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Key Points:
- *Diploastrea heliopora* and *Porites lobata* winter Sr/Ca-SST calibration are robust and allow for a reconstruction of the PDO
- *Diploastrea heliopora* interannual $\delta^{18}O_c$-SSS records a freshening trend, consistent with *Porites lobata* $\delta^{18}O_c$ and instrumental SSS
- The multiproxy multicoral approach of this study further strengthens the evidence for *Diploastrea* as an alternate climate archive

Supporting Information:
- Supporting Information S1
- Table S2

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Diploastrea heliopora Sr/Ca and $\delta^{18}O$ records from northeast Luzon, Philippines: An assessment of interspecies coral proxy calibrations and climate controls of sea surface temperature and salinity

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Abstract The Indo-Pacific coral *Diploastrea heliopora* reveals regional multidecadal- to centennial- scale climate variability using coral carbonate $\delta^{18}O$ ($\delta^{18}O_c$) as a combined proxy for sea surface temperature (SST) and sea surface salinity (SSS). However, to assess the coral's full potential in resolving climatic events, an independent SST proxy would be more advantageous. We examined both Sr/Ca and $\delta^{18}O$ of *Diploastrea* against an adjacent *Porites lobata* core collected from northeast Luzon, Philippines. Winter Sr/Ca data from *Diploastrea* show a significant correlation to SST ($r = -0.41$, $p < 0.05$, (root-mean-square of the residual) RMSR = 0.81°C) and provide a proxy with similar sensitivity as *Porites* ($r = -0.57$, $p < 0.05$, RMSR = 0.62°C). An interspecies SST record is shown to be robust and used for a reconstruction of the Pacific Decadal Oscillation during boreal winter ($r = -0.70$, $p = 0.02$). While we were unable to generate a robust *Diploastrea* $\delta^{18}O$-SSS calibration at interannual timescale, the freshening trend toward the present, commonly observed in the region, is qualitatively captured in *Diploastrea* $\delta^{18}O$. Comparison with *Porites* $\delta^{18}O$ and instrumental SSS records shows that the magnitude of freshening is consistent between coral species. Wet and dry season *Porites* $\delta^{18}O$ provide support for the relative influence of El Niño–Southern Oscillation events and local precipitation to SSS variability at our site. The multiproxy, multispecies approach of this study further strengthens the evidence for *Diploastrea* as an alternate climate archive in the Indo-Pacific region and seals its potential in helping resolve less understood global-scale climate phenomena.

1. Introduction

The relatively short length of observational climate records, particularly in the tropics, limits our understanding of the natural drivers of long-term climate variability and our ability to constrain future changes [*Gagan et al.*, 2000; *Lough*, 2004, 2010]. Paleoclimate proxy reconstructions provide a means to extend climate data prior to both instrumental records and anthropogenic influences [*Dunbar and Cole*, 1999; *Gagan et al.*, 2000].

Tropical massive corals are a key source of paleoclimate records [*Dunbar and Cole*, 1999; *Gagan et al.*, 2000; *Felis and Patzold*, 2004; *Lough*, 2010]. Coral skeletons incorporate isotopic and geochemical tracers, which vary based on the environment, allowing for subannual reconstruction of climate parameters such as sea surface temperature (SST) and sea surface salinity (SSS) [*Dunbar and Cole*, 1999; *Gagan et al.*, 2000]. Visible banding in coral X-radiographs reflect changes in climate systems including El Niño–Southern Oscillation (ENSO), Asian Monsoon, and ocean circulation [*Druffel*, 1997; *Dunbar and Cole*, 1999; *Gagan et al.*, 2000; *Felis and Patzold*, 2004; *Grottoli and Eakin*, 2007].

Two of the most extensively used geochemical tracers are the ratios of Sr/Ca and $\delta^{18}O$ [*Druffel*, 1997; *Dunbar and Cole*, 1999; *Eakin and Grottoli*, 2006]. Coral Sr/Ca is an exceptional paleothermometer where the elemental ratio of strontium-to-calcium is inversely related to the SST in which a coral grew [*Smith et al.*, 1979; *Beck et al.*, 1992; *Alibert and McCulloch*, 1997]. Coral $\delta^{18}O$ is influenced by both SST variations and the $\delta^{18}O$ of the ambient seawater, which is a function of the hydrological balance between evaporation, precipitation, runoff, and water mass advection [*Dunbar and Wellington*, 1981; *Gagan et al.*, 1994; *Linsley et al.*, 2004; *Lough*, 2010; *Dassié et al.*, 2014]. Sr/Ca and $\delta^{18}O$ measurements when combined allow for isolation of SSS [e.g., *Gagan et al.*, 1998; *Hendy et al.*, 2002; *Ren et al.*, 2003; *Correge et al.*, 2004; *Kilbourne et al.*, 2004; *Linsley et al.*, 2004; *Shen et al.*, 2005; *Cahyarini et al.*, 2008; *Felis et al.*, 2009; *Nurhati et al.*, 2011].

Porites lobata/lutea species are the most targeted massive coral for reconstructing climate variability [e.g., *Dunbar and Cole*, 1999; *Gagan et al.*, 2000; *Sadler et al.*, 2014]. However, few ($n < 20$) *Porites*-based proxy records extend beyond the past 200 years in the Indo-Pacific [*Gagan et al.*, 2000; *Lough*, 2004, 2010; *Corrège*, 2006; *Grottoli and Eakin*, 2007; *Tierney et al.*, 2015]. In addition, most of these records are based on a single core where nonclimatic influences such as vital and kinetic effects or bleaching events may be difficult to detect and may compromise the quality of the geochemical record [*McConnaughey*, 1989b; *Lough*, 2004, 2010; *Suzuki et al.*, 2003]. Hence, replication of coral geochemical records is important in discriminating localized nonclimatic influences from regional climatic signals [*Lough*, 2004; *DeLong et al.*, 2007, *Dassié et al.*, 2014].

Diploastrea heliopora, common in the Indo-Pacific region [*Veron*, 2000], offers an alternative resource for paleoclimate studies. Due to extension rates of 2 to 6 mm/yr, roughly half that of *Porites lobata*, *Diploastrea* cores contain approximately 2 to 3 times longer temporal coverage than a similarly sized *Porites* core [*Watanabe et al.*, 2003; *Bagnato et al.*, 2004, 2005]. *Diploastrea's* dense skeletons are resistant to boring organisms, grazing fish, and damaging crown-of-thorns starfish [*Veron*, 2000] supporting a longer life span (i.e., >800 years) [*Bagnato et al.*, 2004]. Limited studies on *Diploastrea* have demonstrated high reproducibility relative to a *Porites* collected at the same site and across study sites within the same geographic region (e.g., cores collected at New Caledonia and Alor, Indonesia [*Watanabe et al.*, 2003], and cores collected at Fiji Islands [*Bagnato et al.*, 2004; *Dassié and Linsley*, 2015]). Therefore, utilizing *Diploastrea* as a climate archive to replicate and extend *Porites*-based records will help improve reconstructions of long-term regional climate variability.

Inherent to *Diploastrea's* slow extension rates and complicated skeletal architecture are concerns regarding the reliability of its geochemical records. Kinetic effects were observed in offsets between the coral $\delta^{18}O$ records of *Diploastrea* and *Porites* [*Watanabe et al.*, 2003; *Bagnato et al.*, 2004; *Dassié and Linsley*, 2015]. For example, kinetic isotope disequilibrium models predict that slow growing corals should reach close to isotopic equilibrium and thus have preferential enrichment of ^{18}O compared to fast-growing corals [*McConnaughey*, 1989a, 1989b]. Absolute values of *Diploastrea* $\delta^{18}O$ are consistently enriched compared to those of *Porites* with the offset equivalent to about ~1.69°C [*Watanabe et al.*, 2003; *Bagnato et al.*, 2004; *Dassié and Linsley*, 2015]. However, the mean $\delta^{18}O$ offset was considered small, likely because while extension is slow, *Diploastrea* has high calcification rates leading to high skeletal bulk density [*Watanabe et al.*, 2003]. Consequently, recognition of kinetic effects is crucial in evaluating the accuracy of isotopic reconstructions [*McConnaughey*, 1989a; *Guilderson and Schrag*, 1999].

Another factor that may influence the geochemistry of corals is skeletal architecture. *Diploastrea* corallites have a straight inner mesh-like structure called the *columella*, surrounded by denser teeth-like radial structures called the *septa*. Based on previous studies, isotopic offsets from simultaneous subsampling of both *columella* and *septa* could reach up to 0.5‰ difference which may lead to erroneous climate reconstructions as these skeletal materials are deposited at different times throughout their growth [*Watanabe et al.*, 2003; *Bagnato et al.*, 2004; *Damassa et al.*, 2006]. Experiments on subsampling *Diploastrea* exclusively on either part favored reconstructions from the *columella* as it yielded more robust interannual records [*Watanabe et al.*, 2003; *Bagnato et al.*, 2004; *Damassa et al.*, 2006]. Exclusive sampling of the *columella* at 0.5 mm intervals to yield bimonthly records was found to be the optimal temporal resolution given their growth rates of ~4 mm/yr, enough to capture the full annual $\delta^{18}O$ cycle and minimizing the effects of any sampling artifacts introduced either by the coral's intricate skeletal architecture or slow extension [*Dassié and Linsley*, 2015].

While the above challenges in sampling *Diploastrea* are well constrained for its $\delta^{18}O$ records, the reliability of its Sr/Ca composition has not been thoroughly investigated. Here we further investigate the paleoutility of both Sr/Ca and $\delta^{18}O$ proxies in *Diploastrea* relative to an adjacent *Porites*, to evaluate the coral's ability to reconstruct regional climate behavior.

2. Coral Sampling and Analytical Methods

2.1. Core Sites and Sampling

Palaui Island (18.54°N, 122.15°E) lies along the northeastern coast of the Philippines facing the Pacific Ocean (Figure 1). The island is surrounded by warm waters and receives rainfall throughout the year. Based on

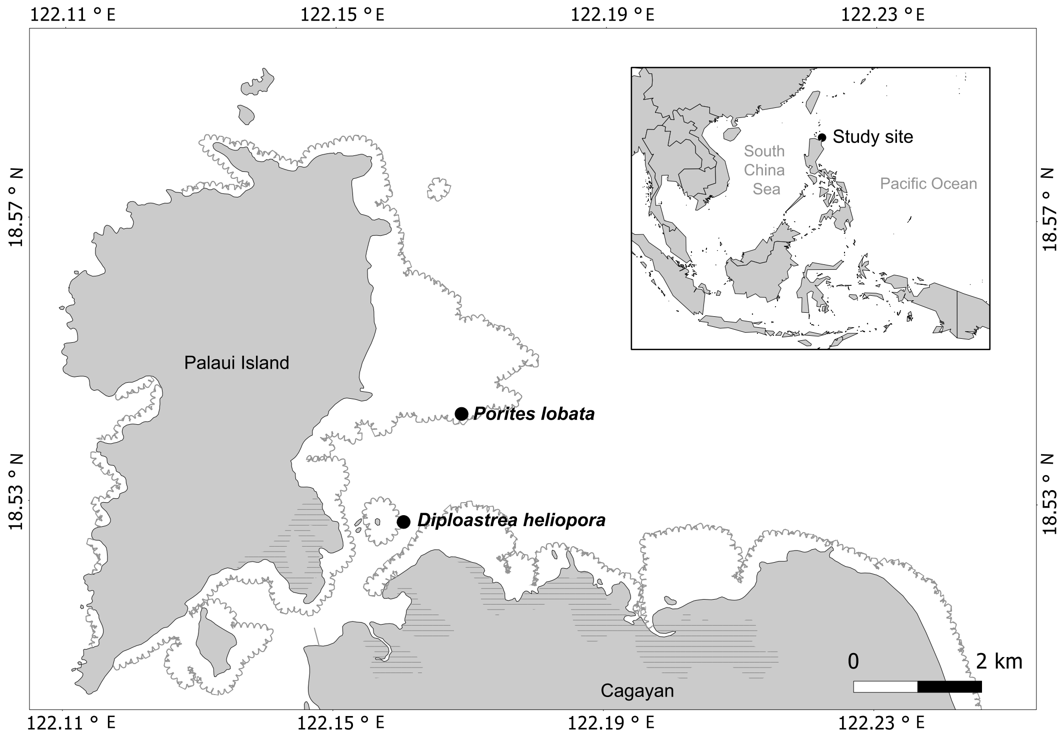

Figure 1. Coral colonies of *Diploastrea heliopora* and *Porites lobata*, approximately 2 km apart, were collected off the coast of Palaui Island in May 2012. Palaui Island lies along the northeastern coast of the Philippines facing the Pacific Ocean (inset).

satellite-derived data products (See section 2.3 for details.), the average annual SST range here is 27.4°C to 28.8°C. The average annual rainfall is ~2000 mm (Philippine Atmospheric, Geophysical and Astronomical Services Administration), whereas the mean annual salinity ranges from 33.9 to 34.7 practical salinity unit (psu). At seasonal timescales, the amount of rainfall is controlled by the direction of the dominant monsoon winds, such that northeasterly (southeasterly) monsoon winds, prevailing during boreal winter (summer), bring in dry (wet) conditions [*Chang et al.*, 2005]. At interannual and decadal timescales, temperature and rainfall variability is primarily controlled by El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO)-related changes in the temperature, position, and size of the Indo-Pacific Warm Pool [*Yan et al.*, 1992; *Gagan et al.*, 2000; *Lin et al.*, 2013].

Vertical cores of *Diploastrea heliopora* and *Porites lobata*, approximately 2 km apart, were collected from 4 to 5 m water depth off the coast of Palaui Islands in May 2012 (Figure 1). The cores were drilled using a pneumatic drill, and the coring holes were plugged with cement to protect the inner parts of the corals from burrowing organisms. Following the procedures outlined in *Bolton et al.* [2014], the drilled cores were cleaned with freshwater and subsequently cut along their maximum growth axes into 7 mm thick slabs. Prior to subsampling and chemical analyses, each slab was cleaned thrice in an ultrasonic bath of deionized water for 15 min to remove any surface contaminants. The cleaned slabs were oven dried at 50°C for a minimum of 48 h. The dried slabs were then X-rayed to visualize the banding pattern and to delineate the major growth axis along which subsamples were microdrilled (Figure S1 in the supporting information). The X-rays were taken at 50 kV, 10 mA with a source-to-object distance of 1 m and an exposure time of $<$1 s at the Diagnostic Imaging Lab, National University Hospital, Singapore.

Our *Diploastrea* slabs were subsampled for Sr/Ca and $\delta^{18}O$ exclusively along the *columella* following previous works [*Watanabe et al.*, 2003; *Bagnato et al.*, 2004; *Damassa et al.*, 2006; *Dassié and Linsley*, 2015]. Due to the porous structure of the *columella*, we set a manual drill press to a low speed of ~500 rpm to avoid any breakage or sample contamination during sampling. The slabs were drilled with a 1 mm diameter tungsten carbide burr at 0.4 mm intervals at a constant sampling depth of 1 mm, yielding a sampling resolution of ~10 samples per year. The subsamples from the *Porites* slabs were drilled at a similar sampling depth along its maximum growth axis but on a wider interval of 0.5 mm (about 26 samples per year) and at faster drilling speed of 1400 rpm.

2.2. Sr/Ca and $\delta^{18}O$ Measurements

For Sr/Ca measurements, approximately 200 μg from each subsample was dissolved in 2 mL of 5% HNO_3 overnight. Strontium and calcium were measured thrice per sample using an inductively coupled plasma-optical emission spectrometry (Thermo iCAP 6000 Series) at the Earth Observatory of Singapore (EOS). Solution standards were routinely measured to correct for instrument drift and matrix effects from varying calcium concentrations [*Schrag*, 1999]. To evaluate measurement precision, bulk coral powder reference material JCp-1 [*Okai et al*., 2001] with a consensus Sr/Ca value of 0.01932 ppm (±0.0002) or 8.838 mmol/mol (±0.089) [*Hathorne et al*., 2013] was analyzed throughout each run. Repeat measurements of JCp-1 showed good reproducibility (0.019315 ± 0.00005 ppm, 1σ, relative standard deviation = 0.26%, n = 2125).

From the same subsample, $\delta^{18}O$ analyses were performed at the Australian National University (ANU) and EOS. At ANU, 150–200 μg samples were acidified with 105% H_3PO_4 at 90°C in an automated individual-carbonate reaction Kiel device and the resulting CO_2 gas was analyzed in a Finnigan MAT-251 isotope ratio mass spectrometer (IRMS). At EOS, 40–90 μg samples were acidified with 105% H_3PO_4 at 70°C in an automated Kiel IV carbonate device coupled with a ThermoFisher MAT-253 IRMS. All isotopic measurements in both labs were calibrated relative to Vienna Peedee belemnite using National Bureau of Standards (NBS) 19 ($\delta^{18}O$ = −2.20‰) and NBS 18 ($\delta^{18}O$ = −23.2‰) [*Stichler*, 1995]. The reproducibility of NBS 19 is ±0.04‰ (1σ, n = 165) at ANU and ±0.03‰ (1σ, n = 10) at EOS. We also used two standards to cross calibrate the instruments in both laboratories, and results show no measureable offsets between laboratories or against published values. In addition, Estremoz, Carrara, and TSF standards were routinely measured at EOS yielding the following average values and errors: $\delta^{18}O_{Estremoz}$ = −5.956 ± 0.08‰; $\delta^{18}O_{Carrara}$ = −1.938 ± 0.05‰; $\delta^{18}O_{TSF}$ = −2.281 ± 0.07‰ (total of all standards, n = 688).

2.3. Data Sources

In the absence of in situ SST measurements in the study area, monthly 1° by 1° grid resolution (1° ≈ 111 km) SST data from the Integrated Global Ocean Services System Products Bulletin (IGOSS), also referred to as Optimum Interpolation SST v.2 (http://iridl.ldeo.columbia.edu/SOURCES/.IGOSS/.nmc/.Reyn_SmithOIv2/) [*Reynolds et al*., 2002], were used for SST calibration over the 30 year period of 1982–2012. We chose this SST data set for calibration and comparison, rather than, e.g., 4 km resolution advanced very high resolution radiometer pathfinder v.5 [*Kilpatrick et al*., 2001], because IGOSS SST data cover a longer time period and are more continuous.

Monthly gridded 0.25° by 0.25° resolution SSS data were acquired from Simple Ocean Data Assimilation (SODA, http://apdrc.soest.hawaii.edu/dods/public_data/SODA/soda_pop2.2.4, [*Carton and Giese*, 2008]) and monthly gridded 2.5° square resolution precipitation data from Global Precipitation Climatology Project v.2.2 (GPCP, http://www.esrl.noaa.gov/psd/data/gridded/data.gpcp.html) [*Adler et al*., 2003] covering the same time period to investigate the relative influence of salinity in the coral $\delta^{18}O$ record. We found that other commonly used SSS data sets available for the tropical Pacific show opposite trends to the expected and observed climatology over our study site [e.g., *Delcroix et al*., 2011] and have limited temporal coverage (e.g., Aquarius, 2011 to present) [*Lagerloef et al*., 2008].

2.4. Chronology Development

Age-depth models for all cores were developed using the annual density bands and fine-tuned using the seasonal cycles of Sr/Ca ratios in each core. Coral Sr/Ca profile minima, maxima, and inflection points were aligned with their respective SST points each year using the Analyseries software [*Paillard et al*., 1996] to anchor the age-depth model. The Sr/Ca depth series was then resampled into a monthly time series by linear interpolation. The Sr/Ca-SST age model was similarly applied to the coral $\delta^{18}O$ record, which was then interpolated at monthly resolution.

2.5. Determination of Extension Rates and Effects

The annual extension rates of each coral were measured along the distance of two consecutive Sr/Ca maxima, which marks the start of each year, from the Sr/Ca age model. The extension rates were then compared to their respective annual Sr/Ca and $\delta^{18}O$ records to check for growth rate effects.

3. Coral Sr/Ca and SST

3.1. Monthly Calibration

Least squares linear regressions of monthly Sr/Ca to IGOSS SST from 1982 to 2012 show significant inverse relationship in both corals (Figure 2a). The regression equations are summarized in equations (1) and (2):

$$\begin{aligned} &\textit{Diploastrea}\,\mathrm{Sr/Ca} = 10.657\ (\pm 0.050) – 0.057\ (\pm 0.002) \times \mathrm{SST}\ (^{\circ}\mathrm{C}) \\ &r = -0.86, r^2 = 0.74, p \ll 0.0001, \mathrm{RMSR} = 0.86^{\circ}\mathrm{C}, n = 365 \end{aligned} \tag{1}$$

$$\begin{aligned} &\textit{Porites}\,\mathrm{Sr/Ca} = 10.790\ (\pm 0.043) – 0.068\ (\pm 0.002) \times \mathrm{SST}\ (^{\circ}\mathrm{C}) \\ &r = -0.92, r^2 = 0.84, p \ll 0.0001, \mathrm{RMSR} = 0.61^{\circ}\mathrm{C}, n = 365 \end{aligned} \tag{2}$$

where root-mean-square of the residual (RMSR) measures the difference between the instrumental and reconstructed SST.

Diploastrea Sr/Ca values are consistently higher than *Porites* Sr/Ca (Figure 2a) as detected in *Bagnato et al.* [2004] and *Correge et al.* [2004] (Table 1). This interspecies offset is similarly observed in other paired *Diploastrea-Porites* studies [e.g., *Watanabe et al.*, 2003; *Bagnato et al.*, 2004] (Table 1) investigating δ^{18}O as dsiscussed later. The offsets are suspected to result from kinetic effects [*McConnaughey*, 1989a, 1989b; *de Villiers et al.*, 1994; *Cohen et al.*, 2001; *Watanabe et al.*, 2003; *Bagnato et al.*, 2004]. Our mean Sr/Ca offset is ~0.182 mmol/mol or equivalent to ~2.6°C calculated using our *Porites* calibration slope, 0.068 mmol/mol °C^{-1} (equation (2)). This value is comparable with mean offsets estimated from *Diploastrea-Porites* Sr/Ca from Alor, Indonesia, and New Caledonia (e.g., ~0.135 mmol/mol or ~2.2°C) [*Correge et al.*, 2004] but higher compared with offsets reported from Fiji corals (e.g., 0.07 mmol/mol or 1.2°C) [*Bagnato et al.*, 2004]. In the Fiji study, *Diploastrea* Sr/Ca was only sampled along the *septa*, which may explain its discrepancy relative to the other studies above. The direction in which Fiji *Diploastrea* Sr/Ca is offset from *Porites* Sr/Ca is also different from what the kinetic equilibrium model predicts [*McConnaughey*, 1989a], such that Fiji *Diploastrea* Sr/Ca values are lower than paired *Porites* Sr/Ca. The Fiji *Diploastrea* Sr/Ca samples were also taken from septal material extending at an angle with respect to the major growth direction, which is along the *columella* [*Watanabe et al.*, 2003; *Bagnato et al.*, 2004; *Dassié and Linsley*, 2015].

Our *Diploastrea* and *Porites* calibration slopes are slightly different, likely due to a greater Sr/Ca signal aliasing when sampling the slow-growing *Diploastrea* (*t* test, df = 726, $p < 0.0001$). Nonetheless, both species generated SST reconstructions that are within error of each other (Figures 2b and 2c). Both calibration slopes are within the range of slopes reported in other paired *columella Diploastrea* Sr/Ca records (e.g., −0.054 to −0.062 mmol/mol °C^{-1}) [*Bagnato et al.*, 2004; *Correge et al.*, 2004], other *Porites*-based studies from the same region as our site (e.g., −0.042 to −0.061 mmol/mol °C^{-1}) [*Mitsuguchi et al.*, 1996; *Shen et al.*, 1996; *Sun et al.*, 2005; *Yu et al.*, 2005; *Wei et al.*, 2000] and other slow-growing corals, i.e., less than 0.8 cm/yr (e.g., −0.045 to −0.059 mmol/mol °C^{-1}) [*Cardinal et al.*, 2001; *Goodkin et al.*, 2005, 2007; *DeLong et al.*, 2011; *Xu et al.*, 2015]. These results give indication that *Diploastrea* Sr/Ca has SST sensitivity similar to that of *Porites*.

3.2. Interannual Calibrations

To further evaluate the reliability of our proxy calibrations, we derived interannual Sr/Ca-SST relationships by applying the monthly calibration equations (equations (1) and (2)) to 4 month summer (JJAS—June to September) and 4 month winter (DJFM—December to March) average Sr/Ca, which are based from the mean monthly climatology. We used the monthly calibration equations, instead of the statistically significant mean annual or winter SST calibrations (Text S1 in the supporting information), to minimize reconstructions errors that may result from the limited SST variability at interannual timescale at our site (i.e., mean annual SST range of ~1.3°C). Using the mean annual and winter Sr/Ca-SST relationships ($p < 0.04$), for example, increase errors to 55% to 86% more, respectively, compared to the monthly calibration equations as discussed below.

Diploastrea summer SST reconstructions show no relationship to instrumental summer SST ($r = 0.17$, $p = 0.45$). *Porites* summer SST, on the other hand, significantly captures summer SST variability ($r = -0.53$, $p = 0.003$) with an RMSR of 0.42°C, or equivalent to ~25% of mean annual summer range, 1.66°C. *Diploastrea* and *Porites* winter SST reconstructions capture SST variability significantly with an RMSR of 0.81°C and 0.62°C, respectively ($r_{Diploastrea} = -0.41$, $r_{Porites} = -0.57$, $p < 0.05$; Figure 3a). Winter RMSRs are equivalent to 40% and 31% of the mean winter SST range of 2.03°C for *Diploastrea* and *Porites*, respectively.

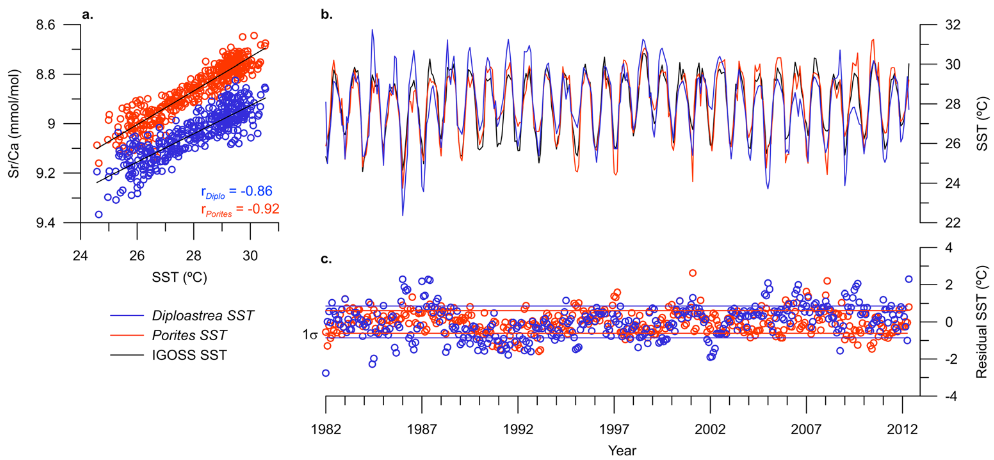

Figure 2. SST calibrations and reconstructions. (a) Monthly *Diploastrea* (blue) and *Porites* (red) Sr/Ca ratios lineary regressed against IGOSS SST. The regression results are highly correlated, $r = -0.86$ and $r = -0.92$ for *Diploastrea* and *Porites*, respectively (both $p \ll 0.0001$). (b) SST reconstruction from *Diploastrea* (blue), *Porites* (red), and IGOSS SST (black). IGOSS SST is centered at 18.5°N, 122.5°E. (c) Coral SST anomalies from IGOSS SST, *Diploastrea* (blue circles) and *Porites* (red circles).

Building composite records from two or more individual corals minimizes local effects that are not climate related [*Lough*, 2004; *DeLong et al.*, 2007] and, thus, increases our confidence in reconstructing longer climate records. Palaui *Diploastrea* and *Porites* Sr/Ca winter SST reconstructions are not statistically different with each other (t test, df = 56, $p = 0.50$). This indicates that while *Diploastrea* and *Porites* are distinctive species and have contrasting growth rates and patterns, both are recording the same SST conditions in which they lived. For this reason, we derived an interspecies composite record from the two coral time series. We averaged the winter *Diploastrea* and *Porites* reconstructed SSTs, now referred to as the Palaui interspecies record, and compared with IGOSS SST.

The Palaui interspecies winter SST record shows a higher regression coefficient and lowered RMSR value than the individual calibrations over the same period ($r = 0.57$, $p = 0.001$, $n = 10$, RMSR = 0.59°C). Compared with the instrumental mean annual winter SST, the interspecies winter SST reconstruction shows greater variability (Figure 3b). The reconstructed winter SST has twice the range of the instrumental record. In particular, the large range was due to higher coral Sr/Ca (colder) in 1986–1987 and 2005 to 2008 and lower coral Sr/Ca (warmer) in 1990 to 1994.

One possible source of the observed discrepancy between the reconstructed winter SST and instrumental record is ENSO years. The years contributing to greater SST variability correspond to El Niño events that may introduce skeletal growth anomalies such as slowed growth or die-offs due to bleaching [e.g., *Suzuki et al.*, 2003]. In general, *Porites* Sr/Ca records show no significant correlation between annual extension rates and Sr/Ca ratios at any season ($r < 0.10$, $p > 0.50$). The *Porites* coral extended ~1.3 cm/yr, which is within the range of rates with minimal growth rate effects [*McConnaughey*, 1989a, 1989b; *Felis and Patzold*, 2004; *Sadler et al.*, 2014]. In contrast, *Diploastrea*, with extension rate of ~4 mm/yr, shows averaged annual and winter Sr/Ca ratios that are significantly correlated to annual extension rates (Sr/Ca versus growth: annual $r = -0.46$, winter $r = -0.56$, $p < 0.04$) with similar significance to SST correlation (Sr/Ca versus SST: annual $r = -0.36$, winter $r = -0.37$, $p < 0.04$). We found, however, that the coral Sr/Ca anomalies are neither

Table 1. Palaui *Diploastrea-Porites* Mean Sr/Ca and $\delta^{18}O$ Offsets

	Mean Sr/Ca (mmol/mol)	Mean $\delta^{18}O$ (‰)
Diploastrea	9.04	−4.66
Porites lobata	8.86	−4.91
Interspecies offset	0.18	0.25
°C equivalent	2.6[a]	1.6[b]

[a]Calculated from our *Porites* Sr/Ca-SST calibration slope of 0.068 mmol/mol °C^{-1}.
[b]Calculated from our *Diploastrea* $\delta^{18}O$-SST calibration slope of 0.16‰ °C^{-1}.

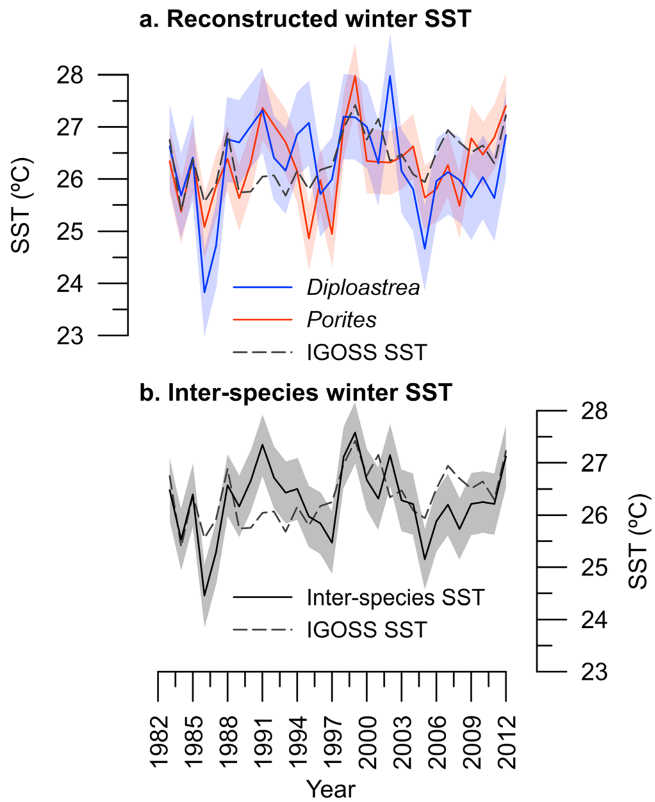

Figure 3. (a) Winter SST reconstruction for *Diploastrea* (blue) and *Porites* (red) against IGOSS SST (dashed). Shaded areas represent $RMSR_{Diploastrea}$ = 0.81°C and $RMSR_{Porites}$ = 0.62°C. (b) The winter interspecies record (black), derived by taking the average of the two coral time series, shows higher regression coefficient (r = 0.57, p = 0.001) and lowered RMSR value (0.59°C, gray shaded area) than the individual coral reconstructions.

consistent among ENSO events nor associated with unusual extension rates in each coral indicating that the high variability is not caused by growth effects.

Another possible source is errors associated with conventional microsampling of our corals impacting the resolution of our records through time and artificially dampening the calibration slope [*Goodkin et al.*, 2005, 2007; *Maupin et al.*, 2008; *Dassié and Linsley*, 2015]. However, the possibility of sampling (or analytical) errors as sources of discrepancies also disagrees with the directionally consistent interannual signals in both corals (Figure 2c). A more plausible explanation of the discrepancy may lie in the spatial range each record is able to resolve. Gridded SSTs average multiple observations over a large area (1° by 1°), and it is possible that this grid misrepresents local SST experienced by the corals. The Palaui cores were collected on a shallow coastal platforms where greater SST variability than the open ocean can be expected. The coral record shows high variability both before and within the calibration period and still shows strong correlations to instrumental data, indicating support for local SST variations greater than regional variations. The above concerns may imply an overestimation in the winter SST variability back in time, though relative variability compared to present should be consistent. Nevertheless, the individual coral and overall means of the records are consistent (26.3°C), and the trends are in good agreement with each other (r = 0.54, p = 0.01).

3.3. Decadal SST Trends

We compared our interspecies coral winter (DJFM) SST record to the Pacific Decadal Oscillation (PDO), defined as the leading mode of SST anomalies over the North Pacific poleward of 20°N at decadal timescales [*Mantua et al.*, 1997]. Prominent PDO variability is commonly detected in boreal winters [*Felis et al.*, 2010], as atmospheric circulation variability over the North Pacific is the strongest during this season [*Trenberth et al.*, 1998; *Deser et al.*, 2004]. The Palaui interspecies winter SST record is significantly correlated with the PDO index for DJFM months (http://research.jisao.washington.edu/pdo/PDO.latest)

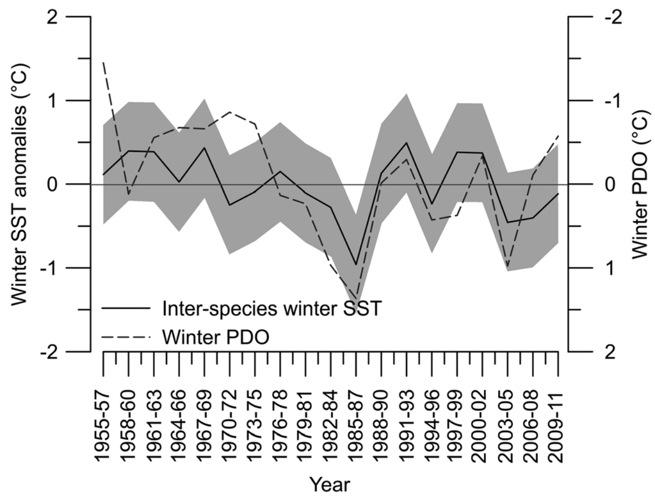

Figure 4. Palaui interspecies winter SST record (black) is significantly correlated to the Pacific Decadal Oscillation (dashed) over DJFM months at annual and 3 year binned timescales (3 year binned data shown; $r = -0.56$, $p = 0.01$, $n = 19$). Gray shaded area represents RMSR = 0.59°C based on the interspecies winter SST calibration.

[*Mantua et al.*, 1997] ($r = -0.43$, $p = 0.02$, $n = 30$) over our calibration period. The inverse correlation indicates that warm (positive phase) PDO events are characterized by anomalously cool SSTs in the western Pacific and in the central North Pacific Ocean [*Mantua et al.*, 1997; *Felis et al.*, 2010; *Gedalof and Smith*, 2001]. The coral records represent regional winter SST variability in the western tropical Pacific and the PDO index represents SST anomalies averaged over a larger area in the North Pacific. Therefore, we averaged 3 year bins in both time series to suppress local high-frequency variability in our coral SST reconstructions and to enhance signal-to-noise ratio in comparison to the PDO without artificially increasing the correlation coefficient. The correlation between the binned data is higher and remains statistically significant even after reducing the degrees of freedom ($r = -0.70$, $p = 0.02$, $n = 10$). Coral winter SST correlates to the interdecadal PDO index better than IGOSS SST data do at both timescales (IGOSS-PDO $r_{annual} = -0.19$, $p = 0.32$, $n = 30$; $r_{3\ yr\_bin} = -0.45$, $p = 0.19$, $n = 10$).

Beyond the calibration interval (back to 1955), the correlation between the 3 year binned Palaui winter SST and PDO index remains statistically significant ($r = -0.56$, $p = 0.01$, $n = 19$; Figure 4). Temporally, our winter SST record reflects known PDO regime shifts. In particular, the well-known 1976–1977 PDO regime shift to warm (positive) phase [e.g., *Newman et al.*, 2016] is captured by our coral record as anomalously colder winters in the region. The 1988–1989 and 1997–1998 shifts to cool (negative) PDO phases [e.g., *Newman et al.*, 2016] are likewise captured as positive excursions in our coral record. Compared with the only available coral-based PDO reconstruction in the subtropical northwestern Pacific [e.g., *Felis et al.*, 2010], our results are of the same order of correlation at both annual and interannual timescales, i.e., $r_{annual} = 0.30$ and $r_{3\ yr\_running} = 0.50$ from Ogasawara coral Sr/Ca and U/Ca records. The PDO is one of the most significant climate phenomena influencing climate and ocean circulation in the western Pacific region [*Mantua et al.*, 1997; *Newman et al.*, 2016]. Our understanding of drivers and mechanisms of the PDO is limited, especially its link with tropical climate [*Gedalof and Smith*, 2001; *D'Arrigo et al.*, 2006; *Newman et al.*, 2016]. We find that the endemic *Diploastrea* corals have the ability to record interdecadal climate phenomena similar to *Porites*. In addition, the interspecies approach of this study has demonstrated its advantage by generating more reliable reconstructions. With *Diploastrea*'s longer lifespan than *Porites*, it has the potential to resolve centennial-scale variability in this important climate system.

4. Coral $\delta^{18}O$ and SSS

4.1. Monthly Calibration

Monthly *Diploastrea* coral carbonate $\delta^{18}O$ ($\delta^{18}O_c$) records are positively correlated with SSS ($r = 0.34$, $p < 0.0001$) and negatively correlated with SST ($r = -0.62$, $p < 0.0001$). *Porites* monthly $\delta^{18}O_c$ shows statistically significant correlations to SSS ($r = 0.67$, $p < 0.0001$) and to SST ($r = -0.66$, $p < 0.0001$) with higher r values compared to *Diploastrea*. The monthly $\delta^{18}O_c$ records are also strongly correlated with their paired monthly Sr/Ca values (*Diploastrea* $r = 0.63$ and *Porites* $r = 0.61$; $p < 0.0001$), which is expected as both proxies are a function of SST (Figure S2). Additionally, monthly SODA SSS and IGOSS SST are correlated over the calibration period ($r = 0.51$, $p < 0.0001$), indicating that they impact $\delta^{18}O_c$ in opposite directions, serving to dampen the seasonal $\delta^{18}O_c$ signal.

To compare our data to the literature, we first calibrated our coral $\delta^{18}O_c$ directly to SST. Our columellar *Diploastrea* and *Porites* $\delta^{18}O_c$ records yield an SST dependence of −0.16 and −0.14‰ °C^{-1}, respectively. This lies on the lower end of the range of calibration slopes reported for other columellar *Diploastrea* $\delta^{18}O_c$ studies, (e.g., −0.16 to −0.19‰ °C^{-1}) [*Watanabe et al.*, 2003; *Bagnato et al.*, 2004; *Dassié and Linsley*, 2015] and to typical *Porites* δ^{18}O-SST sensitivity (e.g., −0.15 to −0.22‰ °C^{-1}) [*Gagan et al.*, 2000]; *Lough*, 2004; *Corrège*, 2006]. This agrees with the instrumental data suggesting that our coral $\delta^{18}O_c$ records should have an attenuated seasonal signal due to the combined effects of SST and SSS.

The disequilibrium offsets we observed between *Diploastrea* and *Porites* Sr/Ca are also evident in their $\delta^{18}O_c$ records. The mean δ^{18}O offset is ~0.25‰ or equivalent to 1.6°C using our *Diploastrea* calibration slope and is comparable with offsets reported from *Diploastrea-Porites* δ^{18}O pairs in Fiji (e.g., 0.31‰ or 1.7°C) [*Bagnato et al.*, 2004] and Alor, Indonesia, and New Caledonia (e.g., 0.32‰ or 1.8°C) [*Watanabe et al.*, 2003] (Table 1).

4.2. Interannual Calibrations

Similar to our Sr/Ca data, we further evaluated our $\delta^{18}O_c$ records at interannual timescales over the same calibration period to better constrain the limits of our proxy calibration. The wet season in this region coincides with boreal summer (JJAS), and the dry season coincides with winter (DJFM). *Porites* $\delta^{18}O_c$ shows significant relationships with SSS for both wet and dry seasons. Wet season *Porites* $\delta^{18}O_c$, is strongly correlated to wet SSS (r = 0.60, p = 0.0006), but it is not correlated to either wet SST or Sr/Ca ($p > 0.40$, Figure S3b and Table S1). Dry *Porites* $\delta^{18}O_c$ is significantly correlated with both dry SST (r = −0.58, p = 0.0002) and SSS (r = 0.48, p = 0.01) but not with its dry Sr/Ca pair ($p > 0.20$, Figure S3b). On the contrary, wet season *Diploastrea* $\delta^{18}O_c$ is correlated to neither wet SST (r = 0.24, p = 0.20) nor wet SSS (r = 0.03, p = 0.85) but is significantly correlated to its Sr/Ca pair (r = 0.46, p = 0.01, Figure S3a and Table S1). Dry season *Diploastrea* $\delta^{18}O_c$ is not correlated to either SST or SSS nor to its paired Sr/Ca ($r < 0.15$, $p > 0.50$, Figure S3a). These results indicate that SSS records from *Porites* may be isolated by examining $\delta^{18}O_c$ during the wet and dry seasons separately, as will be discussed later.

As previously described in the interannual Sr/Ca relationships, summer *Diploastrea* Sr/Ca is not correlated to summer SST. One possible reason is the small summer SST range in Palaui, ~1.5°C, making it difficult to identify a significant relationship during this period. However, we were able to determine a significant summer Sr/Ca-SST relationship for the adjacent *Porites* core, and therefore, the small summer mean SST range cannot be the only explanation. If we consider the wet season, which is also coincident with the summer period, *Diploastrea* $\delta^{18}O_c$ is found to have no relationship with SSS, while the SSS range for this season is larger than the dry SSS range (0.94 psu versus 0.73 psu). We would expect to determine a significant and more robust relationship between wet $\delta^{18}O_c$ and SSS than during the dry season, similar to what we have obtained for our *Porites* record, but the relationship is absent.

Although skeletal extension rates may also impact Sr/Ca (see discussion in section 3.2), we found no relationship between summer *Diploastrea* Sr/Ca and linear extension (r = −0.26, p = 0.16). However, we hypothesize that similar to *Diploria labyrinthiformis* (a slow-growing coral from the tropical Atlantic), the summer growth in *Diploastrea* extends quickly and is subsequently infilled by secondary calcification during the following winter, mixing the Sr/Ca and $\delta^{18}O_c$ signals [*Cohen et al.*, 2004; *Goodkin et al.*, 2005]. Hence, the full amplitude of the annual cycle in *Diploastrea* $\delta^{18}O_c$ may be attenuated and harder to resolve, a problem compounded by conventional microsampling. Moreover, in places of low SSS range like our study site, i.e., annual range of ~0.66 psu, and where SST and SSS dampen the $\delta^{18}O_c$ amplitude, both SST and SSS signals will be harder to isolate from $\delta^{18}O_c$ data. Therefore, *Diploastrea* $\delta^{18}O_c$ may be more useful in places where SST and SSS signals combine to enlarge the $\delta^{18}O_c$ amplitude, as previously investigated throughout the Pacific [*Hughen et al.*, 1999; *Watanabe et al.*, 2003; *Bagnato et al.*, 2004, 2005; *Correge et al.*, 2004; *Damassa et al.*, 2006; *Dassié and Linsley*, 2015].

4.3. SSS Variability Using *Porites* $\delta^{18}O_c$

Annual and 3 year binned $\delta^{18}O_c$ for the wet and dry seasons are statistically and significantly correlated to SSS (equations (3) and (4) and Figure 5):

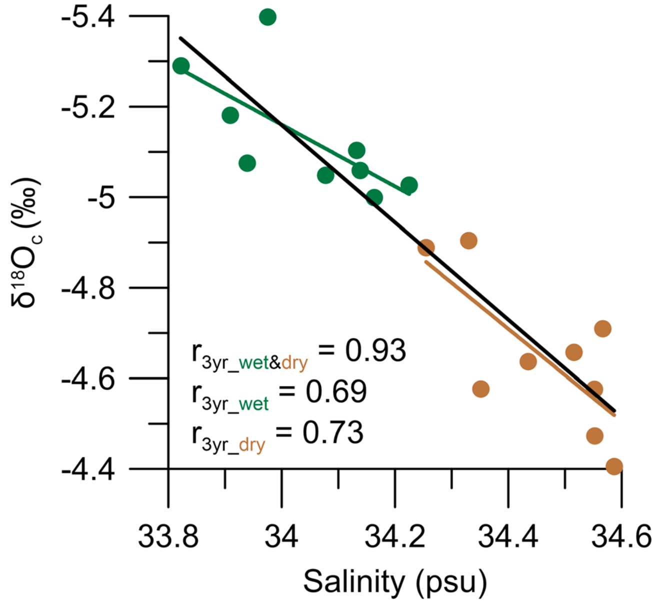

Figure 5. Three year binned *Porites* $\delta^{18}O_c$ values for the combined wet (green) and dry (brown) seasons are statistically and significantly correlated to SODA SSS (r = 0.93, $p < 0.0001$). $\delta^{18}O_c$ values for the wet and dry seasons separately also show strong correlations with SSS (r_{3yr_wet} = 0.69, p = 0.03 and r_{3yr_dry} = 0.73, p = 0.02).

$$\begin{aligned}&\textit{Porites}\,\delta^{18}O_{c\_annual\_wet\&dry} = -33.776\ (\pm 3.033) + 0.843\ (\pm 0.089)^{*}\ \text{SODA SSS}_{annual\_wet\&dry},\\ &r = 0.78, r^2 = 0.62, p < 0.0001, \text{RMSR} = 0.22\ \text{psu}, n = 57\end{aligned} \quad (3)$$

$$\begin{aligned}&\textit{Porites}\,\delta^{18}O_{c\_3yr\_wet\&dry} = -41.722\ (\pm 3.792) + 1.075\ (\pm 0.111)^{*}\ \text{SODA SSS}_{3year\_wet\&dry},\\ &r = 0.93, r^2 = 0.86, p < 0.0001, \text{RMSR} = 0.09\ \text{psu}, n = 18\end{aligned} \quad (4)$$

where RMSR of 0.22 and 0.09 psu are equivalent to ~33% and ~14%, respectively, of the mean annual SSS range, ~0.66 psu. The 3 year binned record has a higher correlation coefficient as a result of suppressing mismatched high-frequency SSS variability that is expected from comparing a single data point to a large spatial average.

The SSS reconstructions for the wet and the dry seasons show comparable correlation strength with SODA SSS ($r_{3\ yr\_wet}$ = 0.69, p = 0.03 and $r_{3\ yr\_dry}$ = 0.73, p = 0.02; Figure 5), and the associated reconstruction errors between seasons are consistent (RMSR ≈ 0.09 psu). However, a few anomalies are notable. The 3 year binned wet season SSS reconstruction shows higher salinity estimates, ~0.14 psu, than SODA SSS for the period 1994–1996 (Figure 6a). The dry season reconstruction conversely shows large departures from SODA SSS of about ~0.19 and ~0.15 psu for the periods 1988–1990 and 1997–1999, respectively (Figure 6b).

We compared our SSS reconstructions with satellite-derived precipitation data (GPCP) [*Adler et al.*, 2003] and the Southern Oscillation Index (SOI, https://www.ncdc.noaa.gov/teleconnections/enso/indicators/soi/), together with SODA SSS to assess the factors controlling our reconstructions. Over our calibration period, the reconstructed SSS for both wet and dry seasons shows good agreement with the SOI ($r_{3yr\_wet} = -0.82$; p = 0.007 and $r_{3yr\_dry} = -0.74$, p = 0.02, Figure 6c). The SOI is a measure of large-scale variability in air pressure across the Pacific that changes during ENSO episodes and, thus, provides a good test of ENSO impacts on the monsoon strength and fluctuations in the Intertropical Convergence Zone over our study site. A negative (positive) SOI indicates El Niño (La Niña) phase. In the western Pacific, El Niño (La Niña) is characterized by anomalously cooler (warmer) SSTs and drier (wetter) conditions leading to droughts (above normal rainfalls) as the warm pool moves toward the central equatorial Pacific (western Pacific), together with atmospheric convection and rainfall centers [*Rasmusson and Carpenter*, 1983; *Ropelewski and Halpert*, 1987]. The 1997–1999 period covers one of the strongest back-to-back El Niño-La Niña phase changes for the past 30 years. The wet season $\delta^{18}O_c$ record for the 1997–1999 period captures the wet phase SODA SSS well (Figure 6a), while the dry season $\delta^{18}O_c$ anomaly reflects "wetter" (less dry) conditions (Figure 6b). The wetter than average condition coincides well with SOI (Figure 6c) indicating that our site received above average

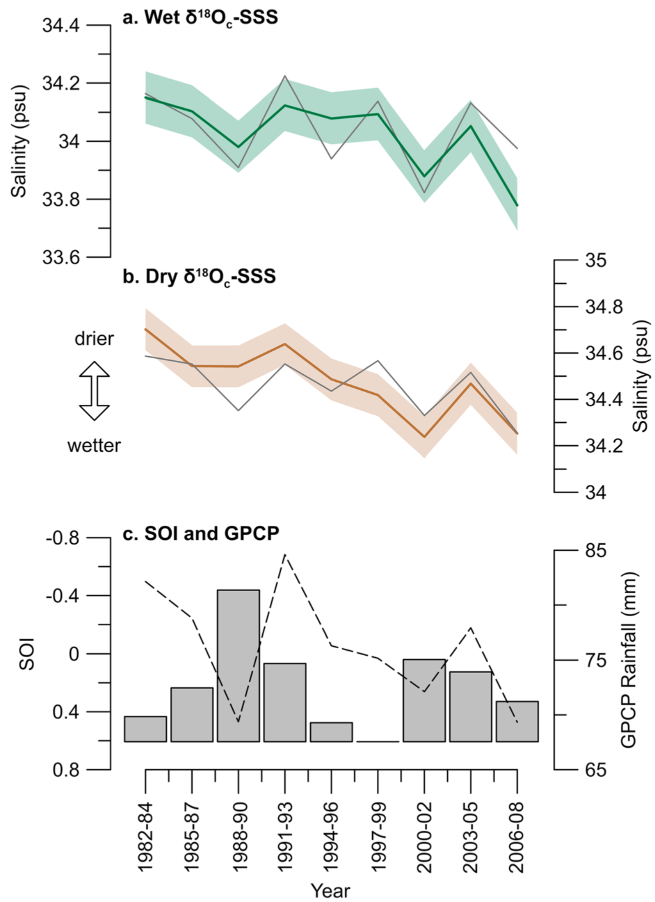

Figure 6. (a) Wet season *Porites* SSS reconstruction (green) against SODA SSS (gray). (b) Dry SSS reconstruction (brown) against SODA SSS (gray). (c) Differences between the SSS reconstructions in Figures 6a and 6b may be explained by changes in SOI (dashed lines), an indicator of ENSO events, and rainfall patterns from GPCP (gray bars). Shaded areas represent RMSR = 0.09 psu, based on the 3 year binned wet and dry season SSS calibrations.

rainfall expected during strong La Niña episodes. The strong La Niña in 1998–1999 developed during the winter/dry months, explaining the observed signal strength during this season.

An offset in timing between minimum salinity and precipitation may explain some of the differences between our reconstructions and SODA SSS (Figure 6c). The years 1994–1996 in our reconstruction show higher salinity estimates than SODA SSS during the wet season (Figure 6a). GPCP rainfall data show that this period received one of the least amounts of rainfall over our calibration period that may not be ENSO related. ENSO for these years is considered weak to moderate; thus, impacts on rainfall variability may be minimal.

4.4. Application of Calibration Equation and Comparison to SOI Variability

Beyond the calibration period of 1982–2012, the 3 year binned *Porites* wet SSS reconstructions remained significantly correlated with SODA SSS when including data back to 1955 (r = 0.56, p = 0.015), allowing for robust SSS reconstruction (Figure 7a). However, the *Porites* dry SSS to SODA SSS did not remain significant (r = 0.14, p = 0.55, Figure 7b). The SOI is not correlated to wet SSS (r = −0.08, p = 0.75) but is significantly correlated to dry SSS (r = −0.48, p = 0.04) (Figure 7b). These results may be the outcome of less reliable SODA SSS data before ~1970s due to the limited number of observations [*Delcroix et al.*, 2011] or may indicate that salinity variability between seasons is governed by different factors.

Porites wet SSS generally tracks local salinity (Figure 7a). However, "drier" (less wet) excursions in the record, e.g., 1958–1960, 1964–1966, and 1976–1978, not reflected in the SODA time series, may be explained by SOI. These years are predominantly weak to moderate El Niño years (with the year 1965–1966 as one of the strong El Niño events in the past ~65 years), resulting in drier conditions at our site. *Porites* dry SSS, on the other hand, may record more regional changes in salinity based on its sustained relationship with SOI on longer timescales (Figure 7b). The annual SOI averages are essentially a combined signal from the two seasonal extremes, and therefore, defining each season separately may be more advantageous. ENSO onset begins during the dry season. If SOI values are averaged for DJFM months and compared to our dry SSS reconstruction, the correlation strength between the time series becomes stronger (r = −0.64, p = 0.003).

While we are unable to generate a robust *Diploastrea* $\delta^{18}O_c$-SSS reconstruction for the wet and dry seasons, long-term records indicate a freshening trend toward the present (Figure 8). *Diploastrea* $\delta^{18}O_c$ has a decreasing slope of −0.0174 ‰/yr (r = 0.81, p = 0.002) from the early 1950s to the present. If this is partly due to warming, we expect to see a significant increase in *Diploastrea* Sr/Ca and in the adjacent *Porites* record. Both coral Sr/Ca records are essentially flat ($m_{Diploastrea}$ = 0.0008 mmol/yr and $m_{Porites}$ = 0.0007 mmol/yr); hence, the

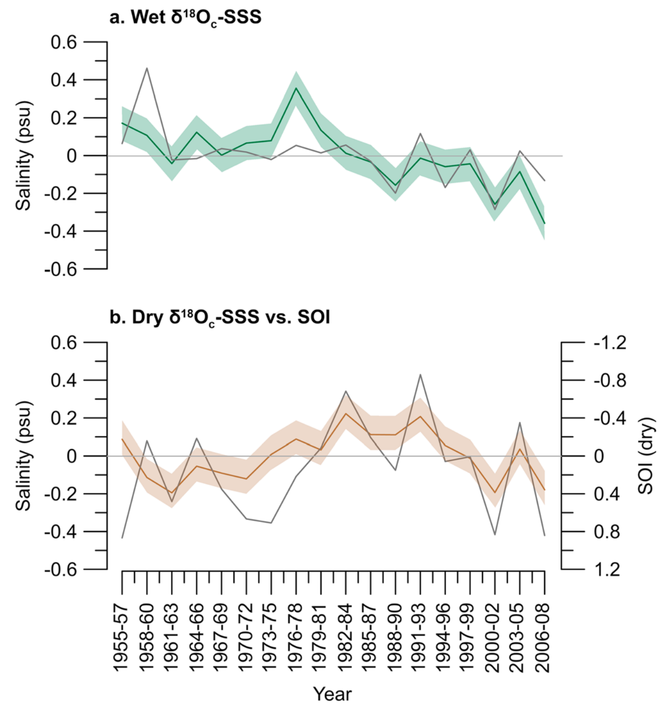

Figure 7. (a) Wet season *Porites* SSS reconstruction back to 1955 is significantly correlated to SODA SSS observations ($r = 0.56$, $p = 0.015$). (b) Dry season $\delta^{18}O_c$ may be better at recording SOI at longer timescales ($r = -0.64$, $p = 0.003$). Shaded areas represent RMSR = 0.09 psu, based on the 3 year binned wet and dry season SSS calibrations.

Diploastrea $\delta^{18}O_c$ trend is likely due to freshening. *Porites* wet SSS reconstructions and SODA SSS show a freshening trend equivalent to ~0.007 and ~0.009 psu/yr. If we convert the slope of *Diploastrea* $\delta^{18}O_c$ to salinity using equation (4), it will result in a comparable magnitude of freshening of 0.016 (±0.00464) psu/yr.

Lower salinity toward the present is a common trend in the western and central Pacific [*Cobb et al.*, 2003; *Delcroix et al.*, 2007; *Gagan et al.*, 2000; *Nurhati et al.*, 2009, 2011], pointing to the intensification of the hydrological patterns [*Cobb et al.*, 2003; *Nurhati et al.*, 2009, 2011; *Osborne et al.*, 2014] since the start of the twentieth century as the cause. Freshening trends obtained from both coral and instrumental records have been estimated to be on the order of 0.1 to 0.3 psu/decade [e.g., *Delcroix et al.*, 2007] to up to 0.6 to 1.2 psu/century [*Nurhati et al.*, 2009, 2011]. *Porites* wet SSS and instrumental data have the same magnitude of freshening approximately ~0.35 psu and ~0.30 psu, respectively, for the past six decades. The wet *Diploastrea* SSS record, in contrast, shows a greater amount of freshening, ~0.85 psu, which likely arises from the uncertainties in the *Diploastrea* calibrations as previously discussed.

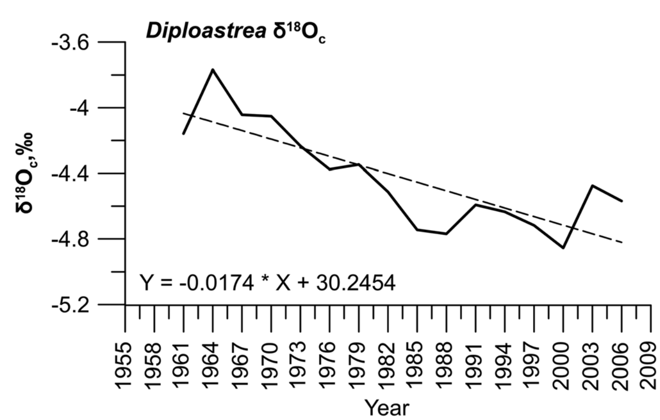

Figure 8. Long-term freshening trend observed from decreasing *Diploastrea* $\delta^{18}O_c$ values.

5. Conclusions

This study investigated a *Diploastrea heliopora* coral relative to an adjacent *Porites* from northeast Luzon (Palaui), Philippines, to evaluate both Sr/Ca and $\delta^{18}O$ paleoclimate proxies and *Diploastrea*'s ability to reconstruct regional climate behavior. Sr/Ca from *Diploastrea* has only been used as a chronological marker in previous studies [e.g., *Bagnato et al.*, 2004, 2005]. Winter Sr/Ca data from *Diploastrea* are an excellent SST proxy and have a similar sensitivity to an adjacent *Porites* core. The interspecies SST (averaged *Diploastrea-Porites* SST) record reflects the PDO and allows for a reconstruction of long-term PDO variability.

Salinity variability for the past half century are qualitatively captured in the Palaui *Diploastrea* $\delta^{18}O_{c,}$ showing a freshening trend consistent with *Porites* $\delta^{18}O_c$, instrumental SSS, and coral-based records within the Indo-Pacific region. However, a robust *Diploastrea* $\delta^{18}O_c$ and SSS calibration at interannual timescales was not achieved as a result of the competing SST and SSS influences dampening the $\delta^{18}O_c$ signal and compounding effects of continuing coral calcification during different seasons. *Diploastrea* $\delta^{18}O_c$ should be useful in places where there is high salinity range (mean annual salinity >~1.5 psu) and where SST and SSS signals combine to enlarge the $\delta^{18}O_c$ amplitude as previously investigated in the central and South Pacific regions.

The multiproxy, multispecies approach of this study further strengthens justification for the use of *Diploastrea* as an alternate climate archive in the Indo-Pacific region and demonstrates its potential in helping resolve global-scale climate phenomena we poorly understand.

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