Paleoceanography and Paleoclimatology

RESEARCH ARTICLE
10.1029/2019PA003571

Key Points:
- Proxy coral-based SST records were generated from a mid-Holocene reef in the western tropical Atlantic (WTA)
- The coral thermometer Sr-U was validated on two modern corals and applied to reconstruct mid-Holocene SSTs
- WTA SSTs were cooler in the Mid-Holocene than in the early LIA and 20th century, suggesting no mid-Holocene Climatic Optimum in the region

Supporting Information:
- Supporting Information S1

Correspondence to:
A. L. Cohen and L. G. Rodriguez,
acohen@whoi.edu;
lrodriguez@whoi.edu

Citation:
Rodriguez, L. G., Cohen, A. L., Ramirez, W., Oppo, D. W., Pourmand, A., Edwards, R. L., et al. (2019). Mid-Holocene, coral-based sea surface temperatures in the western tropical Atlantic. *Paleoceanography and Paleoclimatology*, *34*, 1234–1245. https://doi.org/10.1029/2019PA003571

Received 24 JAN 2019
Accepted 20 MAY 2019
Accepted article online 31 MAY 2019
Published online 31 JUL 2019

Mid-Holocene, Coral-Based Sea Surface Temperatures in the Western Tropical Atlantic

Luis G. Rodriguez[1,2], Anne L. Cohen[1], Wilson Ramirez[2], Delia W. Oppo[1], Ali Pourmand[3], R. Lawrence Edwards[4], Alice E. Alpert[5], and Nathaniel Mollica[5]

[1]Woods Hole Oceanographic Institution, Woods Hole, MA, USA, [2]Department of Geology, University of Puerto Rico-Mayagüez, Mayagüez, Puerto Rico, [3]Department of Marine Geosciences, RSMAS, University of Miami, Miami, FL, USA, [4]Department of Earth Sciences, University of Minnesota, Minneapolis, MN, USA, [5]Massachusetts Institute of Technology/Woods Hole Oceanographic Institution Joint Program in Oceanography/Applied Ocean Science and Engineering, Woods Hole Oceanographic Institution, Woods Hole, MA, USA

Abstract The Holocene is considered a period of relative climatic stability, but significant proxy data-model discrepancies exist that preclude consensus regarding the postglacial global temperature trajectory. In particular, a mid-Holocene Climatic Optimum, ~9,000 to ~5,000 years BP, is evident in Northern Hemisphere marine sediment records, but its absence from model simulations raises key questions about the ability of the models to accurately simulate climate and seasonal biases that may be present in the proxy records. Here we present new mid-Holocene sea surface temperature (SST) data from the western tropical Atlantic, where twentieth-century temperature variability and amplitude of warming track the twentieth-century global ocean. Using a new coral thermometer Sr-U, we first developed a temporal Sr-U SST calibration from three modern Atlantic corals and validated the calibration against Sr-U time series from a fourth modern coral. Two fossil corals from the Enriquillo Valley, Dominican Republic, were screened for diagenesis, U-series dated to 5,199 ± 26 and 6,427 ± 81 years BP, respectively, and analyzed for Sr/Ca and U/Ca, generating two annually resolved Sr-U SST records, 27 and 17 years long, respectively. Average SSTs from both corals were significantly cooler than in early instrumental (1870–1920) and late instrumental (1965–2016) periods at this site, by ~0.5 and ~0.75 °C, respectively, a result inconsistent with the extended mid-Holocene warm period inferred from sediment records. A more complete sampling of Atlantic Holocene corals can resolve this issue with confidence and address questions related to multidecadal and longer-term variability in Holocene Atlantic climate.

1. Introduction

The Holocene Climatic Optimum (HCO), spanning approximately 9,000 to 5,000 years BP, serves as an important reference for the response of the climate system to a change in radiative forcing and as a testbed for Global Climate Model projections of future climate (Lorenz et al., 2006; Wanner et al., 2008). Also known as the Holocene Hypsithermal, Altithermal, and Holocene Thermal Maximum, this interval has been described as a 1–5 °C warming in the Northern Hemisphere over peak Little Ice Age (LIA) conditions (Lamb, 2013; Renssen et al., 2009, 2012) and is attributed to an orbitally induced increase in summertime insolation (e.g., Kaufman et al., 2004; Laepple & Lohmann, 2009).

While the HCO warming relative to LIA temperatures is clearly defined in many Northern Hemisphere paleorecords, it is not well known whether the world, on average, was warmer during the mid-Holocene and whether current temperatures exceed mid-Holocene warmth. These gaps in knowledge stem, at least in part, from a paucity of data from the tropics and Southern Hemisphere and inconsistencies among existing marine and terrestrial data sets (Liu et al., 2014; Marcott et al., 2013; Marsicek et al., 2018; Shakun, 2018). Global Climate Model simulations suggest that mid-Holocene warming in response to rising CO_2 and the retreat of ice sheets has continued into the preindustrial era (e.g., Liu et al., 2014). This contrasts with a period of warmth peaking in the mid-Holocene followed by cooling into the LIA that is implied by many marine and terrestrial paleorecords (e.g., Marcott et al., 2013). This mismatch, referred to as the "Holocene Conundrum," has been attributed to seasonal biases in temperature estimates from marine sediment cores or from the inability of climate models to accurately simulate unequal insolation changes across the globe (Laepple & Lohmann, 2009; Liu et al., 2014; Shakun, 2018).

A recent compilation of pollen records from North America and Europe suggests a warming trend from the early to late Holocene, without a peak warmth in the mid-Holocene, that is consistent with climate simulations (Community Climate System Model version 3 [CCSM3]; Marsicek et al., 2018). This result, combined with high Northern Hemisphere summer insolation, raises the possibility that mid-Holocene warmth implied by North Atlantic sediment records reflects a summertime bias. As these high-latitude marine records dominated the "global" stack (Marcott et al., 2013), they may have caused "global" mid-Holocene peak warmth and subsequent cooling trend in the reconstruction. It thus seems possible that globally, and in the annual mean, the HCO was not as warm as once thought, at least in the North Atlantic. However, accurate estimates of mid-Holocene mean annual temperature from undersampled regions are needed to fully characterize the mid-Holocene and to provide context for late 20th and early 21st century warming.

Estimating the Holocene global annual mean sea surface temperature (SST) trend by generating records across the global ocean is a daunting task. An alternative approach is to generate records from regions where SSTs are highly correlated with global mean annual SSTs in the instrumental era. One such region is the western tropical Atlantic (WTA; Figure S1), the focus of this study. There are few existing mid-Holocene SST estimates from the WTA. Some are based on Mg/Ca of planktonic foraminifera, which may also be seasonally biased (e.g., Wurtzel et al., 2013), and one is based on alkenones and foraminifera Mg/Ca (Rühlemann et al., 1999), but lack of overlap with the instrumental record precludes a comparison with late twentieth-century SSTs.

In the tropics, corals generally grow throughout the year and coral-based estimates of SST have potential to overcome biases caused by seasonal growth of other biological archives. A mid-Holocene coral-based SST record exists for the WTA, derived from Sr/Ca ratios of U-series-dated fossil colonies from Bonaire, in the southern Caribbean (Giry et al., 2012). However, absolute SSTs derived from Sr/Ca of the modern corals in the study area fail to capture twentieth-century SSTs at this site, and different Sr/Ca-SST calibration equations yield very different absolute SSTs and trends (Figure S2). This erodes confidence in the interpretation of patterns of variability and trends derived from the fossil coral Sr/Ca (Figure S2).

Here we present new coral-based SST estimates for the WTA for two multidecade-long windows during the mid-Holocene, derived using a new coral paleothermometer, Sr-U (Alpert et al., 2017; DeCarlo et al., 2016). The mid-Holocene-aged corals were sampled from the Enriquillo Valley, Dominican Republic, where coral reefs were established as global sea level rose and flooded the valley about 9,000 years ago (Figure 1). Fringing reefs developed and thrived for about 4,000 years. As sea level rise slowed, sedimentation occurred near the distal end of the valley, the seaway became restricted, and reef-building ceased (Winsor et al., 2012). Holocene, mostly aragonitic, sediments buried the reefs. Erosional gullies below modern sea level have since exposed complete reef sequences, from initial colonization to burial (Mann et al., 1984).

Sr-U combines Sr/Ca and U/Ca ratios to correct for the "vital effects" on coral Sr/Ca that give rise to inconsistencies in derived SSTs (DeCarlo et al., 2016). In the initial application of the Sr-U thermometer, a spatial Sr-U SST calibration, composed of averaged Sr-U values of multiple corals spanning a wide temperature range, was used to reconstruct a 100-year-long SST record spanning the twentieth century (Alpert et al., 2017). The Sr-U-derived SSTs captured the mean and twentieth-century trend in the instrumental record but overestimated the interannual variability. In this study, we derived a temporal Sr-U calibration based on multidecade-long Sr-U time series generated from three living corals. We validated the calibration against a 46-year-long (1959–2005) Sr-U record from a fourth coral collected live in Martinique. We then applied the calibration to two U-series-dated, mid-Holocene-aged corals from the Enriquillo Valley, Dominican Republic, to reconstruct mid-Holocene SSTs. In addition, we applied the new temporal calibration to existing Sr-U data from a LIA coral spanning the time period 1445–1669 Common Era (CE; Alpert, 2016) and present an averaged LIA SST estimate from that coral for comparison with average mid-Holocene and twentieth-century SSTs.

2. Materials and Methods

2.1. Study Sites

2.1.1. Modern Corals

Three corals of two different species collected at two Caribbean reefs were used to construct a temporal Sr-U SST calibration (Figure 1a and Table 1). Sr/Ca and U/Ca data and Sr-U estimates from two of the cores were

10.1029/2019PA003571

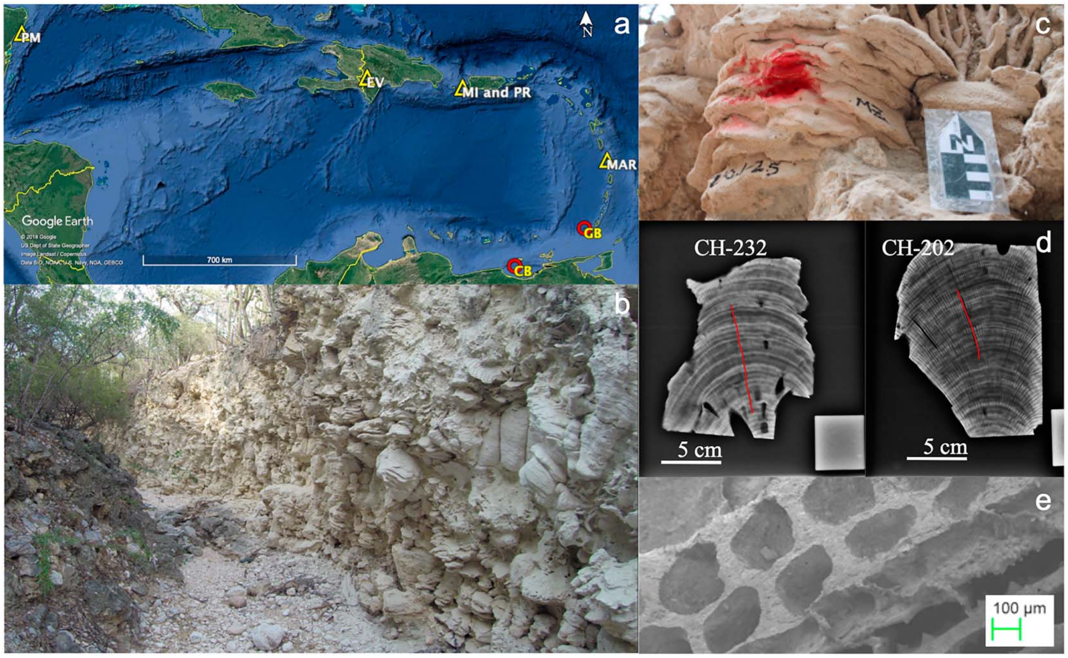

Figure 1. (a) Locations of modern and fossil corals (yellow triangles) analyzed for this study. PM = Puerto Morelos; EV = Enriquillo Valley; MI = Mona Island; PR = Puerto Rico (Pinnacles site); MAR = Martinique. Locations of sediment cores referred to in the study are indicated by red circles: GB = Grenada Basin; CB = Cariaco Basin. (b and c) Photographs of the Enriquillo Valley site showing outcrop of in situ coral colonies encased in loose sediment. In (c), scale bar is 10 cm. (d) X-rays of slabs cut from the EV corals analyzed in this study. Red lines demarcate the sampling track for each coral. (e) Scanning electron microscope image showing microscale structure and condition of the skeleton of EV coral CH-232. The absence of secondary aragonite crystals in the pore spaces indicates the pristine condition of the coral. Additional information about coral condition comes from X-ray diffraction analyses (Figure S3).

published previously. They are rebinned and the Sr-U values recalculated here (Alpert, 2016; Alpert et al., 2017). One core was extracted from a living *Siderastrea siderea* colony in the Puerto Morelos Reef Park, Yucatan Peninsula (core ID# Jardin C), and one from a living *Orbicella faveolata* colony in Mona Island, Puerto Rico (core ID# PR-OF-001). Sr/Ca and U/Ca data from an additional *Siderastrea siderea* coral (core ID# Jardin A), also from the Puerto Morelos Reef Park site (Vásquez-Bedoya et al., 2012), were generated for this study and included in the calibration.

The temporal calibration was validated with new data generated from a modern *Siderastrea siderea* coral from Grande Cai, Martinique (core ID #719). The live colony was cored in December 2013 at a depth of 4.5 m. The core was computerized tomography (CT) scanned intact (Figure S4) and slabbed through the center to reveal the skeletal architecture and sampling track. Subsamples were extracted at approximately seasonal resolution spanning an estimated 53 years, of which 46 were used in the study. Sr-U values were generated from paired Sr/Ca and U/Ca data and used to validate the thermometer against the instrumental SST record.

2.1.2. Fossil Corals

Two nonliving coral *Orbicella* spp. colonies of mid-Holocene age, collected in the Enriquillo Valley, western Dominican Republic, were analyzed for this study (Figure 1 and Table 1). In addition, we rebinned

Table 1
Metadata for the Coral Samples Analyzed in This Study

Coral ID	Species	Location	Depth (m)	Age range
PR-OF-001 (Mona Island, PR)	*Orbicella faveolata*	18.1153°N, 67.9374°W	7	1901–1997
Jardin C (Yucatan)	*Siderastrea siderea*	20.8321°N, 86.8789°W	3	1998–2007
Jardin A (Yucatan)	*Siderastrea siderea*	20.8321°N, 86.8789°W	4	1979–2006
E1P (Parguera, PR)	*Orbicella faveolata*	17.9368°N, 67.0184°W	7	1445–1669
MAR-719 (Martinique)	*Siderastrea siderea*	14.4512°N, 60.929°W	4.5	1959–2012
CH-232 (Dominican Republic)	*Orbicella faveolata*	18.5079°N, 71.5676°W	30	5,199 ± 26
CH-202 (Dominican Republic)	*Orbicella faveolata*	18.5079°N, 71.5676°W	30	6,427 ± 81

previously generated Sr/Ca and U/Ca data (A. Alpert, 2016) for the early LIA, recalculated the Sr-U values, and applied the new temporal calibration to derive LIA SSTs. At the Enriquillo Valley Canada Honda fossil reef site, 11 corals were initially sampled from strata with an estimated age range of 7,000 to 5,000 years BP (Collazo, 2015; Cuevas et al., 2009; Hubbard et al., 2004; Figures 1b and 1c). The corals were cut to 5-mm-thick slabs and X-rayed (Figure 1d) and screened for secondary aragonite growth, dissolution, and calcite recrystallization using scanning electron microscope (SEM) imaging and X-ray diffraction (XRD), respectively (Cohen & Hart, 1997; Sayani et al., 2011; Figures 1e and S3). Colonies CH-202 and CH-232 were selected for U-series dating based on their pristine condition, returning ages of 6,427 ± 81 and 5,199 ± 26 years BP, respectively, from samples extracted at the base of each slab. U-series dating was conducted using the method detailed in Pourmand et al. (2014). These estimates are consistent with their stratigraphic position within the reef. Detailed U-series information is provided in supporting information Table S1. The coral slabs were subsampled at seasonal resolution, and Sr-U values were generated from paired Sr/Ca and U/Ca data and used to calculate SST.

Sr-U values were also calculated from Sr/Ca and U/Ca data previously generated from a fossil *Orbicella faveolata* coral from Pinnacles Reef, Puerto Rico (Alpert, 2016; Table 1). U-series dates of the coral E1P indicate the colony died around 1670 CE (Kilbourne et al., 2010). We then used the new temporal calibration to derive SST estimates from the data. We present an average SST estimate from this coral, centered on ~1557 CE, for comparison with mid-Holocene and twentieth-century average SSTs.

2.2. Subsampling and Analysis

CT scans and X-rays were used to construct the age models and identify the sampling tracks (Figure 1d). Slabs were ultrasonicated in deionized water to remove debris and dried overnight in a 50 °C oven. Using a dental drill fitted with a 0.3-mm diamond bit, approximately 50 to 80 μg of coral powder was extracted at 0.5-mm intervals under a Nikon SMZ1500 stereo microscope, targeting the solid thecal wall. Sample powders were dissolved in Optima grade nitric acid and analyzed either on the ThermoFisher Element2 inductively coupled plasma mass spectrometry (ICP-MS; fossil corals) following the method detailed in Alpert et al. (2017) or on the ThermoFisher Quadropole iCAP ICP-MS (Martinique), both at Woods Hole Oceanographic Institution. Sr/Ca and U/Ca intensity ratios were converted to molar ratios using a standard curve constructed from coral skeleton (JCp-1; Okai et al., 2002), fish otoliths (FEBS-1, NIES; Sturgeon et al., 2005; Yoshinaga et al., 2000), and limestone (NBS-19; Fernandez et al., 2011). A consistency standard accounted for instrumental drift. Reported error of the measurements on the Element2 is quantified by repeated measurements over 2 years of the consistency coral standard and indicates an external precision of ±0.04 mmol/mol for Sr/Ca (1σ, $n = 274$) and ±0.02 μmol/mol for U/Ca (1σ, $n = 274$) as reported by Alpert (2016). Error on the iCAP was calculated using the same consistency standard and indicates a precision of ±0.05 mmol/mol for Sr/Ca (1σ, $n = 29$) and ±0.01 μmol/mol for U/Ca (1σ, $n = 29$).

2.3. Age Model

CT scans revealed high- and low-density band couplets along the axis of maximum growth. A high-/low-density band couplet is interpreted to represent 1 year of growth. We used CT scans to build age models for the modern (Figure S4) and LIA corals. Annual bands in the Enriquillo Valley samples (Figure 1d) were relatively obscure, likely due to the anomalous growth architecture of the corals (Figure 1c). Thus, we developed age models from the seasonally resolved Sr/Ca, B/Ca, and U/Ca cycles that we generated for the Sr-U thermometer. We checked these estimates against an independent estimate of growth: dissepiment spacing (Figure 2). Dissepiments are fine horizontal plates accreted by the coral once a month (DeCarlo & Cohen, 2017; Winter & Sammarco, 2010). Thus, 12 to 13 dissepiments represent 1 year of growth, and the distance between successive dissepiments reflects the monthly extension of the coral. We used the number of dissepiments per annual growth band and the dissepiment spacing to corroborate the band-based age model. We also compared dissepiment spacing with our subsampling resolution to exclude the possibility of seasonal bias in the sampling. To count and measure dissepiments, the cut face of the core was photographed under a Nikon SMZ1500 stereo microscope and imaged with SEM. Dissepiments were counted, and their spacing was measured from the photographs using ImageJ with calibrated SEM images.

10.1029/2019PA003571

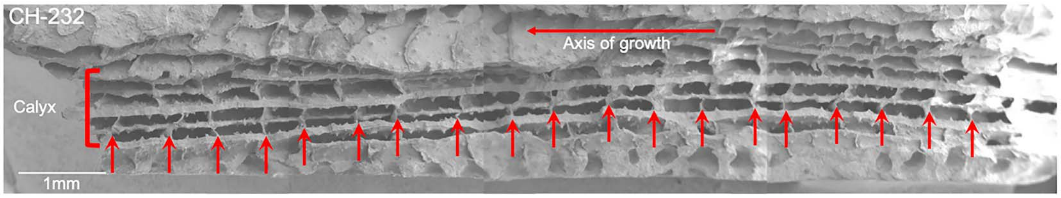

Figure 2. A scanning electron microscope (SEM) image of a corallite of the Enriquillo Valley coral CH 232, U-series dated to 5,199 years BP. Scale bar is 1 mm. Note the corallite is positioned perpendicular to the actual growth direction for purposes of display. The SEM image reveals the intact structural elements of the fossil coral skeleton and absence of secondary aragonite infilling. The dissepiments (red arrows) are clearly visible. These fine structures, oriented perpendicular to the axis of upward growth, provide support for the coral polyp as it builds the skeleton and are accreted on the lunar cycle. In this study we used the number of dissepiments per annual growth band and the spacing between them as a critical gauge of the strength of seasonality in coral growth and a check on whether the corals ceased growth at certain times of the year. Strong seasonality or growth cessation would skew the proxy sea surface temperature record toward the time of year when growth occurs.

2.4. Sr-U Calculations

Sr-U values were calculated from 2 to 3 years of seasonally resolved, paired Sr/Ca and U/Ca data following methods described in DeCarlo e al. (2016) and Alpert et al. (2017). Sr-U is defined as follows:

$$\mathrm{Sr{-}U} = f(\mathrm{U/Ca})\ \mathrm{U/Ca} = 1.1\ \ \mu\mathrm{mol/mol} \tag{1}$$

where f(U/Ca) is the slope and intercept resulting from ordinary least squares regression of Sr/Ca on U/Ca for a specified time period generated from an individual coral colony. Since a distribution of Sr/Ca and U/Ca values is needed to determine their relationship, Sr/Ca and U/Ca data spanning at least 1 year are required to generate a single Sr-U value. This constrains the temporal resolution of Sr-U-derived SSTs to a minimum of 1 year and depends on the number of data points we are able to generate per year of coral growth.

For all previously generated and published Sr/Ca and U/Ca data used in this study (Alpert, 2016; Alpert et al., 2017) we rebinned the Sr/Ca and U/Ca data and recalculated the Sr-U values. Bins of 3 years (staggered to achieve 1.5-year nominal resolution) were used on the Mona Island coral, and bins of 2 years (1-year nominal resolution) were used on the Yucatan and Martinique corals. The Enriquillo Valley Sr/Ca and U/Ca data were also binned at 2 years, providing 1-year nominal resolution. The E1P coral (LIA) was binned at 3 years (1.5-year nominal resolution). In each case the SST estimates from every other bin are independent. While the SST estimates from the remaining bins utilize data from each of two neighboring bins, these SST estimates are not the same as the average of the two neighboring bins (e.g., direct interpolation) because new regressions, Sr-U, and SST estimates are determined from data within these bins.

To establish the Sr-U SST calibration, each resulting Sr-U value was related to its respective observed SST from the Hadley Centre Sea Ice and Sea Surface Temperature (HADISST) version 1 data set (Rayner et al., 2003). The SST data were binned at the same resolution as the respective coral data for each site. SST Loggers deployed in Mona Island indicate that the average temperatures recorded by the logger are ~0.2 °C cooler than satellite-derived SSTs for the site (Alpert et al., 2017). Thus, HADISST data in the calibration were adjusted by −0.2 °C for the Mona site.

The 1σ uncertainty on each Sr-U value was calculated from the standard error of prediction on the U/Ca-versus-Sr/Ca regression (equation 2 in Alpert et al., 2017). The standard error of prediction of the Sr-U SST prediction as well as the 1σ uncertainty of the derived SST is calculated using equations 3 and 6 in Alpert et al. (2017).

3. Results

3.1. Coral Preservation

XRD analyses of the Enriquillo Valley fossil corals (Figure S3) reveal prominent aragonite spectral peaks, but there are no calcite peaks in the spectra from either coral, despite subaerial exposure for thousands of years. With SEM, we identified secondary aragonite needles lining some skeletal pore spaces, but levels of secondary aragonite were low and never caused pore space closure (Figures 1e and 2; e.g., Cohen & Hart, 2004). Nevertheless, during subsampling, we carefully targeted the thecal walls, avoiding the pore spaces to ensure only pristine material was analyzed.

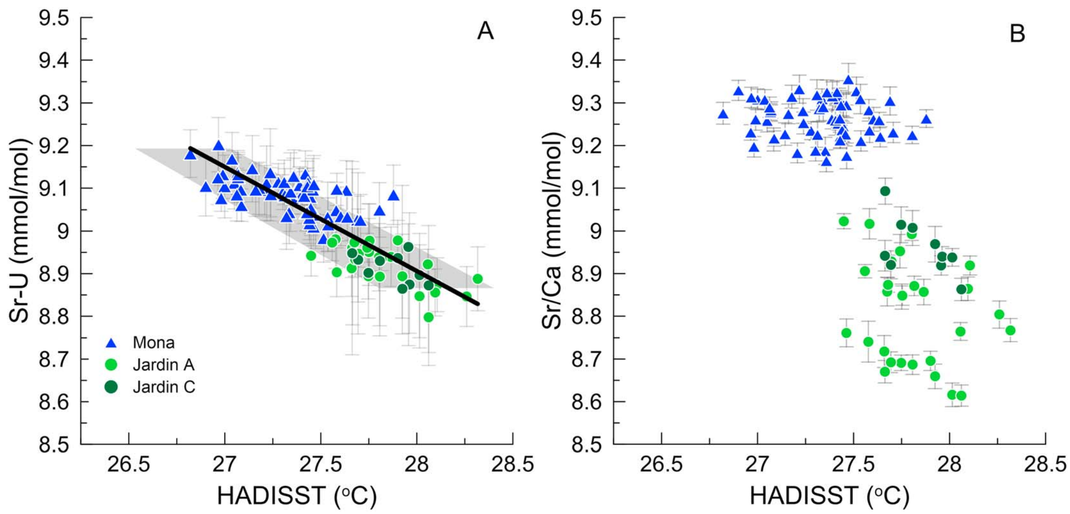

Figure 3. (a) Sr-U values generated from three modern Atlantic corals collected at two sites, plotted against HADISSTs from the same sites. Sr/Ca and U/Ca values are generated at approximately monthly resolution, and Sr-U is estimated from 2 or 3 years of data depending on the number of samples achieved per year. The Sr-U SST correlation is significant ($r^2 = 0.74$, $p < 0.001$). Error bars on the Sr-U values represent 1σ error of the predicted Sr-U value. Shading represents 1σ error on the predicted SST for a given Sr-U value. (b) Sr/Ca values only, generated from the same corals, plotted against SST. Sr/Ca and SSTs are binned the same way as for Sr-U. Error on Sr/Ca represents 1σ of the standard error of the mean. HADISST = Hadley Centre Sea Ice and Sea Surface Temperature; SST = sea surface temperature.

3.2. Dissepiment Spacing

The distance between successive dissepiments in the Enriquillo Valley corals was measured from the SEM images (Figure 2) over a distance of approximately 9 mm. The maximum dissepiment distance in CH-232 is 0.7 mm and the minimum 0.3 mm, with an average spacing of 0.5 mm along the length of the measured section, implying an average monthly coral extension rate of ~500 μm. For CH-202, the average dissepiment spacing was 0.4 mm (minimum 0.3 mm, maximum 0.6 mm). These values imply an average monthly coral extension rate of 4.5 μm and an average annual growth rate of 5.4 mm, consistent with our estimate derived from examination of annual bands and the wavelength of Sr/Ca cycles. Critically, the minimum growth rate of 0.3 mm/month is equivalent to the maximum diameter of the drill bit, indicating that a minimum of monthly resolution sampling was achieved.

3.3. Temporal Calibration of the Sr-U Thermometer and Its Validation With Modern Corals

Sr-U values and respective HADISSTs ($n = 100$) from the modern Mona Island and Yucatan corals are plotted in Figure 3a. There is a significant correlation of Sr-U and SST in the temporal domain ($r^2 = 0.74$, $p < 0.001$). An equivalent regression between Sr/Ca average values ($n = 100$) and temperature indicates that the two are not significantly correlated (Figure 3b). The relationship between Sr-U and SST is described by the following equation:

$$\text{Sr}-\text{U} = (-0.2437 \pm 0.015^{*}\text{SST}) + 15.730 \pm 0.40 \quad (2)$$

The temporal calibration (equation 2) was applied to Sr-U values calculated from the modern Martinique coral to reconstruct 46 years of SST (Figure 4). The Martinique coral was not included in the calibration. The derived SST record captures the mean absolute SST, interannual variability, and the recent warming trend in Martinique indicated by the instrumental record. Application of the temporal calibration improves the SST reconstruction relative to that derived using the original spatial calibration (Alpert et al., 2017; DeCarlo et al., 2015), which exaggerated the amplitude of the derived SSTs.

Sr-U and Sr/Ca data from 2005 to 2012 in the Martinique coral were not included in the reconstructions. A group of anomalously low density features appear in the coral CT scan over this time period, and the Sr-U data are similarly anomalous (Figure S4). It is possible that the skeletal and geochemical anomalies relate to the severe 2005 bleaching event in the Lesser Antilles (Eakin et al., 2010). Since the viability of Sr-U

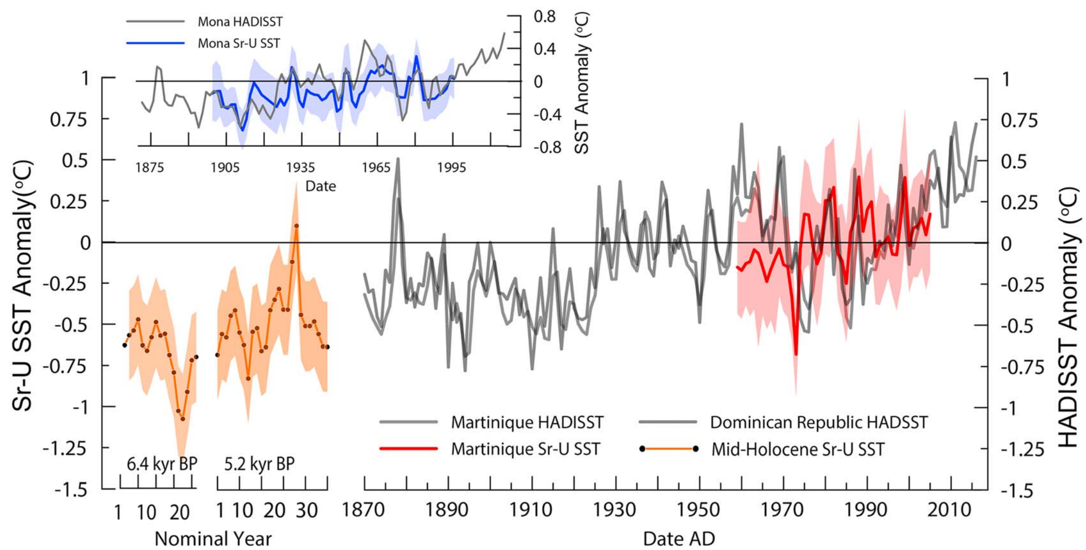

Figure 4. Main figure: Instrumental (HADISST) SST anomalies at Martinique (light gray) and Dominican Republic (dark gray) from 1870 to 2016 compared with the Sr-U-derived SST anomaly record from the modern Martinique coral (red) and mid-Holocene-aged corals from the Dominican Republic (light red, black dots). Instrumental and coral records are annually resolved; error bars are 1σ. Anomalies are calculated using site-specific HADISST climatology from 1961 to 1990. Inset: HADISST and Sr-U-derived SST from Mona Island, Puerto Rico. A Mona Island coral Sr-U SST record was published previously (Alpert et al., 2017) using the spatial calibration of DeCarlo et al. (2016). Here the Sr/Ca and U/Ca data are rebinned and the Sr-U SSTs recalculated using the temporal calibration (Figure 3). HADISST = Hadley Centre Sea Ice and Sea Surface Temperature; SST = sea surface temperature.

thermometer has not yet been evaluated through visible skeletal growth anomalies, we excluded these data from the study.

The temporal calibration was also applied to the century-long record generated from the PR-OF-001 coral from Mona Island (Figure 4, inset). Alpert et al. (2017) applied the spatial Sr-U SST calibration to this coral, which resulted in an exaggeration of the interannual variability in the derived SST. Application of the temporal calibration yields mean SST, interannual variability, and trend consistent with the instrumental record. Note, however, that the Mona data are included in the new temporal calibration, and thus, in contrast to the Martinique reconstruction, the Mona reconstruction does not represent an external validation or application of the Sr-U thermometer.

We applied published Sr/Ca-SST calibration equations to estimate SSTs from the Martinique and Mona Sr/Ca data (Giry et al., 2012; Hetzinger et al., 2006; Swart et al., 2002). All Sr/Ca calibrations result in unrealistically cold or warm temperatures and overestimates of variability and show a cooling trend in Mona and Martinique, which is inconsistent with the instrumental record (Figure S5). The challenges inherent in interpreting SSTs derived from the application of a Sr/Ca-SST calibration equation derived from one coral, to a different coral, are fairly widely recognized (e.g., Abram et al., 2009; Alpert et al., 2017; Felis & Patzold, 2004; Giry et al., 2012). This is because different corals have different Sr/Ca-SST relationships. Several studies attempt to address this issue by deriving a universal equation that combines the Sr/Ca-SST equations from multiple corals. The resulting equation has larger uncertainties on the derived SSTs (Alpert et al., 2017; Giry et al., 2012). The Sr-U thermometer reduces these uncertainties by correcting for the "vital effects" that cause the differences in Sr/Ca-SST among different corals.

3.4. Mid-Holocene and LIA Sr-U SST Estimates

Two Sr-U-derived SST time series were constructed from the mid-Holocene corals at annual resolution using equation 2 (Figure 4). Time series from colony CH-202 (6,427 ± 81 years BP) and colony CH-232 (5,199 ± 26 years BP) spanned 17 and 27 years, respectively. Average derived SSTs from CH-202 were 26.97 °C ± 0.05 standard deviation (minimum 26.81 °C, maximum 27.74 °C) with an average error on the derived SSTs of 0.27 °C. For the younger coral CH-232, average SSTs were 27.16 °C ± 0.18 standard deviation (minimum

10.1029/2019PA003571

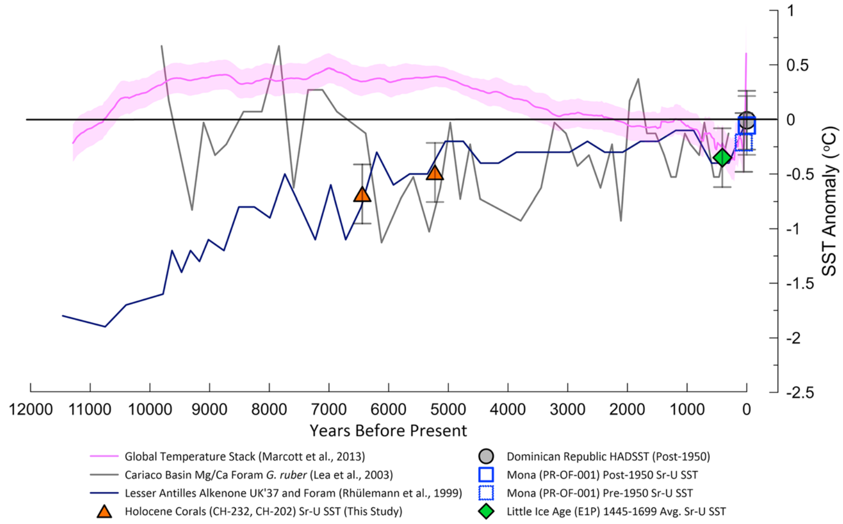

Figure 5. Sr-U SST anomalies derived from the mid-Holocene Enriquillo Valley, Little Ice Age Pinnacles Reef, and twentieth-century Mona Island corals compared with sediment core (alkenone and foram Mg/Ca) reconstructions from the Lesser Antilles (orange) and Cariaco Basin (gray), and the global temperature stack of Marcott et al. (2013; pink). Anomalies are calculated using site-specific HADISST climatology from 1961 to 1990. The Lesser Antilles (Rühlemann et al., 1999) record's core top temperature is adjusted to match the average modern SST for the site. HADISST = Hadley Centre Sea Ice and Sea Surface Temperature; SST = sea surface temperature.

26.57 °C, maximum 27.17 °C) with an average error on the derived SSTs of 0.28 °C. The two Holocene time series exhibit equal variances ($F < F$ critical one tail, $p > 0.05$), but their mean SSTs are statistically different (unpaired t-test equal variance, $p = 0.001$), with the older coral yielding significantly cooler mean SSTs than does the coral that grew on the reef ~1,200 years later. By comparison, average annual instrumental SSTs in a 1°-by-1° grid centered on the southeastern coast of the Dominican Republic, close to the entrance of the paleoseaway for the Enriquillo Valley, were 27.3 °C ± 0.2 in the earliest part of the record (1870 to 1900 AD) and 27.7 °C ± 0.2 in the late 20th/early 21st century (1980 to 2010 AD). Both time periods of the mid-Holocene reconstructed here were significantly cooler than the early instrumental period (unpaired t-test equal variance, $p < 0.01$), by ~0.4 and ~0.2 °C, respectively. They were also significantly colder than the late 20th/early 21st century period. Conversely, variability in the mid-Holocene time series was not statistically different from the early instrumental period or the post-1965 detrended time series ($F < F$ critical one tail, $p > 0.05$).

We derived an average SST estimate for the early LIA (~1465.5–1564.5 CE) from Sr-U values obtained from an *Orbicella* coral from Pinnacles Reef, Puerto Rico (Kilbourne et al., 2010; Alpert, 2016; Figure 5). Applying equation 2 to the Sr-U time series generated from the early LIA coral yielded averaged SSTs of 27.1 °C ± 0.16, which is not significantly different from the younger mid-Holocene coral ($p = 0.43$) but significantly warmer than SSTs derived from the older mid-Holocene coral ($p = 0.002$). To make a direct comparison between early LIA and twentieth-century SSTs, we compared Sr-U SSTs from the Mona coral with Sr-U SSTs from the LIA coral E1P. Our analysis indicates that SSTs during the early LIA were not significantly different from that during the early instrumental period but were significantly colder, by ~0.5 °C than the late 20th/early 21st century SSTs. Note that the LIA period represented here is not considered the coolest period of the LIA and more data are needed to capture the timing and full extent of the LIA cooling in the WTA.

To provide a broader context for our data, we compared our results to longer but lower-resolution estimates of mean global temperatures (Marcott et al., 2013) and regional Caribbean temperature reconstructions derived from foraminifera Mg/Ca and alkenone measurements on marine sediment cores (Lea et al., 2003; Rühlemann et al., 1999) (Figure 5). The SST anomalies for each reconstruction are calculated using published SST estimates and the respective site's HADISST for 1961–1990. To enable comparison with published data, SSTs generated in this study are converted to SST anomalies using a climatological mean calculated from 1961 to 1990. Whereas the Marcott et al. (2013) reconstruction shows a clear HCO followed by a cooling trend, the WTA and Caribbean records show either a warming trend (Rühlemann et al., 1999) or variable temperatures with no clear long-term trend (Lea et al., 2003). Our result is more consistent with these latter records (Figure 5).

4. Discussion

The Holocene is considered a time period of relative climate stability, but significant data-model discrepancies exist that preclude consensus of the postglacial global temperature trajectory into the present day. Several proxy records indicate peak early–middle Holocene warming followed by a cooling trend that is inconsistent with global climate simulations of a postglacial warming trend (Liu et al., 2014). Resolving this "conundrum" is important for understanding the response and sensitivity of current climate to external and internal forcing and for putting present and future climate into the broader context of the current interglacial period. Critically, the nature of the postglacial temperature trend determines the timing and extent to which current, anthropogenically forced climate has exceeded the Holocene range.

Since seasonal biases in paleoclimate proxies have contributed to this discrepancy, paleoclimate records generated from archives that grow throughout the year in locations that reflect the global mean temperature will contribute to its resolution. In the tropics, many corals grow throughout the year, and coral-based estimates of SST have potential to overcome biases caused by seasonal growth of biological archives. However, traditional single-element coral-based SST proxies cannot be reliably applied to fossil corals because different coral colonies have different element:calcium (E/Ca) relationships to temperature. Consequently, a single Sr/Ca-SST calibration, for example, cannot be developed on one coral and applied to another with any degree of confidence. The results from our own analysis presented here, in which we applied multiple existing Atlantic coral-based Sr/Ca-SST calibrations to Sr/Ca records generated in our study, demonstrate this issue clearly (Figure S5). None of the existing Sr/Ca-SST calibrations capture actual mean SSTs, variability, or trends, even those calibrations based on annually resolved data (e.g., Giry et al., 2012).

In this study, we applied a novel coral thermometer, Sr-U, to reconstruct mid-Holocene SSTs in the Enriquillo Valley, WTA. Sr-U thermometry was developed from an understanding of the mechanisms of coral biomineralization and the factors driving aragonite-seawater partitioning of U/Ca and Sr/Ca (DeCarlo et al., 2015, 2016; Gaetani & Cohen, 2006). As the first application of the Sr-U SST "spatial" calibration captured mean SSTs and the twentieth-century trend in the WTA but exaggerated the amplitude of interannual variability, we developed a new "temporal" calibration in which three long, annually resolved Sr-U time series were regressed against similarly resolved long time series of instrumental SST. The new calibration was validated using a record generated from a modern coral not included in the calibration before it was used to construct Holocene SSTs.

Sr-U-derived SSTs from the modern Martinique coral capture mean SSTs, interannual variability, and the warming trend at this site indicated by the instrumental record, providing validation of the new temporal Sr-U SST calibration for Atlantic species. The temporal calibration also performs well on the century-long coral from Mona Island, Puerto Rico, although it is important to note that this coral was included in the calibration.

The post-2005 decoupling of Sr-U from instrumental SSTs in Martinique, possibly caused by a bleaching-induced change in coral metabolism, as well as the anomalous Sr-U values within bleaching-induced stress bands of the Mona coral points to aspects of the Sr-U thermometer that are not yet well understood. Until these unknowns are resolved, interpretation of Sr-U values from areas of skeleton with obvious skeletal anomalies, such as stress bands, should be avoided.

4.1. Mid-Holocene and LIA Temperatures in the Northern Caribbean Sea

Our new data, while spanning only short intervals, do not provide support for mid-Holocene warmth in the Caribbean Sea. Moreover, given (1) that instrumental SSTs from the WTA are an excellent indicator of the amplitude of global mean SST trends and (2) that our coral-based SST estimates are not seasonally biased; the cooler mean SSTs indicated by Sr-U supports the notion that the mid-Holocene warmth implied by the global SST stack (Marcott et al., 2013) reflects the dominant influence of seasonally biased high-latitude SST (Liu et al., 2014; Marsicek et al., 2018). However, Sr-U-based SST estimates from corals spanning the full interval of Holocene warmth implied by the global stack (Figure 5) would be needed to confirm the lack of a HCO on a mean annual basis.

Our new estimates of mid-Holocene Caribbean SST agree with previous estimates from southern Caribbean sediment archives. Average Sr-U SSTs from the Holocene corals are similar to the multiproxy (alkenone and Mg/Ca) SST estimates from the Grenada Basin (Rühlemann et al., 1999), both in absolute estimated SST and in the slight warming between 5.2 and 6.4 kyr BP. Given even relatively small uncertainty in the Cariaco Basin sediment core chronology, our estimates are also within uncertainty of the Mg/Ca-based SST estimates (Lea et al., 2003) from this site (Figure 5). The sediment records diverge just before our oldest data point, suggesting the apparent agreement at ~5.2 and 6.4 kyr BP may be fortuitous, and we are not yet in the position to determine which, if either, of the early Holocene trends implied by the sediment archives is accurate; this divergence underscores the need for Sr-U-based SST estimates from older fossil corals to fully characterize the pre-6.4 kyr BP Holocene Caribbean SST trend.

The short length of our fossil records precludes full characterization of interannual to decadal variability in the Holocene, but the character and amplitude of variability in each of our Holocene fossil records appear comparable to variability during similar-length intervals of the instrumental period (Figure 4). The reconstructed time series from the Holocene appears to show quasi-decadal cycles observed in modern SST records from the Caribbean and the HADISST temperatures from the Dominican Republic (Jury, 2009). Such cycles are comparable to reported quasi-decadal cycles in Sr/Ca values reported by Giry et al. (2012) for mid-Holocene corals from Bonaire. However, the short span of our reconstructions prevents a robust analysis of any cyclicity that may be present.

The Sr/Ca data from fossil Bonaire corals show an average increase over the Holocene, also suggesting warming (Giry et al., 2012). However, as noted by Giry et al. (2012), the magnitude and variability of the absolute SSTs derived from Sr/Ca cannot be interpreted with confidence because (i) application of the local calibration to twentieth-century corals return SSTs as much as 3.5 °C too warm and (ii) the different Sr/Ca-SST calibration equations used in the study return very different Holocene temperatures (Figure S2). Application of multielement thermometry such as Sr-U may help to correct for these and similar challenges arising from use of single-element thermometers.

5. Conclusion and Future Work

Our study shows promising early results from the application of the independent Sr-U thermometer to modern and fossil corals and reveals that SSTs in this region of the Caribbbean during parts of the HCO were significantly cooler than during both the early and late instrumental periods at this site. Given that the amplitude of the regional centennial instrumental SST trend is similar to that of global SST, our results provide support for the hypothesis that the conflict between model and data estimates of mid-Holocene temperature trends is due at least in part to a seasonal bias in SST records derived from high-latitude archives, which have a large influence on the “global” SST reconstruction of Marcott et al. (2013). A more complete sampling of Holocene corals from the region is needed to resolve this issue with confidence, as well as to address questions related to multidecadal and longer-term variability. The Enriquillo Lake site has the potential to provide a 4,000-year record of accurate SST estimates during an important time period in the recent geologic past. Other sources of Holocene corals, such as well-dated storm coral rubble or reef core material, can provide unique and valuable insights into the climate of the Holocene period.

Acknowledgments
This study was supported by NSF OCE 1747746 to Anne Cohen and by NSF OCE 1805618 to Anne Cohen and Delia Oppo. Eric Loss and his crew on Pangaea Exploration's Sea Dragon enabled fieldwork in Martinique, and George P. Lohman, Thomas DeCarlo, and Hanny Rivera assisted with coral coring. Kathryn Pietro and Julia Middleton assisted in the laboratory, and Louis Kerr provided technical support on the SEM at MBL. Gretchen Swarr provided technical support on the Element and iCap ICPMS at WHOI. We also thank Edwin Hernandez, Jose Morales, and Amos Winter for discussion. All data generated in this study will be made publicly available at http://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets

References

Abram, N. J., McGregor, H. V., Gagan, M. K., Hantoro, 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*(25–26), 2794–2803. https://doi.org/10.1016/j.quascirev.2009.07.006

Alpert, A. (2016). *Little Ice Age climate in the western tropical Atlantic inferred from coral geochemical proxies*. PhD thesis. Massachusetts Institute of Technology and Woods Hole Oceanographic Institution Joint Program in Oceanography, Woods Hole, MA. https://doi.org/10.1575/1912/8410

Alpert, A., Cohen, A. L., Oppo, D. W., DeCarlo, T. M., Gaetani, G. A., Hernandez-Delgado, E. A., et al. (2017). Twentieth century warming of the tropical Atlantic captured by Sr-U paleothermometry. *Paleoceanography*, *32*, 146–160. https://doi.org/10.1002/2016PA002976

Cohen, A. L., & Hart, S. R. (1997). The effect of colony topography on climate signals in coral skeleton. *Geochimica et Cosmochimica Acta*, *61*(18), 3905–3912. https://doi.org/10.1016/S0016-7037(97)00200-7

Cohen, A. L., & Hart, S. R. (2004). Deglacial sea surface temperatures of the western tropical Pacific: A new look at old coral. *Paleoceanography*, *19*, PA4031. https://doi.org/10.1029/2004PA001084

Collazo, J. A. M. (2015). *Reconstructing sea surface temperatures in the Caribbean during the early-mid Holocene from a reef exposure in Cañada Honda, Enriquillo Valley, Dominican Republic*. University of Puerto Rico Mayaguez. Retrieved from http://grad.uprm.edu/tesis/moralescollazo.pdf

Cuevas, D., Sherman, C. E., & Ramirez, W. (2009). Coral growth rates from the Holocene Cañada Honda fossil reef, southwestern Dominican Republic: Comparisons with modern counterparts in high sedimentation. *Article in Caribbean Journal of Science.*, *45*(1), 94–109. https://doi.org/10.18475/cjos.v45i1.a13

DeCarlo, T. M., & Cohen, A. L. (2017). Dissepiments, density bands and signatures of thermal stress in Porites skeletons. *Coral Reefs*, *36*(3), 749–761. https://doi.org/10.1007/s00338-017-1566-9

DeCarlo, T. M., Gaetani, G. A., Cohen, A. L., Foster, G. L., Alpert, A. E., & Stewart, J. A. (2016). Coral Sr-U thermometry. *Paleoceanography*, *31*, 626–638. https://doi.org/10.1002/2015PA002908

DeCarlo, T. M., Gaetani, G. A., Holcomb, M., & Cohen, A. L. (2015). Experimental determination of factors controlling U/Ca of aragonite precipitated from seawater: Implications for interpreting coral skeleton. *Geochimica et Cosmochimica Acta*, *162*, 151–165. https://doi.org/10.1016/j.gca.2015.04.016

Eakin, C. M., Morgan, J. A., Heron, S. F., Smith, T. B., Liu, G., Alvarez-Filip, L., et al. (2010). Caribbean corals in crisis: Record thermal stress, bleaching, and mortality in 2005. *PLoS ONE*, *5*(11), e13969. https://doi.org/10.1371/journal.pone.0013969

Felis, T., & Patzold, J. (2004). Climate reconstructions from annually banded corals. *Global Environmental Change in the Ocean and on Land*, 205–227.

Fernandez, D. P., Gagnon, A. C., & Adkins, J. F. (2011). An isotope dilution ICP-MS method for the determination of Mg/Ca and Sr/Ca ratios in calcium carbonate. *Geostandards and Geoanalytical Research*, *35*(1), 23–37. https://doi.org/10.1111/j.1751-908X.2010.00031.x

Gaetani, G. A., & Cohen, A. L. (2006). Element partitioning during precipitation of aragonite from seawater: A framework for understanding paleoproxies. *Geochimica et Cosmochimica Acta*, *70*(18), 4617–4634. https://doi.org/10.1016/J.GCA.2006.07.008

Giry, C., Felis, T., Kölling, M., Scholz, D., Wei, W., Lohmann, G., & Scheffers, S. (2012). Mid- to late Holocene changes in tropical Atlantic temperature seasonality and interannual to multidecadal variability documented in southern Caribbean corals. *Earth and Planetary Science Letters*, *331-332*, 187–200. https://doi.org/10.1016/j.epsl.2012.03.019

Hetzinger, S., Pfeiffer, M., Dullo, W. C., Ruprecht, E., & Dieter, G. S. (2006). Sr/Ca and δ^{18}O in a fast-growing *Diploria strigosa* coral: Evaluation of a new climate archive for the tropical Atlantic. *Geochemistry, Geophysics, Geosystems*, *7*, Q10002. https://doi.org/10.1029/2006GC001347

Hubbard, D. K., Ramirez, W., Davis, A., Lawson, G. R., Oram, J., Pparsons-Hubbard, K., et al. (2004). A preliminary model of Holocene coral-reef development in the Enriquillo Valley, SW Dominican Republic. In *Geological Society of America Annual Meeting*.

Jury, M. R. (2009). An intercomparison of observational, reanalysis, satellite, and coupled model data on mean rainfall in the Caribbean. *Journal of Hydrometeorology*, *10*(2), 413–430. https://doi.org/10.1175/2008JHM1054.1

Kaufman, D. S., Ager, T. A., Anderson, N. J., Anderson, P. M., Andrews, J. T., Bartlein, P. J., et al. (2004). Holocene thermal maximum in the western Arctic (0–180°W). *Quaternary Science Reviews*, *23*(5–6), 529–560. https://doi.org/10.1016/j.quascirev.2003.09.007

Kilbourne, K. H., Quinn, T. M., Webb, R., Guilderson, T., Nyberg, J., & Winter, A. (2010). Coral windows onto seasonal climate variability in the northern Caribbean since 1479. *Geochemistry, Geophysics, Geosystems*, *11*, Q10006. https://doi.org/10.1029/2010GC003171

Laepple, T., & Lohmann, G. (2009). Seasonal cycle as template for climate variability on astronomical timescales. *Paleoceanography*, *24*, PA4201. https://doi.org/10.1029/2008PA001674

Lamb, H. H. (2013). *Climate: Present, Past and Future* (*Routledge Revivals*). https://doi.org/10.4324/9780203804308

Lea, D. W., Lea, D. W., Pak, D. K., Peterson, L. C., & Hughen, K. A. (2003). Synchroneity of tropical and high-latitude Atlantic temperatures over the last glacial termination. *Science*, *301*(5638), 1361–1364. https://doi.org/10.1126/science.1088470

Liu, Z., Zhu, J., Rosenthal, Y., Zhang, X., Otto-Bliesner, B. L., Timmermann, A., et al. (2014). The Holocene temperature conundrum. *Proceedings of the National Academy of Sciences*, *111*(34), E3501–E3505. https://doi.org/10.1073/pnas.1407229111

Lorenz, S. J., Kim, J. H., Rimbu, N., Schneider, R. R., & Lohmann, G. (2006). Orbitally driven insolation forcing on Holocene climate trends: Evidence from alkenone data and climate modeling. *Paleoceanography*, *21*, PA1002. https://doi.org/10.1029/2005PA001152

Mann, P., Taylor, F. W., Burke, K., & Kulstad, R. (1984). Subaerially exposed Holocene coral reef, Enriquillo Valley, Dominican Republic. *Geological Society of America Bulletin*, *95*(9), 1084–1092. https://doi.org/10.1130/0016-7606(1984)95<1084:SEHCRE>2.0.CO;2

Marcott, S. A., Shakun, J. D., Clark, P. U., & Mix, A. C. (2013). A reconstruction of regional and global temperature for the past 11,300 years. *Science (New York, N.Y.)*, *339*(6124), 1198–1201. https://doi.org/10.1126/science.1228026

Marsicek, J., Shuman, B. N., Bartlein, P. J., Shafer, S. L., & Brewer, S. (2018). Reconciling divergent trends and millennial variations in Holocene temperatures. *Nature*, *554*(7690), 92–96. https://doi.org/10.1038/nature25464

Okai, T., Suzuki, A., Kawahata, H., Terashima, S., & Imai, N. (2002). Preparation of a new Geological Survey of Japan geochemical reference material: Coral JCp-1. *Geostandards and Geoanalytical Research*, *26*(1), 95–99. https://doi.org/10.1111/j.1751-908X.2002.tb00627.x

Pourmand, A., Tissot, F. L. H., Arienzo, M., & Sharifi, A. (2014). Introducing a comprehensive data reduction and uncertainty propagation algorithm for U-Th geochronometry with extraction chromatography and isotope dilution MC-ICP-MS. *Geostandards and Geoanalytical Research*, *38*(2), 129–148. https://doi.org/10.1111/j.1751-908X.2013.00266.x

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*(D14), 4407. https://doi.org/10.1029/2002JD002670

Renssen, H., Seppä, H., Crosta, X., Goosse, H., & Roche, D. M. (2012). Global characterization of the Holocene Thermal Maximum. *Quaternary Science Reviews*, *48*, 7–19. https://doi.org/10.1016/j.quascirev.2012.05.022

Renssen, H., Seppä, H., Heiri, O., Roche, D. M., Goosse, H., & Fichefet, T. (2009). The spatial and temporal complexity of the Holocene Thermal Maximum. *Nature Geoscience*, *2*(6), 411–414. https://doi.org/10.1038/ngeo513

Rühlemann, C., Mulitza, S., Müller, P. J., Wefer, G., & Zahn, R. (1999). Warming of the tropical Atlantic Ocean and slowdown of thermohaline circulation during the last deglaciation. *Nature*, *402*(6761), 511–514. https://doi.org/10.1038/990069

Sayani, H. R., Cobb, K. M., Cohen, A. L., Elliott, W. C., Nurhati, I. S., Dunbar, R. B., et al. (2011). Effects of diagenesis on paleoclimate reconstructions from modern and young fossil corals. *Geochimica et Cosmochimica Acta*, *75*(21), 6361–6373. https://doi.org/10.1016/j.gca.2011.08.026

Shakun, J. D. (2018). Pollen weighs in on a climate conundrum. *Nature*, *554*(7690), 39–40. https://doi.org/10.1038/d41586-018-00943-4

Sturgeon, R. E., Willie, S. N., Yang, L., Greenberg, R., Spatz, R. O., Chen, Z., et al. (2005). Certification of a fish otolith reference material in support of quality assurance for trace element analysis. *Journal of Analytical Atomic Spectrometry*, *20*(10), 1067. https://doi.org/10.1039/b503655k

Swart, P. K., Elderfield, H., & Greaves, M. J. (2002). A high-resolution calibration of Sr/Ca thermometry using the Caribbean coral *Montastraea annularis*. *Geochemistry, Geophysics, Geosystems*, *3*(11), 8402. https://doi.org/10.1029/2002GC000306

Vásquez-Bedoya, L. F., Cohen, A. L., Oppo, D. W., & Blanchon, P. (2012). Corals record persistent multidecadal SST variability in the Atlantic Warm Pool since 1775 AD. *Paleoceanography*, *27*, A3231. https://doi.org/10.1029/2012PA002313

Wanner, H., Beer, J., Bütikofer, J., Crowley, T. J., Cubasch, U., Flückiger, J., et al. (2008). Mid- to Late Holocene climate change: An overview. *Quaternary Science Reviews*, *27*(19–20), 1791–1828. https://doi.org/10.1016/j.quascirev.2008.06.013

Winsor, K., Curran, H. A., Greer, L., & Glumac, B. (2012). Unusual Holocene serpulid-tufa bioherms, Enriquillo Valley, Dominican Republic: Morphologies and paleoenvironmental implications. *Palaios*, *27*(10), 693–706. https://doi.org/10.2110/palo.2011.p11-118r

Winter, A., & Sammarco, P. W. (2010). Lunar banding in the scleractinian coral *Montastraea faveolata*: Fine-scale structure and influence of temperature. *Journal of Geophysical Research - Biogeosciences*, *115*, G04007. https://doi.org/10.1029/2009JG001264

Wurtzel, J. B., Black, D. E., Thunell, R. C., Peterson, L. C., Tappa, E. J., & Rahman, S. (2013). Mechanisms of southern Caribbean SST variability over the last two millennia. *Geophysical Research Letters*, *40*, 5954–5958. https://doi.org/10.1002/2013GL058458

Yoshinaga, J., Nakama, A., Morita, M., & Edmonds, J. S. (2000). Fish otolith reference material for quality assurance of chemical analyses. *Marine Chemistry*, *69*(1–2), 91–97. https://doi.org/10.1016/S0304-4203(99)00098-5