with maximum SST) and the timing of sub-seasonal Sr/Ca variability tuned to instrumental SST. For samples prior to 1970, the chronology was based on annual density banding and by setting annual minimum Sr/Ca to February (average month of maximum SST) and annual maximum Sr/Ca value to August (average month of minimum SST). The final age model for core TH1 Sr/Ca from 1791 to 2004 is identical to that developed using the annual $\delta^{18}O_c$ record by *Linsley et al.* [2008]. Sub-seasonal age estimates were linearly interpolated to six points per year (bimonthly) based on the new Sr/Ca results using the ARAND software package TIMER program [*Howell et al.*, 2006].

[11] Coral Sr/Ca-SST calibration is first established at bimonthly resolution using the 1° latitude by 1° longitude gridded Reynolds-Smith Optimum Interpolated SST version 2 (Reynolds-Smith OI-SST) from 1981 to 2004 [*Reynolds et al.*, 2002]. We applied Least Square Linear Regression calibration to facilitate comparison to the many published *Porites* Sr/Ca-SST relationship slopes [*Corrège*, 2006]. Additionally, an annualized Sr/Ca calibration to annual average Reynolds-Smith OI-SST is established to test the two different Sr/Ca-SST calibrations. Making the assumptions that coral Sr/Ca variability is entirely due to SST variability and that $\delta^{18}O_c$ variability is due to SST and $\delta^{18}O_{sw}$ variability, we calculated $\delta^{18}O_{sw}$ using Sr/Ca and $\delta^{18}O_c$ based on the method of *Ren et al.* [2002].

3. Results and Discussion

3.1. Intra-colony Sr/Ca Variability of a *Porites* Microatoll From Tonga

[12] Despite a very shallow water depth habitat, *Porites* microatolls have been utilized to reconstruct past sea levels and also to generate high-resolution regional paleoclimate records [*Woodroffe and McLean*, 1990; *Woodroffe and Gagan*, 2000; *McGregor et al.*, 2011]. The Tonga TH1 colony had a dead, flat, bio-eroded top with live tissue on the lateral edges and down the sides. *Linsley et al.* [2008] showed that colony TH1 did not exhibit differing degrees of oxygen isotopic disequilibrium between the $\delta^{18}O_c$ records of the distal (top maximum growth axis) and lateral growing surfaces [*McConnaughey*, 1989]. *Linsley et al.* [2008]

Figure 2. X-ray collage of the Tonga microatoll colony with cores TH1-H4 (dead top surface) and TH1-H5 (live lateral surface). Oxygen isotopic ($\delta^{18}O$) from this coral core was originally presented in *Linsley et al.* [2008] at millimeter scale from 1944 to 2004 A.D. and at annual average resolution below. For this new study, we re-sampled the core at 1 mm intervals below 1944 A.D. The original annual-scale sampling transect was re-sampled at every 1 mm by deepening and widening the sampling transect for the every other 1 mm Sr/Ca analysis of this study. The chronology is based on the combination of the stable isotope data [*Linsley et al.*, 2008], density banding, and the new Sr/Ca data. The data from TH1-H5 are spliced together with data from TH1-H4.

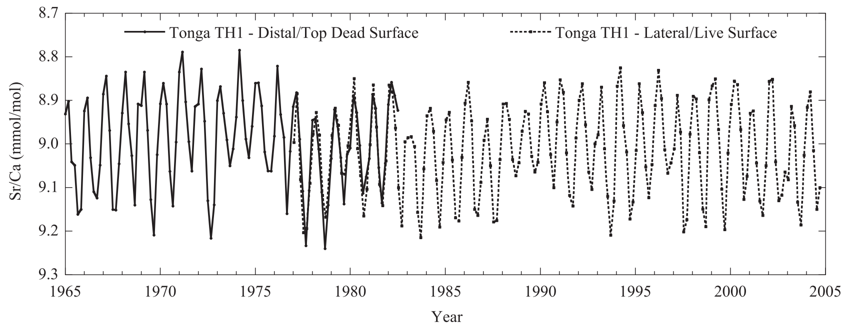

Figure 3. Two separate coral cores collected at Ha'fera, Tonga, from a microatoll *P. lutea* colony, sub-sampled at every millimeter, and analyzed at every other millimeter by ICP-OES. The intra-colony Sr/Ca records through the overlapping period of 1977–1982 display no significant difference in mean (Sr/Ca = 9.01 − 9.02 ± 0.10 mmol/mol) and in agreement ($r = 0.71$; $p < 0.001$) between lateral/live surface (dash) and distal/top dead surface (solid). The procedure enabled us to merge and integrate the two separate cores' (one live with growth tissue and another with dead central growth axis with a floating time window) geochemical records by splicing it together into a single continuous record designated Tonga TH1. This splicing agreed with the previously splicing done with only coral $\delta^{18}O$ data [*Linsley et al*., 2008].

generated a continuous $\delta^{18}O_c$ record spanning 1790–2004 (near-monthly from 1945 to 2004 and annual average from 1790 to 1944) by splicing data from a short core collected on the live growing lateral edge onto the floating time series generated from a core collected from the dead central growth axis. TH1 Sr/Ca record developed from the two cores was spliced together with the year of calcification of the dead surface determined to be 1982 and overlapped from 1977 to 1982 (Figures 2 and 3). Our new Sr/Ca results reinforces the use of *Porites* microatolls for SST reconstructions as the intra-colony mean Sr/Ca values from the overlapping lateral and central axis surfaces are almost identical (mean = 9.015 ± 0.102 mmol/mol and 9.019 ± 0.100 mmol/mol). The intra-colony overlap of the five annual cycles highly correlates ($r = 0.71$, $p < 0.001$) and shows no significant offset (Figure 3) demonstrating the accuracy and usefulness of this type of *Porites* coral to splice together long time series paleoclimate reconstructions.

3.2. Comparison of Different Sr/Ca Analytical Resolutions in *Porites* Corals

[13] One often-invoked criticism of every other 1 mm analysis is the possible aliasing effect on SST (or other seasonally varying climate parameter) calibration. This effect can potentially underestimate the entire magnitude of annual SST variability compared to the 1 mm analysis. The Tonga TH1 bimonthly Sr/Ca record (every other 1 mm) actually contains larger seasonal amplitudes (0.29 mmol/mol) than that of monthly Fiji 1F (0.19 mmol/mol, analyzed every 1 mm; Figure 4). This difference is in part due to the fact that Fiji lies closer to the edge of the WPWP than Tonga causing it to experience smaller amplitude annual SST fluctuations (Figure 1).

[14] For comparing the bimonthly Sr/Ca records from Tonga to the monthly record from Fiji, we interpolated the latter into a bimonthly resolved time series (Figure 4A). This procedure produces a departure (0.02 mmol/mol) of the maximum Sr/Ca during winter and spring, with higher values for the monthly record. Since the departure is within the average measurement error (±0.04 mmol/mol) and average standard deviation (±0.05 mmol/mol), it is unlikely that the conversion aliases the reconstruction. Correlation between bimonthly Fiji 1F and bimonthly Tonga TH1 was high ($r = 0.70$) with a significant relationship ($p < 0.001$). This comparison between Tonga TH1 and Fiji 1F indicates that there is no significant loss in the skill of capturing the entire annual cycle or aliasing the annual signal when analyzing every other 1 mm samples in *Porites* corals growing at ~1.0 to 1.5 cm yr^{-1}.

3.3. Coral Sr/Ca Reproducibility and Calibrations to SST

[15] Some high-resolution coral Sr/Ca results from different coral colonies living in the same location have indicated inter-colony offsets in mean Sr/Ca [*Alibert and McCulloch*, 1997; *Bagnato et al*., 2004; *Corrège*, 2006; *DeLong et al*., 2007]. These differences have been attributed to growth rate differences, species/subspecies effects, inter-laboratory differences, and water depth differences [e.g., *Weber*, 1973; *Marshall and McCulloch*, 2002; *Bagnato et al*., 2004; *Cohen and Hart*, 2004; *Corrège*, 2006; *DeLong et al*., 2007; *Saenger et al*., 2008]. In this study, mean TH1 Sr/Ca (1792–2004) equals 9.06 mmol/mol (standard deviation, SD = ±0.123) with a mean offset of 0.06 mmol/mol from Fiji 1F (1792–1997; mean Sr/Ca = 9.12 mmol/mol, SD = ±0.081; Figure 5A).

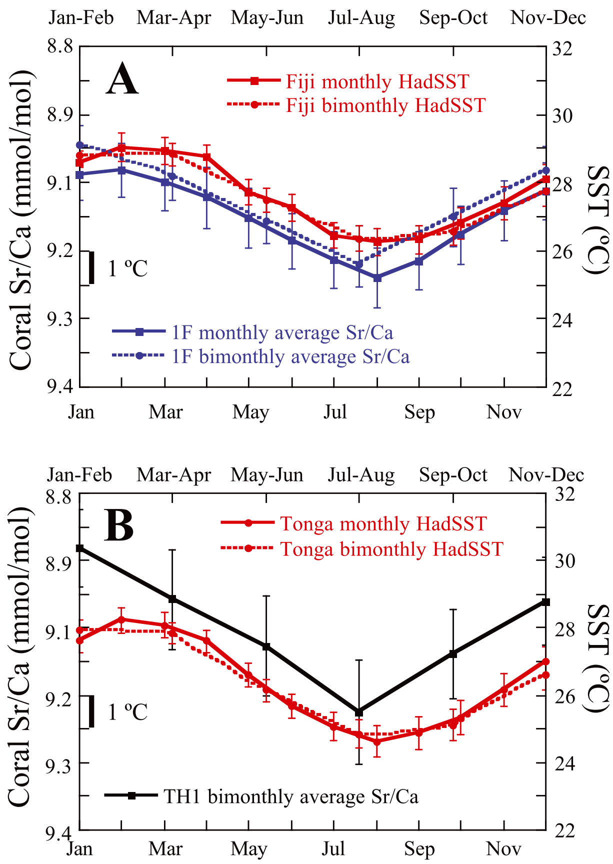

Figure 4. (A) Monthly (solid blue) and bimonthly (dashed blue) mean Fiji 1F colony (sampled at every millimeter) in comparison to monthly (solid red) and bimonthly (dashed red) mean of 1° × 1° grid Hadley Centre Sea Ice and Sea Surface Temperature version 1 (HadSST) [*Rayner et al.*, 2003] at Fiji between 1950 and 1997, a time period with the most-accurate instrumental SST. (B) Comparison of the bimonthly mean Tonga TH1 colony (black) sampled at every other millimeter to monthly (solid red) and bimonthly (dashed red) Tonga HadSST over the period between 1950 and 2004.

[16] The difference between Tonga TH1 and Fiji 1 F mean Sr/Ca cannot be due to analytical resolution (discussed in section 3.2) or inter-laboratory offsets (Linsley et al., 2006). This inter-colony offset is peculiar because Tonga located at ~20°S generally experiences cooler SST conditions than Fiji (Figures 1A and 1B). Thus, the corals of Tonga should contain higher Sr/Ca values. However, the higher Sr/Ca values were recorded in the Fiji 1F coral instead of Tonga TH1 (Figure 5A). Possible explanation for this includes the water depth difference of coral collection sites with the top of colony TH1 near ~1 m at low tide and Fiji 1F at 10 m water depth. Although we lack in situ water temperature measurements at Fiji and Tonga, the amplitude of the annual cycle recorded by in situ temperature measurements made at Rarotonga by a temperature logger placed into an exposed reef front at 18 m depth is identical to gridded weekly Reynolds-Smith OI-SST (Figure 5B). This provides more confidence that the first 20 m of the water column at these open-water locations in the SPCZ are well mixed and that water depth difference is likely not the reason for the Sr/Ca offset between Fiji 1F and Tonga TH1. It is highly possible that growth mechanisms and effects [*Cohen et al.*, 2004; *Goodkin et al.*, 2007] contributed to the inter-colony offset even though both corals appear to be *P. lutea*. Cryptic genetic differences of the same species [*Forsman et al.*, 2009] could also have caused this offset, but this issue is beyond the scope of this study.

[17] The calibration of bimonthly Tonga TH1 Sr/Ca to bimonthly Reynolds-Smith OI-SST (centered on 19.5°S, 174.5°W over the period of November/December 1981 to September/October 2004) has an $R^2 = 0.68$. A similar degree of correlation ($R^2 = 0.67$) is found between bimonthly Fiji 1F Sr/Ca to bimonthly Reynolds-Smith OI-SST (centered on 16.5°S, 179.5°E over the period of November/December 1981 to January/February 1997). The calculated sensitivities of -0.062 mmol/mol°C^{-1} for Tonga TH1 and -0.058 mmol/mol°C^{-1} for Fiji 1F are within the published sub-seasonal calibration range of *Porites* Sr/Ca-SST sensitivities [*Corrège*, 2006] (Figure 5C; Table 1). With these calibrations, the offset between Sr/Ca at Fiji and Tonga (0.06 mmol/mol, Figure 5A) equates to a temperature difference of ~1°C. Annualized Sr/Ca data calibrated to annual Reynolds-Smith OI-SST over the same calibration period as the bimonthly calibrations were not as high ($R^2 = 0.30$–0.34) with calibration relationships lying outside the sub-seasonal range suggested by *Corrège* [2006] (Table 1).

3.4. Reproducibility of Sr/Ca-SST Reconstructions and Verification to Hadley SST

[18] Over the verification period of 1950–2004 for Tonga (Figure 6A) and of 1950–1997 for Fiji (Figure 6C), bimonthly coral Sr/Ca-derived SST time series are significantly correlated to bimonthly 1° × 1° gridded Hadley Centre Sea Surface Temperature version 1 (HadSST) [*Rayner et al.*, 2003] (TH1, $r = 0.79$, $p < 0.001$; 1F, $r = 0.76$, $p < 0.001$). A likely contributing factor to the high correlations of bimonthly Sr/Ca-derived SST and bimonthly HadSST comes from the chronology development method employed by tuning Sr/Ca peaks to the

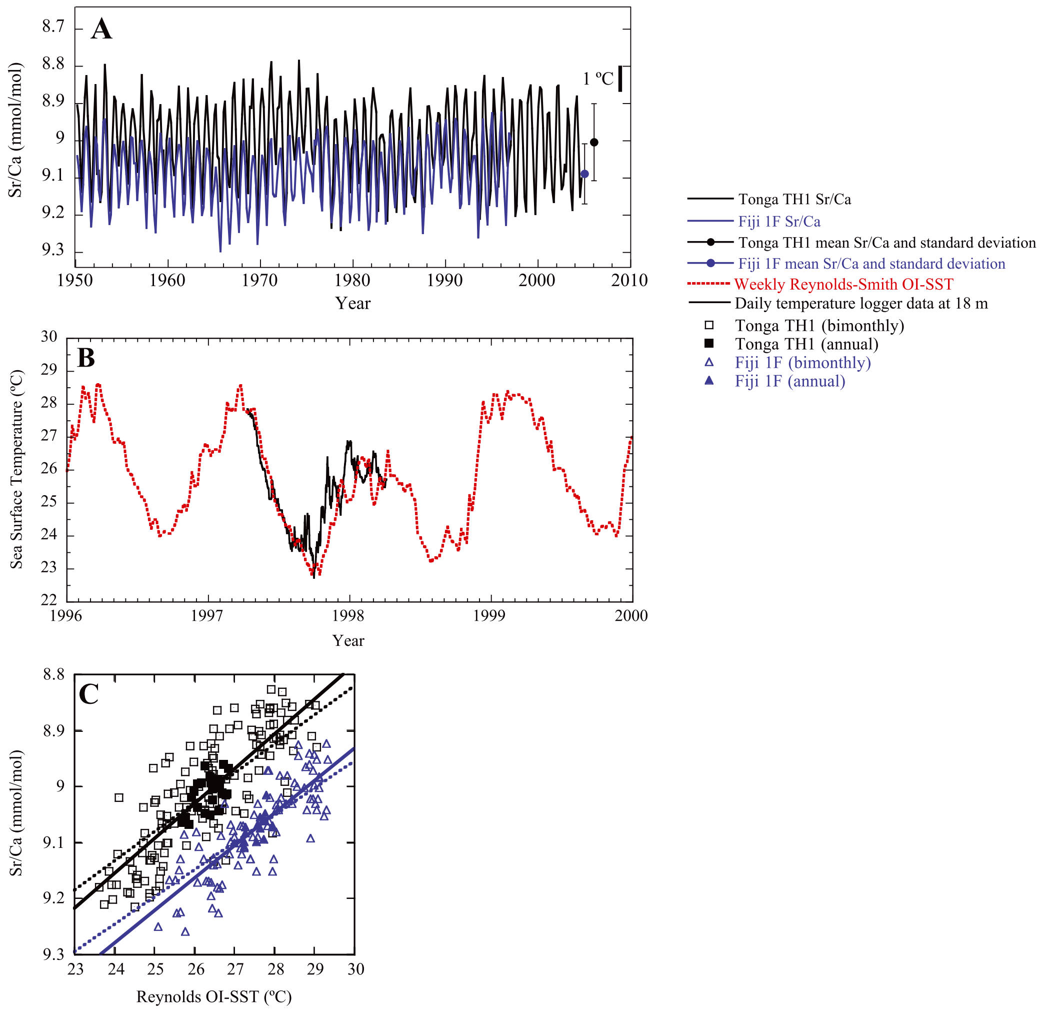

Figure 5. (A) Inter-colony Sr/Ca offset (1950–2004 section shown) between Tonga TH1 (black; analyzed at every other millimeter resolution; mean = 9.06 mmol/mol; standard deviation, SD = 0.123) and Fiji 1F (blue; analyzed at 1-mm resolution; mean = 9.12 mmol/mol; SD = 0.081) [*Linsley et al.*, 2004]. (B) Agreement between in situ water temperature logger readings (in situ temperature data from B. K. Linsley and G. M. Wellington) taken daily in Rarotonga at 18 m and gridded weekly Reynolds-Smith Optimum Interpolated SST (Reynolds-Smith OI-SST) version 2 [*Reynolds et al.*, 2002] centered on 21.5°S, 159.5°W. (C) Annual (dashed lines) and bimonthly (solid lines) resolved Sr/Ca to 1° × 1° grid Reynolds Optimum Interpolated Sea Surface Temperature (SST) [*Reynolds et al.*, 2002] by Least Square Linear Regression. Key: Tonga TH1 (black; calibration period = 1981–2004) and Fiji 1F (blue; calibration period = 1981–1997) with Tonga grid centered on 19.5°S, 174.5°W and the Fiji grid centered on 16.5°S, 179.5°E.

Table 1. Least Square Linear Regression Calibration Equations of Bimonthly and Annually Resolved Sr/Ca of a Microatoll *Porites* Coral from Tonga (TH1) to 1° by 1° Grid Reynolds-Smith Optimum Interpolated Sea Surface Temperature (Reynolds-Smith OI-SST) Centered on 19.5°S, 174.5°W (Figure 5C) [*Reynolds et al.*, 2002][a]

	Bimonthly Resolved Calibration		Annually Resolved Calibration	
	Calibration Equation	R^2	Calibration Equation	R^2
Tonga	$Sr/Ca = 10.65 - 0.062 \times SST_{Tonga}$	0.67	$Sr/Ca = 10.38 - 0.052 \times SST_{Tonga}$	0.30
Fiji	$Sr/Ca = 10.67 - 0.058 \times SST_{Fiji}$	0.68	$Sr/Ca = 10.41 - 0.048 \times SST_{Fiji}$	0.34

[a]Previously analyzed Sr/Ca from Fiji 1F colony [*Linsley et al.*, 2004] calibrated to Fiji Reynolds-Smith OI-SST centered on 16.5°S, 179.5°E (Figure 5c). The calibration period for Tonga TH1 is November/December 1981 to September/October 2004 and November/December 1981 to January/February 1997 for Fiji 1F.

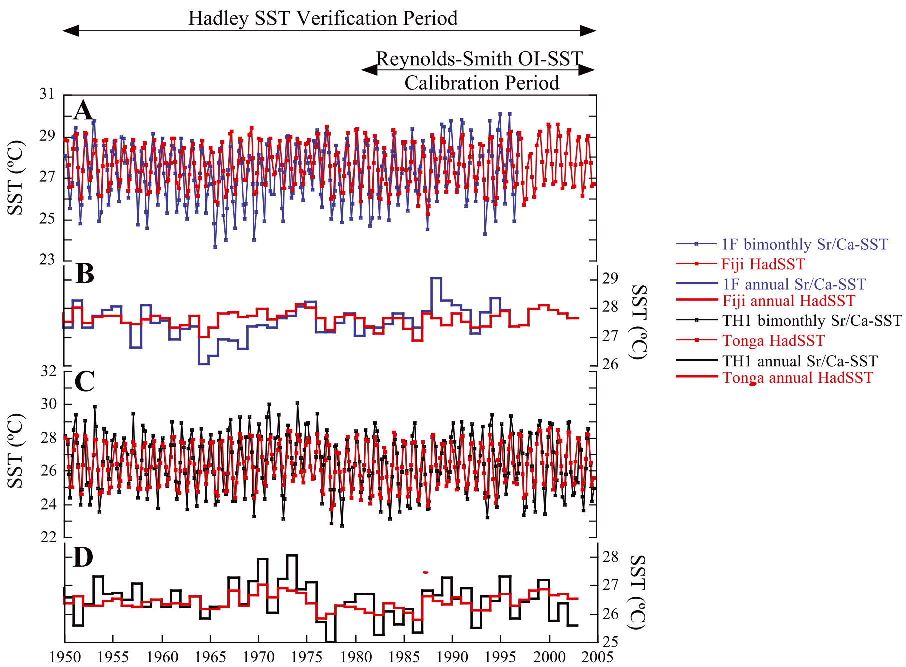

Figure 6. (A) Verification by Pearson Product-Moment correlation of bimonthly resolved Fiji 1F coral Sr/Ca-derived SST (blue) to 1° × 1° grid Hadley Centre Sea Ice and Sea Surface Temperature version 1 (HadSST; red) [*Rayner et al.*, 2003] at Fiji between 1950 and 1997 ($r = 0.76$, $p < 0.001$; grid centered on 16.5°S, 179.5°E). (B) Fiji 1F coral Sr/Ca derived SST (blue) based on the annual calibration relationship in Table 1 in comparison to annual HadSST at Fiji between 1950 and 1997 (red; $r = 0.44$, $p < 0.01$). (C) Verification of bimonthly resolved Tonga TH1 coral Sr/Ca derived SST (black) to bimonthly HadSST at Tonga between 1950 and 2004 (red; $r = 0.79$, $p < 0.001$; grid centered on 19.5°S, 174.5°W). (D) Verification of annual calibration Tonga TH1 coral Sr/Ca-derived SST (black) to Tonga annual HadSST between 1950 and 2004 (red; $r = 0.60$, $p < 0.001$).

annual SST cycle based on two tie points per year (maximum and minimum temperatures). The correlation coefficients between annualized Sr/Ca-derived SST and annual HadSST using the annual calibration listed in Table 1 are not as high as the bimonthly calibration results but are equally significant ($r = 0.60$ for Tonga, $r = 0.44$ for Fiji, $p < 0.001$; Figures 6B and 6D). Noticeable in both the bimonthly and annual coral Sr/Ca-derived SST time series are the consistently cooler SST than the gridded HadSST (Figure 6). This result implies a coral bias to overestimate SST variations that includes the amplitude of the annual SST range. One possible explanation may be due to coral skeletal growth mechanisms and effects such as differing calcification rates between summer and winter growing seasons [*Alibert and Kinsley*, 2008]. Thus, to minimize the potential growth effects on SST overestimation based on sub-seasonally resolved Sr/Ca, the best approximation of instrumental SST in our study area is by using the steeper slopes of the bimonthly calibration.

[19] Sr/Ca-derived SST records from Fiji and Tonga display secular (non-linear) trends of 1.2°C at Fiji and 1.8°C at Tonga over the twentieth century, while analysis of HadSST [*Rayner et al.*, 2003] data from the individual 1° × 1° grids indicates smaller trends of 0.31°C and 0.27°C for Fiji and Tonga, respectively (Figures 7A and 7B). Night Time Marine Air Temperature (NMAT) data from Fiji and Tonga also show this same ~0.3°C warming over the last 90 years [*Folland et al.*, 2003 and data from J. Salinger, personal communication]. However, *Folland et al.* [2003] reported an SST warming trends of ~0.5 to 0.6°C from a regional analysis of the HadSST data for a large region extending east to west (including Fiji and Tonga) that was also larger than the individual 1° × 1° gridded records. To the west of Fiji and Tonga along the southern edge of the SPCZ, a stacked average coral Sr/Ca-SST record at New Caledonia [*DeLong et al.*, 2007, 2012] also documented a +0.73°C SST warming in the twentieth century that exceeded the gridded instrumental SST warming similar to our records. The Fiji and Tonga Sr/Ca-derived SST records thus indicate a warming trend in the last 100 years that is approximately twice as large as the trend in instrumental SST data. A third coral Sr/Ca record from Rarotonga, southeast of Tonga in the Cook Islands (Figure 1: 21°S, 159°W) [*Linsley et al.*,

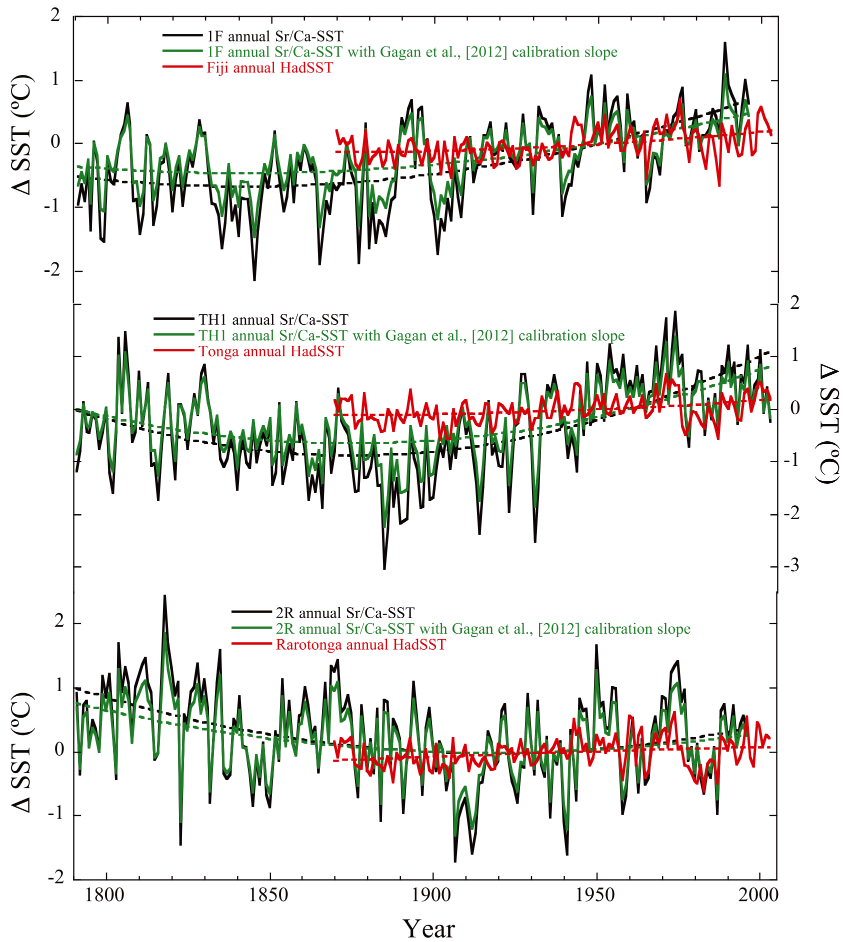

Figure 7. Centered (twentieth century mean removed) of 1° by 1° gridded annual HadSST (red lines) [*Rayner et al.*, 2003] at Fiji, Tonga, and Rarotonga compared to centered (twentieth century mean removed) annualized bimonthly Sr/Ca-derived SST (black lines) of (A) Fiji 1F [*Linsley et al.*, 2004], (B) Tonga microatoll TH1 (this study), and (C) Rarotonga 2R [*Linsley et al.*, 2000]. Shown in each panel is the rescaled result of the centered annualized bimonthly Sr/Ca-derived SST by *Gagan et al.* [2012] calibration slope (-0.084 mmol/mol°C^{-1}) to correct bio-smoothing effects (green lines). The reconstructed SST records display slight differences in absolute range but not the overall longer-term variability and secular trend. HadSST data were centered on the same grids as Figure 6 and on 21.5°S, 159.5°W for Rarotonga.

2000] recorded a similar SST warming trend of 0.9°C relative to Fiji and Tonga that is still larger than the warming observed in HadSST (+0.16°C; Figure 7C). Multidecadal length *Porites* Sr/Ca records from other locations in the Pacific have also found such discrepancies compared to instrumental temperature records [*Alibert and McCulloch*, 1997; *Crowley et al.*, 1999, 2000; *Nurhati et al.*, 2011]. *Alibert and McCulloch* [1997] found an increase of 1.3°C in Great Barrier Reef coral-derived SST from 1965 to 1993 that was not consistent with the increase of ~0.4°C from southern hemisphere land and marine temperature records, similar to our findings. Sr/Ca-derived SST records in the Atlantic utilizing other coral genera (*Diploria*) have also noted the overestimation of SST changes compared to instrumental SST [*Goodkin et al.*, 2008].

[20] Reduced correlations of coral Sr/Ca to SST in our reconstructions back in time are not surprising. Instrumental SST for a particular grid cell at any point in time is based on statistical relationships among observations that were taken with irregular spatial and temporal resolution that dramatically declines back in time. Due to a lack of actual observations in many near-shore areas, local SST variability at reef sites may be under-represented. *DeLong et al.* [2007, 2012] also noted a lower correlation to gridded instrumental SST back in time at New Caledonia and attributed the lower correlation to decreasing instrumental SST observations. It is highly likely that meso-scale atmospheric and oceanographic processes, such as upwelling, can influence local SST and coral Sr/Ca. These local processes at some sites are most likely not captured

Table 2. The $\delta^{18}O_{sw}$ Reconstruction Following the Method of *Ren et al.* [2002][a]

	$\delta^{18}O_c$ to SST (‰ °C^{-1})	Sr/Ca to SST (mmol/mol°C^{-1})	Average $\delta^{18}O_{sw}$ (‰)
Tonga	−0.14	−0.062	0.473
Fiji	−0.14	−0.058	0.325
Rarotonga	−0.21	−0.062	0.57

[a]For Tonga: the initial $\delta^{18}O_c$ to SST relationship is from *Linsley et al.* [2008], Sr/Ca-SST relationship from Table 1, initial average $\delta^{18}O_{sw}$ value from *Schmidt et al.* [1999] available from [http://data.giss.nasa.gov/o18data/]. The initial values for Fiji are derived from *Linsley et al.* [2006]. Initial values for Rarotonga are adopted from *Ren et al.* [2002].

by large-scale gridded data sets and climatology. This could be particularly true for the Savusavu Bay site where our Fiji coral was collected and also for our Ha'afera Island site in Tonga. Thus, Sr/Ca in our Fiji and Tonga corals could be influenced by local SST, a conclusion that would agree with the re-analysis of 13 modern Sr/Ca records by *Scott et al.* [2010] who concluded that gridded instrumental SST could only explain 60% of the total average Sr/Ca variance.

[21] Finally, we consider the possibility that the larger amplitude decadal and secular-scale Sr/Ca-SST trends may be related to growth effects in the tissue layer of these *Porites* corals that may attenuate the sensitivity of the Sr/Ca-SST paleothermometry [*Gaetani et al.*, 2011; *Gagan et al.*, 2012]. The rescaling of our coral Sr/Ca relationship slope from −0.06 mmol/mol°C^{-1} to a steeper slope of −0.084 mmol/mol°C^{-1} [*Gagan et al.*, 2012] reduces much of the observed variability (Figure 7). The observed-differences in overall SST variance declined by 1.0 to 1.8°C, and the long-term warming trend of all three records decreased by 0.1 to 0.3°C. This demonstrates that annualizing the higher resolution bimonthly record is effective and sufficient in minimizing the bio-smoothing effect suggested by *Gagan et al.* [2012]. However, the rescaling does not change the observation of the larger interannual, decadal, and secular trends in coral Sr/Ca-derived SST that are almost two times larger than the SST warming trend at these frequencies in HadSST or NMAT (~ + 0.3°C; Figure 7).

3.5. Coral Reconstructed Bimonthly $\delta^{18}O_{sw}$ Variability and the Relationship to SSS

[22] Because $\delta^{18}O_c$ is a function of both SST and $\delta^{18}O_{sw}$ while coral Sr/Ca appears to be more directly related to SST at our study sites, deconvolving the $\delta^{18}O_{sw}$ signal is straightforward assuming that only the above two parameters are involved based on the *Ren et al.* [2002] method. Multiple $\delta^{18}O_{sw}$ reconstruction techniques have been proposed, and the *Ren et al.* [2002] method provides essentially the same result as the *Cahyarini et al.* [2008] method. The *McCulloch et al.* [1994] and *Gagan et al.* [1998] simple subtraction method is unsuitable for the SPCZ region because of the strong influence of both SSS and $\delta^{18}O_{sw}$ on $\delta^{18}O_c$ leading to biased reconstructions [*Cahyarini et al.* 2008]. We calculated instantaneous bimonthly $\delta^{18}O_{sw}$ at Tonga, Fiji, Rarotonga using the $\delta^{18}O_c$ data, $\delta^{18}O_c$-SST relationship, and Sr/Ca-SST relationships listed in Table 2.

[23] Mean reconstructed bimonthly $\delta^{18}O_{sw}$ over the calibration period for Tonga TH1 is 0.85‰, 0.26‰ in Fiji 1 F, and 0.78‰ in Rarotonga 2R (Figure 8). The $\delta^{18}O_{sw}$ results show an average of 0.59‰ offset in bimonthly $\delta^{18}O_{sw}$ between Fiji 1F and Tonga TH1 corals, while the offset for Rarotonga 2R is 0.52‰ and 0.07‰ to Fiji 1F and Tonga TH1, respectively (Figure 8). The offset appears to reflect the salinity gradient in the surface ocean but may also be in part an artifact of the reconstruction process that is influenced by both the chosen initial $\delta^{18}O_{sw}$ values and the different coral $\delta^{18}O_c$-SST and Sr/Ca-SST relationships (Table 2). The Pearson Product-Moment correlation coefficients between instrumental SSS [*Delcroix et al.*, 2011] and bimonthly $\delta^{18}O_{sw}$ of Tonga and Fiji are 0.64 and 0.67, respectively ($p < 0.001$; Figures 8B and 8E; Table 3). The bimonthly $\delta^{18}O_{sw}$ are processed with a six-point running mean to remove annual cycles for better comparison to the instrumental SSS. A robust correlation is also found between Rarotonga reconstructed bimonthly $\delta^{18}O_{sw}$ (six-point running mean) [*Linsley et al.*, 2000, 2004] and Rarotonga SSS ($r = 0.61$, $p < 0.0001$; Figure 8H; Table 3). This level of correlation is equivalent to that obtained at nearby Vanuatu ($r = 0.47$ with $\delta^{18}O_c$ and $r = 0.71$ with $\delta^{18}O_c$ anomaly) [*Kilbourne et al.*, 2004], which supports the conclusion that these coral-derived $\delta^{18}O_{sw}$ time series are reflecting SSS variability over multiple timescales. The 0.14–0.19‰ S_p^{-1} slopes of the reconstructed $\delta^{18}O_{sw}$ and instrumental SSS relationship (Table 3) are less steep than the equatorial Pacific relationship of 0.27‰ S_p^{-1} found by *Fairbanks et al.* [1997]. Our reconstructed $\delta^{18}O_{sw}$-SSS relationships are also lower than the local relationships of 0.36‰ S_p^{-1} from Vanuatu [*Kilbourne et al.*, 2004] and 0.42‰ S_p^{-1} from Palau [*Morimoto et al.*, 2002]. Nonetheless, these differences are not surprising given the spatial heterogeneity of precipitation-evaporation and water advection rates and sources across the tropical ocean. Without

long-term water sampling data at our research locations, the cause for the slope differences in estimated $\delta^{18}O_{sw}$-SSS relationship to other published results cannot be determined.

[24] Interestingly, the bimonthly $\delta^{18}O_{sw}$ correlation to bimonthly cumulative precipitation (Pacific Rainfall Database; PACRAIN; http://pacrain.evac.ou.edu) is not significant at Tonga or Fiji but is significant at Rarotonga (Figures 8C, 8F, and 8I; Table 3). This result points to the difference in location and the different factors influencing local SSS between the western SPCZ (Fiji and Tonga, advection of surface water in the area) and eastern SPCZ (Rarotonga, precipitation and advection), which will be further discussed in the next section.

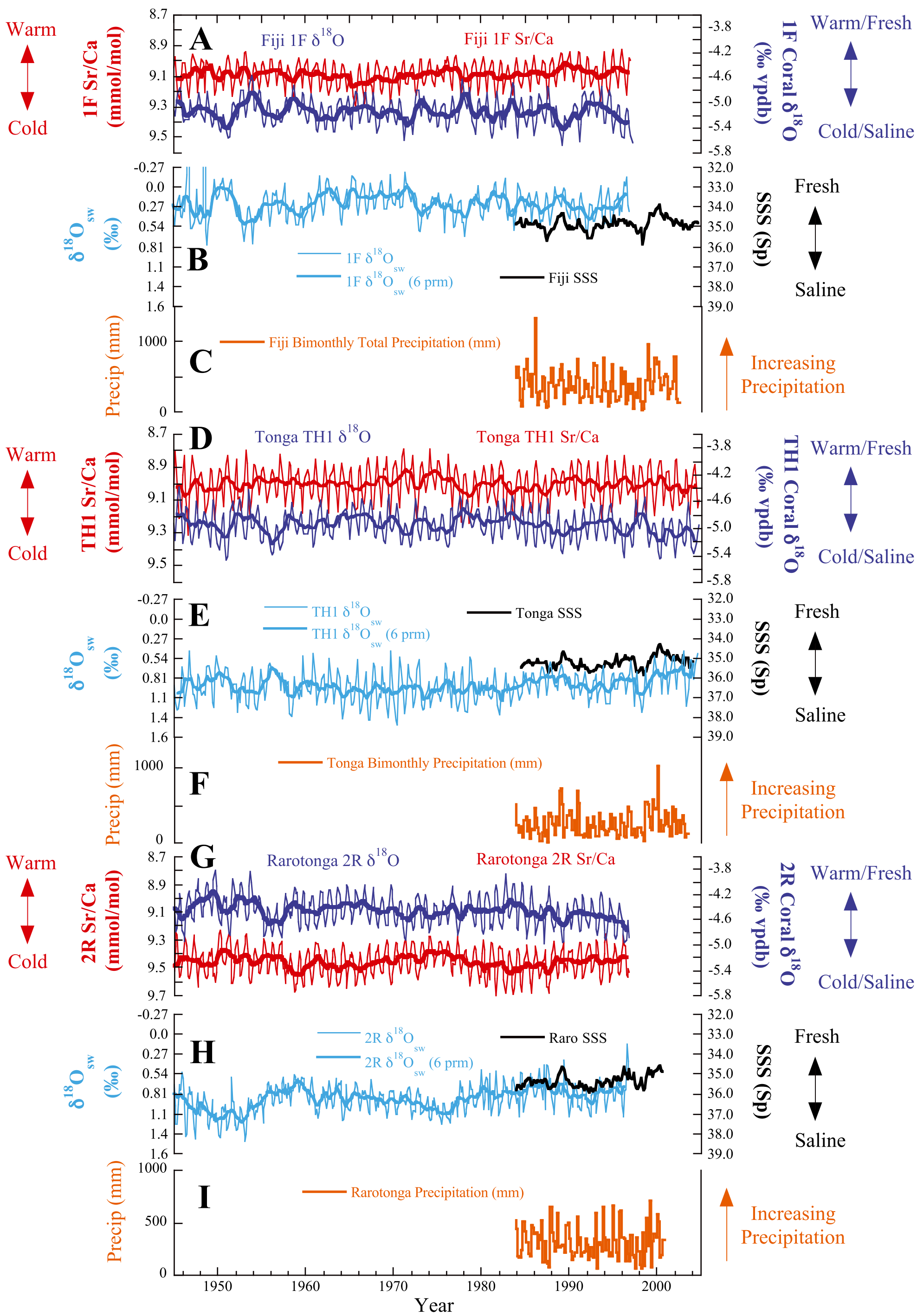

Figure 8

Table 3. Pearson Product-Moment Correlation Coefficients (r) of the Bimonthly Inter-colony $\delta^{18}O_{sw}$ Records (six Point Running Mean; to Remove the Annual Cycles of $\delta^{18}O_{sw}$; Figure 8) From Tonga, Fiji, and Rarotonga Relative to Gridded Instrumental SSS Records (1984–2004) [*Delcroix et al.*, 2011] and Cumulative Bimonthly Precipitation Collected from the Pacific Rainfall Database (PACRAIN; http://pacrain.evac.ou.edu)[a]

	Tonga $\delta^{18}O_{sw}$ (6 prm)	Fiji $\delta^{18}O_{sw}$ (6 prm)	Rarotonga $\delta^{18}O_{sw}$ (6 prm)
$\delta^{18}O_{sw}$-SSS relationship slope (‰ S_p^{-1})	0.19	0.19	0.14
Fiji SSS (bimonthly)	–	[0.67]	–
Tonga SSS (bimonthly)	[0.64]	–	–
Rarotonga SSS (bimonthly)	–	–	[0.61]
Fiji precipitation	–	0.10	–
Tonga precipitation	−0.16	–	–
Rarotonga precipitation	–	–	[0.38]

[a]The precipitation record for Fiji is an average of nine individual weather stations, but Tonga and Rarotonga precipitation records were collected from one observation station. Values in brackets are significant with a p-value greater than 0.001.

3.6. Lower Frequency Coral Sr/Ca Variability in the SPCZ

[25] The decadal variability (9-year low-pass filtered results) indicates a broadly similar timing of decadal coral-derived SST variability between Fiji and Tonga as previously discussed for just Fiji and Rarotonga [*Linsley et al.*, 2004] (Figures 9a, 9c, and 9e). Low-pass filtered Fiji and Tonga coral Sr/Ca records show decadal-scale amplitude of 0.13 mmol/mol (2.2°C when converted to °C) and 0.19 mmol/mol (3.2°C), respectively. The Rarotonga record also contains a similarly large decadal-scale variability of 0.16 mmol/mol (2.7°C). Our finding of a ~2–3°C fluctuation in decadal variability across Fiji-Tonga-Rarotonga (Figure 9) is larger but similar in order of magnitude to the ~1.4°C decadal fluctuation observed in New Caledonia coral Sr/Ca [*DeLong et al.*, 2012].

[26] From the earliest part of the record to 1890, Fiji displays no clear secular trend (Figure 9A). To the east, Tonga (Figure 9C) and Rarotonga (Figure 9E) both display trends of increasing Sr/Ca (SST cooling) into the late 1800s. *DeLong et al*. [2012] attributed this cold period of the nineteenth century recorded in New Caledonia coral Sr/Ca to increased volcanic activity and the Dalton sunspot minimum [*Solomon et al.*, 2007]. However, ;it is peculiar that the Fiji 1F Sr/Ca record did not record this cold period. This may be due to Fiji 1F colony's location in a large bay rather than open ocean conditions like the other colonies. After ~1890, our records show decreasing Sr/Ca trends (SST warming) as previously discussed in section 3.4.

[27] Decadal variability in coral Sr/Ca at Tonga is sometimes more similar with Fiji coral Sr/Ca (e.g., 1865–1885, 1900–1910) and sometimes more similar to Rarotonga coral Sr/Ca (e.g., 1915–1925). This result suggests that oceanographic conditions at Tonga are intermittently influenced by stronger tropical (more Fiji-like) or subtropical (more Rarotonga-like) conditions. Because Rarotonga lies close to the edge of the South Pacific gyre, the climate is influenced by different mechanisms than Fiji. Using a modeling approach, *Takahashi and Battisti* [2007] have concluded that the South Pacific gyre (southeast Pacific dry zone) with cooler SST is climatically controlled from the east by

Figure 8. Bimonthly reconstructed $\delta^{18}O_{sw}$ (light blue; ‰) from coral Sr/Ca (red) and $\delta^{18}O_c$ (blue) in comparison to bimonthly 1° × 1° gridded instrumental sea surface salinity (SSS; black) [*Delcroix et al.*, 2011]. The units of each $\delta^{18}O_{sw}$ and SSS panels are scaled and equate to 1 S_p unit per 0.27‰ [*Fairbanks et al.*, 1997]. Below each $\delta^{18}O_{sw}$ and SSS panel are the cumulative precipitation (mm) records for each location. (A) The original Fiji 1F Sr/Ca (red) and $\delta^{18}O_c$ (blue) [*Linsley et al.*, 2006] with six-point running mean (bold lines) to remove the annual cycle for the (B) reconstruction of $\delta^{18}O_{sw}$ (blue) following the method of *Ren et al*. [2002] in comparison to gridded bimonthly instrumental SSS (black) from 1984 to 1996 with Pearson Product-Moment correlation relationship of 0.67 ($p < 0.001$). (C) The average cumulative precipitation (mm) of nine weather stations at Fiji from the Pacific Rainfall Database (PACRAIN; http://pacrain.evac.ou.edu) with low correlation to bimonthly Fiji 1F $\delta^{18}O_{sw}$ ($r = 0.10$, $p > 0.001$). (D) Tonga TH1 Sr/Ca (red; this study) and $\delta^{18}O_c$ (blue) [*Linsley et al.*, 2008] both with six-point running mean (bold lines) in comparison to (E) reconstructed bimonthly $\delta^{18}O_{sw}$ (blue) with six-point running mean and SSS (black) from 1984 to 2004 with significant correlation relationship of 0.64 ($p < 0.001$). (F) Low correlation of $\delta^{18}O_{sw}$ to bimonthly cumulative precipitation (mm) from a Tonga weather station PACRAIN ($r = -0.16$, $p > 0.001$). (G) Bimonthly Rarotonga 2R Sr/Ca (red) and $\delta^{18}O_c$ (blue) [*Linsley et al.*, 2004]. (H) Reconstructed bimonthly $\delta^{18}O_{sw}$ (blue) with six-point running mean (bold line) in comparison to SSS (black) from 1984 to 1996 with correlation relationship of 0.61 ($p < 0.001$) and (i) significant correlation to bimonthly cumulative precipitation (mm; $r = 0.38$, $p < 0.001$).

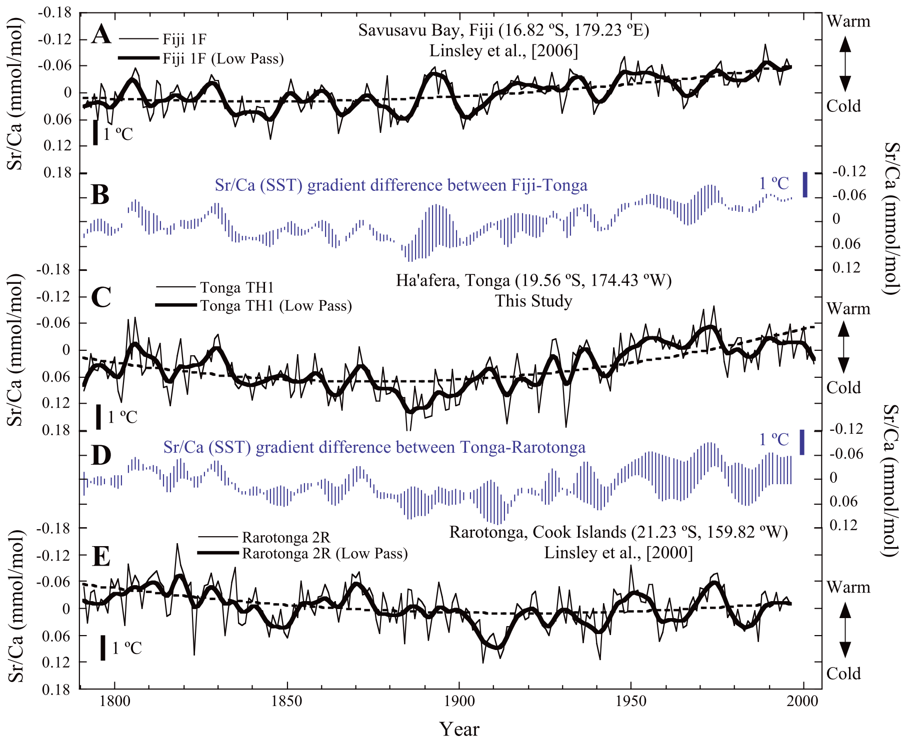

Figure 9. Plots of centered annually averaged *Porites* corals Sr/Ca (thin lines) with 9-year low-pass band filtered results highlighting the decadal and lower frequency variability (bold lines) with best-fit trend lines of (A) Savusavu, Fiji colony 1F [*Linsley et al*., 2006], (C) Tonga TH1 (this study), and (E) Rarotonga, Cook Islands [*Linsley et al*., 2000]. The high-low plots in (B) and (D) are the maximum-minimum difference of the 9-year low-pass filtered Sr/Ca results between each pair of locations (i.e., Fiji-Tonga and Tonga-Rarotonga).

subsiding air movement over the Andes rather than the shifting SST from the west. Thus, the secular SST cooling (Sr/Ca increase) seen in Tonga prior to 1890 could be due to the controlling influence or repositioning of the South Pacific gyre and dry zone and the increasing influence of the South Equatorial Current (SEC) influence from the east. Yet since ~1930, the decadal Sr/Ca variability at Tonga is indicating a more Fiji-like condition with similar timings of phases (Figures 9A and 9C). It can also be inferred from the Sr/Ca gradient between Fiji and Tonga (Figure 9B) that the SST gradient in the twentieth century is larger than before ~1890 but relatively constant between ~1900 and 1980. Additionally, the gradient between Tonga and Rarotonga from ~1900 and 1980 is generally large and varies from periods with a small gradient to periods where the gradient is close to ~2°C (Figure 9D). During the last 20 years, the collapse of the Sr/Ca gradient (SST gradient) between Fiji and Tonga is most likely indicating the more rapid expansion of the WPWP as noted by *Cravatte et al*. [2009]. The change to a more rapid WPWP expansion is more striking given the long-term warming trend that began around ~1900. The south Pacific SST trend over the last 20 years is likely related to the SST warming observed in the central Pacific [*Nurhati et al*., 2011].

[28] Our decreasing reconstructed $\delta^{18}O_{sw}$ (SSS freshening) trends at Fiji (-0.17 S_p; Figure 10A) and Tonga (-0.22 S_p; Figure 10D) are consistent with re-analysis results of instrumental SSS that found an overall mean decreasing SSS trend (-0.20 S_p) in the past 50 years in the south Pacific [*Delcroix et al*., 2007; *Cravatte et al*., 2009; *Singh and Delcroix*, 2011]. Additionally, Tonga $\delta^{18}O_{sw}$ is likely indicating the same SSS influence as observed at Fiji based on the decrease in the $\delta^{18}O_{sw}$ gradient over the last ~50 years (Figure 10C). Since the correlation between precipitation at Fiji (Figure 10B) and Tonga (Figure 10E) to coral reconstructed $\delta^{18}O_{sw}$ is insignificant (Table 3), our results indicate that $\delta^{18}O_{sw}$ and SSS may be only partially influenced by SPCZ-related precipitation-evaporation variability and instead is more dominated by advection of water of differing SSS and $\delta^{18}O_{sw}$. Overall, the decadal variability in the $\delta^{18}O_{sw}$ gradient results suggests that Tonga is periodically influenced by subtropical conditions from the South Pacific gyre and the influence of the SEC from the east (e.g., 1860–1890; Figure 10F). While Tonga is also subject to

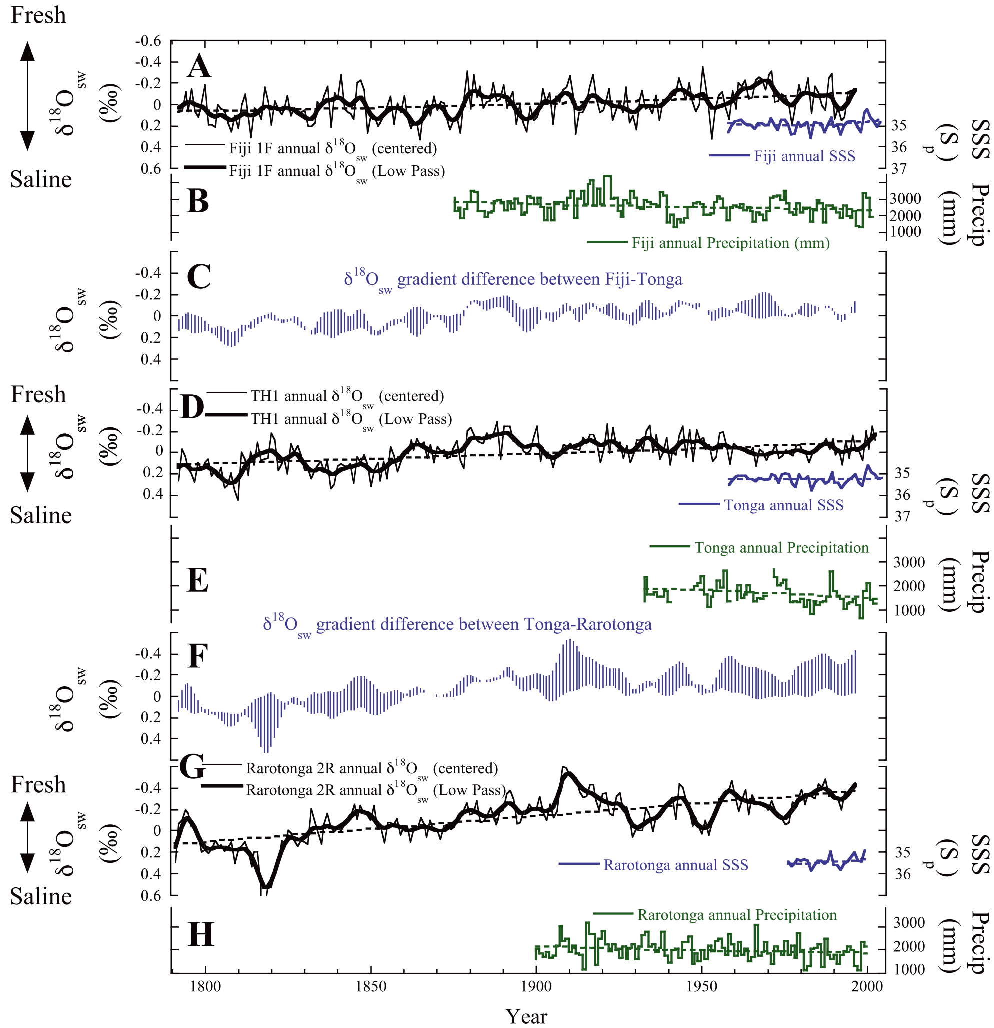

Figure 10. The centered annually averaged reconstructed $\delta^{18}O_{sw}$ (thin black) from three coral colonies in the SPCZ: (A) Fiji [*Linsley et al.*, 2006], (D) Tonga (this study), and (G) Rarotonga [*Linsley et al.*, 2000, 2004]) with 9-year low-pass band filtered results (bold black). Plotted with each $\delta^{18}O_{sw}$ panel is the annually averaged 1° by 1° gridded instrumental SSS (blue) [*Delcroix et al.*, 2011] in comparison to (B, E, and H) total annual precipitation of each area of the SPCZ (green; PACRAIN database). The high-low plots in (C) and (F) are the maximum-minimum difference of the 9-year low-pass filtered $\delta^{18}O_{sw}$ results between each pair of locations in the SPCZ (i.e., Fiji-Tonga and Tonga-Rarotonga).

influence from the west from the Subtropical Counter Current (STCC) [*Qiu et al.*, 2008] reflecting similarities to Fiji (e.g., 1910–1930; Figure 10C).

[29] Furthermore, the evolving difference between decadal changes in Tonga and Rarotonga $\delta^{18}O_{sw}$ (Figure 10F) suggests that the $\delta^{18}O_{sw}$ (SSS) gradient between the sites has been consistently increasing since ~1900 by at least ~2 S_p based on our ~0.2‰ S_p^{-1} $\delta^{18}O_{sw}$-SSS relationship. Thus, Rarotonga is becoming more disparate and less similar to the western SPCZ region in the recent decades. This may be due to the strengthening of the South Pacific gyre influence from the east. *Hill et al.* [2011] argued that the strong quasi-decadal oscillation in the South Pacific gyre has increased and shifted the gyre to the south over the last 50 years. This change in the gyre could be due to possible decadal variations in ENSO [*Sasaki et al.*, 2008] or changes to the high latitude annular mode. Interestingly, total annual precipitation over the last 100 years is decreasing in all three regions (Figures 10B, 10E, and 10H) allowing us to rule out both the "amount effect" and "latitude effect" on $\delta^{18}O$ of precipitation [*Dansgaard*, 1964; *Siegenthaler and Oeschger*, 1980]. This suggests that the trends in annual reconstructed $\delta^{18}O_{sw}$ at Tonga may be due to water mass advection effects on salinity and not precipitation.

[30] Overall, the decadal variability in Tonga coral Sr/Ca and reconstructed $\delta^{18}O_{sw}$ gradient across the

SPCZ is a reflection of Tonga's location in between the tropics (Fiji) and the subtropics (Rarotonga). Additionally, the complex bottom topography with numerous volcanic and carbonate islands in the region is responsible for the breakup of the SEC into a series of westward flowing zonal jets steering around the topographic highs of Tonga and Fiji [*Webb*, 2000; *Stanton et al*., 2001; *Ridgway and Dunn*, 2003; *Couvelard et al*., 2008]. Given this situation, it can be expected that decadal-scale variability in SST and SSS may differ across the region and that decadal-scale variability in these coral Sr/Ca-SST time series is not always coherent. However, there are enough time periods of coherent changes in both Sr/Ca and $\delta^{18}O_{sw}$ at all three sites (i.e., post-1930, 1870s, 1820s–1850s) that environmental conditions (presumably SST) must be the key forcing parameter.

4. Summary

[31] A sub-seasonally resolved Sr/Ca record from a microatoll *P. lutea* colony in Tonga demonstrates a high degree of reproducibility to other high-resolution *P. lutea* Sr/Ca records in the region over multiple timescales. The coral Sr/Ca also records the pervasive long-term warming trend observed by many studies across the Pacific. These results support the use of this type of *Porites* coral morphology in paleoclimate reconstruction and found no discernable differences between an analytical resolution at 1 mm increments (near-monthly) or every other 1 mm increments (~bimonthly) in *P. lutea* corals growing at ~1.0 to 1.5 cm year^{-1}. A long-term secular decrease in coral Sr/Ca of approximately similar magnitude was observed at both Fiji and Tonga since approximately 1900. Using the modern bimonthly calibration, coral geochemical records in the SPCZ region indicate a warming between 1.2 and 1.8°C. Rescaling the Sr/Ca records to compensate for any bio-smoothing effect [*Gagan et al*., 2012] decreases the warming trends to 0.7–0.9°C in line with re-analysis [*Folland et al*., 2003] but is still larger by ~0.3°C than instrumental SST products (HadSST and NMAT). This result agrees with other studies using coral Sr/Ca and suggests that local effects on SST near islands generate larger amplitude variability than gridded SST products.

[32] Despite the magnitude of the warming trend since the 1900s, we interpret the secular change in Fiji towards lower Sr/Ca (SST warming) to be the result of a gradual expansion of the WPWP. In contrast, Tonga and Rarotonga Sr/Ca trends indicate cooling in the subtropical South Pacific gyre up until the early twentieth century possibly related to increased volcanic activity and/or the Dalton sunspot minimum as observed in coral Sr/Ca from New Caledonia [*DeLong et al*., 2012]. Subsequent to the early 1900s, Tonga's climate variability appears to be dominated by the expanding WPWP with a decrease in SST gradient between Fiji and Tonga. The Sr/Ca difference between Fiji and Tonga suggests that the expansion of the WPWP is occurring more rapidly over the last 20 years. Together with the secular trends in annual reconstructed $\delta^{18}O_{sw}$, our Tonga coral results provide additional evidence that enhanced freshening is occurring across the SPCZ with a decreasing SSS gradient between Fiji and Tonga. These oceanographic changes may be related to the warming and freshening observed in the central Pacific [*Nurhati et al*., 2011]. The warming and freshening of the surface ocean in our study area supports the argument for a long-term southward displacement of the SPCZ [*Linsley et al*., 2006; *Cravatte et al*., 2009]. A southeastward shift of the SPCZ is in agreement with observed southward shift of the South Pacific gyre over the last 50 years [*Hill et al*., 2011] in response to strengthened westerly winds associated with the Southern Annular Mode. Our results also highlight the complexity of ocean dynamics on decadal and centennial timescales of this region and the need for replicated proxy records to correctly understand paleoclimatic variations on these timescales.

Acknowledgments

[33] We thank the following people and organizations for their assistance over the many phases of this project: S. Tuilaucala (Director of Fisheries) and A. Batibasaga (Principal Research Officer) of the Government of Fiji (Ministry of Fisheries and Forests); The University at Albany Graduate Student Organization for Research Travel Grant to HCW; G. Wellington; S. Tudhope; J. Caselle; D. Mucciarone; T. Potts; S. Bagnato; O. Hoegh-Guldberg, S. Kafka, G. Brosnan (Broz), K. McGrath, A. Paulin, A. Stolorow; J. M. Cousteau Resort (Fiji) for assistance in various field sampling campaigns. We also thank two reviewers for their constructive feedback and comments on the manuscript. HCW was a graduate student in the laboratory of BKL during the execution of this project. Major funding for this work was provided to BKL by the National Science Foundation (OCE-0318296) and National Oceanic and Atmospheric Administration (Office of Global Programs).

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