Geochemistry, Geophysics, Geosystems

RESEARCH ARTICLE
10.1029/2019GC008420

Key Points:
- Sr/Ca-SST calibration slopes differ significantly among overlapping coral records, ranging from −0.062 to −0.12 mmol mol^{-1} °C^{-1}
- Intercolony offsets in mean Sr/Ca and δ^{18}O can produce errors of ±1.3 °C in reconstructions of absolute SST based on single corals
- Replicating coral proxy records from a given time period minimizes the uncertainties associated with intercolony variability

Supporting Information:
- Supporting Information S1
- Data Set S1

Correspondence to:
H. R. Sayani,
hsayani@gatech.edu

Citation:
Sayani, H. R., Cobb, K. M., DeLong, K., Hitt, N. T., & Druffel, E. R. M. (2019). Intercolony δ^{18}O and Sr/Ca variability among *Porites* spp. corals at Palmyra Atoll: Toward more robust coral-based estimates of climate. *Geochemistry, Geophysics, Geosystems*, *20*, 5270–5284. https://doi.org/10.1029/2019GC008420

Received 29 APR 2019
Accepted 24 SEP 2019
Accepted article online 14 OCT 2019
Published online 25 NOV 2019

Intercolony δ^{18}O and Sr/Ca variability among *Porites* spp. corals at Palmyra Atoll: Toward more robust coral-based estimates of climate

Hussein R. Sayani[1], Kim M. Cobb[1], Kristine DeLong[2], Nicholas T. Hitt[3,1], and Ellen R. M. Druffel[4]

[1]School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA, USA, [2]Department of Geography and Anthropology and Coastal Studies Institute, Louisiana State University, Baton Rouge, LA, USA, [3]School of Geography, Environment and Earth Sciences, Victoria University of Wellington, Wellington, New Zealand, [4]Department of Earth System Science, University of California, Irvine, CA, USA

Abstract Quantitative estimates of natural climate variability are required to detect anthropogenic climate trends in the tropical Pacific; however, instrumental records from this region are too short and scarce. Coral oxygen isotopic (δ^{18}O) and strontium to calcium (Sr/Ca) records are often used to extend instrumental observations; however, differences in the mean Sr/Ca and δ^{18}O values of *Porites* spp. colonies from the same reef can introduce large uncertainties in coral-based climate reconstructions. To quantify intercolony variability at Palmyra Atoll, we generate monthly resolved Sr/Ca and δ^{18}O time series from five *Porites* spp. colonies that grew between 1980 and 2010. Monthly to interannual variability in Sr/Ca and δ^{18}O is well-reproduced among different colonies; however, we document intercolony offsets in mean Sr/Ca of ±0.09 mmol/mol (1σ) or ~1 °C, and in mean δ^{18}O of ±0.12‰ (1σ) or ~0.1 °C. The sensitivity of each proxy to climate also varies across colonies, with Sr/Ca-SST slopes ranging from −0.06 to −0.1 mmol mol^{-1} °C^{-1} and δ^{18}O-SST slopes ranging from −0.25 to −0.35‰ °C^{-1}. Intercolony variability in both coral Sr/Ca and δ^{18}O reduces the reproducibility of coral-based $\delta^{18}O_{sw}$ reconstructions across overlapping colonies. Accounting for both intercolony variability and slope error suggests that SST reconstructions using Sr/Ca from a single Palmyra coral have an uncertainty of ±1.3 °C (1σ); however, replicating Sr/Ca records across multiple colonies can greatly reduce this uncertainty. A composite Sr/Ca record built using five modern cores, for example, offers a reduced error of ±0.6 °C (1σ) in mean SST reconstructions, ~2.5 times smaller than errors associated with reconstructions from single corals.

1. Introduction

Improving the accuracy and precision of decadal-to-centennial climate projections requires accurate and precise estimates of natural climate variability on these time scales. However, in the tropical Pacific, where sea surface temperature (SST) variations profoundly influence global temperature and rainfall patterns on interannual (McPhaden et al., 2006) and decadal-to-centennial time scales (Fyfe et al., 2016; Kosaka & Xie, 2013; Meehl et al., 2016), the availability of instrumental climate data decreases significantly prior to 1950 (Deser et al., 2010; Solomon & Newman, 2012; Tokinaga et al., 2012), and is virtually nonexistent prior to 1900 (Woodruff et al., 1987). Paleoclimate reconstructions spanning the last several centuries can effectively extend the instrumental climate record, allowing for the quantification of temperature variations on interannual to centennial time scales of interest (e.g., Abram et al., 2016; Emile-Geay et al., 2013; Evans et al., 2000; Mann et al., 2009; McGregor et al., 2015; Tierney et al., 2015; Wilson et al., 2010).

Massive reef-building corals are routinely used to develop sea surface temperature reconstructions from the tropical Pacific, as they provide monthly resolved records that can span several centuries (e.g., Corrège, 2006). Coral-based climate reconstructions often employ the genus *Porites* and rely on oxygen isotopic (δ^{18}O) ratios, a proxy that reflects combined variations in SST and seawater oxygen isotopic ratio ($\delta^{18}O_{sw}$; Epstein et al., 1953; Weber and Woodhead, 1972; Corrège, 2006, and references therein). SST and salinity changes in the equatorial Pacific covary on interannual time scales, but may be decoupled on decadal and longer time scales (e.g., Oppo et al., 2009; Rustic et al., 2015; Sachs et al., 2009; Tierney et al., 2010), requiring the use of an independent SST proxy to separate the temperature and salinity contributions to coral δ^{18}O records.

Extensive empirical data underscores the utility of coral Sr/Ca ratios as a robust proxy for ocean temperature (Beck et al., 1992; DeLong et al., 2013; Inoue et al., 2007; Kuffner et al., 2017; Quinn & Sampson, 2002; Sinclair, 2015; Smith et al., 1979; Weber, 1973), even though a complete mechanistic framework for temperature-dependent incorporation of Sr into coral skeletal aragonite remains elusive (Allison et al., 2011; Gaetani & Cohen, 2006; Gagnon et al., 2012; Sinclair et al., 2006). Paired measurements of coral Sr/Ca and coral $\delta^{18}O$ allow for the quantification of both SST and $\delta^{18}O_{sw}$ variations in the past (e.g., Ren et al., 2002; *Cahyarini et al.*, 2008a). While still relatively rare due to the amount of labor required, this paired approach does afford a more complete understanding of natural versus anthropogenic temperature and/or hydrological changes across the tropics (e.g., Carilli et al., 2014; Felis et al., 2009; Hetzinger et al., 2010; Nurhati et al., 2009; Nurhati et al., 2011; Toth et al., 2015). Nonetheless, the use of coral Sr/Ca and $\delta^{18}O$ reconstructions, either together or independently, poses a number of challenges to investigating past climate changes that we review in the following paragraphs.

Several studies comparing proxy records from *Porites* spp. colonies from the same reef observe offsets in absolute $\delta^{18}O$ and Sr/Ca values that cannot be explained by small-scale environmental variability. While these "intercolony offsets" do not impact climate reconstructions from modern corals that can be benchmarked to instrumental SST (which constitute the vast majority of coral paleoclimate literature), they present a significant obstacle for absolute temperature reconstructions from fossil corals. Intercolony $\delta^{18}O$ offsets among *Porites* spp. corals from the same site may be as large as 0.4‰ (Felis et al., 2003; *Cobb et al.*, 2003a; Stephans et al., 2004; Linsley et al., 2008; Dassié et al., 2014), equivalent to 2 °C in $\delta^{18}O$-derived SST (based on the empirical $\delta^{18}O$-SST relationship of −0.22‰ °C^{-1} from Epstein et al. (1953)). Intercolony Sr/Ca offsets among *Porites* spp. corals may be as large as 0.14 mmol/mol (de Villiers et al., 1995; Felis et al., 2004; Linsley et al., 2006; Pfeiffer et al., 2008; *Cahyarini et al.*, 2008a; Abram et al., 2009; DeLong et al., 2011; Alpert et al., 2016), equivalent to ~2 °C in Sr/Ca-derived SST (based on the average Sr/Ca-SST relationship of 0.06 mmol mol^{-1} °C^{-1} for *Porites* spp. from Corrège (2006)). Similar intercolony $\delta^{18}O$ and Sr/Ca offsets are also observed among *Porites* corals grown in closely regulated tanks (Hayashi et al., 2013; Inoue et al., 2007; Suzuki et al., 2005), suggesting that nonenvironmental factors, commonly dubbed "vital effects" may influence the absolute coral $\delta^{18}O$ and Sr/Ca values recorded by a colony. At this point, it is unclear whether these intercolony offsets differ from site to site or, more likely, represent an intrinsic feature of *Porites* spp. corals that remain poorly characterized by available studies.

The sensitivity of coral Sr/Ca to SST also varies among *Porites* spp. colonies, both within and across different sites. Differences in Sr/Ca-SST calibrations for *Porites* spp. corals growing at different sites are well documented (e.g., Alibert & McCulloch, 1997), with published Sr/Ca-SST slopes ranging from −0.04 to −0.12 mmol mol^{-1} °C^{-1}, with an average of −0.06 mmol mol^{-1} °C^{-1} (Corrège, 2006; Sinclair, 2015). The lack of interlaboratory Sr/Ca standards (Hathorne et al., 2013) and differences in coral slabbing, microsampling techniques, regression methods, and SST data sets used for calculating Sr/Ca-SST relationships can explain some of the observed spread in coral Sr/Ca-SST slopes (Corrège, 2006; DeLong et al., 2013). Yet studies examining contemporaneous corals from the same site also observe a similar range (−0.03 to 0.09 mmol mol^{-1} °C^{-1}) of Sr/Ca-SST slopes (Alibert & McCulloch, 1997; Alpert et al., 2016; DeCarlo et al., 2016). Identification of *Porites* corals at a species level is difficult and interspecific differences may explain some, but not all, of this observed intercolony variability.

Like coral Sr/Ca, coral $\delta^{18}O$-SST relationships for *Porites* spp. corals also vary appreciably between sites, ranging from −0.16 to −0.47‰ °C^{-1} (Grottoli & Eakin, 2007). Spatial $\delta^{18}O_{sw}$ variability can explain some site-specific differences in coral $\delta^{18}O$-SST slopes (Grottoli & Eakin, 2007; Russon et al., 2013). However, similar ranges of −0.23 to −0.53‰ °C^{-1} in $\delta^{18}O$-SST slopes have been observed among *Porites* spp. corals from the same site (e.g., Linsley et al., 1999; Stephans et al., 2004), suggesting that factors other than SST and $\delta^{18}O_{sw}$ might influence $\delta^{18}O$-SST sensitivity. Intercepts for both coral $\delta^{18}O$-SST and Sr/Ca-SST equations also vary, reflecting intercolony offsets in both coral proxies as noted previously.

Intercolony variability represents a significant hurdle for paleoclimate reconstructions based on fossil corals, which requires attributing changes in geochemistry between nonoverlapping corals to shifts in mean climate (Tudhope et al., 2001; *Cobb et al.*, 2003a; Corrège et al., 2004; Felis et al., 2004; DeLong et al., 2010; Cobb et al., 2013; Felis et al., 2014; Toth et al., 2015). In some instances, intercolony offsets can inflate mean temperature estimates far beyond the 1–2 °C SST change expected in the tropical Pacific across the Holocene on decadal to

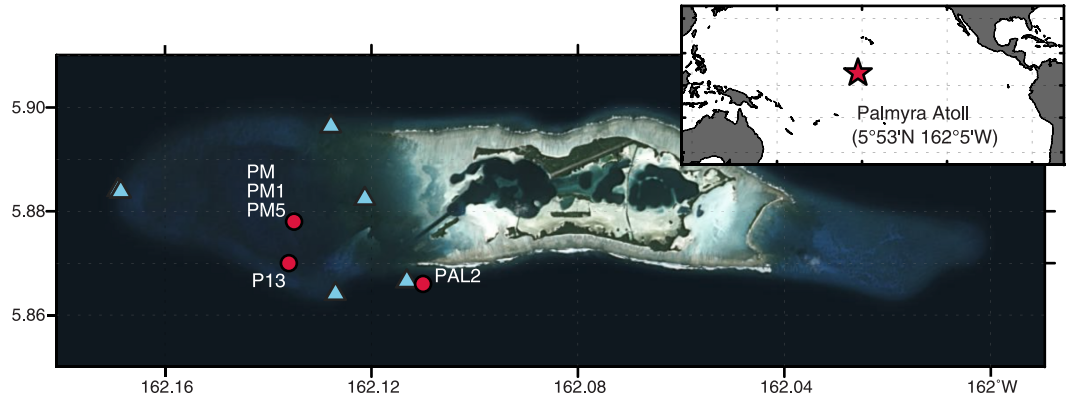

Figure 1. Locations of *Porites* colonies (red circles) and in situ temperature loggers (blue triangles) deployed by NOAA's Coral Reef Ecosystem Program, at Palmyra Atoll.

centennial time scales (e.g., Koutavas & Joanides, 2012; Oppo et al., 2009; Visser et al., 2003). A potential strategy for overcoming intercolony variability is to use multiple overlapping coral Sr/Ca and $\delta^{18}O$ records to constrain the mean climate of a target time period. Such ensembles can then be used to more accurately characterize differences in mean climate between two nonoverlapping time periods. While many studies have documented intercolony variability, and some have used replication to improve the accuracy of coral Sr/Ca or $\delta^{18}O$ records (e.g., Hendy, 2002; *Cobb et al.*, 2003a), to our knowledge, no study has used intercolony variability to quantify uncertainties in coral-based SST reconstructions.

Here, we use five overlapping coral cores recovered from Palmyra Atoll (5°53′N, 162°5′W) to assess intercolony differences in coral Sr/Ca and $\delta^{18}O$, and their relationship to instrumental SST between 1980 and 2010. We use these estimates of intercolony variability to quantify uncertainties in Sr/Ca-based and $\delta^{18}O$-based climate reconstructions from both single and multiple colony reconstructions (e.g., *Cobb et al.*, 2003a). We also assess the potential impact of intercolony Sr/Ca and $\delta^{18}O$ variability on coral-based $\delta^{18}O_{sw}$ reconstructions from Palmyra Atoll. Finally, we discuss the implications of our coral reproducibility study for the design of future coral reconstruction projects and multi-proxy synthesis studies that employ coral reconstructions.

2. Materials and Methods

We present new data from *Porites* spp. cores recovered from colonies growing on the western and southern reef terraces of Palmyra Atoll (5°53′N, 162°5′W) in the central tropical Pacific (Figure 1 and Table 1). Cores PM1 and PM5 were collected in May 1998 from two colonies growing <100 m apart, at unrecorded depths of <10 m, near the center of Palmyra's western reef terrace by K.M. Cobb. Core P13 was collected in June 2007 (by E.R.M. Druffel and R. Dunbar) from a colony growing at a depth of 11 m on the atoll's southern reef. Core PAL2 was collected in June 2010 by NOAA Coral Reef Ecosystem Program (CREP) from a colony growing at a depth of 12.5 m near the lagoon channel. A coral Sr/Ca record from core PAL2 is published in DeCarlo et al. (2016); however, here we present a new and extended Sr/Ca record from this core employing our analytical methodology and standards to ensure uniformity across all coral data sets in this study. The fifth core, hereafter referred to as PM, has previously published $\delta^{18}O$ (Cobb et al., 2001) and Sr/Ca (Nurhati et al., 2009, 2011) records from a 112-year-long core recovered in May 1998 by K.M. Cobb. We also use the following instrumental data sets in this study: (i) in situ Palmyra SST data spanning 2000–2002 published in Nurhati et al. (2009) and logger SST covering 2004–2012 collected by NOAA Coral Reef Ecosystem Program (CREP and PIFSC, 2017), (ii) gridded temperatures and SST error estimates from the ERSSTv3b grid box (6°N, 162°W) containing Palmyra (Smith et al., 2008), and (iii) gridded surface salinity by Delcroix et al. (2011) from the (6°N, 162°W) grid box.

Table 1
Location and Extension Rates of Cores Used in This Study

Core	Location	Average extension rate (mm/year)
PM	5°52′41″N, 162°8′30″W	19.0 ± 0.9
PM1	5°52′41″N, 162°8′30″W	16.2 ± 0.7
PM5	5°52′41″N, 162°8′30″W	15.8 ± 1.0
P13	5°52′12″N, 162°8′9.6″W	16.9 ± 0.6
PAL2	5°51′57.6″N, 162°6′36″W	6 ± 1.0

Coral cores were prepared for geochemical analysis and SEM imaging following standard procedures. First, cores were cut into ~5–10-mm-thick

longitudinal slabs to reveal the growth axes and subsequently sonicated and rinsed in deionized water. The coral slabs were X-rayed at the Stamps Health Services at Georgia Tech to reveal the underlying skeletal architecture. Optimal sampling transects were selected close to the coral's primary growth axis, while taking care to avoid problematic areas of the core such as steeply angled corallites (oblique to the surface of the slab), merging corallite fans, and/or disorganized corallites, which have been shown to significantly bias coral $\delta^{18}O$ and Sr/Ca values (Alibert & McCulloch, 1997; Cohen & Hart, 1997; DeLong et al., 2013). Corals were screened for diagenetic alteration using either a Hitachi S-800 field emission gun scanning electron microscope (SEM) or a LEO 1530 thermally assisted field emission SEM using procedures outlined in Sayani et al. (2011).

Coral Sr/Ca was measured using a Horiba Jobin-Yvon Ultima 2C Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) located at Georgia Tech. Samples for ICP-OES analysis were prepared by drilling 150–200 μg of coral powder using a 1-mm drill bit at 1-mm intervals along a transect parallel to the primary growth axis, and then digesting in 2–2.7 mL of 2% trace-metal grade HNO_3 to obtain Ca concentrations of ~30 ppm. Analytical precisions for Sr/Ca of < ±0.1% or ±0.010 mmol/mol (1σ) are routinely obtained by bracketing each sample with an internal standard and applying a nearest-neighbor correction (Schrag, 1999). Repeat measurements of an in-house coral-based standard, measured 3–5 times per run, show negligible long-term instrumental drift across different runs. Coral Sr/Ca presented here are not corrected to carbonate standard JCp-1b (Hathorne et al., 2013); however, repeated analyses of this standard over time yield a Sr/Ca value of 8.99 ± 0.01 mmol/mol ($n = 25$).

Coral $\delta^{18}O$ ratios were measured using either a Thermo Scientific Delta V or a Thermo MAT 253 isotope ratio mass spectrometer located at Georgia Tech, both equipped with Finnigan Kiel IV carbonate devices. Samples are prepared by drilling 60–100 μg of coral power at 1-mm intervals along the same transects used for Sr/Ca measurements. Analytical precision based on repeated analyses of a homogenized aragonite standard is estimated to be <±0.070‰ (1σ) for $\delta^{18}O$ and ±0.050‰ (1σ) for $\delta^{13}C$ on both the Delta V and the MAT 253. For each run of coral powders, a powdered coral standard of known isotopic composition was analyzed 8–10 times during a single run to monitor precision as well as long-term drift.

Age models for each coral Sr/Ca record were constructed by identifying annual cycles across a number of 1-mm-spaced analyses, guided by well-established extension rates for *Porites* corals growing at Palmyra Atoll (12–20 mm/year; Cobb, 2002). Following Cobb et al. (2001), we assigned the highest (lowest) Sr/Ca values an initial calendar date of 1 February (1 September), corresponding to peak winter (summer) temperatures, based on monthly SST climatology for Palmyra Atoll derived from the Extended Reconstructed Sea-surface Temperature data set version 3b (ERSSTv3b; Smith et al., 2008). Ages between these winter and summer tie points were estimated using linear interpolation, assuming constant extension rates between tie points. A manual check of the resulting age models against subseasonal features reflected in both coral Sr/Ca and ERSSTv3b time series resulted in small shifts of one to two months for a subset of the coral data to obtain the final chronologies. Extension rates for cores PM, PM1, PM5, and P13, estimated by counting the number of 1-mm Sr/Ca data points per year, and range from 10 to 28 mm/year in any given year. The annual extension rate for cores PM, PM1, PM5, and P13, averaged across the interval analyzed on each core, are 19, 16, 16, and 17 mm/year, respectively. In contrast, extension rates for core PAL2 were significantly lower, ranging from 5 to 8 mm each year, averaging 6 mm/year between 2002 and 2010. Initial age models for the new $\delta^{18}O$ records from cores PM1 and PM5 are based on the final Sr/Ca-derived chronologies for cores, as the new records were developed by resampling along the same transects used for coral Sr/Ca records. To account for human error during resampling, age models for each coral $\delta^{18}O$ record were finalized by manually checking each record against ERSSTv3b, which resulted in shifts of one to two months for a small subset of the record. The monthly coral $\delta^{18}O$ and Sr/Ca records presented here have a noncumulative error of one to two months at any given point.

Coral-based $\delta^{18}O_{sw}$ records presented here are derived using the centering method of *Cahyarini et al.* (2008b), with a few notable changes. Paired coral Sr/Ca and $\delta^{18}O$ records were measured by resampling the same transect at different times rather than using splits of the same powder. As this resampling can potentially introduce subtle age discrepancies of one to two months in overlapping Sr/Ca and $\delta^{18}O$ records, we apply a six-month running mean filter to both proxy records before computing $\delta^{18}O_{sw}$. Keeping in line with previous work from Palmyra Atoll (Nurhati et al., 2009, 2011), we use the coral Sr/Ca-SST relationships for cores PM, PM1, and PM5 presented in section 3.2 and the empirical $\delta^{18}O$-SST relationship of −0.21‰ C^{-1}

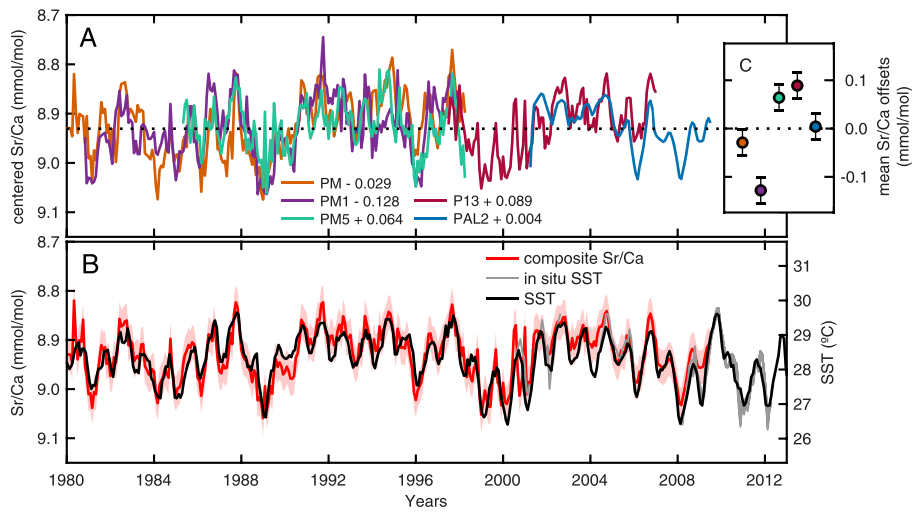

Figure 2. (a) Monthly Sr/Ca records, with offsets applied, from cores PM (orange; Nurhati et al., 2009, 2011), PM1 (purple), PM5 (green), P13 (red), and bimonthly Sr/Ca from PAL02 (blue). (b) Composite modern coral Sr/Ca, computed using records in (a), compared to both in situ SST (gray) and ERSSTv3b (black; Smith et al., 2008). Red shading represents analytical uncertainty compounded with intercolony Sr/Ca variability scaled by the number of cores in the composite. (c) Offsets in mean Sr/Ca values of each records shown in (a). Error bars (3σ) represent analytical precision of measurements in each record.

(Epstein et al., 1953) to calculate $\delta^{18}O_{sw}$. The uncertainty in reconstructed $\delta^{18}O_{sw}$ is calculated by propagating the Sr/Ca-SST slope error and analytical uncertainty for both Sr/Ca and $\delta^{18}O$ measurements through the $\delta^{18}O_{sw}$ derivation.

3. Results

3.1. Reproducibility Among Coral Sr/Ca Records

Between 1985 and 1998, overlapping monthly coral Sr/Ca time series from PM, PM1, and PM5 are well correlated with each other ($R = 0.56$ to 0.59, $p < 0.05$; Figure 2a). Likewise, between 1997 and 2007, bimonthly coral Sr/Ca from core P13 and PAL2 are well correlated with each other ($R = 0.53$, $p < 0.05$; Figure 2a). Smoothing each time series by three months or more substantially improves correlations among the different colonies, as it minimizes the contribution of chronological uncertainties (monthly time assignment) to each record (DeLong et al., 2013). Coral Sr/Ca records from cores PM, PM1, PM5, and PAL2 are well correlated with ERSST3b ($R = -0.71$ to -0.76, $p < 0.05$). Between 1997 and 2007, coral Sr/Ca from core P13 is highly correlated with ERSSTv3b ($R = -0.78$). However, prior to 1997, P13's coral Sr/Ca record diverges considerably from SST and overlapping Sr/Ca from cores PM, PM1, and PM5 (Figure S1). SEM screening shows no evidence of diagenesis in core P13 between 1997 and 2007; however, downcore from 1997, we observe considerable secondary aragonite infilling (Figure S2). As such, we only use the unaltered portion of P13 for reconstruction of SST in this study.

The amplitude of seasonal cycles in coral Sr/Ca are largely consistent among the five cores across periods where they overlap (Table 2). Between 1985 and 1998, cores PM, PM1, and PM5 exhibit statistically indistinguishable seasonal amplitudes of 0.072 ± 0.017, 0.080 ± 0.023, and 0.066 ± 0.021 mmol/mol, respectively (Figure S3 and Table 2). Between 2002 and 2010, P13 and PAL2 display similar seasonal amplitudes of 0.079 ± 0.010 and 0.069 ± 0.029 mmol/mol, respectively (Figure S3 and Table 2).

As with monthly and seasonal variability, interannual variability is also largely consistent among the different cores and SST over their respective overlaps (Table 2). Following Cobb et al. (2013), interannual coral Sr/Ca variability was isolated by removing the seasonal cycle and applying a 13-month running mean filter to each record (Figure 3), approximating a two-year low-pass filter. Interannual variability is estimated by computing the standard deviation of each filtered record. Cores PM and PM1 exhibit similar interannual variability (±0.044 mmol/mol; 1σ) between 1985 and 1998, whereas core PM5 exhibits somewhat muted interannual variations (±0.029 mmol/mol; 1σ) across this interval (Figure 3). Cores P13 and PAL2 exhibit

Table 2
Comparison of Mean, Seasonal Amplitudes, and Interannual Variability in Sr/Ca and $\delta^{18}O$ From Overlapping Corals

	Sr/Ca (mmol/mol)				
Core	Record Span	Mean	Offset	Seasonal amplitude	Interannual amplitude
PM	1980–1998	8.96	−0.029	0.072 ± 0.017	0.044
PM1	1981–1998	9.06	−0.13	0.081 ± 0.023	0.045
PM5	1985–1998	8.87	0.064	0.066 ± 0.021	0.029
P13	1997–2007	8.84	0.089	0.079 ± 0.010	0.015
PAL2	2001–2010	8.93	0.004	0.069 ± 0.029	0.017
	$\delta^{18}O$ (‰)				
Core	**Record Span**	**Mean**	**Offset**	**Seasonal amplitude**	**Interannual amplitude**
PM	1980–1998	−5.24	−0.022	0.32 ± 0.04	0.13
PM1	1983–1998	−5.25	−0.017	0.32 ± 0.04	0.10
PM5	1985–1998	−5.30	0.039	0.26 ± 0.05	0.10

much lower interannual variability (±0.015 and ±0.017 mmol/mol; 1σ, respectively) between 2002 and 2006, consistent with weaker El Niño–Southern Oscillation (ENSO) variability during the early 2000s. Interannual coral Sr/Ca records are well correlated with interannual SST ($R = 0.79$ to 0.96, $p < 0.05$).

Despite exhibiting similar variability, the coral Sr/Ca records are systematically offset from one another in terms of absolute (mean) Sr/Ca values during overlapping intervals (Figure 2c). The intercolony offsets in mean coral Sr/Ca range from −0.13 to +0.09 mmol/mol, relative to the centered composite of modern coral records (Figure 2b). The distribution (standard deviation) of observed intercolony offsets in coral Sr/Ca at Palmyra (±0.09 mmol/mol; 1σ, $n = 5$) is comparable to published intercolony offsets from *Porites* corals growing across the Line Islands (Alpert et al., 2016; Carilli et al., 2014; DeCarlo et al., 2016; Nurhati et al., 2009) and at other sites in the tropics with *Porites* spp. (Linsley et al., 2004, 2006; Abram et al., 2008, 2009). In total, the difference between the highest and lowest mean coral Sr/Ca value is 0.22 mmol/mol, equivalent to ~4 °C when converted to SST using the average of published coral Sr/Ca-SST calibrations of 0.06 mmol mol^{-1} $°C^{-1}$ for *Porites* corals (Corrège, 2006).

By subtracting the offset from each record and then averaging them together, we create a composite coral Sr/Ca record that tracks SST better than any of the individual coral Sr/Ca records across all of the time scales discussed. On monthly time scales, the coral Sr/Ca composite is better correlated with SST ($R = -0.82$, $p < 0.05$) than any individual Sr/Ca record (Figure 2b). On interannual time scales, the composite coral Sr/Ca is also well correlated with two-year low-pass-filtered SST ($R = -0.89$, $p < 0.05$; Figure 3), and is a more accurate reflection of interannual SST variability than any individual coral Sr/Ca record.

3.2. Sr/Ca-SST Calibrations and Uncertainties in Sr/Ca-Based SST

Empirical Sr/Ca-SST calibration equations for Palmyra Atoll corals fall within the range of published calibrations for *Porites* corals (Corrège, 2006). Calibration equations for each core (Figure 4 and Table 3) were

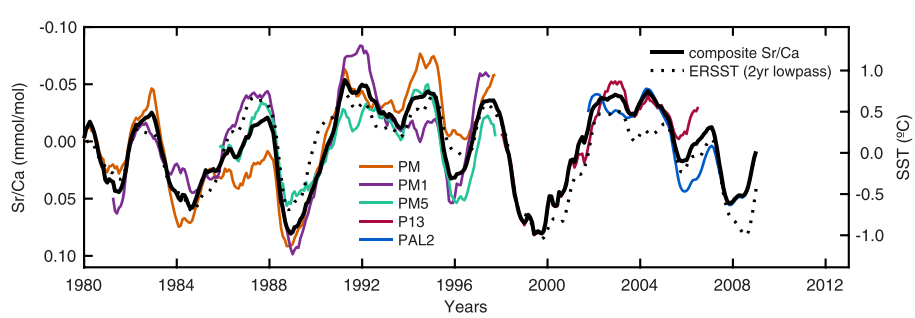

Figure 3. Interannual coral Sr/Ca variability in records from cores PM (orange), PM1 (purple), PM5 (green), P13 (red), PAL2 (blue), and the composite coral Sr/Ca record (black, solid), compared with two-year low-pass-filtered temperature from ERSSTv3b (black, dotted).

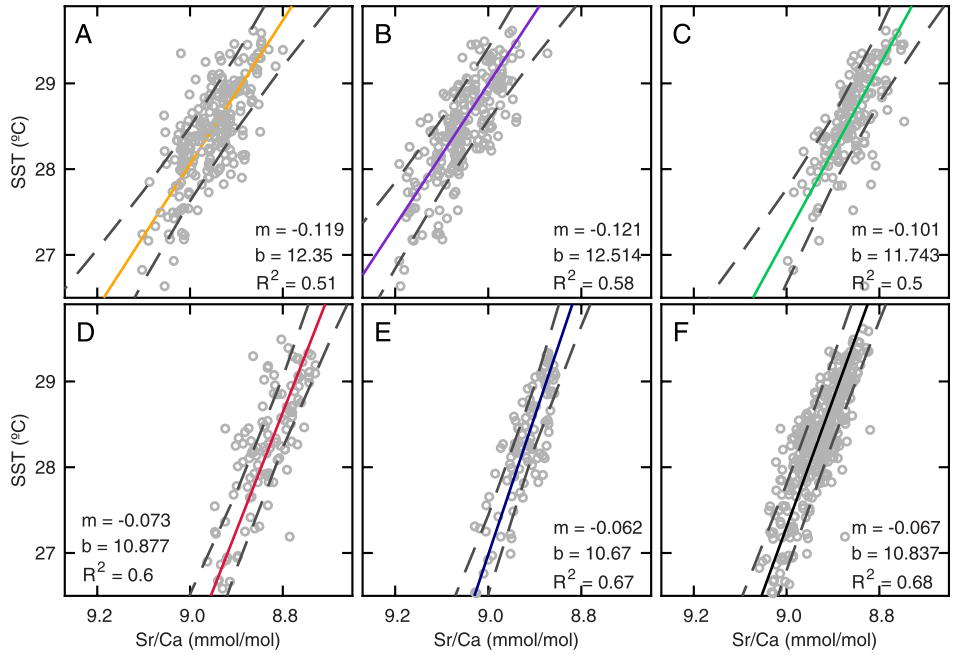

Figure 4. Coral Sr/Ca-SST calibrations for cores (a) PM, (b) PM_1, (c) PM_5, (d) P13, (e) PAL2, and (f) coral Sr/Ca composite. Coral Sr/Ca and SST pairs used in each calibration are shown in gray, *m* and *b* represent the slope and intercept for the equation Sr/Ca = m * SST + b, and dashed lines represent the 95% prediction bounds for each calibration.

computed using a weighted least squares regression (York et al., 2004), which accounts for uncertainty in gridded SST and analytical precision of Sr/Ca. The coral Sr/Ca-SST calibration slopes for cores PM and PM1 (Figures 4a and 4b) are statistically identical at −0.119 ± 0.003 and −0.121 ± 0.003 mmol mol^{-1} °C^{-1}, respectively. Cores PM5, P13, and PAL2 yield different coral Sr/Ca-SST slopes (Figures 4c–4e) of −0.101 ± 0.003, −0.073 ± 0.002, and −0.062 ± 0.002 mmol mol^{-1} °C^{-1}, respectively. The coral Sr/Ca composite yields a Sr/Ca-SST slope of −0.067 ± 0.005 mmol mol^{-1} °C^{-1} (1σ), indistinguishable from the average coral Sr/Ca-SST slope of −0.06 mmol mol^{-1} °C^{-1} reported by Corrège (2006). Intercepts for these coral Sr/Ca-SST calibrations ranges from 10.67 ± 0.054 to 12.52 ± 0.077 (1σ), primarily reflecting the intercolony Sr/Ca offsets observed among these records.

Relative to the observed discrepancies in coral Sr/Ca-SST sensitivity among Palmyra corals, intercolony offsets are the largest source uncertainty in absolute coral Sr/Ca-based temperature reconstructions. For a 0.10-mmol/mol change in coral Sr/Ca (ΔSr/Ca), calibration slopes for PM, PM1, and PM5 predict similar change in SST of ~0.9 °C. For the same ΔSr/Ca of 0.10 mmol/mol, the steeper calibration slopes for cores P13 and PAL2 predict larger temperature changes of 1.4 °C and 1.7 °C, respectively. Thus, applying a Sr/Ca-SST slope derived from one core to coral Sr/Ca measurements from a different core could potentially overestimate/underestimate SST variability by ±0.4 °C (1σ).

Table 3
Sr/Ca-SST and $\delta^{18}O$-SST Relationships

	Sr/Ca versus SST			$\delta^{18}O$ versus SST	
Core	slope (mmol/mol °C^{-1})	Intercept	*R*	slope (‰ °C^{-1})	*R*
PM	−0.096 ± 0.003	11.69 ± 0.085	−0.72	−0.35 ± 0.013	−0.79
PM1	−0.102 ± 0.003	11.97 ± 0.086	−0.76	−0.30 ± 0.012	−0.84
PM5	−0.078 ± 0.003	11.09 ± 0.091	−0.71	−0.25 ± 0.012	−0.83
P13	−0.069 ± 0.003	10.79 ± 0.075	−0.78	-	-
PAL2	−0.057 ± 0.003	10.53 ± 0.088	−0.81	-	-
Composite	−0.066 ± 0.005	10.81 ± 0.145	−0.82	−0.28 ± 0.007	−0.85

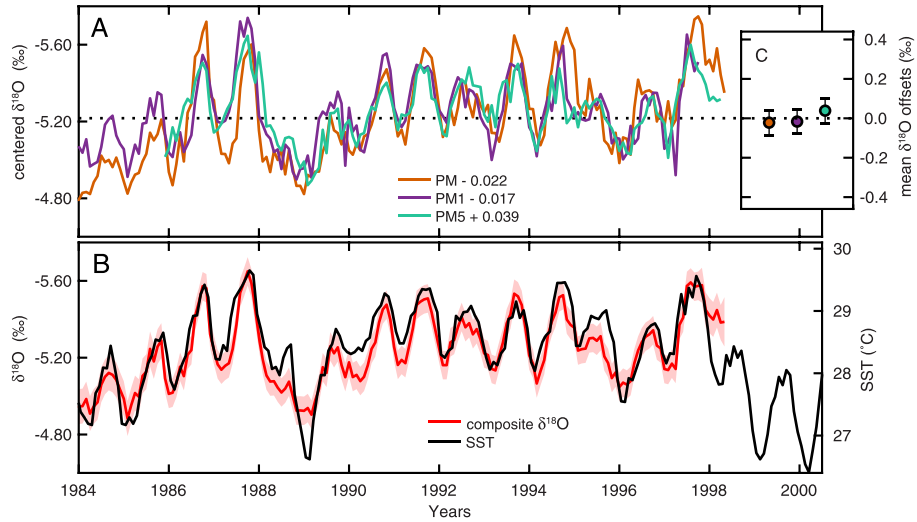

Figure 5. (a) Monthly $\delta^{18}O$ records, with offsets applied, from cores PM (orange; Cobb et al., 2001), PM1 (purple), and PM5 (green). (b) Composite modern coral $\delta^{18}O$ composite (red), derived using records in (a), compared with ERSSTv3b (black). Red shading represents analytical uncertainty compounded with intercolony Sr/Ca variability scaled by the number of cores in the composite.

For calculation of absolute temperature from coral Sr/Ca, intercolony differences in both the slope and intercept of the SST versus Sr/Ca must be considered, which contribute to a large spread in reconstructed absolute SST values for a given coral Sr/Ca value. Indeed, for a coral Sr/Ca value of 9.0 mmol/mol, calibrations based on cores PM, PM1, and PM5 yield absolute temperatures of 28.1±0.1 °C, 29.0±0.1 °C, and 27.3±0.1 °C, respectively. For the same coral Sr/Ca value, calibrations based on cores P13 and PAL2 yield temperature estimates of 25.7±0.2 °C and 27±0.2 °C, respectively. This spread in Sr/Ca-derived SST (±1.2 °C; 1σ) is an order of magnitude larger than the root-mean-square error for Sr/Ca-SST calibrations for PM, PM1, PM5, and P13 (±0.6 to ±0.7 °C, 1σ), highlighting that intercolony differences in the coral Sr/Ca versus SST relationship are highly significant.

3.3. Reproducibility Among Coral $\delta^{18}O$ Records

Monthly coral $\delta^{18}O$ records from Palmyra cores PM, PM1, and PM5 (Figure 5a) are well-correlated to each other ($R = 0.73$ to 0.79, $p < 0.05$) and with ERSST ($R = -0.78$ to -0.83, $p < 0.05$). Between 1985 and 1998, coral $\delta^{18}O$ from cores PM and PM1 have similar seasonal amplitudes of 0.32‰ (Figure S4a and Table 2). The amplitude of seasonal cycles in core PM5 is lower 0.26 ± 0.05‰ (1σ), but still within error of cores PM and PM1. We isolate interannual $\delta^{18}O$ variability using the same approach outlined above for the coral Sr/Ca record. Interannual variability is consistent between cores PM1 and PM5 (±0.10‰, 1σ) between 1985 and 1998 (Figure 6). Across the same interval, core PM exhibits larger interannual variability (±0.13‰, 1σ), suggesting that this colony might be more sensitive to ENSO. Obviously, longer coral $\delta^{18}O$ records would be required from each core in order to assess whether there is a systematic difference in the recording of interannual coral $\delta^{18}O$ variability for a given coral core, versus a slight underestimation of an isolated El Niño event. Unfortunately, such samples from Palmyra do not currently exist.

As with our coral Sr/Ca records, mean coral $\delta^{18}O$ values from cores PM, PM1, and PM5 are also systematically offset from each other. The distribution (standard deviation) of intercolony offsets (±0.02‰; 1σ, $n = 3$) are much smaller than analytical uncertainty (±0.07‰; 1σ) and thus not significant. However, larger intercolony $\delta^{18}O$ offsets of ±0.12‰ (1σ) have been observed among overlapping fossil corals from Palmyra (*Cobb et al.*, 2003a) and offsets >0.2‰ (1σ) have been observed at other sites (Dassié et al., 2014; Felis et al., 2003; Grottoli & Eakin, 2007), suggesting that the coral $\delta^{18}O$ records presented here may not fully capture intercolony $\delta^{18}O$ variability at our site. If interpreted purely in terms of temperature, intercolony $\delta^{18}O$ offsets are equivalent to ±0.1 °C (based on a $\delta^{18}O$-SST slope of 0.21‰ $°C^{-1}$)—an order of magnitude smaller offsets in Sr/Ca-based SST from the same cores.

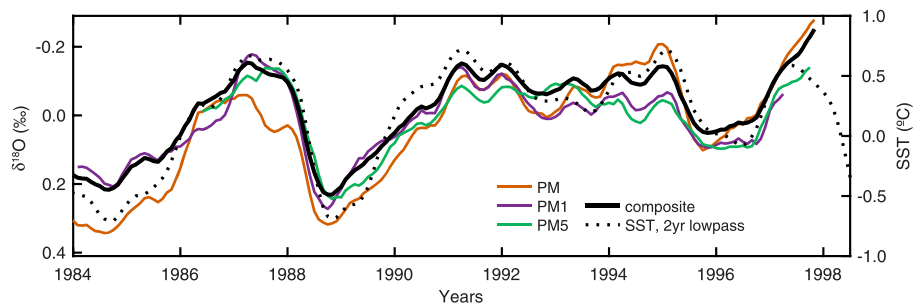

Figure 6. Interannual variability in coral $\delta^{18}O$ from cores PM (orange), PM1 (purple), PM5 (green), and the composite of all three records (black, solid) compared with two-year low-pass-filtered temperatures from ERSSTv3b (black, dotted).

We create a composite coral $\delta^{18}O$ record by subtracting the offsets from each coral record and then averaging them together (Figure 5b). Similar to our composite Sr/Ca record, the composite $\delta^{18}O$ record is a better realization of SST than any individual coral record. On monthly time scales, the composite $\delta^{18}O$ record is better correlated with SST than any individual coral $\delta^{18}O$ record ($R = -0.85$, $p < 0.05$). On interannual time scales, the composite $\delta^{18}O$ record is strongly correlated with two-year low-pass-filtered SST ($R = -0.95$, $p < 0.05$; Figure 6), and accurately captures all ENSO extremes between 1985 and 1998.

As with coral Sr/Ca, we use $\delta^{18}O$-SST slopes to assess whether coral $\delta^{18}O$ is equally sensitive to climate variability across different *Porites* spp. colonies. As with coral Sr/Ca-SST calibrations, we use a weighted least squares regression to compute $\delta^{18}O$-SST relationships for cores PM, PM1, and PM5 across the common interval of 1985–1998 (Table 3). Core PM has a steeper $\delta^{18}O$-SST slope at $-0.35 \pm 0.013(1\sigma)$ ‰ °C^{-1}, while core PM5 has a shallower slope at $-0.25 \pm 0.012(1\sigma)$ ‰ °C^{-1}, as expected given that the PM $\delta^{18}O$ record exhibits a larger seasonal amplitude compared to PM5. In terms of SST alone, $\delta^{18}O$-SST slopes for cores PM, PM1, and PM5 would predict a temperature change 0.3 to 0.4 °C for the same 0.1‰ change in coral $\delta^{18}O$. Regressing our composite $\delta^{18}O$ record against SST between 1985 and 1998 yields an average $\delta^{18}O$-SST slope -0.29 ± 0.011 (1σ) ‰ °C^{-1}, which is well within the range of published $\delta^{18}O$-SST slopes (e.g., Grottoli & Eakin, 2007).

3.4. Reproducibility of Coral-Derived $\delta^{18}O_{sw}$ Records

Cores PM, PM1, and PM5 show seasonal $\delta^{18}O_{sw}$ cycles across 1985–1998 that are largely consistent with the low seawater $\delta^{18}O$ variability previously modeled at our site (Stevenson et al., 2015). Coral-based $\delta^{18}O_{sw}$ reconstructions (Figure 7a) from cores PM1 and PM5 are correlated with $\delta^{18}O_{sw}$ from core PM ($R = 0.36$ and 0.48, respectively), but do not agree with each other ($R = 0.057$, $p < 0.05$). Cores PM and PM1 exhibit similar seasonal $\delta^{18}O_{sw}$ amplitudes (0.099 ± 0.026‰ and 0.099 ± 0.023‰, respectively); however, core PM5 which exhibits a relatively lower coral $\delta^{18}O$ seasonality also yields a lower $\delta^{18}O_{sw}$ amplitude (0.043 ± 0.023‰; Figure S4b).

The $\delta^{18}O_{sw}$ reconstructions from the three colonies do not exhibit common seasonal and interannual signals that exceed the combined error envelopes. Even across moderate ENSO extremes during 1986/1987 and 1994/1995, each coral $\delta^{18}O_{sw}$ record suggests a different timing and amount of freshening. Despite these discrepancies, all three reconstructions are significantly correlated with gridded SSS (Delcroix et al., 2011; $R =$ 0.41 to 0.48, $p < 0.05$) and SST (ERSSTv3b; $R = -0.38$ to -0.67, $p < 0.05$), which reflects a modest climatic imprint on each of the coral $\delta^{18}O_{sw}$ reconstructions that explains only 10–40% of the $\delta^{18}O_{sw}$ variance over this interval.

A composite $\delta^{18}O_{sw}$ reconstruction produced by averaging the $\delta^{18}O_{sw}$ records from cores PM, PM1, and PM5 is no better at tracking SSS ($R = 0.40$, $p < 0.05$) or SST ($R = -0.66$, $p < 0.05$) than any individual record (Figure 7b). Unlike our Sr/Ca and $\delta^{18}O$ composites, this $\delta^{18}O_{sw}$ composite does not offer improved accuracy in reconstructing SSS over the time period in question, assuming that the Delcroix et al. (2011) data set accurately reflects SSS variability in this data-poor region.

3.5. Potential Sources of Intercolony Sr/Ca and $\delta^{18}O$ Variability

Intercolony Sr/Ca and $\delta^{18}O$ offsets observed at Palmyra cannot be explained by diagenesis, despite ample evidence that diagenesis can introduce significant artifacts in coral Sr/Ca and $\delta^{18}O$ records (Sayani et al.,

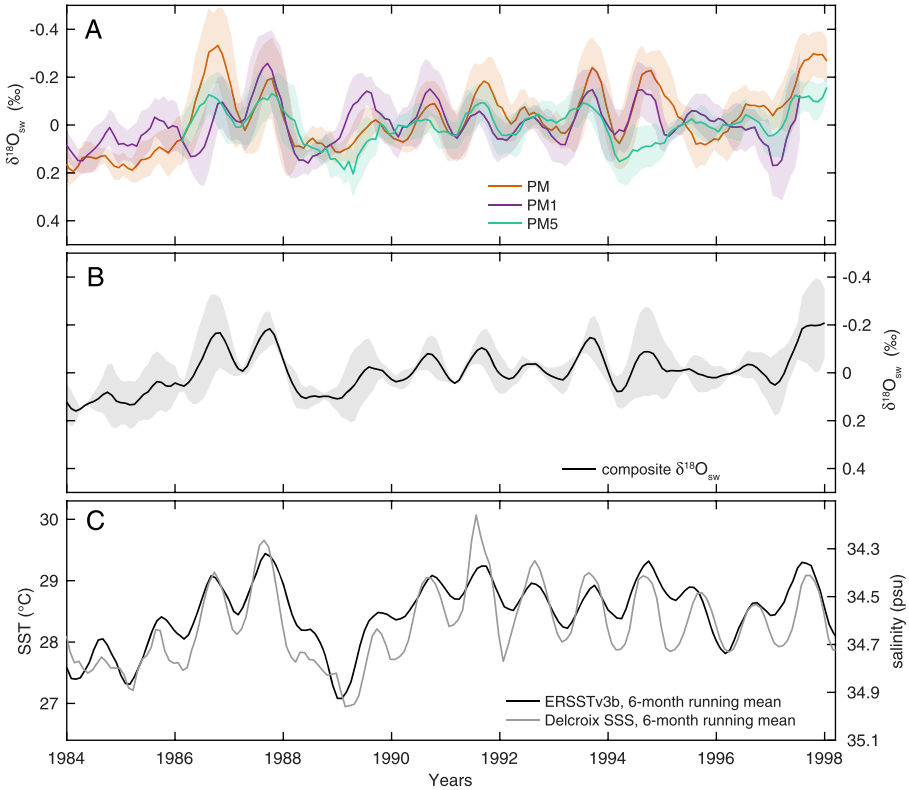

Figure 7. (a) Seasonal δ^{18}Osw reconstructions from cores PM (orange), PM1 (purple), and PM5 (green), compared to (b) a composite of all three records in (a), and (c) six-month running means of temperature (black line) from ERSSTv3b and SSS (gray line) from Delcroix et al. (2011). Shading in (a) represents the compounded 2σ uncertainty for each record, accounting for analytical uncertainties and Sr/Ca-SST calibration errors, whereas the shading in (b) (gray shading) is the standard error (2σ) compounded with the uncertainties shown in (a).

Diagenesis levels can vary significantly on millimeter scales in any given coral core (e.g., Bar-Matthews et al., 1993; Hathorne et al., 2011; Hendy et al., 2007), and typically produce large, nonclimatic fluctuations in coral Sr/Ca and δ^{18}O instead of uniform offsets observed in our ensemble of modern coral records (e.g., Druffel-Rodriguez et al., 2012). Furthermore, with the exception of the pre-1997 section of P13, SEM images do not show evidence of significant or consistent alteration in any of the remaining cores (Figure S5).

SST variability across an individual reef has been linked to intercolony Sr/Ca variability at some sites (e.g., Alpert et al., 2016; Pfeiffer et al., 2008; Wu et al., 2014; Zinke et al., 2016). There are no in situ SST data that cover the exact location and time spans for the cores presented here. However, temperature loggers deployed around Palmyra Atoll (locations shown in Figure 1) by NOAA CREP from 2007 to 2011 show that temperatures across Palmyra's western reef terrace, where four of our cores were drilled, deviate by ±0.1 °C (1σ; Figure 2b). This spatial temperature variability is an order of magnitude smaller than the ±1 °C SST variability needed to explain the mean Sr/Ca offsets of ±0.086 mmol/mol (1σ) observed between cores PM, PM1, and PM5.

Skeletal extension and/or calcification rates have been invoked to explain, and in some cases correct for (Maier et al., 2004; Goodkin et al., 2005, 2007) intercolony Sr/Ca and δ^{18}O offsets in a variety of coral species (e.g., Alibert & McCulloch, 1997; Cohen & Hart, 2004; Gagan et al., 2012; Goodkin et al., 2007; Kuffner et al., 2012, 2017; Lough & Barnes, 1997; Suzuki et al., 2005). Coral biomineralization models suggest that corals incorporate less Sr^{2+} relative to Ca^{2+} when they calcify faster, and vice versa (Gaetani & Cohen, 2006), consistent with experiments that manipulate inorganic aragonite precipitation rates (Holcomb et al., 2009). Likewise, precipitation rates may influence fractionation of oxygen between seawater and coral aragonite (Devriendt et al., 2017). As such, faster growing colonies would have lower mean Sr/Ca and δ^{18}O values, while corals that are growing much slower would have higher mean Sr/Ca and δ^{18}O values. Studies

examining large numbers of *Porites* colonies, primarily from the Great Barrier Reef, do indeed show a relationship between extension rate and mean SST, extension rate and mean Sr/Ca, and calcification rate and mean Sr/Ca (e.g., Lough & Barnes, 1997; Lough & Cooper, 2011). However, our data do not show any statistically significant relationships between coral Sr/Ca and extension rates ($R = 0.29$, $p = 0.63$, $n = 5$), or between coral $\delta^{18}O$ and extension rates ($R = 0.9$, $p = 0.2$, $n = 3$) on the modern-day reef at Palmyra Atoll. Moreover, core PAL2, whose extension rate ranges from 5 to 8 mm/year, does not have the highest Sr/Ca values, as expected from the biomineralization models. Lastly, other studies have shown that coral biomineralization rates cannot explain differences in mean coral Sr/Ca values between fast and slow growing coral species in the same location (e.g., DeLong et al., 2011) when extension rates are above the threshold for growth related effects, which is <0.6 mm/year for *Porites* spp. (de Villiers et al., 1995; DeLong et al., 2013; Felis et al., 2003; McConnaughey, 1989).

4. Discussion

Our results demonstrate that overlapping coral Sr/Ca and $\delta^{18}O$ records from Palmyra Atoll exhibit similar variability on monthly-interannual time scales, but exhibit different proxy-SST sensitivities and their mean values are consistently offset. Of these two types of intercolony variabilities, our results highlight that intercolony Sr/Ca offsets contribute significantly larger uncertainties to paleo-SST reconstructions than differences in Sr/Ca-SST slopes (±1.2 °C versus ±0.4 °C, 1σ). Intercolony variability in Palmyra corals cannot be explained by local SST variability, extension rate, or diagenesis. As such, we conclude that the observed variability is either due to interspecies differences, which are often not accounted for in most studies, or vital effects, biological variability that is often overprinted on climate signals recorded by biogenic carbonates. We reiterate that intercolony variability does not impact climate reconstructions from modern corals that grew during the instrumental period, as these records can be benchmarked against observations. However, intercolony variability makes it difficult to determine whether geochemical differences observed between a modern and a fossil coral are due to climate or vital effects. At Palmyra Atoll, intercolony Sr/Ca and $\delta^{18}O$ offsets prevent us from resolving mean SST changes smaller than ±1.2 °C and ±0.1 °C, respectively, between nonoverlapping corals. As demonstrated here and in recent studies (e.g., Hendy, 2002; Lough, 2004; Stephans et al., 2004; *Cahyarini et al.*, 2008a; DeLong et al., 2013; Dassié et al., 2014), composite records are better at isolating common climate signals and can vastly improve the robustness of coral-based climate reconstructions. Building on this composite approach, we outline a strategy for reducing uncertainties in coral-based paleoclimate reconstructions that stem from intercolony offsets.

The existence of similar intercolony offsets in *Porites* spp. corals at multiple sites suggests that for any given temperature, there exists a finite range of possible coral Sr/Ca and $\delta^{18}O$ values distributed about a mean. For contemporaneous corals from Palmyra, the standard deviation in mean coral Sr/Ca values is ±0.09 mmol/mol (1σ) and the standard deviation in mean coral $\delta^{18}O$ is ±0.1‰ (1σ). If we assume these spreads in mean coral Sr/Ca or $\delta^{18}O$ values are defined by a normal distribution (and there are no data to support nonnormal distributions), we can then use multiple, overlapping coral Sr/Ca or $\delta^{18}O$ records to constrain the temperature for a given time period to a desired level of accuracy. The uncertainty in the mean coral Sr/Ca or $\delta^{18}O$ values for such a multicoral composite would scale by $\sqrt{N}$, where N is the number of overlapping corals used to construct the climate record. For example, uncertainty in single coral Sr/Ca record would be ±0.09 mmol/mol (1σ); however, the uncertainty of five coral composite Sr/Ca record presented here would be $\pm 0.09/\sqrt{5}$, or ±0.04 mmol/mol (1σ). The uncertainty of Sr/Ca-based SST reconstructions can be estimated as the squared sum of intercolony offsets (discussed above) and Sr/Ca-SST slope error (-0.067 ± 0.005 mmol mol^{-1} °C^{-1}). As such, temperature estimates from a single coral Sr/Ca record would have an uncertainty of ±1.3 °C (1σ), temperature estimates from a composite of two Sr/Ca records would have an uncertainty of ±0.9 °C (1σ), whereas a composite of five corals would offer an uncertainty of ±0.6 °C (1σ). Therefore, it is possible to resolve relatively small changes in absolute SST, such as those that occurred during the Little Ice Age (LIA; 1500–1850) in the central tropical Pacific (Emile-Geay et al., 2013), by using multiple, overlapping corals.

Our results also suggest that intercolony Sr/Ca and $\delta^{18}O$ variability are a significant source of uncertainty in coral-based $\delta^{18}O_{sw}$ estimates. Temperature and salinity variability in the central tropical Pacific are strongly tied to ENSO. At Palmyra, coral-based $\delta^{18}O_{sw}$ reconstructions reproduce the timing of ENSO-driven salinity

changes but not their magnitude. Intercolony variability, coupled with the low signal-to-noise ratio in reconstructed $\delta^{18}O_{sw}$, suggests that corals from this site may not be able to resolve $\delta^{18}O_{sw}$ changes <0.25‰. However, as our study periods do not span multiple strong ENSO events, it remains unclear if Palmyra corals can reliably reproduce large $\delta^{18}O_{sw}$ changes.

Furthermore, the lack of reliable instrumental $\delta^{18}O_{sw}$ or salinity observations from the central tropical Pacific during our study period makes it difficult to fully assess the accuracy of our coral-based $\delta^{18}O_{sw}$ reconstructions. Low correlations between our coral-derived $\delta^{18}O_{sw}$ records and interpolated SSS data sets, like Delcroix et al. (2011), suggest that salinity explains a relatively small fraction (~25%) of variability observed in our reconstruction. However, we note that very few instrumental SSS observations are available from the central tropical Pacific during our study period, and as such, interpolated SSS products like the Delcroix et al. (2011) data set may not accurately represent salinity changes at our site. For example, we expect to see a large freshening signal in local $\delta^{18}O_{sw}$ at our study site during the 1997/1998 El Niño event, which is reflected in negative $\delta^{18}O_{sw}$ excursions apparent in all three of our coral $\delta^{18}O_{sw}$ records, yet is absent in gridded SSS (Figure 7). Without an appropriate benchmark to test the accuracy of our $\delta^{18}O_{sw}$ records, the efficacy of this approach for reconstructing small changes in SSS remains unclear. Our study calls for additional reproducibility and calibration studies of coral $\delta^{18}O_{sw}$ reconstructions in order to quantify the limits of this proxy for paleo-SSS reconstruction.

5. Conclusion

Modern corals from Palmyra Atoll show that intercolony variability is a significant source of uncertainty in both absolute SST and coral-based $\delta^{18}O_{sw}$ reconstructions that utilize non-overlapping modern and fossil corals. Replicating coral Sr/Ca and $\delta^{18}O$ records across multiple overlapping colonies can potentially resolve absolute SST changes smaller than ±1.2 °C; however, replication may not similarly improve coral-based $\delta^{18}O_{sw}$ reconstructions. Replication significantly increases the number coral colonies and accompanying geochemical analyses needed to complete a reconstruction of mean climate during the preindustrial era, and as such may not be a practical strategy for all sites. For sites like Palmyra Atoll and neighboring Kiritimati Island (Christmas Island, 2°N, 157°W), where overlapping corals are abundant (*Cobb et al.*, 2003b; Grothe et al., 2016), this composite approach has a strong potential to yield robust paleoclimate records with well-quantified uncertainties. More extensive replication studies are needed for existing and new coral proxies, such as Sr-U (DeCarlo et al., 2016) and Li/Mg (e.g., Montagna et al., 2014), to fully quantify intercolony reproducibility and constrain uncertainties in coral-based reconstructions of absolute SST and/or SSS.

Acknowledgments
AcknowledgementsWe would like to thank the NOAA Coral Reef Ecosystem Program for providing in situ temperature data from Palmyra and one of the modern coral cores used in this study. We also thank Anne Cohen, Thomas DeCarlo, and Sheila Griffin for the assistance with the coral samples used here, and Yolande Berta and Georgia Tech's Center for Nanostructure Characterization for providing access to their SEM facility. Funding for this work was provided by the National Science Foundation (award 1502832 to K.M.C.), the National Oceanic and Atmospheric Administration (award NA11OAR4310165 to K.M.C.), NSF Chemical Oceanography Program (award OCE-0137207 and OCE-0526463 to E.R.M.D.), and the Jenkins Foundation. ERSST V3b data were provided by the NOAA PSD, Boulder, CO, USA, from their website (http://www.cdc.noaa.gov/). The coral proxy records presented in this study are archived on the Paleoclimatology section of the NOAA National Centers for Environmental Information data repository (https://www.ncdc.noaa.gov/data-access).

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