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Comparison of equatorial Pacific sea surface temperature variability and trends with Sr/Ca records from multiple corals

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Key Points:
- Relationship of Sr/Ca to temperature varies among corals growing within 100 m
- Decadal Sr/Ca trends from adjacent corals are contradictory
- Average range on Sr/Ca-based SST estimates at Jarvis is 3.7°C

Supporting Information:
- Texts S1 and S2 and Figures S1–S5
- Data Set S1

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Abstract Coral Sr/Ca is widely used to reconstruct past ocean temperatures. However, some studies report different Sr/Ca-temperature relationships for conspecifics on the same reef, with profound implications for interpretation of reconstructed temperatures. We assess whether these differences are attributable to small-scale oceanographic variability or "vital effects" associated with coral calcification and quantify the effect of intercolony differences on temperature estimates and uncertainties. Sr/Ca records from four massive *Porites* colonies growing on the east and west sides of Jarvis Island, central equatorial Pacific, were compared with in situ logger temperatures spanning 2002–2012. In general, Sr/Ca captured the occurrence of interannual sea surface temperature events but their amplitude was not consistently recorded by any of the corals. No long-term trend was identified in the instrumental data, yet Sr/Ca of one coral implied a statistically significant cooling trend while that of its neighbor implied a warming trend. Slopes of Sr/Ca-temperature regressions from the four different colonies were within error, but offsets in mean Sr/Ca rendered the regressions statistically distinct. Assuming that these relationships represent the full range of Sr/Ca-temperature calibrations in Jarvis *Porites*, we assessed how well Sr/Ca of a nonliving coral with an unknown Sr/Ca-temperature relationship can constrain past temperatures. Our results indicate that standard error of prediction methods underestimate the actual error as we could not reliably reconstruct the amplitude or frequency of El Niño–Southern Oscillation events as large as ± 2°C. Our results underscore the importance of characterizing the full range of temperature-Sr/Ca relationships at each study site to estimate true error.

1. Introduction

Precise and accurate sea surface temperature (SST) estimates are critical for extending the instrumental record in the tropical Pacific and for separating internal climate variability from long-term trends. Instrumental reconstructions extending back to the midnineteenth century [e.g., *Smith et al*., 2008] rely on sparse observational sampling both in space and in time and are unreliable prior to 1950 in some places [*Vecchi et al*., 2008; *Deser et al*., 2010; *Tokinaga et al*., 2012]. For example, the estimated trend in the central equatorial Pacific over the twentieth century from three different SST data products ranges from +0.36°C per century to +0.74°C per century [*Nurhati et al*., 2011]. Identifying the true rate of warming is important for estimating the sensitivity of Pacific SST to global warming, as well as for understanding the full impact of tropical Pacific SSTs on recent and future global temperatures and climate [*DiNezio et al*., 2009].

Annually banded tropical corals have potential to provide continuous seasonally resolved records of ocean variability and trends over the last several centuries and, with application of accurate dating techniques, even further back in time using data extracted from nonliving colonies. Coral Sr/Ca is currently the most widely used coral paleothermometer [*Smith et al*., 1979; *Beck et al*., 1992] and is based on the generally negative correlation over seasonal cycles between skeletal Sr/Ca and the temperature of the water in which the coral grew. While the goal of many studies has been to reconstruct SSTs during the preinstrumental era [e.g., *Kuhnert et al*., 2005; *Goodkin et al*., 2008; *Kilbourne et al*., 2008; *Hetzinger et al*., 2010; *DeLong et al*., 2012, 2014], several recent applications attempt to resolve inconsistencies in twentieth century SST variability and trends among the different SST data products or where instrumental coverage is sparse [e.g., *Nurhati et al.*, 2011; *Carilli et al.*, 2014; *Linsley et al.*, 2015], applications that require both accurate and precise reconstructed temperatures.

Despite their widespread use, potential sources of uncertainty exist in paleotemperature records derived from coral Sr/Ca. Within a single coral colony, offsets in mean Sr/Ca occur along different growth axes [*de Villiers et al.*, 1994; *Alibert and McCulloch*, 1997; *DeLong et al.*, 2007], and experimental culture studies have shown that the Sr/Ca of corals responds to changes in seawater pH and light, even when temperature is constant [*Reynaud et al.*, 2004; *Cohen et al.*, 2009; *Gagnon et al.*, 2012]. Nutrients and possibly gender have also been shown to affect the Sr/Ca of corals [*Atkinson et al.*, 1995; *Carricart-Ganivet et al.*, 2013]. Many of these discrepancies have been attributed to "vital effects," the result of processes that occur during coral biomineralization (skeletal growth).

The recognition of vital effects has led to the application of targeted sampling strategies intended to minimize their impact [e.g., *DeLong et al.*, 2013]. Yet despite careful, targeted sampling strategies, inconsistencies remain. For example, offsets in mean Sr/Ca of neighboring colonies collected on the same reef have been observed, as have differences in the Sr/Ca sensitivity to temperature [*Goodkin et al.*, 2005; *Linsley et al.*, 2006; *Saenger et al.*, 2008; *Cahyarini et al.*, 2009; *Pfeiffer et al.*, 2009]. *Grove et al.* [2013] reported different long-term SST trends derived from Sr/Ca of two *Porites* corals on a Madagascar reef, with one suggesting warming and one suggesting cooling. *Carilli et al.* [2014] reported a cooling trend in corals from the central tropical Pacific over a time period when satellite SSTs showed a clear warming trend. Also in the tropical Pacific, *Nurhati et al.* [2011] reported decadal-scale variability in a Sr/Ca-based coral SST record that was not observed in the instrumental SST record from the region. Such inconsistencies between coral Sr/Ca-derived SST and instrumental SST have sometimes been attributed to uncertainties in the instrumental record or to real SST variability within the reefal system [e.g., *Pfeiffer et al.*, 2009]. These are valid concerns. First, there are significant uncertainties and biases in the early part of the instrumental record due mainly to a lack of standardization in the way the measurements were made (e.g., *Rayner et al.*, [2006], *Kennedy et al.*, [2011]). In areas where data coverage is sparse there are inconsistencies in data even after 1950 [*Casey and Cornillon*, 1999]. Second, many reefal environments are morphologically complex and SST gradients can exist between exposed barrier environments and more sheltered back reefs and lagoons where large *Porites* often grow [*Linsley et al.*, 2004]. Therefore, differences in Sr/Ca-derived SST records from coral colonies sampled on the same reef may reflect real differences that are not resolved by satellite or Voluntary Observing Ships data.

Despite these issues, the origin of the observed inconsistencies between Sr/Ca-derived SST and instrumental SST, whether vital effects, real oceanographic variability, or errors in the instrumental SST record, has never been directly addressed. As a result, the ability of coral Sr/Ca to return reliable SST variations and trends over a relatively small temperature range remains in question.

We generated Sr/Ca records from *Porites* corals collected on Jarvis, a small (4.5 km^2), island in the central equatorial Pacific (159°59′W, 0°22′S) fringed by a submerged coral reef. Jarvis Island is situated in the path of the Equatorial Undercurrent (EUC), a subsurface (20–400 m) current that brings cool water along the equator from the western to the eastern Pacific [*Philander*, 1973; *Wyrtki and Kilonsky*, 1984]. The EUC upwells when it encounters Jarvis, creating a patch of cooler surface water on the west side of the island [*Gove et al.*, 2006]. EUC strength and upwelling at Jarvis are affected by El Niño–Southern Oscillation (ENSO). El Niño events are associated with a weaker EUC, reduced upwelling, and warming [*Firing et al.*, 1983; *Gove et al.*, 2006]. The converse is true during La Niña events. Temperature loggers deployed at several stations and depths across the reef provide nearly a decade of in situ temperature data that enable quantification of the cross-island difference, the response of island SST to interannual variability driven by ENSO, and the global warming trend.

Analysis of coral skeletons collected on each side of the island offers an opportunity to assess the ability of coral Sr/Ca to resolve the cross-island temperature gradient and to capture the frequency and amplitude of ENSO events, as well as any longer-term trend. Our data show that temperature estimates derived from Sr/Ca of four Jarvis corals are associated with large uncertainties and that they do not consistently record either the ENSO events or the long-term trend indicated by the logger data. We conclude that inconsistencies among the Jarvis coral Sr/Ca records do not reflect actual SST variability around the island and that absolute SSTs, decadal trends, and records of interannual variability reconstructed using coral Sr/Ca ratios must be interpreted with caution.

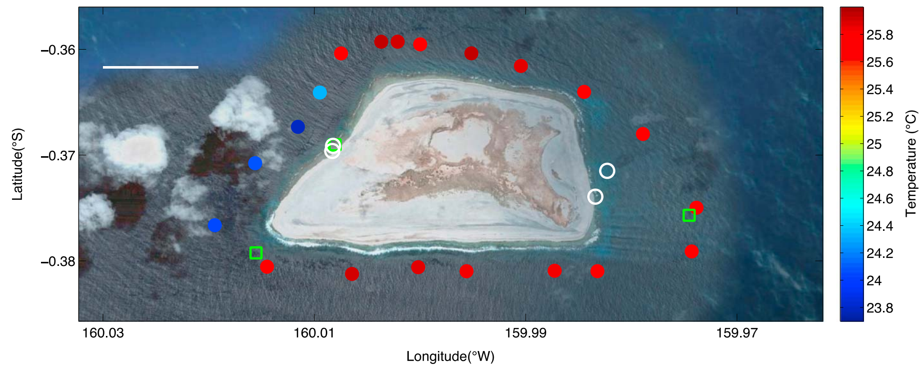

Figure 1. Jarvis Island showing locations of temperature loggers (green squares) and coral colonies sampled for this study (white circles). The filled circles represent the water temperature at 10 m from conductivity-temperature-depth (CTD) casts conducted in March 2000 [*Gove et al.*, 2006]. Colder west side temperatures result from topographic upwelling of the Equatorial Undercurrent. The scale bar indicates the 1 km distance.

2. Material and Methods

In April 2010, and May and September 2012, five skeletal cores were collected from two live coral colonies (*Porites lobata*) on each of the east and west sides of Jarvis Island (Figure 1). Using pneumatic drills, cores W037 (April 2010) and W497 (September 2012) were collected from a single colony on the west side at 13 m depth, and core W490 was collected from the west side (September 2012) approximately 80 m away at 8 m depth. On the east side of the island, core E016 was collected in May 2012 at 5 m depth. Core E500 was collected in September 2012 approximately 300 m away, also at 5 m depth.

Sea-Bird Electronics (SBE) 39 Temperature Recorder loggers deployed on both sides of the island by NOAA's Coral Reef Ecosystems Program of the Pacific Islands Fisheries Science Center (Figure 1) recorded temperature every 30 min. The drift of the SBE recorders is 0.0002°C per month and the precision is ±0.002°C. We averaged the logger data into monthly bins. We constructed a composite west side temperature record using data from three loggers: W022 (7 m) and W013 (11 m), within 75 m of both west side corals, and W001 (15 m), located 1400 m from both corals (Figures 1 and S1 in the supporting information). When data exist from multiple loggers over the same time period, the values are averaged; the mean difference between concurrent values is only 0.26°C. The east side record is composed of records from loggers E006 (2004–2010, 13 m) and E020 (2010–2012, 10 m) at the same location within 1100 m of both corals (Figures 1 and 2). As logger

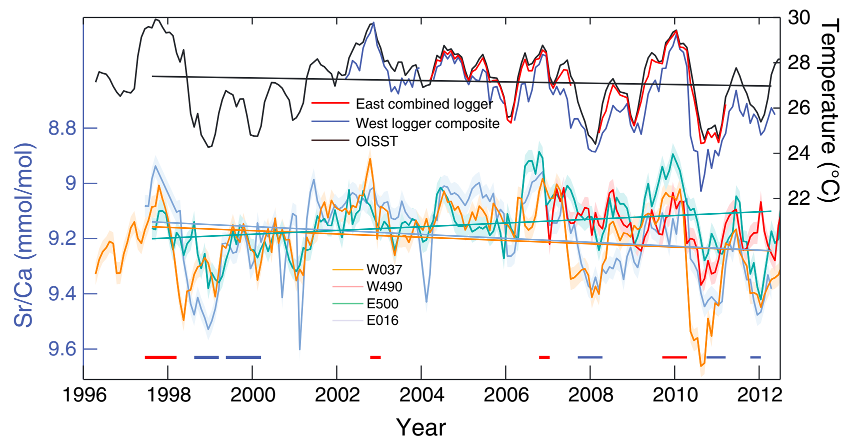

Figure 2. (top) Average monthly OISST-gridded temperatures [*Reynolds et al.*, 2002] from the 1° × 1° box centered on Jarvis Island (black) compared with the average monthly west side logger composite (blue) and average monthly east side combined logger (red). (bottom) Sr/Ca records (mmol/mol) from all four corals with 1σ analytical error (0.04 mmol/mol) shaded. The thick red horizontal lines indicate the El Niño periods as defined by Oceanic Niño Index (ONI: 3 month running mean of ERSST v3b SST anomalies in the Niño 3.4 region 5°N–5°S, 120–170°W [*Smith et al.*, 2008]) ≥1.0, and the heavy blue horizontal lines indicate the La Niña periods as defined by ONI ≤ −1.0. The solid lines denote the 1997–2012 trends in OISST (black) and coral Sr/Ca records (colors). Slopes and errors are provided in Table 2.

E020 essentially replaced logger E006, there is no overlapping period for the two east side logger records. However, a composite logger record is not needed because both east side logger records closely match contemporaneous monthly optimal interpolation SSTs (OISSTs v. 2) [*Reynolds et al.*, 2002] (see section 3) for a 1° × 1° grid box centered on Jarvis Island. The OISST analysis combines in situ and satellite SSTs and is adjusted for biases. Weekly resolution fields are linearly interpolated to daily resolution and then averaged over each month. We use this relatively coarse resolution data product to test whether temperatures at Jarvis Island are representative of regional surface conditions.

The 30 mm diameter coral cores were scanned using a Siemens volume zoom spiral computerized tomography (CT) scanner at the Woods Hole Oceanographic Institution (WHOI) following methods described in *DeCarlo et al.* [2015] (Figure S2). Cores were slabbed to 2 mm thickness and ultrasonicated in deionized water to remove coral dust. The 50–80 μg coral powder was milled at 1 mm intervals in a continuous sampling transect using a Minicraft MB170 drill with a 1 mm diameter diamond bit. Counts of ^{88}Sr and ^{48}Ca were collected on two single-collector Element 2 inductively coupled plasma mass spectrometers at WHOI. Sr/Ca ratios were determined by calibration to published standards derived from coral skeleton (JCp-1) [*Okai et al.*, 2002; *Hathorne et al.*, 2013a], fish otoliths (FEBS-1 [*Sturgeon et al.*, 2005] and National Institute for Environmental Studies (NIES) [*Yoshinaga et al.*, 2000]), and limestone (National Bureau of Standards (NBS)-19) [*Fernandez et al.*, 2011]. The R^2 values between measured ^{88}Sr/^{48}Ca counts and published molar Sr/Ca ratios were typically >0.999. The JCp-1 standard has a Sr/Ca ratio (8.838 ± 0.042 mmol/mol) similar to our coral samples (8.8–9.7 mmol/mol), whereas Sr/Ca ratios of FEBS-1, NIES, and NBS-19 are all less than 3 mmol/mol. As a result, our calibration curves for Sr/Ca determinations are controlled mainly by the JCp-1 standard. Repeated measurements of an in-house secondary coral standard indicate an external precision of ±0.035 mmol/mol (1σ, $n = 140$, 0.4% relative) and were stable throughout our study. Our uncertainty estimates take this analytical precision into account through our calculation of the standard error of prediction. To evaluate the accuracy of our method and facilitate comparison to Sr/Ca ratios measured in other laboratories, we measured the Sr/Ca ratio of JCp-1 by calibration to an independent set of standards. Single-element standards (High-Purity Standards) were mixed to simulate coral skeleton (40 ppm Ca and variable concentrations of Mg, Sr, Ba, and U). Three aliquots of JCp-1 powder were dissolved, and each was measured in duplicate by calibrating to the simulated coral standards (calibration curve $R^2 > 0.9999$). We measured the Sr/Ca ratio of JCp-1 as 8.870 ± 0.028 mmol/mol, which is within uncertainty of the mean, and within the range of precision, reported from JCp-1 analyses conducted in 21 different laboratories [*Hathorne et al.*, 2013a].

Sr/Ca of overlapping time periods of cores W037 and W497, drilled from the same colony, were combined into a single record, hereafter referred to as W037 (Figure S4). The period of 1996–2010.3 derives from core W037 and 2010.3-2012.2 derives from core W497. Annual density bands visible in 3-D CT scans of the cores were used to construct a first-order chronology with an estimated error of ±1 year. Using Arand software [*Howell et al.*, 2006], we fine-tuned the Sr/Ca variability to the in situ temperature variations [e.g., *Guilderson et al.*, 2004]. Note that this method maximizes the correlation between Sr/Ca and temperature. The average adjustment of the band-based chronology was <1 month for cores W497, W037, and E500 and 4 months for W490 and E016. The maximum adjustment of any point was 8 months.

3. Results

3.1. Logger and OISSTs

The mean and variance of both east side logger records E006 and E020 are statistically indistinguishable from those of contemporaneous monthly satellite-derived OISST for a 1° × 1° grid box centered on Jarvis Island (two-sample t test; $r = 0.99$, $p = 0.34$, and $n = 67$ and $r = 0.98$, $p = 0.60$, and $n = 12$, respectively), indicating that temperatures on the east side are uniform and reflect regional SSTs. The mean (27.17°C) and variance (1.53°C) of the combined east side logger record are also statistically indistinguishable from OISST (mean 27.41°C and variance 1.44°C; $p = 0.44$, $n = 75$), and their correlation coefficient is high ($r = 0.99$). Furthermore, the mean difference between contemporaneous monthly resolved values is only 0.24°C. By contrast, the mean (26.49°C) and variance (2.31°C) of the west side composite logger record are statistically different from those of OISST over the same period ($p < 0.05$, $n = 75$), and the correlation coefficient is lower ($r = 0.91$). While the relatively large (1° × 1°) OISST grid box cannot resolve these differences due to their small spatial scale, the

Table 1. Regressions of Sr/Ca on Temperature and Temperature on Sr/Ca

Coral	Depth (m)	Mean Sr/Ca 2006–2012 (mmol/mol)	Regression of Sr/Ca on In Situ Logger: Slope (mmol/mol/°C)	b (mmol/mol)	R, $p < 0.05$	n	Error of prediction (°C)	Regression of Sr/Ca on OISST: Slope (mmol/mol/°C)	b (mmol/mol)	R, $p < 0.05$	n	Error of prediction (°C)
W037	13 m	9.26 ± 0.02	−0.09 ± 0.01	11.6 ± 0.3	−0.84	95		−0.09 ± 0.02	11.7 ± 0.5	−0.72	98	
W490	8 m	9.16 ± 0.01	−0.03 ± 0.01	10.0 ± 0.3	−0.58	65		−0.03 ± 0.01	9.9 ± 0.4	−0.47	65	
E500	5 m	9.13 ± 0.01	−0.06 ± 0.01	10.6 ± 0.4	−0.70	78		−0.06 ± 0.01	10.7 ± 0.3	−0.69	98	
E016	5 m	9.26 ± 0.02	−0.09 ± 0.01	11.6 ± 0.4	−0.81	78		−0.09 ± 0.01	11.7 ± 0.4	−0.81	98	

Coral	Depth (m)	Mean Sr/Ca 2006–2012 (mmol/mol)	Regression of In Situ Logger on Sr/Ca: Slope (°C/mmol/mol)	b (°C)	R, $p < 0.05$	n	Error of prediction (°C)	Regression of OISST on Sr/Ca: Slope (°C/mmol/mol)	b (°C)	R, $p < 0.05$	n	Error of prediction (°C)
W037	13 m	9.26 ± 0.02	−8 ± 1	98 ± 9	−0.84	95	0.798 ± 0.006[a]	−6 ± 1	78 ± 13	−0.72	98	0.967 ± 0.009[a]
W490	8 m	9.16 ± 0.01	−10 ± 1	122 ± 34	−0.58	65	1.21 ± 0.01[a]	−8 ± 4	98 ± 33	−0.47	65	1.19 ± 0.01[a]
E500	5 m	9.13 ± 0.01	−9 ± 2	98 ± 19	−0.70	78	0.904 ± 0.006[a]	−9 ± 2	98 ± 33	−0.69	98	0.874 ± 0.009[a]
E016	5 m	9.26 ± 0.02	−8 ± 1	96 ± 11	−0.81	78	0.744 ± 0.004[a]	−9 ± 2	112 ± 15	−0.81	98	0.773 ± 0.006[a]
Stack regression								−11 ± 2	124 ± 17	−0.82	65	±1.9[b]
Global regression			−7.9 ± 0.9	99 ± 8	−0.72	359	±1.9[b]					

[a]Standard error of prediction ± 1σ.
[b]Range of predicted temperatures.

logger data indicate that corals on the west side of Jarvis experienced significantly colder mean temperatures (26.49°C) than their counterparts on the east side (27.17°C, $p < 0.05$, $n = 75$).

Interannual temperature variabilities on both sides of the island are dominated by ENSO (Figure 2). The cross-island temperature gradient is most pronounced during La Niña, when west side temperatures are up to 1°C cooler than they are on the east side (e.g., the peak month of the 2010–2011 La Niña; Figure 2). This reflects the increase in the strength of the EUC and consequently, EUC upwelling on the west side of Jarvis during La Niña events [*Gove et al.*, 2006]. OISST and logger records reveal a significant decade-long (2002–2012) cooling trend determined by the ordinary least squares (OLS) regression method (−0.204 ± 0.130°C/yr, $p < 0.05$; Table 4), consistent with an equatorial Pacific cooling trend reported by *Kosaka and Xie* [2013]. However, over the full period covered by the longest coral records (1997–2012), there is no significant trend in the OISST (Table 2).

3.2. Sr/Ca Coral Records

Over the period common to all corals (2007–2012), mean Sr/Ca values of each colony are statistically different from one another, with the exception of one west side (W037) and one east side (E016) coral ($p > 0.99$; Table 1). Corals E500 and E016, both growing on the east (warmer) side of the island, have lowest (warmest) and highest (coolest) mean Sr/Ca, respectively.

Trends in the Sr/Ca records do not follow expected patterns and in some cases, contradict each other. Over the full length of the records (1997–2012), Sr/Ca of one east side coral (E016) shows a statistically significant increase, implying cooling, whereas Sr/Ca of the other (E500) shows a statistically significant decrease, implying warming (Figure 2 and Table 2). Over the length of the logger records (2002–2012), Sr/Ca of E016 and W037 suggest cooling, consistent with the logger records, but that of E500 does not (Figure 2 and Table 3).

Table 2. Trend Slopes Over Period Common to Three Long Corals (1997–2012)

Time Series	Slope	Trend[a]	95% Confidence Interval
W037 Sr/Ca	0.006 mmol/mol/yr[b]	**Cooling**	0.001 to 0.011 mmol/mol/yr
E016 Sr/Ca	0.007 mmol/mol/yr[b]	**Cooling**	0.002 to 0.012 mmol/mol/yr
E500 Sr/Ca	−0.007 mmol/mol/yr[c]	**Warming**	−0.010 to −0.003 mmol/mol/yr
OISST	−0.029°C/yr	No trend	−0.076 to 0.018°C/yr

[a]Trends significant at 95% confidence level in bold.
[b]Statistically indistinguishable from each other.
[c]Statistically different from other two coral trends.

Table 3. Trend Slopes Over Period Common to West Logger Composite and OISST (2002–2012)

Time Series	Slope	Trend[a]	95% Confidence Interval
W037 Sr/Ca	0.028 mmol/mol/yr[b]	**Cooling**	0.021 to 0.036 mmol/mol/yr
E016 Sr/Ca	0.030 mmol/mol/yr[b]	**Cooling**	0.024 to 0.037 mmol/mol/yr
E500 Sr/Ca	0.005 mmol/mol/yr[c]	No trend	−0.001 to 0.011 mmol/mol/yr
West logger	−0.300°C/yr[d]	**Cooling**	−0.373 to −0.227°C/yr
OISST	−0.196°C/yr[d]	**Cooling**	−0.263 to −0.130°C/yr

[a]Trends significant at 95% confidence level in bold.
[b]Statistically indistinguishable from each other.
[c]Statistically different from other two coral trends.
[d]Statistically indistinguishable from other temperature trend.

3.3. Sr/Ca-Temperature Regressions

We used the OLS regression method to assess how the Sr/Ca time series generated for each individual coral captured recorded temperature variability through time. Monthly interpolated Sr/Ca from all four cores were regressed onto in situ temperature for the period of 2004–2012, over which loggers recorded in situ temperatures on both sides of the island (Figure 3a and Table 4). Slopes range from −0.03 ± 0.01 to −0.09 ± 0.01 (mmol/mol/°C), within the range of values reported in *Corrège* [2006].

Analysis of variance (ANOVA) performed between Sr/Ca and logger temperature regressions identified statistically different slopes (95% confidence level) among most combinations of coral pairs ($p < 0.05$; Table 1). However, the slopes of W490 and E500 versus temperature are different at the 90% confidence level and of W037 and E016 are the same at the 99% confidence level. Sr/Ca-temperature correlation coefficients range from −0.58 ($n = 65$, $p < 0.05$) in core W490 to −0.84 ($n = 95$, $p < 0.05$) in core W037, which are comparable with those generated for *Porites* corals at other tropical Pacific sites [*Cahyarini et al.*, 2009; *Nurhati et al.*, 2011; *Carilli et al.*, 2014]. Regressing Sr/Ca onto OISST rather than logger temperature yielded similar results (Figure 3b), with slopes all significantly different except for W037 versus E016. Sr/Ca-SST correlation coefficients range from −0.47 ($n = 65$, $p < 0.05$) in core W490 to −0.81 ($n = 98$, $p < 0.05$) in core E016. Slopes of the regression of Sr/Ca on OISST and of the regression of Sr/Ca on logger temperatures are statistically identical for each coral ($p < 0.05$; Table 1).

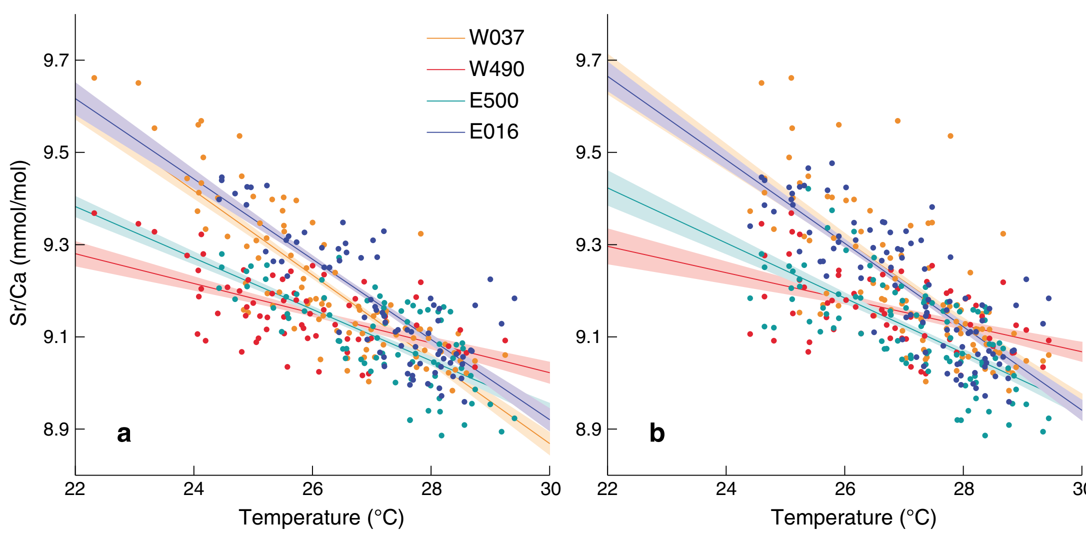

Figure 3. (a) Regression of coral Sr/Ca from each of the four cores onto in situ logger data (west side composite for west side corals and east side combined logger for east side corals). The shaded error bars represent the regression errors. Slopes are statistically different except W037 versus E016 ($p > 0.99$) and W490 versus E500 ($p < 0.10$; Table 1). Population means are all statistically different except for W037 versus E016. Slopes and errors are provided in Table 1. (b) Regression of coral Sr/Ca onto OISST for each of the four cores for the period of 2006–2012. The shading represents the regression errors. Slopes are statistically different except W037 and E016, which are within error ($p > 0.99$; Table 1).

Table 4. Trend Slopes Over Period Common to West Logger Composite, Combined East Logger, and OISST (2004–2012)

Time Series	Slope	Trend[a]	95% Confidence Interval
W037 Sr/Ca	0.039 mmol/mol/yr[b]	**Cooling**	0.025 to 0.053 mmol/mol/yr
E016 Sr/Ca	0.041 mmol/mol/yr[b]	**Cooling**	0.029 to 0.052 mmol/mol/yr
E500 Sr/Ca	0.001 mmol/mol/yr[c]	No trend	−0.009 to 0.011 mmol/mol/yr
West logger	−0.379°C/yr[d]	**Cooling**	−0.524 to −0.233°C/yr
East logger	−0.223°C/yr[d]	**Cooling**	−0.345 to −0.101°C/yr
OISST	−0.204°C/yr°C/yr[d]	**Cooling**	−0.334 to −0.074°C/yr

[a]Trends significant at 95% confidence level in bold.
[b]Statistically indistinguishable from each other.
[c]Statistically different from other two coral trends.
[d]Statistically indistinguishable from other temperature trends.

3.4. Temperature-Sr/Ca Regressions

In order to use Sr/Ca to estimate temperatures, we regressed logger temperature on Sr/Ca. Except for W037 versus E500, the regressions are not within error of each other (Figure 4), although an ANOVA showed statistically indistinguishable slopes of the regressions ($p < 0.05$; Table 1). Correlation coefficients are identical to those reported above in section 3.3. We calculated the standard error of prediction of temperature $\mathrm{SE}(\hat{T})$ for a single derived temperature estimate using the following expression from *Brownlee* [1965]:

$$\mathrm{SE}(\hat{T}) = \hat{\sigma}\sqrt{\left[\frac{1}{n} + \frac{\left(\mathrm{Sr/Ca} - \overline{\mathrm{Sr/Ca}}\right)^2}{\hat{\beta}_1{}^2 \sum_{j=1}^{n}\left(T_j - \overline{T}\right)^2 + 1}\right]} \tag{1}$$

where $\hat{\sigma}$ is the standard deviation of the estimated temperature values, $\hat{\beta}_1$ is the estimated slope of the regression, n is the number of samples, overbars indicate the time series means, T_j is the temperature measured at all times j, from 1 to n. This statistic is not a propagation of error; rather, it estimates the error on temperature derived from a Sr/Ca ratio of the same coral from which the regression was derived. Standard errors of prediction for logger temperature regressions on Sr/Ca range from 0.7°C in E016 to 1.21°C in W490 (Table 1). Regressing OISST on Sr/Ca yielded similar results (Table 1), and slopes of the regression of Sr/Ca on OISST and of the regression of Sr/Ca on logger temperatures are statistically identical for each coral ($p < 0.05$; Table 1). However, equation (1) represents only the error of prediction internal to a particular coral record (i.e., the calibration equation is applied to the same coral with which it was developed). When temperature reconstructions are performed using multiple corals, equation (1) drastically underestimates the true error as a result of variations in Sr/Ca-temperature relationships among corals (section 4.2.1 below).

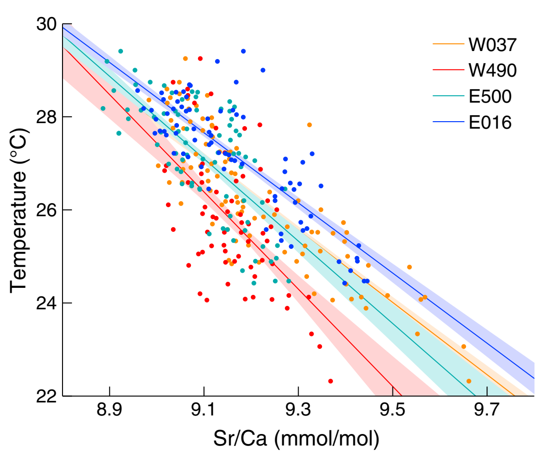

Figure 4. Regression of in situ logger data onto coral Sr/Ca from each of the four cores. Although only the regressions of W037 and E500 are within error, the slopes for all four corals are within error (Table 1). Standard errors of inverse prediction range from 0.744 ± 0.001°C (1σ, $n = 78$) for E016 to 1.21 ± 0.01°C (1σ, $n = 65$) for W490.

4. Discussion

4.1. Vital Effects or Real Oceanographic Variability

Analysis of the Sr/Ca records generated from contemporaneous *Porites* corals sampled from the west and east sides of Jarvis Island reveal inconsistencies that cannot be attributed to island-scale oceanographic variability. The mean Sr/Ca of E016 is 0.13 mmol/mol higher than that of E500 growing adjacent to it over the same time period. At the Sr/Ca-temperature sensitivities of these corals (Table 1), this difference represents 1.4–2.2°C. At Jarvis, such a large temperature difference is unlikely, given that the corals are both located on the east side of the island, at the same depth, in unsheltered locations, and east side logger records are

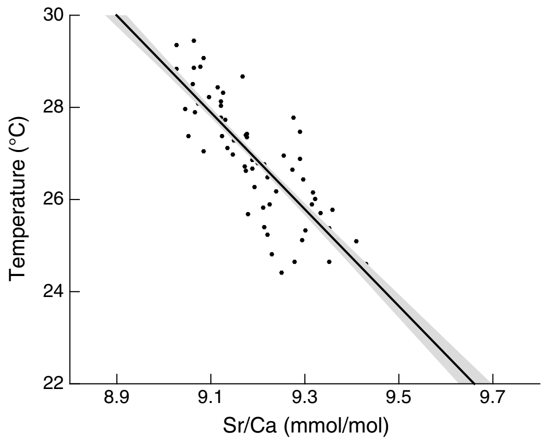

Figure 5. Regression of stacked Sr/Ca (black circles) onto OISST (black, with shading indicating the error on regression). Standard error of inverse prediction is 0.779 ± 0.006°C (1σ, $n = 65$).

each statistically identical to satellite temperature indicating the homogeneity of the temperature field bathing the corals there. Similarly, the 0.10 mmol/mol difference in mean Sr/Ca between the corals on the west side suggests a temperature difference of 1.1–3.3°C. However, the standard deviation of absolute differences in temperatures from multiple in situ loggers deployed on the west side is 0.07°C and the distance between the loggers is an order of magnitude greater than the distance between the corals.

Moreover, mean Sr/Ca of corals occupying the west, and thus the cooler, side of the island are not consistently higher than those of corals occupying the east side of the island, as would be predicted from the generally inverse relationship between Sr/Ca and temperature. Together these observations exclude the possibility that the Sr/Ca differences among corals are due to micro-oceanographic heterogeneity and point toward vital effects as a source of the inconsistencies.

4.2. Evaluation of Sr/Ca-Derived Temperature Records From Nonliving Corals

Like our study, previous studies have reported offsets in mean Sr/Ca translating to 1–4°C [*Goodkin et al.*, 2005; *Linsley et al.*, 2006; *Saenger et al.*, 2008; *Cahyarini et al.*, 2009; *Pfeiffer et al.*, 2009; *Wu et al.*, 2014] from multiple corals from the same genus and the same reef or island. Our attribution of the offsets we find to vital effects poses a problem for interpretation of long-term temperature records from multiple, nonoverlapping nonliving corals [*Guilderson et al.*, 1994; *McCulloch et al.*, 1996; *Beck et al.*, 1997; *Gagan et al.*, 1998; *Hughen et al.*, 1999; *Abram et al.*, 2009; *Kilbourne et al.*, 2010; *Toth et al.*, 2015]. For example, if E016 was a nonliving coral and E500 was a modern coral, we could erroneously infer that there had been a 1.4–2.2°C increase in mean temperature at this site, when in fact, we have shown that the difference in Sr/Ca is not due to temperature.

Like ours, other studies have found statistically distinct regression slopes of Sr/Ca on temperature [*Saenger et al.*, 2008; *Cahyarini et al.*, 2009; *Pfeiffer et al.*, 2009]. Here we use several approaches to further investigate the implications of such differences in mean Sr/Ca and regression slopes for temperatures reconstructed from nonliving corals.

4.2.1. Stacking Records

Several studies present a Sr/Ca "stack" or "master" record constructed by averaging concurrent Sr/Ca values from multiple cores and regressing temperature on the stacked Sr/Ca. This has been applied in cases when the regression slopes of multiple corals were distinct [*Linsley et al.*, 2006; *Cahyarini et al.*, 2009; *Pfeiffer et al.*, 2009; *Wu et al.*, 2014], as well as another in which multiple corals had regression slopes within error and no offsets [*DeLong et al.*, 2007]. We replicated this method to create an averaged stack of Sr/Ca from all four corals over the time covered by all coral records (2007–2012) and regressed OISSTs onto this stack (Figure 5 and Table 1). The mean error of prediction of the stack regression is 0.779 ± 0.006°C (1σ, $n = 260$; Table 1), calculated following *Brownlee* [1965].

To simulate the application of this regression to a single coral with unknown temperature-Sr/Ca relationship (i.e., a nonliving coral that is analyzed to extend the record back in time), we applied the stack regression to each of the four Sr/Ca records generated in this study (Figure 6). We assume that our living corals have captured the full range of possible temperature-Sr/Ca relationships at this site. Using the same stack regression however, the different corals suggest different temperature histories, including inconsistencies that are exaggerated during cold (La Niña) events. For example, corals E500 and W490 do not record the strong cooling during the 2007–2008 La Niña and the derived 2010 cooling is smaller in these corals than that suggested by E016 and W037. Coral W490 shows warming during the 2012 cooling. Corals E016 and W037 register large cool events in 2007–2008, 2010, and 2012, although they disagree on the magnitude of the

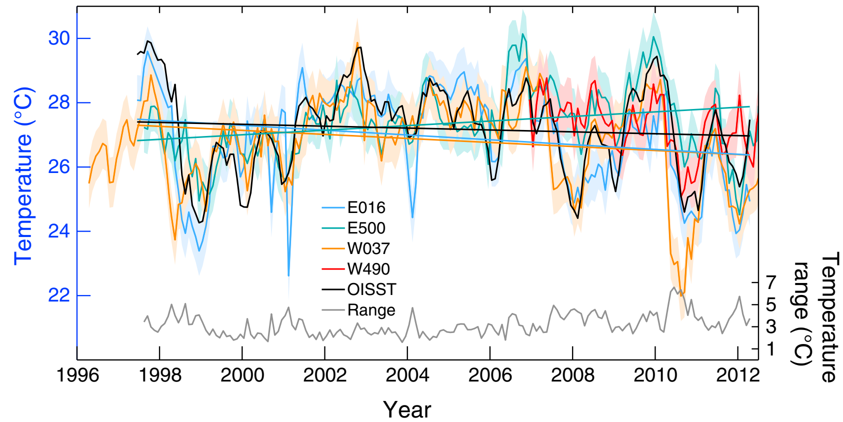

Figure 6. Derived temperatures from all four corals generated using the regression of stacked Sr/Ca on OISSTs (Figure 5). The shading indicates the standard error of prediction for the stack regression, 0.779 ± 0.006°C (1σ, $n = 65$; Table 1). The gray solid line below tracks the maximum difference between temperatures derived from each of the corals at a given time point. This difference averages 3.8°C over the period covered by all four corals. The solid lines denote the 1997–2012 trends in OISST (black) and coral Sr/Ca records (colors). Although OISST suggests no trend and two corals suggest cooling trend (E016 and W037), these trend slopes are within error of each other and are not significant. Conversely, the trend in E500 is significant ($p < 0.02$) and indicates that the east side of Jarvis Island warmed over this time period.

2008 cooling. Using only one of these records, we might draw erroneous conclusions with respect to the amplitude or frequency of large cold events at this site. Differences also exist among the colonies in the estimated temperature and amplitude of warm events, although they are not as large as the discrepancies during cool events.

Inconsistencies between coral records extend beyond amplitude of variability. As expected from the differences in mean Sr/Ca, the mean SSTs derived from the stack regression for the four corals are not all within standard error of one another: 27.7 ± 0.1°C ($n = 65$), 27.3 ± 0.1°C ($n = 65$), 26.3 ± 0.2°C ($n = 65$), and 27.3 ± 0.1°C ($n = 65$), for corals E500, W490, W037, and E016, respectively, with differences among sites inconsistent with their growth temperatures.

Long-term trends in reconstructed SST are also inconsistent. Over the period covered by all three corals (1998–2012), the trends in W037, E016, and OISST are positive and statistically indistinguishable from one another (Figure 6). However, the trend in estimated temperatures for E500 is cooling and statistically distinct. Similar discrepancies are seen in a record from Butaritari [*Carilli et al.*, 2014], where the post-1976 Sr/Ca-derived trend is cooling, when the instrument-based data indicate warming [*Karnauskas et al.*, 2015], and in two Sr/Ca records from the same site in Madagascar [*Grove et al.*, 2013] having opposite trends. These observations imply that coral Sr/Ca may suggest temperature trends opposite to those actually experienced. Thus, interpretations of long-term trends derived from coral Sr/Ca should be viewed cautiously, and any implied trend should be replicated in several corals.

The large spread in Sr/Ca-derived temperatures and the often nonoverlapping error of the derived temperatures indicate that the standard error of prediction for the stack underestimates the true error of applying this calibration to a nonliving coral or any coral with an unknown SST-Sr/Ca relationship. The departures of the Sr/Ca-temperature points of each of the individual corals have a systematic relationship with SST; the departures from the stack regression are correlated, rather than randomly distributed. For example, since the regression from E016 lies above the stacked regression (Figure 5), the estimates from coral E016 are largely too cool, while the estimates from E500, lying below the stack regression, are largely too warm. A more realistic estimate of the potential range of temperatures takes the difference between the concurrent maximum and minimum temperature estimates from the four corals, including the error bars constructed using one standard error of prediction (Figure 6, bottom, gray curve). This approach yields an average range on temperatures derived from Sr/Ca of 3.8 ± 1.0°C (1σ, $n = 65$), with the largest values at low temperatures (for example, 6.4°C at an OISST of 25.1°C; Figure 6, bottom, gray curve) and smallest values at high temperatures (for example, 2.2°C at an OISST of 28.5°C; Figure 6, bottom, gray curve).

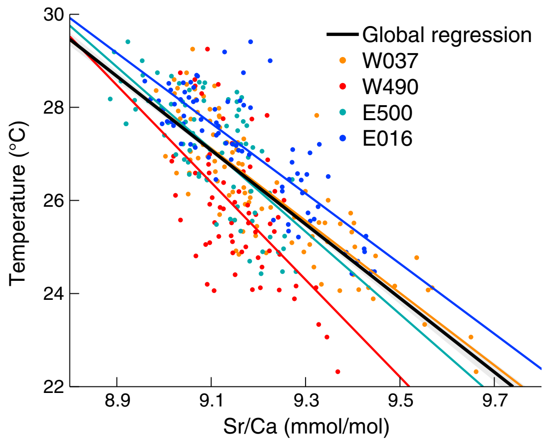

Figure 7. Global regression of Sr/Ca onto logger temperatures (black, with shading indicating standard error of prediction, 1.023 ± 0.003°C, 1σ, n = 359). Sr/Ca values and coral-specific regressions for W037, W490, E016, and E500 are plotted in orange, red, blue, and green, respectively.

4.2.2. "Global" Regression

Given the uncertainties of applying a regression based on stacked Sr/Ca, another approach is to combine all Sr/Ca values from the four colonies in a single global regression. In contrast to the stack regression in which we averaged concurrent Sr/Ca values from all four corals for a single data set of 65 points, in the global regression we used all 359 original data points (for 2004–2012) employed in the logger-based regressions for all four corals (Figure 4). We then regressed the corresponding logger temperatures on these Sr/Ca values (Figure 7 and Table 1). As with the stack regression, we applied this global regression to each of the four Sr/Ca records as if they were from nonliving corals with unknown relationship to temperature (Figure 8). The average standard error of prediction is 1.023 ± 0.003°C (1σ, n = 316; Table 1) calculated according to *Brownlee* [1965]. The results of this method are similar to those using the stack; there is little consensus among the corals on the amplitude of large warm and cold events, with the uncertainty especially large during cold events. Depending on which coral was selected from the set of corals and analyzed for Sr/Ca, the results could indicate strong ENSO-driven interannual variability (E016 or W037) or virtually none (W490).

Similar to the results of the stack regression, the mean temperature predictions among corals are not within standard error of each other and differences among sites are inconsistent with their growth temperatures. Trend results are the same as for the stack regression (Figure 8) and are not sensitive to the period over which the trends are calculated.

Like the estimates based on the stack regression, the standard error of prediction for the global regression underestimates the true range of temperatures resulting from the application of this calibration to a coral with an unknown SST-Sr/Ca relationship, which we estimate is 3.8 ± 0.8°C (1σ, n = 65) calculated the same way as for the stack regression.

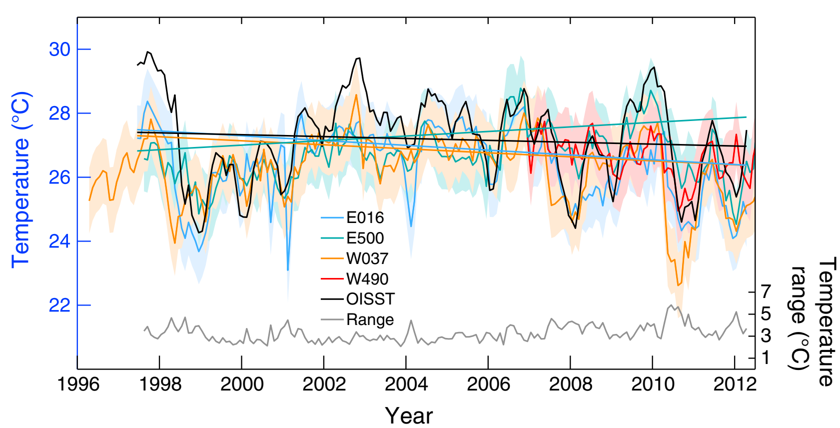

Figure 8. Derived temperatures from all four corals generated using the global regression on logger temperature (Figure 7). The shading indicates the standard error of prediction for the global regression, 1.023 ± 0.003°C (1σ, n = 359; Table 1). The difference between maximum and minimum derived temperatures from all corals at a given time point is plotted in gray and averages 3.8°C over the period covered by all four corals. The solid lines denote the 1997–2012 trends in OISST (black) and coral Sr/Ca records (colors). All trend slopes are within error of each other except for E500, which suggests significant ($p < 0.02$) warming.

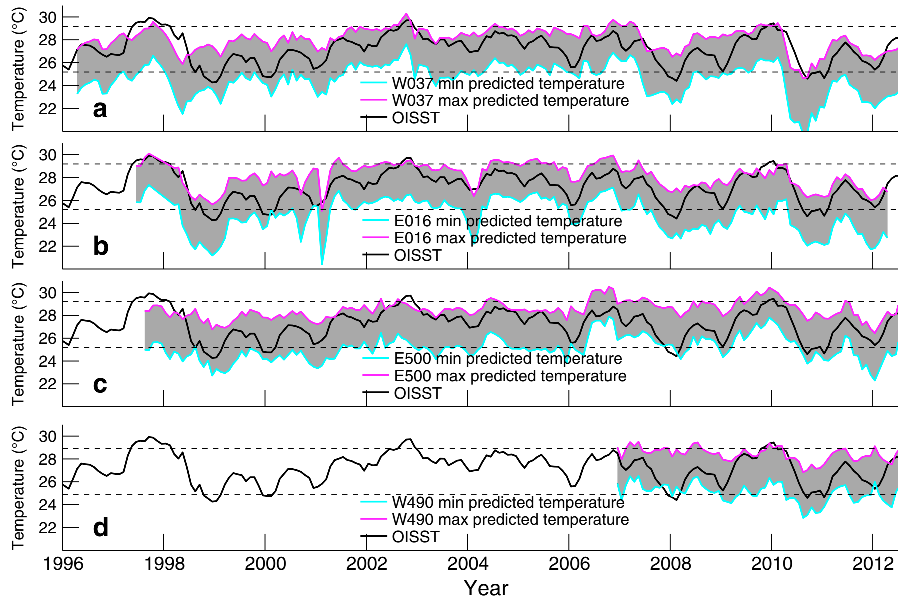

Figure 9. (a) Derived temperatures from W037 generated by applying all four regressions on logger temperatures (Figure 4) to its Sr/Ca record. The magenta line marks the maximum estimate plus one standard error of prediction, and the blue line marks the minimum estimate minus one standard error of prediction. The gray shading represents the range of possible estimates within ± 1 standard error of prediction. OISST is indicated by the black line, with dashed horizontal lines indicating ± 2°C from the mean for the period covered by the three long records: W037, E016, and E500. (b–d) Same as in Figure 9a but for E016, E500, and W490, respectively. The average difference between maximum and minimum derived temperatures over the range of Sr/Ca values measured is 3.7°C.

4.2.3. Application of All Individual Regressions

We investigated one additional method for estimating temperatures and associated errors for a Sr/Ca record from a nonliving coral from Jarvis, applying all regressions to each single Sr/Ca record. The range of estimates is graphically represented by the difference between the maximum and minimum temperatures for a given Sr/Ca value, based on any of the four regressions on logger temperatures (Figure 4), and their associated estimates, as discussed below.

We applied all regressions to each coral and took the maximum and minimum temperatures returned by the four regressions as the maximum and minimum temperature estimates for that time point. To account for the errors of prediction of the regressions, we added the standard error of prediction of the regression used to construct the maximum estimate (W490, 1.21°C) to the initial maximum estimate and subtracted the standard error of prediction of the regression used to construct the minimum estimate (E016, 0.74°C) to the initial minimum estimate. The temperatures between the resulting maximum and minimum estimates for each coral indicate the range of potential temperatures estimated by that coral (Figure 9), and these average 3.7 ± 0.7°C (1σ, $n = 78$). Although the range of estimated temperatures includes the OISST estimate for most of all four records, the spread in the derived temperatures is so large that even temperature excursions that are ± 2°C from the mean could not be reliably identified using a Sr/Ca record from a single coral (Figure 9).

5. Conclusions and Outlook

SST records from corals in the tropical Pacific such as those at Jarvis Island have the potential to help answer critical questions about the global climate system and its response to anthropogenic increases in greenhouse gases. In general, SST derived from Sr/Ca captured the occurrence of interannual SST events but the amplitude of these events was not consistently recorded by any of the corals (Figure S5). The slopes of the regressions of temperature on Sr/Ca are within error for all four different corals (Figure 4); however, mean offsets in Sr/Ca, equivalent to ~1.1–3.3°C, between corals experiencing the same temperatures (Table 1) imply that the regressions of temperature on Sr/Ca are not within error. Therefore, deriving a temperature-Sr/Ca relationship from a coral collected live and applying it to another coral has the potential to introduce errors as large as 4°C or more (e.g., Figure 9), comparable to errors found in a compilation of 18 corals [*Moreau et al.*, 2015]. The large uncertainty when any regression is applied to a single coral of unknown temperature-Sr/Ca relationship compromises the utility of Sr/Ca to estimate the amplitude and frequency of ± 2°C temperature oscillations with any confidence.

Calibrating a stack of all four Sr/Ca records against temperature (Figure 5) or combining all coral data into a global regression (Figure 7) yields inconsistent SST estimates when applied to individual corals (Figures 6 and 8). Standard error of prediction based on the expression in *Brownlee* [1965] underestimates the potential errors, based on the ranges of temperature estimates using these methods, by a factor of more than 2.

While the magnitude of the resulting uncertainty is problematic for absolute temperature estimates based on Sr/Ca from nonliving corals, it is also troublesome for determining the amplitude of temperature variability from nonliving corals. Even if the mean is removed, differences in the slope of the Sr/Ca-temperature relationship will result in different amplitudes of variability.

Finally, Sr/Ca trends from different corals living at the same time in the same water temperature are of opposite sign, implying that extreme caution must also be exercised in using a calibration based on a coral collected live to estimate recent or preinstrumental temperature trends.

Our results indicate that temperature estimates derived from coral Sr/Ca must be accompanied by realistic errors that can only be estimated by characterizing the distribution of potential Sr/Ca-SST relationships at the study site. Coral skeleton Li/Mg ratios are potentially a more robust temperature proxy [*Montagna et al.*, 2014], yet unexplained deviations between Li/Mg and temperature remain [*Hathorne et al.*, 2013b]; it is essential to further expand this and other methods to take into account vital effects.

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