Paleoceanography and Paleoclimatology

RESEARCH ARTICLE
10.1029/2019PA003826

Key Points:
• Robust calibrations of sea surface temperature, salinity, and rainfall allow for climate reconstructions at different seasons in Houbihu, southern Taiwan
• ENSO, PDO, and the EAM drive climatic and oceanographic variability at the northern edge of the Western Pacific Warm Pool
• Two centuries of climate reconstructions record cool/dry conditions at the end of the Little Ice Age and warm/fresh conditions in the late twentieth century to the present

Supporting Information:
• Supporting Information S1
• Data Set S1

Correspondence to:
R. D. Ramos, rramos@ntu.edu.sg; ramos34@wpunj.edu

Citation:
Ramos, R. D., Goodkin, N. F., & Fan, T.-Y. (2020). Coral records at the northern edge of the Western Pacific Warm Pool reveal multiple drivers of sea surface temperature, salinity, and rainfall variability since the end of the Little Ice Age. Paleoceanography and Paleoclimatology, 35, e2019PA003826. https://doi.org/10.1029/2019PA003826

Received 28 NOV 2019
Accepted 15 APR 2020
Accepted article online 24 APR 2020

©2020. The Authors.
This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Coral Records at the Northern Edge of the Western Pacific Warm Pool Reveal Multiple Drivers of Sea Surface Temperature, Salinity, and Rainfall Variability Since the End of the Little Ice Age

R. D. Ramos1,2, N. F. Goodkin1,3, and T.-Y. Fan4

1Earth Observatory of Singapore, Nanyang Technological University, Singapore, 2Now at Department of Environmental Science, William Paterson University, Wayne, NJ, USA, 3American Museum of Natural History, New York, NY, USA, 4National Museum of Marine Biology and Aquarium, Pingtung, Taiwan

Abstract Reconstructions of key climate parameters prior to anthropogenic influences serve to constrain decadal to multicentury natural climate variability. In the western Pacific region, relatively few reconstructions exist north of the Western Pacific Warm Pool (WPWP), a region critical to global climate. In this study, we collected a coral core from Houbihu, southern Taiwan, and generated a 225-year reconstruction of annual and wintertime sea surface temperature, dry season sea surface salinity, and wet season rainfall records derived from paired Porites Sr/Ca and δ18O profiles extending back to the end of the Little Ice Age (1850 CE). Multidecadal sea surface temperature trends generally track regional surface temperature reconstructions, indicating the dominant influence of solar and volcanic radiative forcings. Reconstructed dry season sea surface salinity reflects an advection signal linked to the East Asian Winter Monsoon and the Pacific Decadal Oscillation, both influencing variations in the Kuroshio Intrusion across the Luzon Strait. Reconstructed wet season rainfall, on the other hand, reveals influence of the Pacific Decadal Oscillation on the decadal variability of local and regional rainfall patterns. Relative to the late 1900s, our climate reconstructions document cooler and drier (high salinity and low rainfall) conditions during the end of the Little Ice Age, supporting other lines of evidence of a retracted WPWP region during this period. In the late 20th to early 21st century, our climate reconstructions record warming and freshening (low salinity and high rainfall) trends, highlighting the potential impact of anthropogenic forcing in the extension of the WPWP.

1. Introduction

Understanding long-term climate variability involves reconstructions of key climate parameters extending beyond the limits of observational data and anthropogenic influences (Dunbar & Cole, 1999; Gagan et al., 2000; Lough, 2010). Massive corals provide a means of generating high-resolution multicentury climate records, such as sea surface temperature (SST) and sea surface salinity (SSS) (Dunbar & Cole, 1999; Gagan et al., 2000), which in Southeast Asia reflect changes to critical climate variability such as the El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and East Asian monsoon.

The Little Ice Age (LIA) is the most recent climate interval to study naturally forced, widespread climatic change (Bradley & Jones, 1993; Dunbar & Cole, 1999). The LIA is a 400- to 500-year cold interval (1300s to 1800s Common Era, CE) that is primarily identified in the high-latitude Northern Hemisphere (e.g., D’Arrigo, Wilson, Palmer, et al., 2006; Goodkin et al., 2008; Mann et al., 1999; Overpeck et al., 1997). Temperate and high-latitude paleoclimate records indicate cooling of about 0.5 to 5 °C relative to present (Goodkin et al., 2008; Mann et al., 1999; Overpeck et al., 1997). Extensive evidence also exists for cooling in the tropics (e.g., T. Chen et al., 2018; DeLong et al., 2012, 2013; Deng et al., 2017; Newton et al., 2006; Oppo et al., 2009; Watanabe et al., 2001; Yan, Soon, & Wang, 2015) and high-latitude Southern Hemisphere (e.g., Bradley & Jones, 1993). Depending on location, proxy reconstructions mostly from corals, bivalves, marine sediments, and foraminifera in this region reveal a period of cooling, between 0.5 and 2 °C lower than present. These regional cooling estimates coincide with minimum solar forcing and higher volcanic activity (Bradley & Jones, 1993; Crowley, 2000; Mann et al., 1999).
In the western Pacific region where the East Asia-Australia monsoon system prevails, LIA cooling is associated with meridional shifts in hydrological patterns characterized by a drier southeast China, a wetter Western Pacific Warm Pool (WPWP) region, and a drier north Australia region relative to the present (Yan, Wei, et al., 2015, and references therein). This spatial variability is hypothesized to be driven by the expansion or contraction of the Intertropical Convergence Zone rain belt (Griffiths et al., 2016; Yan, Wei, et al., 2015) in response to reduced solar forcing during this period.

As the greatest source of global heat and moisture, the WPWP impacts critical ocean-atmosphere interactions worldwide (D'Arrigo, Wilson, Palmer, et al., 2006; Webster & Lukas, 1992). Changes in WPWP temperature, size, and position thus have considerable impacts on regional and global climate variability (Abram et al., 2009; Cravatte et al., 2009; Emanuel, 2005; Oppo et al., 2009; Yan et al., 1992). Paleoreconstructions based on networks of various climate archives are increasingly generated in various time spans to investigate large-scale atmosphere-ocean interactions related to the WPWP. For example, several coral-derived climate reconstructions beyond the LIA (e.g., Calvo et al., 2007; D'Arrigo, Wilson, Palmer, et al., 2006; DeLong et al., 2012; Hendy et al., 2002; Lough, 2011) have complemented other marine and terrestrial-derived reconstructions in the region (e.g., D'Arrigo, Wilson, Palmer, et al., 2006; Deng et al., 2017; Yan, Wei, et al., 2015) to examine the drivers of spatiotemporal changes in hydrological processes in the western Pacific. However, most of these long (i.e., >100 years) coral-derived records are concentrated in the south equatorial, western, and central tropical Pacific regions (Tierney et al., 2015, and references therein), with sparse coverage around the northern extent of the WPWP region (e.g., T. Chen et al., 2018; Deng et al., 2013; Deng et al., 2017; Ramos et al., 2019), potentially creating a bias in the observed spatiotemporal variability.

In this paper, we present a 225-year reconstruction of SST, SSS, and rainfall derived from paired Porites Sr/Ca-δ18O records from Houbihu, southern Taiwan. We examine the drivers of the observed climatic variability since the end of the LIA at the northern edge of the WPWP expected to be variably influenced by ENSO cycles and the East Asian monsoon system.

2. Methods

2.1. Study Site and Coral Core Collection

In May 2013, a Porites sp. coral core was collected from 6-m water depth off the coast of Houbihu, southern Taiwan (21.9°N, 120.7°E, Figure 1). The 3-m-long core was drilled using an underwater hydraulic drill with an ~85-mm diameter core bit. Houbihu, facing Nanwan Bay and the Luzon Strait to its south, is located at the northern edge of the WPWP. Instrumental SST, salinity, and local rainfall records (see section 2.4) from 1982 to 2013 indicate that June to September are the warmest and wettest months while December to March are the coldest and driest months (supporting information Figure S1). Annual SST ranges from 26.1 to 27.9 °C with a mean amplitude of 1.8 °C and annual SSS ranges from 33.8 to 34.5 psu with a mean amplitude of 0.69 psu. Annual rainfall averages 2000 ± 500 mm/year (1σ, Climate Weather Bureau at Hengchun County; Shen, Lee, et al., 2005; Shen, Liu, et al., 2005). The subtropical climate of southern Taiwan is affected by the East Asian Monsoon, in which maximal rainfall occurs during the southwest monsoon season (May to October) and cold fronts propagate from Siberia during the northeast monsoon season (November to April) (Shen, Lee, et al., 2005). No major input of freshwater from rivers drains into the bay (Shen, Lee, et al., 2005; Shen, Liu, et al., 2005), but tidally induced upwelling delivers cold intermediate water into the bay daily (Lee et al., 1997; Lee, Chao, & Fan, 1999; Lee, Chao, Fan, & Kuo, 1999).

2.2. Coral Subsampling

Following the procedures outlined in Ramos et al. (2017), the coral cores were cleaned, cut into 7-mm-thick slabs, and X-rayed (supporting information Figure S2) prior to subsampling. A micrometer-aided drill press was used in subsampling at 0.5-mm increments along the direction of the extending corallites. Around 24 subsamples were collected per year of extension, yielding a near-biweekly resolution. Approximately 200- and 40- to 90-μg powder sample splits were set aside for Sr/Ca and stable isotope measurements, respectively.
2.3. Sr/Ca and $\delta^{18}$O Measurements

Sr/Ca subsamples were dissolved in 2.5 ml of 5% HNO3 overnight. An inductively coupled plasma-optical emission spectrometry (Thermo iCAP 6000 Series) at the Asian School of the Environment, Nanyang Technological University, was used to measure Sr and Ca simultaneously. Instrument drift and matrix effects resulting from varying calcium concentrations (Schrag, 1999) were corrected using solution standards (0 to 80 ppm) run at constant intervals. Sample unknowns, blanks, and powder standards JCp-1 (Okai et al., 2001) with a consensus Sr/Ca value of 0.01932 ppm (±0.0002) or 8.838 mmol mol$^{-1}$ (±0.089) (Hathorne et al., 2013) and an in-house powder standard (Porites sp.) were simultaneously prepared. Repeat measurements of JCp-1, and in-house coral standard analyzed over a 2-year period showed good reproducibility: 0.019291 ± 0.00004 ppm or 8.824 ± 0.018 mmol mol$^{-1}$ (1σ, relative standard deviation (RSD) = 0.18%, n = 1074) and 0.019289 ± 0.00005 ppm or 8.823 ± 0.023 mmol mol$^{-1}$ (1σ, RSD = 0.25%, n = 396), respectively.

Oxygen stable isotopes, $\delta^{18}$O, were measured in an automated Kiel IV carbonate device coupled with a ThermoFisher MAT-253 isotope ratio mass spectrometer and on a Thermo-Finnigan Delta V Advantage isotope ratio mass spectrometer with Gasbench (GB) II, both at Asian School of the Environment, Nanyang Technological University. Prior to measurement, powdered subsamples were acidified with 105% H$_3$PO$_4$ at 70 °C. Measurements were calibrated relative to Vienna Peedee belemnite using external standards including National Bureau of Standards (NBS) 19 ($\delta^{18}$O = 2.20‰) and NBS 18 ($\delta^{18}$O = 23.2‰) (Stichler, 1995). Repeat measurements of NBS 19 and marble standard, Estremoz ($\delta^{18}$O = −5.95 ± 0.07‰), show no measurable offsets between instruments or against published values (supporting information Table S1).

Due to the length of the core, $\delta^{18}$O was only measured on dry and wet season (see section 2.1 and supporting information Figure S1) samples prior to 1906. The $\delta^{18}$O samples were selected on the basis of the wintertime Sr/Ca depth and time series data, in which $\delta^{18}$O and Sr/Ca minima and maxima coincide seasonally. Each seasonal sample constitutes about four to eight consecutive $\delta^{18}$O measurements that were subsequently averaged to represent the dry and wet season values of each year. The reduction in sample

Figure 1. A coral core of Porites spp. was collected offshore of Houbihu, southern Taiwan (21.9°N, 120.7°E) in May 2013. Houbihu, facing Nanwan Bay and the Luzon Strait to its south, is located at the northern edge of the Western Pacific Warm Pool (inset). The monthly (July) climatological SST (°C) data are based on IGOSS SST from 1970 to 2000 (Reynolds et al., 2002). White dashed lines delineate major western boundary currents, NEC = North Equatorial Current; MC = Mindanao Current; KC = Kuroshio Current; KI = Kuroshio Intrusion.
points is unlikely to create a bias across time periods as we consistently examine seasonal extremes (i.e., winter/dry versus summer/wet) at interannual to multidecadal timescales. Time assignment for the interannual dry season $\delta^{18}O$ followed that of the paired Sr/Ca data (see section 2.5).

### 2.4. Instrumental Data

Monthly 1° by 1° grid resolution (1° $\approx$ 111 km) SST data from the Integrated Global Ocean Services System Products Bulletin (IGOSS v.2), also referred to as Optimum Interpolation SST v.2 (http://iridl.ldeo.columbia.edu/SOURCES/.IGOSS/.nmc/.Reyn_SmithOIv2/), centered at 21.5°N, 120.5°E (Reynolds et al., 2002), was used for SST calibration over a 31-year period, 1982 to 2013. We chose this dataset rather than other finely resolved SST products to obtain a continuous calibration interval. We found that the 4-km resolution Advanced Very High Resolution Radiometer Pathfinder v.5 SST (Kilpatrick et al., 2001) is temporally discontinuous and that the finely resolved version of Optimum Interpolation SST v.2 (i.e., daily SST data at 0.25° grid resolution), yields similar calibration results (supporting information Table S2).

SSS and rainfall data were also acquired to evaluate the relative influence of salinity in the coral $\delta^{18}O$ record. Monthly gridded 0.25° square resolution SSS data was obtained from Simple Ocean Data Assimilation (SODA v. 2.2.4, http://apdrc.soest.hawaii.edu/dods/public_data/SODA/soda_pop2.2.4, Carton & Giese, 2008) data set centered at 21.75°N, 120.75°E at a depth of 5 m. We chose this data set due to its record length and availability in the region. We found that other salinity products are spatially (e.g., Delcroix et al., 2011) and temporally (e.g., Aquarius, Lagerloef et al., 2008) limited. We note, however, that SODA SSS data earlier than the 1960s should be used with caution due to the sparse hydrographic observations during this period (Giese & Ray, 2011). Monthly rainfall data from 1897 to 2013 from a local weather office (Taiwan Climate Weather Bureau) in Hengchun County was used for comparison.

### 2.5. Chronology Development and Calibration

Distinct annual density bands visible in X-radiographs and seasonal cycles of Sr/Ca ratios were used in developing age-depth models. Over the 31-year instrumental and calibration periods, coral Sr/Ca profile minima and maxima were aligned with their respective SST points each year using Analyseries software (Paillard et al., 1996). Inflection points (i.e., spring and fall) were additionally assigned to corresponding SST to optimize age model interpolation (e.g., DeLong et al., 2013) and minimize proxy heterogeneity in corals sampled at high resolution (e.g., Allison & Finch, 2009). Beyond the calibration period, time was assigned using the averaged SST climatology, similarly aligning Sr/Ca and SST minima, maxima, and inflection points. The same tie points in the Sr/Ca-SST age model were applied to the corresponding $\delta^{18}O$ record. Sr/Ca and $\delta^{18}O$ were then linearly interpolated to generate monthly time series. Age model error is expected, including accumulation through time due to years of no growth, years of limited growth, or missed band counting. Seasonal age model error may be expected on individual months due to nonlinear growth or seasons where the coral has limited or no grown due to stress (e.g., Comboul et al., 2014). This may result in 1 to 2 months age error but expected to be noncumulative between years.

Calibrations of Sr/Ca and SST and $\delta^{18}O$ and SSS were performed using reduced major axis (RMA) linear regressions at monthly and interannual timescales, unless otherwise indicated to facilitate comparison. Compared with the commonly used ordinary least squares (OLS) regression method, RMA accounts for potential errors in both dependent and independent variables, simultaneously minimizing the distance perpendicular to the regression line (Clarke, 1980; Harper, 2016). We found that applying the RMA linear regression method in our monthly and interannual calibrations consistently resulted in steeper slopes and reduced reconstruction errors compared with those of the OLS method (supporting information Figure S3 and Table S3).

### 2.6. Data Analysis

The spectral characteristics of the proxy records were estimated using a simple fast Fourier transform algorithm. Significance level (90%) was estimated using 10,000 Monte Carlo simulations. Nonparametric coherence multitaper method and phase analysis with bias correction (https://www.mathworks.com/matlabcentral/fileexchange/22551-multi-taper-coherence-method-with-bias-correction, e.g., Huybers & Denton, 2008) were also performed to evaluate the significant frequencies shared between proxy reconstructions and key climatic indices. Spectral coherence was estimated with 8 windows and 50 iterations on Monte
Carlo error estimates. A Gaussian filter centered at significant frequencies was also applied using the Analyseries software (Paillard et al., 1996), to further isolate and observe specific frequencies through time.

### 3. Results

#### 3.1. Sr/Ca-SST

#### 3.1.1. Monthly Calibration

RMA regression of monthly Sr/Ca to IGOSS SST from 1982 to 2013 (Figure 2a) shows a significant inverse relationship:

\[ r = -0.95, \quad p < 0.0001 \]

\[ r = -0.73, \quad p < 0.0001 \]

\[ r = -0.71, \quad p < 0.0001 \]

**Figure 2.** RMA linear regression between monthly (a, black hollow dots), mean annual (b, blue hollow dots), and winter (c, purple hollow dots) Sr/Ca and SST (left plots). Monthly (a, black line), mean annual (b, blue line), and winter (c, purple line) SST reconstructions compared with IGOSS SST (dotted gray line, right plots). Shaded areas represent \( \text{RMSR}_{\text{annual}} = 0.29 \) °C and \( \text{RMSR}_{\text{winter}} = 0.44 \) °C.
where the root-mean-square of the residual (RMSR) is the difference between the instrumental and reconstructed SSTs. The calibration slope is within the range of slopes reported in Porites-based Sr/Ca-SST calibration studies (i.e., $-0.042$ to $-0.080$ mmol·mol$^{-1}·°C^{-1}$; e.g., Alibert & McCulloch, 1997; Corrège, 2006; Murty et al., 2018).

### 3.1.2. Interannual Calibrations

To further examine the reliability of the Sr/Ca-SST relationships at interannual timescales, we derived mean annual, 4-month summer (June to September, see section 2.1) and 4-month winter (December to March) Sr/Ca-SST relationships over the calibration period. All interannual calibrations capture SST variability significantly. However, the correlation strength between summer Sr/Ca and SST is relatively moderate ($r = 0.48, p = 0.01$) compared with those of winter and mean annual Sr/Ca-SSTs ($r > 0.70, p \ll 0.0001$), raising concerns on the reliability of the SST reconstructions during this season (supporting information Figure S3 and Table S3).

Previous studies in slow growing corals have demonstrated that summer Sr/Ca variability compared to winter is impacted by growth effects (e.g., Goodkin et al., 2005; Goodkin et al., 2007), resulting in dampened interannual Sr/Ca variability. However, earlier Porites-based studies have shown that relatively higher summer Sr/Ca variability compared to gridded SST challenges a robust summer SST reconstruction (e.g., Ramos et al., 2017) likely resulting from the very small interannual variability in summer SSTs. While Houbihu summer Sr/Ca do not correspond to varying extension rates (supporting information Figure S4), interannual SST variability during this season is small (i.e., $1.6 °C$, supporting information Figure S3 and Table S3), potentially preventing us from constraining errors enough to interpret interannual trends. Due to these reasons, we further investigate the SST variability in Houbihu at wintertime and mean annual timescales. RMA regression of annual and winter Sr/Ca to SST is shown in Figures 2b and 2c, respectively, and summarized as

$$\text{Sr/Ca}_{\text{annual}} = 11.022 \pm 0.280 - 0.079 \pm 0.010 \times \text{SST}_{\text{annual}} °C.$$  \hspace{1cm} (2)

$$r = -0.73, p \ll 0.0001, n = 31, \text{RMSR} = 0.29°C$$

$$\text{Sr/Ca}_{\text{winter}} = 11.076 \pm 0.362 - 0.083 \pm 0.015 \times \text{SST}_{\text{winter}} °C.$$  \hspace{1cm} (3)

$$r = -0.71, p \ll 0.0001, n = 31, \text{RMSR} = 0.44°C$$

During the calibration period, annual and winter Sr/Ca-SST have ranges of $1.60$ and $2.77 °C$, respectively, comparable to that of IGOSS SST (i.e., annual and winter range is $1.83$ and $2.66 °C$, respectively, Figures 2b and 2c). The interannual trends between coral Sr/Ca-SST and IGOSS SST show similar patterns of variability, giving indication that relative variability compared to the present should be consistent.

### 3.1.3. Mean Annual and Winter SST Reconstruction

Mean annual and winter Sr/Ca values extending back to 1788 (supporting information Data Set S1) were converted to SST using equations 2 and 3, respectively. The mean annual Sr/Ca-SST reconstruction exhibits interannual to multidecadal-scale variability within a $2.7 °C$ SST range (25.2 to 27.9 °C, Figure 3a). The lowest SSTs were observed during the late nineteenth century, when SST reached $25.2 °C$ in 1874. This period between the late eighteenth century and twentieth century, which shows mean cooling of about $-0.3 °C$ below the record mean, coincides with the end of the LIA (e.g., Hendy et al., 2002; Oppo et al., 2009; Rosenthal et al., 2013). During this period, episodes of distinct warming were also observed in the mid-1840s and at the turn of the twentieth century with similar magnitudes of about $-1 °C$ above the record mean. The warmest SSTs were recorded in the most recent years, reaching an SST maximum of $27.9 °C$ in 2001.

The wintertime SST reconstruction shows increased variability (SST range of $3.7 °C$) relative to the mean annual record (Figure 3a). The annual record is essentially an average of the summer and winter SST extremes where predominance of climatic or oceanographic processes during a season may be reduced. However, overall trends are in good agreement ($r = 0.83, p < 0.0001$) with the coldest and warmest
Figure 3. Comparison of our SST reconstruction with other multiproxy surface temperature reconstructions in the region since the late eighteenth century. (a) Mean annual (thin blue line) and winter (thin purple line) SST record in Houbihu. Superimposed are 11-year smoothed (thick lines) SST records (b) 100-year smoothed (brown, Shi et al., 2014) and interannual (green, D’Arrigo, Wilson, Palmer, et al., 2006) surface temperature reconstruction in Asia and Northern Hemisphere, respectively. The Northern Hemisphere surface temperature records are primarily based on tree ring chronologies (D’Arrigo, Wilson, Palmer, et al., 2006). Temperature records from ice cores and other historical documents are additionally included in Shi et al., 2014. Dashed brown line representing a grid point closest to Taiwan was extracted for a similar-scale comparison. (c) Interannual western Pacific SST reconstruction based on coral Sr/Ca and δ^{18}O records (Tierney et al., 2015). The above regional surface temperature reconstructions (i.e., b and c) show anomalies with respect to the most recent 30 to 40 years of each record as reported in original publications. Radiative forcing data include (d) interannual (thin red line) and 11-year running mean (thick red line) record of solar irradiance (Lean, 2000), (e) reconstructed volcanic forcing (black line, inverted axis) (Crowley, 2000), and (f) well-mixed greenhouse gases (GHGs, olive line, Schmidt et al., 2012).
periods similarly observed in the late 1800s and late twentieth century, respectively. Beginning 1950, both records exhibit a significant warming trend of about ~1.0 °C over the last six decades ($r_{\text{annual}} = 0.64$, $r_{\text{winter}} = 0.43$; $p < 0.01$).

3.1.4. Evaluating Drivers of SST Variability

Spectral analysis on the 225-year mean annual and winter SST record reveal significant variance between multidecadal frequencies of 52 and 70 years per cycle and at interannual frequencies between 2 and 5 years per cycle (Figure 4a), suggesting that our SST records are sensitive to interannual and multidecadal variability influencing the subtropical western Pacific. Spectral coherence between a record of ENSO (i.e., HadSST2-based reconstruction; Emile-Geay et al., 2013), the main driver of interannual climate variability in the region (i.e., significant power between 2 and 6 years per cycle, Figure 4b), and our mean annual and winter SST records reveals significant correlation at multidecadal frequencies >20 years per cycle and interannual frequencies around 2.3 years per cycle (Figure 4b1 and supporting information Figure S5). ENSO and winter SST additionally show significant correlation between 2 and 3 years per cycle (Figure 4b1) that is not as evident in the annual record (supporting information Figure S5). ENSO events typically mature during boreal winter (Rasmusson & Carpenter, 1983), likely explaining the stronger relationship observed during this season. Therefore, we further investigate the influence of ENSO focusing on our winter SST reconstruction.

We filtered our winter SST record and ENSO using a central frequency of 0.4087 ± 0.0817 cycles per year to isolate the significant biennial periods (i.e., average of 2.1 years per cycle). The maximum correlation between records is found when the winter SST record is moved forward in time by a year ($r = 0.34$, $p < 0.0001$, $n = 207$, Figure 5a). This offset relationship may be due to age model uncertainties, where an extra 1 year is artificially added when merging overlapping sampling tracks. The low but significant overall correlation of the band-pass-filtered records is potentially due to the varying phase relationship within the 2-to 3-year band (Figure 4b1). Between 1868 and 1949, ENSO and winter SST are significantly correlated showing the expected phase relationship (Figure 5b). Between 1823 and 1867 coinciding with the end of the LIA,

Figure 4. Spectral analysis of (a) detrended (i.e., linear trend is removed) Houbihu annual (blue) and winter (purple) SST anomalies, (b) an ENSO index, and (c) solar irradiance. Significance level greater than 90% (red lines) is labeled. For (a), labels in black denote significant frequencies in both annual and winter SSTs, while labels in purple are significant frequencies only winter. Spectral coherence and phase analyses were also performed between Houbihu winter SST and (b1) ENSO and (c1) solar irradiance. Significant coherence greater than 90% (red lines) is shaded and labeled. Dashed gray lines indicate 90% confidence interval for the phase.
and 1950 toward the present marking the onset of the recent warming trend in Houbihu, both records exhibit weak correlation (Figure 5b).

Results of the 50-year running variance applied on the band-pass-filtered records exhibit a covarying relationship between ENSO and Houbihu winter SST (Figure 5c). Both records exhibit reduced variance at biennial periods at the end of the LIA and toward the end of the twentieth century, although not of comparable magnitudes. An increased variance, on the other hand, is observed on both records around the turn of the twentieth century. The reduced variance at the end of the LIA and during the recent warming may explain the weak correlation between ENSO and winter SST (Figure 5).

We also compared our winter SST reconstructions with a record of the EAWM (D'Arrigo et al., 2005) and the PDO index (http://research.jisao.washington.edu/pdo/PDO.latest) known to exhibit strong interannual and decadal scale variability. Boreal winter relative to the mean annual is particularly sensitive to the EAWM and PDO; however, we found no significant coherence at expected frequencies between these records (supporting information Figure S6), indicating that their impacts are limited or masked by other atmospheric and oceanic forcing. On the other hand, significant coherence at multidecadal to centennial frequencies (i.e., 26 to 208 years per cycle, Figure 4b1) is observed between our interannual reconstructions and solar irradiance, another possible driver of hemispheric SST variability. Winter SST and solar irradiance additionally show significant coherence and an out of phase relationship at higher frequencies (i.e., 2 to 3 years per cycle, Figure 4b1), likely explained by the ocean’s higher heat capacity and processes such as ocean mixing, delaying oceanic response to atmospheric forcing (e.g., Goodkin et al., 2008; Long et al., 2014).

Figure 5. (a) Band-pass-filtered (2 to 3 years per cycle) winter SST (purple) and ENSO (black) time series. (b) Fifty-year running correlation reveals significant relationship between 1860 and 1950. Horizontal red line represents 95% significance level. (c) Fifty-year running variance of winter SST (purple) and ENSO (black) records reveal changes in decadal behavior.
3.2. δ18O Calibration

3.2.1. Monthly Calibration

Monthly coral carbonate δ18O (δ18Oc) is positively correlated with SSS (r = 0.64, p = 0, n = 348) and negatively correlated with SST (r = −0.81, p < 0.0001, n = 377). The paired δ18Oc and Sr/Ca records are also strongly correlated (r = 0.83, p < 0.0001, n = 377) as both proxies are dependent on SST. The SST dependence of monthly δ18Oc in Houbihu is −0.22‰ °C−1 (−0.19‰ °C−1, OLS regression method), within the range of published Porites δ18Oc-SST sensitivity (i.e., −0.15‰ °C−1 to −0.22‰ °C−1, Corrège, 2006; Gagan et al., 2000; Lough, 2004). The strong δ18Oc relationship to instrumental and Sr/Ca-derived SST records may indicate that seasonal δ18Oc in Houbihu is primarily influenced by SST variations. However, due to the strong correlation between monthly instrumental SST and SSS records (r = −0.75, p < 0.0001, n = 348), the interannual δ18Oc signal may be attenuated as SST and SSS impact δ18Oc in opposite directions at this site. Therefore, we further evaluate the δ18O sensitivity at interannual timescales.

3.2.2. Interannual and 3-year binned timescales, dry season δ18Oc Calibration

At interannual and 3-year binned timescales, dry season δ18Oc is significantly correlated to its Sr/Ca pair and SST over the calibration period (supporting information Text S2). This suggests that the δ18Oc of the seawater (δ18Osw) may be isolated by removing the significant δ18OSS component from the total δ18Oc values. While the resultant δ18Osw is significantly correlated with SSS (supporting information Text S2), the reconstructed δ18Osw-SSS exhibits larger variability than that of the instrumental SSS (supporting information Figure S7), indicating that the reconstruction error is less constrained and may generate unrealistic SSS estimates further back in time. Because SSS dominates the dry season δ18Oc record (i.e., 53%) rather than SST (supporting information Text S2), directly regressing δ18Oc during the dry season to SSS presents to be a more reasonable approach. Doing so yields

\[
\delta^{18}Oc_{\text{yr dry}} = -40.034 \pm 6.847 + 1.027 \pm 0.196 \times \text{SSS}_{\text{dry}} \text{ psu.}
\]

where the RMSR is equivalent to 15% of the mean dry SSS range (i.e., 0.40 psu) (Figure 6). Regressing δ18Oc to SODA SSS reduced the reconstruction error by 50% (supporting information Text S2 and Figure S6), generating reliable SSS estimates. Influence of local rainfall during the dry season on the δ18Oc-SSS variability is limited or absent (r = 0.25, p > 0.05, n = 10), indicating that regional-scale oceanographic processes impact surface salinity variability during this season.

Interannual and 3-year binned wet season δ18Oc, on the other hand, exhibit poor correlation with its Sr/Ca pair and IGOSS SST (r < 0.15, n = 31, r3yr bins < 0.3, n = 10; p > 0.10), suggesting that the δ18OSS component is not significant and that quantifying δ18Osw is ineffective. Directly regressing wet season δ18Oc against SSS similarly resulted in ineffective calibrations (r = 0.02, n = 31, r3yr bins = 0.07, n = 10; p > 0.10), indicating that other climatic processes govern δ18Oc variability during this season. We found that wet season δ18Oc is significantly correlated with local rainfall variability at interannual (r = −0.46, p = 0.009, n = 31) and 3-year binned timescales (equation 5):

\[
\delta^{18}Oc_{\text{yr wet}} = -4.194 \pm 0.355 - 0.003 \pm 8.841^{-4} \times \text{rainfall}_{\text{yr wet}} \text{ mm year}^{-1}.
\]

where RMSR is equivalent to 32% of the wet season rainfall range (i.e., 157.3 mm year−1). This indicates that local rainfall considerably impacts δ18Oc variability as expected during this season.

While we have effectively examined the dominant driving factors in the observed δ18Oc, constrained potential errors in deriving δ18Osw, and increased the signal-to-noise ratio by consistently using a 3-year binned calibration at each season, discrepancies in the absolute values between the instrumental and reconstructed data can still be found. Nevertheless, the overall interannual means and trends among records are similar, giving indication that relative variability should be captured consistently across time.

3.2.3. Dry Season SSS Reconstruction

The extended dry season δ18Oc-SSS record (equation 4) exhibits interannual to multidecadal scale variability stippled with several rapid salinity shifts over a 2-century period (Figure 7a and supporting information Data...
Set S1). From 1826 to 1835, salinity rapidly rose by 0.67 psu, reaching a record maximum of 35.15 psu. Following this period, salinity steeply decreased to 34.48 psu in 1844. Prior to the sharp increase in the early 1860s, salinity reached one of its minimum values in 1856 at 34.36 psu. These abrupt salinity shifts in a period showing higher salinity values (i.e., maximum of ~0.52 psu relative to the mean) and variance relative to the present (Figure 7a), coincide with the end of the LIA. Salinity gradually decreased to one of its lowest values of 34.36 psu in 1940, indicating a freshening trend around the turn of the twentieth century (i.e., 0.005 psu year$^{-1}$ or 0.42 psu over approximately eight decades (1862 to 1940); $r = -0.81$, $p < 0.0001$). After which, salinity began to rapidly shift by ~0.51 psu to more saline values in 1964. From this period toward 2012, a steeper freshening trend relative to the previous period is observed (i.e., 0.012 psu year$^{-1}$ or 0.06 psu) over the past approximately five decades (1964 to 2012; $r = -0.87$, $p < 0.0001$). The above salinity variability is in good agreement with that of SODA SSS record especially during the twentieth century ($r_{1900-2012} = 0.45$, $p = 0.005$, $n = 37$) when the instrumental record is notably more reliable (Giese & Ray, 2011).

### 3.2.4. Wet Season Rainfall Reconstruction

The reconstructed wet season $\delta^{18}O_{\text{c}}$-rainfall record (equation 5, Figure 8a, and supporting information Data Set S1) exhibits no significant long-term trend ($p > 0.70$) over the first ~100 years until 1900. Spanning the following century, rainfall shows greater decadal variability relative to the previous period, consistent with the observed decadal change in its variance (Figure 8a). Rainfall gradually increased after the turn of the twentieth century (i.e., 2.35 mm year$^{-1}$; $r = 0.71$, $p = 0.0003$), reaching a record maximum of 491.37 mm in 1943. Following this period, rainfall rapidly decreased to a record minimum of 225.09 mm in 1958, about 54% reduction of rainfall in 1.5 decades. Rainfall subsequently increased from 1958 until the end of the

---

**Figure 6.** Houbihu dry (a, brown hollow circles) and wet (b, green hollow circles) season $\delta^{18}O_{\text{c}}$ are significantly correlated with SSS and rainfall variability, respectively (left panels). Reconstructed SSS (brown line) and rainfall (green line) show good agreement with instrumental SSS and rainfall data (gray lines), respectively (right panels). Shading represents RMSR = 0.06 psu (brown) and 49.6 mm year$^{-1}$ (green).
record ($r = 0.74$, $p < 0.0001$), indicating greater freshwater input over the recent decades. Compared with both local rainfall data and wet season instrumental SSS, our rainfall estimates during this season is significantly correlated ($r_{local\_rainfall} = 0.46$, $p = 0.003$, $n = 39$, Figure 8a; $r_{SODA\_SSS(1900-2012)} = 0.52$, $p = 0.001$, $n = 37$, Figure 8b) with all records showing similar decadal trends as previously described. This suggests that local hydrological changes drive long-term surface salinity variability through rainfall amount and/or runoff during the peak rainfall season.

4. Discussion

4.1. Proxy Calibrations in Nanwan Bay

Coral Sr/Ca and $\delta^{18}O$ sensitivity to SST and SSS varies within and across different genera (e.g., Corrège et al., 2004; Dassié & Linsley, 2015; Ramos et al., 2017), as well as colonies within and across different sites.
Compared with previous Porites-based Sr/Ca-SST and δ¹⁸O-SST sensitivities in Nanwan Bay (i.e., −0.051 and −0.053 mmol·mol⁻¹·°C⁻¹, Shen et al., 1996; Shen, Lee, et al., 2005; and −0.14‰ °C⁻¹, Chiang et al., 2010), our monthly calibration slopes (i.e., −0.067 mmol·mol⁻¹·°C⁻¹ and −0.22‰ °C⁻¹) are steeper regardless of the regression method used (i.e., OLS regression results in an SST dependence of −0.064 mmol·mol⁻¹·°C⁻¹ and −0.19‰ °C⁻¹). This difference in calibration slopes may be explained by vital effects (e.g., Sayani et al., 2019; Suzuki et al., 2005), although we do not have enough information to account for its impact. Earlier Sr/Ca-SST and δ¹⁸O-SST calibrations were generated from corals collected at the mouth of the water intake pond of a nuclear power plant facility along the coast of Kenting. The collection depth is shallower, 2 and 4 m, compared to our offshore site, which is about 2000 m away from the coast. Presumably, warmer SSTs inside the shallower water intake pond relative to the well-mixed offshore reef waters at our sampling site resulted in a dampened Sr/Ca-SST slope (e.g., Murty et al., 2018). Previous studies also employed a coarser subsampling resolution (i.e., 10 to 15 samples per year), approximately lower by half compared to our sampling yield of 20 to 28 samples per year. The lower sampling resolution may have resulted in attenuated seasonal amplitude impacting the sensitivity and relationship of the slopes and intercepts to SST (e.g., Sadler et al., 2014). A more recent Porites δ¹⁸O-SST dependence of −0.18‰ °C⁻¹ (i.e., OLS method, X. Li et al., 2017) is reported from an offshore site southeast of Nanwan Bay employing a finer sampling resolution at ~22 samples per year. The

Figure 8. (a) Three-year binned wet season rainfall reconstruction (thin line) and 30-year (10-point) moving average (thick line) compared with local rainfall data (gray line). Shading indicated RMSR = 49.6 mm year⁻¹. Dotted black line indicates 30-year running variance. (b) Three-year binned (thin line) and 30-year moving average (thick line) SODA SSS data for the wet season exhibit similar decadal pattern as rainfall. Note that the y axis is inverted to facilitate comparison of overall trends. (c) Three-year binned (thin line) and 30-year moving average (thick line) winter PDO index.
environmental setting and sampling resolution are similar to our study, notably yielding a comparable SST sensitivity of $-0.19\% \degree C^{-1}$ (i.e., OLS regression method). The offshore setting of our site and finer sampling resolution employed in this study highlight the suitability of our calibrations in reconstructing large-scale climate variability in the region.

### 4.2. Hemispherical Controls on Observed Houbihu SST Variability

Possible influences contributing to SST variability include solar, volcanic, and anthropogenic forcing. The Houbihu mean annual and winter SST record broadly reflects trends from a tree-ring-based northern hemisphere surface temperature reconstruction (D’Arrigo, Wilson, & Jacoby, 2006) (Figure 3b) and from a coral-based western Pacific SST reconstruction (Tierney et al., 2015) (Figure 3c). This suggests that subtropical western Pacific climate is largely controlled by hemispherical or global forcing factors such as solar (Lean, 2000) and volcanic radiative forcings (Crowley, 2000) (Figures 3d and 3e). The 11-year smoothed annual and winter SST is significantly correlated with solar irradiance ($r_{\text{annual}} = 0.49$, $r_{\text{winter}} = 0.61$, $p < 0.0001$, $n = 203$), which shows significant power at $-11$ year per cycle (Figure 4c1). Furthermore, significant coherence and in-phase relationship at multidecadal to centennial frequencies between winter SST and solar irradiance (Figure 4c2) are similarly captured by the above regional-scale surface temperature reconstructions from both land and ocean, signifying the role of solar forcing.

The Dalton Minimum, a period of lower solar flux at the beginning of the nineteenth century, coincides with a period of high volcanic activity (Figures 3d and 3e), which is known to induce atmospheric cooling for up to $-4$ years after an eruption (e.g., $-1.5 \degree C$ cooling after Mount Pinatubo eruption, Robock & Mao, 1995; Wigley, 2005). Therefore, solar and volcanic forcings both played a significant role in the LIA cooling (Bradley & Jones, 1993; Crowley, 2000), reflected in the hemispheric-scale records and in our annual and winter SST (Houbihu SST hereafter) reconstructions (Figure 3a). Following the Dalton Minimum, the increase in solar flux likely contributed to an increase in Houbihu SST in the mid-1840s (Figures 3a and 3d), evident in other local and regional surface temperature records (e.g., Shi et al., 2014; Figure 3b). Between 1850 and 1900, the gradual decrease in solar flux and increased volcanic activity (Figures 3d and 3e) do not explain the observed fluctuation in Houbihu SST (Figure 3a). During this time, the Houbihu SST record disagrees with other surface temperature records, indicating that the SST variation during this period may be more locally influenced. At the turn of the twentieth century, the effect of the gradual increase in solar flux (Figure 4d) is likely masked by the relatively high volcanic activity during this period. The expected SST rise at our site is not evident (Figure 3a), whereas some regions in Asia experienced declining temperature (e.g., Shi et al., 2014, Figure 3b). Between 1950 and 2000, solar irradiance plateaued but recorded its highest values over the last two centuries (Figure 3d). During this period, the winter SST at our site shows an overall increasing trend (Figure 3a) likely tied to anthropogenic warming. A record of well-mixed greenhouse gas radiative forcing (Schmidt et al., 2012, Figure 3f) show that its magnitude increased twice as much in the recent 50 years relative to its initial rise in $-1840$. However, this overall warming trend is punctuated with periods of lower SSTs, potentially forced by high volcanic activity occurring during or before these pronounced SST dips (Figures 3a and 3e).

### 4.3. Drivers of Dry Season SSS Variability

Stronger than normal EAWM generally leads to active convection over the tropical western Pacific, the Maritime Continent and the South China Sea (SCS) region and reduced rainfall in Eastern China (D’Arrigo et al., 2005; L. Wang & Chen, 2014), potentially influencing salinity variability in Houbihu and the surrounding region during the dry season. We found that the dry season SSS record in Houbihu is significantly correlated with the EAWM ($r = -0.33$, $p = 0.02$, $n = 48$, Figure 7c) but opposite of the known relationship such that stronger (positive) EAWM corresponds to low salinity or wetter/fresher conditions and vice versa. Because the dry season SSS record also does not exhibit a significant relationship with local rainfall during this season (i.e., $p > 0.40$), the influence of the EAWM may lie in the advection of surface waters across the Luzon Strait, where the western Pacific and SCS waters effectively interact, impacting salinity variability in Houbihu.

The PDO may also impact surface salinity at our site by modulating precipitation and or/water advection (Delcroix et al., 2007). The dry season SSS record is significantly correlated with the winter PDO index ($r = -0.49$, $p = 0.002$, $n = 38$, Figure 7d), where warm (cold) PDO phases correspond to low (high) SSS.
estimates. This correlation is opposite of the known surface salinity-PDO relationship brought about by PDO’s link with ENSO and rainfall (e.g., Delcroix et al., 2007), suggesting that similar to the EAWM, the PDO may impact Houbihu salinity through water advection.

The water exchange across the Luzon Strait is dominated by the Kuroshio Intrusion delivering warmer and more saline western Pacific waters into the SCS (Nan et al., 2015). Both the PDO and the EAWM are known to enhance intrusion across the Luzon Strait and into the SCS. Warm (positive) PDO phases are associated with slower Kuroshio transport and increased intrusion across the strait (C.-R. Wu, 2013), advecting Pacific waters across this region. A stronger winter monsoon, on the other hand, is related to maximum intrusions across the strait (Hsin et al., 2012), where the northeast winds drive Ekman transport westward and into the SCS. If surface salinity in Houbihu is a signal of water mass advection, SSS variability of the surrounding waters (i.e., the western Pacific and SCS) in response to the PDO- and EAWM-related drivers should be reflected at this site. To further investigate, we compared our Houbihu dry season SSS reconstruction with a coral-derived SSS record in Palau (Figure 7a), located at the southern end of the Luzon Strait (Ramos et al., 2017, 2019) and to an instrumental SSS record (Figure 7a) extracted at a grid point in the northern SCS (i.e., 17.8°N, 115.8°E). Between 1880 and the mid-1940s, Palau and Houbihu SSS show similar values (i.e., within error, Figures 7a and 7b) compared to the lower salinity values in the northern SCS (Figure 7a). However, all sites exhibit a significant freshening trend during this period (i.e., 0.25, 0.34, and 0.15 psu over approximately seven decades for Houbihu, Palau and northern SCS, respectively; \( r > 0.40, p < 0.05 \)) likely due to a stronger EAWM, lowering salinity in the western Pacific and the SCS regions through intensified atmospheric convection. This time period coincides with an overall warm PDO phase, which increases the Kuroshio Intrusion (e.g., C.-R. Wu, 2013) facilitating mixing across the Luzon Strait. Around the early 1950s to 1960s, the observed small salinity difference between the northern SCS and Houbihu is likely due to the weakening of the EAWM (Figure 7a), reducing rainfall in the SCS region (e.g., L. Wang & Chen, 2014). Palau, on the other hand, exhibits higher sensitivity to ENSO-related salinity changes when La Niña conditions predominate during this period (Ramos et al., 2017, 2019, Figure 7a). Weaker EAWM and La Niña conditions, during a predominantly cold PDO phase, are unfavorable for intrusion and advection of Pacific waters into the strait (e.g., Hsin et al., 2012; Qu et al., 2004; C.-R. Wu, 2013). Hence, without the input of “new” Pacific waters, mixing between the northern SCS and Houbihu is a more viable explanation for the similarity in SSS between these sites (Figure 7a). Around the mid-1970s, the salinity difference between Houbihu and Palau decreased to similar values (i.e., within error, Figure 7b) compared with the northern SCS surface salinity. This period coincides with stronger EAWM conditions and the predominance of warm PDO phases, indicating that these processes drive surface salinity of the surrounding waters and the advection and mixing of these waters across the Luzon Strait, respectively.

Spectral analysis further provides evidence on the PDO’s role in modifying salinity variability across the Luzon Strait at multidecadal timescales. Spectral coherence between reconstructed SSS records across the Luzon Strait (i.e., Houbihu minus Palau) and winter PDO, which has spectral power at ~55 years per cycle, reveals significant correlation at frequencies >0.026 cycles per year (>38 years per cycle) (Figures 9a and 9b). Both records were filtered using a central frequency of 0.018 ± 0.0045 cycles per year to isolate ~55 cycles per year variability. The low-pass filtered records show a strong negative relationship (\( r = -0.91, \ p < 0.0001, n = 38 \), Figure 9b) despite the PDO leading by 3 years. Accounting for this lead results in a stronger negative relationship (\( r = -0.99, \ p < 0.0001, n = 37 \)), indicating a significant PDO-related impact on the Luzon Strait surface salinity variability at multidecadal timescales.

### 4.4. Drivers of Wet Season Rainfall Variability

Reconstructed wet season rainfall in Houbihu exhibit multidecadal scale variability particularly in the twentieth century. Our coral-derived rainfall record is significantly correlated with the winter PDO leading by 3 to 9 years (\( r_{3-yr \_lead} = 0.45, r_{6-yr \_lead} = 0.46, r_{9-yr \_lead} = 0.64, \ p < 0.01 \)). A significant lead-lag relationship is also observed between instrumental SSS and winter PDO (\( r_{3-yr \_lead} = 0.59, r_{6-yr \_lead} = 0.38, r_{9-yr \_lead} = 0.39, \ p < 0.03 \)). The warm (positive) phases of the PDO may cause higher rainfall anomalies and/or runoff, delivering less saline water to Houbihu. The opposite relationship occurs during cold PDO phases.

Previous meteorological studies show strong PDO-driven decadal imprint on rainfall variability in Taiwan (e.g., J.-M. Chen & Chen, 2011; Huang et al., 2017; Hung et al., 2004; Kao et al., 2018; Kuo et al., 2016) and south and east China (e.g., Chan & Zhou, 2005; X. Wu & Mao, 2017; Yu et al., 2014), as well as coral
\(\delta^{18}O\)-based rainfall and/or summer monsoon reconstructions from northern SCS and east China (e.g., Deng et al., 2013; Watanabe et al., 2014). Increased rainfall during warm PDO phases is attributed to large-scale SST anomalies that induce formation of anomalous low-level anticyclonic circulation southeast of Taiwan, enhancing moisture transport from the SCS to higher latitudes including Taiwan and southeastern China (J.-M. Chen & Chen, 2011; Hung et al., 2004; Kao et al., 2018). However, the exact mechanism relating regional hydrologic changes to PDO remains complex as PDO variably interacts with ENSO (Chan & Zhou, 2005; Kao et al., 2018), the East Asian Summer Monsoon (EASM, J.-M. Chen & Chen, 2011; B. Wang et al., 2017), and tropical cyclones (J.-M. Chen & Chen, 2011) prevalent during the summer/wet season. While we found no direct evidence of the PDO modulating ENSO- or the EASM-related (i.e., index from J.-P. Li & Zeng, 2005) influence on our wet season rainfall reconstruction in Houbihu (i.e., \(r_{PDO-ENSO} = 0.35\); \(p = 0.04\); \(r_{PDO-EASM} = 0.17\); \(p > 0.05\); \(r_{ENSO-rainfall} = 0.29\); \(r_{EASM-rainfall} = 0.11\); \(p > 0.05\)), it is evident that decadal pattern is greater during the twentieth century compared to the previous century, indicating that predominance of driving forces and mechanisms have been variable in the past and may be expected in the future. Higher-resolution rainfall records over greater spatiotemporal coverage are needed to further understand how these changes are initiated and sustained at certain time periods.

4.5. Climatic Conditions in the Northern Edge of the WPWP During the LIA Relative to the Present

Houbihu mean annual and winter SST, dry season SSS, and wet season rainfall reconstructions since the late eighteenth century reveal relatively cooler and drier (i.e., higher salinity and low rainfall) conditions at the end of the LIA compared to the recent century. Houbihu winter (annual) SST exhibits a range of \(0.6 \pm 0.2\) and \(0.45 \pm 0.15 \) °C SST cooling at the end of the LIA (1850 CE, sensu stricto) relative to the twentieth century and the most recent ~30 years, respectively (Table 1). This estimate is within the various LIA cooling
Our records begin in 1788, used as the starting year to calculate mean LIA conditions relative to the twentieth century mean SST, SSS, and rainfall. The summary of conditions at the end of the LIA (1850 CE) relative to the twentieth century mean is given in Table 1.

| End of the LIA conditions relative to the twentieth century mean | Twentieth century mean |
|---------------------------------------------------------------|------------------------|
| SSTannual 0.3 °C cooler                                       | 26.8 °C                |
| SSSdry 0.22 psu more saline                                   | 34.5 psu               |
| Rainfallwet 50 mm less rainfall                               | 395 mm                 |

*Our records begin in 1788, used as the starting year to calculate mean LIA conditions.

The observed reduced winter SST variance at biennial frequencies concurrent with weak correlation between ENSO and our SST record in Houbihu at the end of the LIA (Figure 5) may provide evidence of a restricted warm pool during this period. Dry season surface salinity in Houbihu is higher by 0.22 and 0.32 psu at the end of the LIA (1788 to 1850 CE) relative to the twentieth century and the most recent ~30 years, respectively, suggesting drier conditions at the end of the LIA (Table 1). Our wet season rainfall shows a consistent trend where average annual rainfall lower by ~50 and 60 mm year$^{-1}$ at the end of the LIA relative to the twentieth century and the most recent ~30 years, respectively (Table 1). The start of our records, 1788, to 1850, is past the peak period of the LIA (i.e., 1700 CE) when most marine-based records in the northern SCS and the western Pacific exhibit fresher surface waters and/or wetter conditions relative to the late twentieth century (e.g., 1 to 1.5 psu, Deng et al., 2017; Newton et al., 2006; Oppo et al., 2009). Wetter climate during the LIA is attributed to the strengthening of the Walker Circulation (e.g., H. Yan et al., 2011) and weakening of the EASM (e.g., Deng et al., 2017; Zeng et al., 2012) affecting the hydrological climate over the northern SCS. Additionally, the southward migration of the Intertropical Convergence Zone (e.g., Newton et al., 2006; Oppo et al., 2009; Sachs et al., 2009) and/or contraction of the East Asia-Australia monsoon region due to reduced solar irradiance (e.g., Griffiths et al., 2016; H. Yan, Wei, et al., 2015) resulted in increased precipitation, and hence lower surface salinity in the tropical Western Pacific during the peak LIA period. In contrast, land-derived (i.e., lake sediments, speleothems) proxy reconstructions in middle- to high-latitude China reveal drought conditions during the LIA due to the weakening of the EASM and/or strengthening of the EAWM significantly reducing precipitation in the region (e.g., Liu et al., 2011; Qiao et al., 2011; Tan et al., 2010; H. Yan, Wei, et al., 2015). Relative to the late twentieth to early 21st century, we infer the higher surface salinity and drier conditions in Houbihu to represent a transitional period when the subtropical western Pacific hydrological climate began to recover from wetter conditions during the peak LIA period. Marine-based records from this region (e.g., Newton et al., 2006; Oppo et al., 2009) exhibit a shift toward a more saline surface or drier condition from ~1700 toward the end of the LIA (i.e., 1850) relative to the late twentieth century record (e.g., Deng et al., 2017), likely implying a change to a weaker EAWM, a weaker Pacific Walker Circulation and/or a weaker EASM condition relative to the peak LIA period, all of which are consistent with the earlier proposed restricted WPWP during the end of the LIA. Considering the modern impact of the EAWM on our Houbihu dry season SSS and the surrounding seas, higher surface salinities possibly from the northern SCS are consistent with a weaker EAWM scenario at the end of the LIA. However, marine-based records extending beyond the LIA are rare to absent along the path of the Kuroshio Current and intrusion; therefore, more records are needed to verify the impact of the EAWM during this period. Similarly, due to the scarcity of marine-based records of the PDO extending beyond the LIA, the PDO’s behavior during this period remains uncertain. Using the strong relationship between the modern PDO record and the salinity difference across the Luzon Strait, it may be inferred that a cold PDO regime predominated at the end of the LIA, leading to less intrusions during this period and hence, enhanced mixing between northern SCS and Houbihu surface waters. An independent reconstruction of the Kuroshio Current from a sediment record downstream of the Kuroshio path corroborates this assumption (i.e., Zhang et al., 2019), where the enhanced Kuroshio Current during the LIA interval is likely to reduce intrusion across the Luzon Strait.

Considering the modern impact of the EASM on Taiwan rainfall (S.-Y. Wang & Chen, 2008), the reconstructed below normal rainfall conditions during the end of the LIA is also consistent with a weaker...
EASM scenario during this period. While we did not find a strong relationship between an index of the EASM and our wet season rainfall reconstruction possibly due to the length of overlapping records, the likely dominance of the PDO in the last century may have modulated rainfall variability in this region (Figure 8). Using the modern PDO-rainfall relationship we established in Houbihu, the earlier proposed cold PDO regime during the end of the LIA, corroborates the below average rainfall setting during this period.

In the late 20th to early 21st century, climate reconstructions in Houbihu reveal significant warming and freshening trends, similarly observed in the tropical western Pacific region, though relative magnitudes are expected to vary. Overlapping the onset of the subtropical warming trend in Houbihu (i.e., 0.16 °C per decade since 1950), coral-derived western Pacific SST reconstructions (i.e., Tierney et al., 2015) and a 1° square resolution instrumental winter SST near our site (i.e., Rayner et al., 2003) show an SST rise of 0.032 and 0.22 °C per decade, respectively. Our estimate is comparable to that of the instrumental SST data (i.e., Rayner et al., 2003) near our site in contrast to the ensemble of reconstructions over the western Pacific (i.e., Tierney et al., 2015) due to the latter’s greater spatial coverage and the concentration of proxy reconstructions in the tropical region compared to the subtropics. Differences in magnitude aside, the onset of the SST rise in our site is consistent with the onset of regional warming (i.e., Tierney et al., 2015, and references therein), likely tied to anthropogenic forcing. The freshening trend in Houbihu in terms of surface salinity (i.e., 0.06 psu per decade), on the other hand, which commenced around the mid-1960s, is within the range of the observed freshening trend in the tropical western Pacific over the same time period (e.g., 0.06 psu per decade, Cravatte et al., 2009; 0.03 to 1 psu per decade, Delcroix et al., 2007). Lower surface salinity toward the present, supported with above average annual rainfall conditions, is related to the strengthened hydrological patterns since the start of the twentieth century (Cobb et al., 2003; Nurhati et al., 2009) with strong links to the concurrent warming trend during this century (Cravatte et al., 2009; Nurhati et al., 2009).

### 5. Conclusions

Robust annual and winter Sr/Ca-SST, dry season δ18Oc-SSS and wet season δ18Oc-rainfall calibrations in Houbihu allow for reconstructing subtropical climate variability over the past two centuries. Multidecadal SST trends broadly agree with various surface temperature reconstructions in the region, indicating the dominant control of solar and volcanic radiative forcing factors in the subtropical western Pacific climate variability. These global forcings potentially obscure the influence of the PDO and the EAWM on the winter SST record at interannual to decadal timescales. In contrast, biennial-scale changes evident in the winter SST record are likely driven by ENSO. Dry season SSS reconstruction reflects an advection signal linked to the EAWM and PDO variations. Warm PDO phases combined with stronger EAWM conditions enhance advection of Pacific waters and mixing across the Luzon Strait. Comparing our salinity record with another site across the Luzon Strait (i.e., Palau) provides evidence of the PDO-related changes in salinity associated with the strength of the Kuroshio Intrusion. Wet season rainfall reconstruction exhibits strong decadal variability, especially during the last century, driven by the PDO.

Reconstructed climate records in Houbihu also document <1 °C cooler and <0.5 psu/<100 mm drier conditions, respectively, at the end of the LIA (1850 CE) relative to the late 1900s. These estimates are consistent with other multiproxy records in the region, pointing to changes in the size of the warm pool and strength of the monsoons as probable mechanisms. The role of the PDO in modulating advection and precipitation at different seasons is additionally revealed in this study. In the late 20th to early 21st century, significant warming of ~1 °C per decade and freshening of ~0.06 psu per decade are observed in Houbihu. These trends are in line with other regional records highlighting the impact of anthropogenic forcing in recent climate change.

### References

Abram, N. J., McGregor, H. V., Gagan, M. K., Hanctoro, W. S., & Suwargadi, B. W. (2009). Oscillations in the southern extent of the Indo-Pacific Warm Pool during the mid-Holocene. *Quaternary Science Reviews*, 28, 2794–2803.

Alibert, C. A., & McCulloch, M. (1997). Strontium/calcium ratios in modern Porites corals from the Great Barrier Reef as a proxy for sea surface temperature: Calibration of the thermometer and monitoring of ENSO. *Paleoceanography*, 12(3), 345–363.

Allison, N., & Finch, A. A. (2009). Reproducibility of minor and trace element determinations in Porites coral skeletons by secondary ion mass spectrometry. *Geochemistry, Geophysics, Geosystems*, 10, n/a. https://doi.org/10.1029/2008GC002239
Alpert, A. E., Cohen, A. L., Oppo, D. W., DeCarlo, T. M., Gove, J. M., & Young, C. W. (2016). Comparison of equatorial Pacific sea surface temperature variability and trends with Sr/Ca records from multiple corals. Paleoceanography and Geology, 31, 252–262.

Bradley, R. S., & Jones, P. D. (1993). "Little Ice Age" summer temperature variations: Their nature and relevance to recent global warming trends. The Holocene, 3(4), 367–376.

Calvo, E., Marshall, J. F., Pelejero, C., McEwan, M. T., Gagan, M. K., & Lough, J. M. (2007). Interdecadal climate variability in the Coral Sea since 1708 A.D. Paleoceanography, Paleoecology and Palaeoanthropology, 2481–2–, 190–201.

Carton, J. A., & Giese, B. S. (2008). A reanalysis of ocean climate using Simple Ocean Data Assimilation (SODA). Monthly Weather Review, 136(8), 2999–3017.

Chan, J. C. L., & Zhou, W. (2005). PDO, ENSO and the early summer monsoon rainfall over south China. Geophysical Research Letters, 32, L08810. https://doi.org/10.1029/2004GL020215

Chen, J.-M., & Chen, H.-S. (2011). Interdecadal variability of summer rainfall in Taiwan associated with tropical cyclones and monsoon. Journal of Climate, 24(22), 5786–5798.

Chen, T., Cobb, K. M., Roff, G., Zhao, J., Yang, H., Hu, M., & Zhao, K. (2018). Coral-derived Western Pacific Tropical Sea surface temperatures during the last millennium. Geophysical Research Letters, 45, 3542–3549.

Chiang, H. W., Chen, Y. G., Fan, T. Y., & Shen, C. C. (2010). Change of the ENSO-related $\delta^{18}O$–SST correlation from coral skeletons in northern South China Sea: A possible influence from the Kuroshio Current. Journal of Asian Earth Sciences, 39(6), 684–691.

Clarke, M. R. B. (1980). The reduced major axis of a bivariate sample. Biometrika, 67(2), 441–446.

Cobb, K. M., Charles, C. D., Cheng, H., & Edwards, R. L. (2003). El Nino/Southern Oscillation and tropical Pacific climate during the last millennium. Nature, 424(6946), 271–276. https://doi.org/10.1038/nature01779

Comboul, M., Emile-Geay, J., Evans, M. N., Mirnateghi, N., Cobb, K. M., & Thompson, D. M. (2014). A probabilistic model of chronological errors in layer-counted climate proxies: Applications to annually banded coral archives. Climate of the Past, 10, 825–841.

Corrège, T. (2006). Sea surface temperature and salinity reconstruction from coral geochemical tracers. Paleoceanography, Paleoecology, Palaeoanthropology, 232(2–4), 408–428.

Corrège, T., Gagan, M. K., Beck, J. W., Burr, G. S., Cabilio, G., & Corneel, F. L. (2004). Interdecadal variability in the extent of South Pacific tropical waters during the Younger Dryas event. Nature, 428(6986), 927–929. https://doi.org/10.1038/nature02506

Corrège, T., Quinn, T., Delcroix, T., Le Corne, F., Reey, J., Cabilio, G. (2001). Little Ice Age sea surface temperature variability in the southwest tropical Pacific. Geophysical Research Letters, 28, 3477–3480.

Cravatte, S., Delcroix, T., Zhang, D., McPhaden, M. J., & Leloup, J. (2009). Observed freshening and warming of the western Pacific Warm Pool. Climate Dynamics, 38(4), 565–589.

Crowley, T. J. (2000). Causes of climate change over the past 1000 years. Science, 289(5477), 270–277.

D’Arrigo, R., Wilson, R., & Jacoby, G. (2006). On the long-term context for late twentieth century warming. Journal of Geophysical Research, 111, D03103. https://doi.org/10.1029/2005JD006352

D’Arrigo, R., Wilson, R., Palmer, J., Keusig, P., Curtis, A., Sakulich, J., et al. (2006). The reconstructed Indonesian warm pool sea surface temperatures from tree rings and corals: Linkages to Asian monsoon drought and El Niño Southern Oscillation. Paleoceanography, 21, PA3005. https://doi.org/10.1029/2005PA001256

D’Arrigo, R., Wilson, R., Panagiotopoulos, F., & Wu, B. (2005). On the long-term interannual variability of the East Asian winter monsoon. Geophysical Research Letters, 32, L21706. https://doi.org/10.1029/2005GL023235

Dassal, E. P., & Linsley, B. K. (2015). Refining the sampling approach for the massive coral Diploria strigosa from $\delta^{18}O$-based paleoclimatic applications. Palaeogeography Palaeoecology Palaeoanthropology, 440, 274–282.

Delcroix, T., Alory, G., Cravatte, S., Corrège, T., & McPhaden, M. J. (2011). A gridded sea surface salinity data set for the tropical Pacific with sample applications (1950–2008). Deep Sea Research Part I: Oceanographic Research Papers, 58(1), 38–48.

Delcroix, T., Cravatte, S., & McPhaden, M. J. (2007). Decadal variations and trends in tropical Pacific sea surface salinity since 1970. Journal of Geophysical Research, 112, C00302. https://doi.org/10.1029/2006JC003801

DeLong, K. L., Quinn, T. M., Taylor, F. W., Lin, K., & Shen, C.-C. (2012). Sea surface temperature variability in the southwest tropical Pacific since AD 1649. Nature Climate Change, 2(11), 799–804.

DeLong, K. L., Quinn, T. M., Taylor, F. W., Shen, C.-C., & Lin, K. (2013). Improving coral-based paleoclimate reconstructions by replicating 350 years of coral Sr/Ca variations. Paleoceanography, Paleoecology, Palaeoanthropology, 37, 6–24.

Deng, W., Liu, X., Chen, X., Wei, G., Zeng, T., Xie, L., & Zhao, J.-x. (2017). A comparison of the climates of the medieval climate anomaly, Little Ice Age, and current warm period reconstructed using coral records from the northern South China Sea. Journal of Geophysical Research: Oceans, 122, 264–275.

Deng, W., Wei, G., Xie, L., Re, T., Wang, Z., Zeng, T., & Liu, Y. (2013). Variations in the Pacific Decadal Oscillation since 1853 in a coral record from the northern South China Sea. Journal of Geophysical Research: Oceans, 118, 2358–2366.

Dunbar, R. B., & Cole, J. E. (1999). Annual Records of Tropical Systems (ARTS). In, Clarke, M. R. B. (1980). The reduced major axis of a bivariate sample.

Emile-Geay, J., Cobb, K. M., Mann, M. E., & Wittenberg, A. T. (2013). Estimating central equatorial Pacific SST variability over the past millennium. Part II: Reconstructions and implications. Journal of Climate, 26(7), 2329–2352.

Emanuel, K. (2005). Increasing destructiveness of tropical cyclones over the past 30 years. Nature, 438(7051), 686–688. https://doi.org/10.1038/nature04196

Emile-Geay, J., Cobb, K. M., Mann, M. E., & Wittenberg, A. T. (2013). Estimating central equatorial Pacific SST variability over the past millennium. Part I: Introduction and methodology. Journal of Climate, 26(7), 2329–2352.

Goodkin, N. F., Hughen, K. A., & Cohen, A. L. (2007). A multivariate calibration method to approximate a universal equation relating Sr/Ca and growth rate to sea surface temperature. Paleoceanography, 22, PA1214. https://doi.org/10.1029/2006pa001312

Goodkin, N. F., Hughen, K. A., Cohen, A. L., & Smith, S. R. (2005). Record of the Little Ice Age sea surface temperatures at Bermuda using a growth-dependent calibration of coral Sr/Ca. Paleoceanography, 20, PA4016. https://doi.org/10.1029/2005pa001140

Goodkin, N. F., Hughen, K. A., Curry, W. B., Doney, S. C., & Ostermann, D. R. (2008). Sea surface temperature and salinity variability at Bermuda during the end of the Little Ice Age. Paleoceanography, 23, PA3203. https://doi.org/10.1029/2007pa001532

Griffiths, M. L., Kimbrough, A. K., Gagan, M. K., Drysdale, R. N., Cole, J. E., Johnson, K. R., et al. (2016). Western Pacific hydroclimate linked to global climate variability over the past two millennia. Nature Communications, 7(1), 11719. https://doi.org/10.1038/s84817-1119

Harper, W. V. (2016). Reduced major axis regression. In Wiley StatsRef: Statistics Reference Online (1–6).
Hatherly, E. C., Gagnon, A., Felix, T., Adkins, J., Assami, R., Boer, W., et al. (2013). Interlaboratory study for coral Sr/Ca and other element/Ca ratio measurements. Geochemistry, Geophysics, Geosystems, 14, 3739-3750. https://doi.org/10.1002/ggge.20230

Hendy, E. J., Gagan, M. K., Allibert, C. A., Mculloch, M., Lough, J. M., & Isdale, P. J. (2002). Abrupt decrease in tropical Pacific Sea surface salinity at end of Little Ice Age. Science, 295, 1511–1514.

Hsin, Y.-C., Wu, C.-R., & Chao, S.-Y. (2012). An updated examination of the Luzon Strait transport. Journal of Geophysical Research, Oceans, 117, C03002. https://doi.org/10.1029/2011jc007714

Huang, W.-R., Wang, S. Y. S., & Guan, B. T. (2017). Decadal fluctuations in the western Pacific recorded by long precipitation records in Taiwan. Climate Dynamics, 50(5-6), 1597–1608.

Huang, C. W., Hsu, H.-H., & Lu, M.-M. (2004). Decadal oscillation of spring rain in northern Taiwan. Geophysical Research Letters, 31, L22206. https://doi.org/10.1029/2004gl021344

Huybers, P., & Denton, G. (2008). Antarctic temperature at orbital timescales controlled by local summer duration. Nature Geoscience, 1(11), 787–792.

Kao, P.-K., Hung, C.-W., & Hong, C.-C. (2018). Increasing influence of central Pacific El Niño on the inter-decadal variation of spring rainfall in northern Taiwan and southern China since 1980. Atmospheric Science Letters, 19(12), e684. https://doi.org/10.1002/asl.864

Kilpatrick, K. A., Podestá, G. P., & Evans, R. (2001). Overview of the NOAA/NASA advanced very high resolution radiometer Pathfinder algorithm for sea surface temperature and associated matchup database. Journal of Geophysical Research, Oceans, 106(C5), 9179–9197.

Kuo, Y.-C., Lee, M.-A., & Liu, M.-M. (2016). Association of Taiwan's rainfall patterns with large-scale oceanic and atmospheric phenomena. Advances in Meteorology, 2016, 1–11.

Lagerloef, G., Colombera, F. R., Le Vine, D., Wentz, F., Yueh, S., Ruf, C., et al. (2008). The Aquarius/SAC-D Mission. Oceanography, 21(1), 68–81. https://doi.org/10.5670/oceanog.2008.68

Lean, J. (2000). Evolution of the Sun's spectral irradiance since the maunder minimum. Geophysical Research Letters, 27(16), 2425–2428.

Lee, H.-J., Chao, S.-Y., & Fan, K.-L. (1999). Flood-ebb disparity of tidally induced recirculation eddies in a semi-enclosed basin: Nan Wan Bay. Continental Shelf Research, 19, 871–890.

Lee, H.-J., Chao, S.-Y., Fan, K.-L., & Kuo, T.-Y. (1999). Tide-induced eddies and upwelling in a semi-enclosed basin: Nan Wan. Estuarine, Coastal and Shelf Science, 49, 775–787.

Lee, H.-J., Chao, S.-Y., Fan, K.-L., Wang, Y.-H., & Liang, N.-K. (1997). Tidally induced upwelling in a semi-enclosed basin: Nan Wan Bay. Journal of Oceanography, 53, 467–480.

Li, J.-P., & Zeng, Q.-C. (2005). A new monsoon index, its interannual variability and relation with monsoon precipitation. Climatic and Environmental Research, 10(3), 351–365.

Li, X., Liu, Y., Hsin, Y.-C., Liu, W., Shi, Z., Chiang, H. W., & Shen, C. C. (2017). Coral record of variability in the upstream Kuroshio current during 1953-2004. Journal of Geophysical Research: Oceans, 122, 6936–6946.

Liu, J., Chen, F., Chen, J., Xia, D., Xu, Q., Wang, Z., & Li, Y. (2011). Humid medieval warm period recorded by magnetic characteristics of sediments from Gonghai Lake, Shanxi, North China. Journal of Oceanography, 67, 314–326.

Mann, M. E., Bradley, R. S., & Hughes, M. K. (1999). Northern hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. Geophysical Research Letters, 26(6), 759–762.

Murty, S. A., Bernstein, W. N., Osolinski, J. E., Davis, R. S., Goodkin, N. F., & Hughen, K. A. (2018). Spatial and temporal robustness of Sr/Ca-SST calibrations in Red Sea corals: Evidence for influence of mean annual temperature on calibration slopes. Paleoclimatology and Paleoecology, 3(8), 443–456.

Nan, F., Xia, D., & Yu, F. (2015). Kuroshio intrusion into the South China Sea: A review. Progress in Oceanography, 137, 314–333.

Newton, A., Thunell, R., & Stott, L. (2006). Climate and hydrographic variability in the Indo-Pacific Warm Pool during the last millennium. Geophysical Research Letters, 33, L19710. https://doi.org/10.1029/2006gl027234

Nurhati, I. S., Cobb, K. M., Charles, C. D., & Dunbar, R. B. (2009). Late 20th century warming and freshening in the central tropical Pacific. Geophysical Research Letters, 36, L21060. https://doi.org/10.1029/2009gl040270

Okai, T., Suzuki, A., Kawaihata, H., Terashima, T., & Imai, N. (2001). Preparation of a new geological survey of Japan geochemical reference samples. Geostandards Newsletter, 21, 10-26.

Oppenheimer, C., Lea, D. W., & Stott, L. (2009). 2000-year-long temperature and hydrology reconstructions from the Indo-Pacific warm pool. Nature, 460(7259), 1113–1116. https://doi.org/10.1038/nature08233

Overpeck, J. T., Hughen, K., Hardy, D., Chao, S.-Y., Case, R., & Douglas, M. (1997). Arctic environmental change of the last four centuries. Science, 278(5341), 1251–1256. https://doi.org/10.1126/science.278.5341.1251

Paillard, D., Labeyrie, L., & Yiou, P. (1996). Macintosh program performs time-series analysis. Eos. Trans. AGU, 77(39), 379. https://doi.org/10.1029/96EO002359

Qiao, S., Yang, Z., Liu, J., Sun, X., Xiang, R., Shi, X., et al. (2011). Records of late-Holocene East Asian winter monsoon in the East China Sea: Key grain-size component of quartz versus bulk sediments. Quaternary International, 230(1–2), 106–114. https://doi.org/10.1016/j.quaint.2010.01.020

Qu, T., Kim, Y. Y., & Yaremchuk, M. (2004). Can Luzon Strait transport play a role in conveying the impact of ENSO to the South China Sea? Journal of Climate, 17, 3644–3657.

Ramos, R. D., Goodkin, N. F., Siringan, F. P., & Hughen, K. A. (2017). Diploastrea heliopora Sr/Ca and δ18O records from northeast Luzon, Philippines: An assessment of interspecies coral proxy calibrations and climate controls of sea surface temperature and salinity. Paleoclimatology, 32, 424–438.

Ramos, R. D., Goodkin, N. F., Siringan, F. P., & Hughen, K. A. (2019). Coral records of temperature and salinity in the Tropical Western Pacific reveal influence of the Pacific Decadal Oscillation since the late nineteenth century. Paleoclimatology and Paleoclimatology, 34(8), 1344–1358. https://doi.org/10.1029/2019pa003684

Rasmussen, E. M., & Carpenter, T. H. (1983). The relationship between eastern equatorial Pacific sea surface temperature and rainfall over India and Sri Lanka. Monthly Weather Rev, 111, 517–528.
Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., et al. (2003). Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. Journal of Geophysical Research, 108, 4407. https://doi.org/10.1029/2002JD002670

Reynolds, R. W., Rayner, N. A., Smith, T. M., Stokes, D. C., & Wang, W. (2002). An improved in situ and satellite SST analysis for climate. Journal of Climate, 15, 1699–1625.

Robock, A., & Mao, J. (1995). The volcanic signal in surface temperature observations. Journal of Climate, 8, 1086–1103.

Rosenthal, Y., Linsley, B. K., & Oppo, D. W. (2013). Model Development for the Last Millennium (v1.1). Geoscientific Model Development, 5(1), 185–191. https://doi.org/10.5194/gmd-5-185-2012

Schrag, D. P. (1999). Rapid analysis of high-precision Sr/Ca ratios in corals and other marine carbonates. Paleoceanography, 14(2), 97–102.

Shen, C.-C., Li, E., Chen, C.-Y., Wang, C.-H., Dai, C.-F., & Li, L.-A. (1996). The calibration of D[Sr/Ca] versus sea surface temperature relationship for Porites corals. Geochimica et Cosmochimica Acta, 60(20), 3849–3858.

Shen, C.-C., Li, E., Liu, K.-K., Hsu, H.-H., Edwards, R. L., Wang, C.-H., et al. (2005). An evaluation of qualitative reconstruction of past precipitation records using coral skeletal Sr/Ca and δ18O data. Earth and Planetary Science Letters, 237(3–4), 370–386. https://doi.org/10.1016/j.epsl.2005.06.042

Shen, C.-C., Liu, K.-K., Lee, M.-Y., Lee, T., Wang, C.-H., & Lee, H.-J. (2005). A novel method for tracing coastal water masses using Sr/Ca ratios and salinity in Nanwan Bay, southern Taiwan. Estuarine, Coastal and Shelf Science, 65(1–2), 135–142.

Shi, X., Wu, Y., and Zhao, M., et al. (2014). Multi-proxy reconstruction for Kuroshio responses to northern hemispheric oceanic climate and the Asian Monsoon since Marine Isotope Stage 5.1 (88 ka). Climate of the Past, 10(5), 1735–1750. https://doi.org/10.5194/cp-10-1735-2014

Stichler, W. (1995). Interlaboratory comparison of new materials for carbon and oxygen isotope ratio measurements. Paper presented at the Reference and intercomparison materials for stable isotopes of light elements, IEAA, Vienna.

Suzuki, A., Hibino, K., Iwase, A., & Kawahata, H. (2005). Inter colony variability of skeletal oxygen and carbon isotope signatures of cultured Porites corals: Temperature-controlled experiments. Geochimica et Cosmochimica Acta, 69(18), 4453–4462.

Tan, L., Cai, Y., An, Z., Edwards, R. L., Cheng, H., Shen, C.-C., & Zhang, H. (2010). Centennial- to decadal-scale monsoon precipitation variability in the semi-humid region, northern China during the last 1600 years: Records from stalagmites in Huangye Cave. The Holocene, 20(2), 287–296.

Tierney, J. E., Abram, N. J., Anchukaitis, K. J., Evans, M. N., Giry, C., Kilbourne, K. H., et al. (2015). Tropical sea surface temperatures for the past four centuries reconstructed from coral archives. Paleoceanography, 30, 226–252. https://doi.org/10.1002/2014PA002717

Wang, B., Li, J., & He, Q. (2017). Variable and robust East Asian monsoon rainfall response to El Niño over the past 60 years (1957–2016). Advances in Atmospheric Sciences, 34(10), 1235–1248.

Wang, L., & Chen, W. (2014). An intensity index for the east Asian winter monsoon. Journal of Climate, 27(6), 2361–2374.

Wang, S.-Y., & Chen, T.-C. (2008). Measuring east Asian summer monsoon rainfall contributions by different weather systems over Taiwan. Journal of Applied Meteorology and Climatology, 47(7), 2086–2080.

Watanabe, T., Kawamura, T., Yamasaki, A., Murayama, M., & Yamano, H. (2014). A 106 year monthly coral record reveals that the East Asian summer monsoon modulates winter PDO variability. Geophysical Research Letters, 41, 3609–3614.

Watanabe, T., Winter, A., & Oba, T. (2001). Seasonal changes in sea surface temperature and salinity during the Little Ice Age in the Carribbean Sea deduced from Mg/Ca and 18O/16O ratios in corals. Marine Geology, 173, 21–35.

Webster, P. J., & Lukas, R. (1992). TOGA COARE: The coupled ocean-atmosphere experiment. Bulletin of American Meteorological Society, 73(9), 1377–1416.

Wigley, T. M. L. (2005). Effect of climate sensitivity on the response to volcanic forcing. Journal of Geophysical Research, 110, D09107. https://doi.org/10.1029/2004JD005557

Wu, C.-R. (2013). Interaannual modulation of the Pacific Decadal Oscillation (PDO) on the low-latitude western North Pacific. Progress in Oceanography, 110, 49–58.

Wu, W., Tan, W., Zhou, L., Yang, H., & Xu, Y. (2012). Sea surface temperature variability in southern Okinawa Trough during last 2700 years. Geophysical Research Letters, 39, L14705. https://doi.org/10.1029/2012GL052749

Wu, X., & Mao, J. (2017). Intercdecadal variability of early summer monsoon rainfall over South China in association with the Pacific Decadal Oscillation. International Journal of Climatology, 37(2), 706–721.

Yan, H., Soon, W., & Wang, Y. (2015). A composite sea surface temperature record of the northern South China Sea for the past 2500 years: A unique look into seasonality and seasonal climate changes during warm and cold periods. Earth-Science Reviews, 141, 122–135.

Yan, H., Sun, L., Oppo, D. W., Wang, Y., Liu, X., Zou, J., et al. (2011). South China Sea hydrological changes and Pacific Walker Circulation variations over the last millennium. Nature Communications, 2(1), 293. https://doi.org/10.1038/ncomms1297

Yan, H., Wei, W., Soon, W., An, Z., Zhou, W., Liu, Z., et al. (2015). Dynamics of the intertropical convergence zone over the western Pacific during the Little Ice Age. Nature Geoscience, 8(4), 315–320. https://doi.org/10.1038/ngeo2375

Yan, X.-H., Ho, C.-R., Zheng, Q., & Klemas, V. (1992). Temperature and size variabilities of the western Pacific Warm Pool. Science, 258(5088), 1643–1645. https://doi.org/10.1126/science.258.5088.1643

Yu, L., Furevik, T., Otterå, O. H., & Gao, Y. (2014). Modulation of the Pacific Decadal Oscillation on the summer precipitation over East China: A comparison of observations to 600-years control run of Bergen Climate Model. Climate Dynamics, 44(1–2), 475–494.

Zeng, Y., Chen, J., Zhu, Z., Li, J., Wang, J., & Wan, G. (2012). The wet Little Ice Age recorded by sediments in Huguangyan Lake, tropical South China. Quaternary International, 263, 55–62.

Zhang, Y., Zhou, X., He, Y., Jiang, Y., Liu, Y., Xie, Z., et al. (2019). Persistent intensification of the Kuroshio Current during late Holocene cool intervals. Earth and Planetary Science Letters, 506, 15–22. https://doi.org/10.1016/j.epsl.2018.10.018