Corals record persistent multidecadal SST variability in the Atlantic Warm Pool since 1775 AD

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[1] Accurate low-latitude sea surface temperature (SST) records that predate the instrumental era are needed to put recent warming in the context of natural climate variability and to evaluate the persistence of lower frequency climate variability prior to the instrumental era and the possible influence of anthropogenic climate change on this variability. Here we present a 235-year-long SST reconstruction based on annual growth rates (linear extension) of three colonies of the Atlantic coral *Siderastrea siderea* sampled at two sites on the northeastern Yucatan Peninsula, Mexico, located within the Atlantic Warm Pool (AWP). AWP SSTs vary in concert the Atlantic Multidecadal Oscillation (AMO), a basin-wide, quasiperiodic (~60–80 years) oscillation of North Atlantic SSTs. We demonstrate that the annual linear growth rates of all three coral colonies are significantly inversely correlated with SST. We calibrate annual linear growth rates to SST between 1900 and 1960 AD. The linear correlation coefficient over the calibration period is r = −0.77 and −0.66 over the instrumental record (1860–2008 AD). We apply our calibration to annual linear growth rates to extend the SST record to 1775 AD and show that multidecadal SST variability has been a persistent feature of the AWP, and likely, of the North Atlantic over this time period. Our results imply that tropical Atlantic SSTs remained within 1°C of modern values during the past 225 years, consistent with a previous reconstruction based on coral growth rates and with most estimates based on the Mg/Ca of planktonic foraminifera from marine sediments.

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1. Introduction

[2] The instrumental record of North Atlantic sea surface temperature (SST) includes a secular warming trend superimposed upon a multidecadal oscillation. Surface warming since the early 1900s (~0.1°C/decade) has apparently escalated since the mid-1970s. This warming may have contributed to an increase in Atlantic hurricane activity, a rapid decrease in Greenland ice sheet volume, and an increase in the frequency and severity of coral reef bleaching events documented over the corresponding time period [*Emanuel*, 1987; *Strong et al.*, 1998; *Serreze and Francis*, 2006].

[3] The multidecadal SST variation, having a period of roughly 60–80 years, is encapsulated by the Atlantic Multidecadal Oscillation (AMO) Index, the 120-month smoothed average of SSTs in the North Atlantic basin [*Enfield et al.*, 2001]. Atlantic multidecadal SST variability may arise from internal variability linked to the Atlantic Meridional Overturning Circulation [*Delworth and Mann*, 2000; *Knight et al.*, 2005; *Zhang et al.*, 2007; *Zhang*, 2008] although several studies suggest that the multidecadal SST variability is linked to global warming [e.g., *Mann and Emanuel*, 2006; *Trenberth and Shea*, 2006]. While several lines of evidence, including paleoclimatic evidence, suggest that at least some portion of the AMO is natural, isolating the natural from the forced component is critical to accurate projections of its climatic impacts [*Enfield and Cid-Serrano*, 2010].

[4] Interaction between the secular SST trend and multidecadal SST variability have resulted in a nonlinear warming trend over the last 100 years, with relatively cool periods from 1900 to 1930 and again from 1960 to 1990, both intervals when the AMO Index was in a negative (cool) phase. During these multidecade-long intervals, summer climate cooled in both the U.S. and Europe [*Enfield et al.*, 2001; *Sutton and Hodson*, 2005], and hurricanes were reduced in both frequency and intensity [*Goldenberg et al.*, 2001; *Holland and Webster*, 2007].

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Thus, Atlantic multidecadal SST variability can mitigate or amplify regional climate change, and will likely play a significant role in modulating the 21st century North Atlantic SST increase and rainfall patterns [*Enfield et al.*, 2001] projected by global climate model simulations (e.g., IPCC AR4). Key questions therefore, involve the predictability of the amplitude and timing of these oscillations. Numerical models have proven incapable of predicting future phase shifts in AMO in a deterministic manner [*Enfield and Cid-Serrano*, 2006] and probability-based projections are hampered by the short (130–150 years) duration of the instrumental record, which captures just two multidecadal cycles.

[5] Temperatures of the Atlantic Warm Pool (AWP), which includes the Caribbean, the Gulf of Mexico, and the western tropical North Atlantic, parallel the AMO [*Wang et al.*, 2006], and appear to provide the link between the AMO and the development of Atlantic hurricanes, and to precipitation anomalies in the northeastern Pacific, Central America, and the southeastern U.S. [*Wang et al.*, 2008]. The AWP also hosts the majority of the Atlantic's coral reef ecosystems. Given the importance of AWP SST variability as a driver of tropical climate and ecosystem changes over much of the Atlantic sector, and more generally, of North Atlantic SST for climate variability on broader spatial scales, there is considerable interest in accurate projections of their SST trajectories over the next several decades.

[6] In the absence of instrumental data (or direct observations) such records must be generated from proxy climate archives. For example, *Enfield and Cid-Serrano* [2006] used a multicentury tree ring based reconstruction of AMO generated by *Gray et al.* [2004] to develop a statistical (probabilistic) approach to predicting the future behavior of AMO. Their analysis suggests that the likelihood of North Atlantic temperatures switching to cool phase by 2025 is about 85%. The *Gray et al.* [2004] reconstruction, as well as a more recent multiproxy reconstruction [*Mann et al.*, 2009], is based primarily on northern hemisphere tree ring data that collectively capture AMO-like variability in the instrumental era. On this basis, it is argued that the multiproxy and/or tree ring record can be used to extend the record of AMO into the pre-industrial era. However, the mechanism linking Atlantic basin-averaged SST variability with the northern hemisphere tree ring response is not fully understood. For example, it is not known whether the link between AMO and northern hemisphere climate persists through time, whether tree ring variability can be decoupled from AMO variability, or whether the link is stable during periods of global or regional climate change.

[7] Proxy records of Atlantic SST variability from marine archives are needed to assess the persistence of Atlantic multidecadal SST variability, and, if it is persistent, to begin to parse out natural and forced components. Ideally, such archives would be geographically situated in a region where the multidecadal SST signal is strong and persistent through the instrumental record. These archives should also be capable of capturing this variability on annual to interannual timescales with a high degree of accuracy, since SST anomalies that define the AMO Index fluctuate within 0.5°C on multidecadal time-scales. To date, there are few records from marine archives that capture SST with the level of accuracy and temporal resolution required to reconstruct multidecadal variability in North Atlantic SST. Massive, long-lived corals have this potential but the widely used temperature proxy - skeletal Sr/Ca ratios - has proven difficult to interpret in terms of regional SST. Specifically, different coral colonies collected at the same site can have different short- and long-term trends in Sr/Ca ratios and those trends can differ significantly from the instrumental record of SST [*Smith et al.*, 2006; *Stephans et al.*, 2004]. Mean Sr/Ca ratios in multiple colonies from the same site can be offset by the equivalent of several °C [e.g., *Goodkin et al.*, 2005; *Saenger et al.*, 2008] and finally, as we discuss further below, the two published Atlantic multicentury-length Sr/Ca-based SST records have not accurately captured multidecadal, regional instrumental SST variability outside of the short calibration period, a problem that also appears to plague Sr/Ca-based SST reconstructions from other ocean basins [*Scott et al.*, 2010].

[8] *Saenger et al.* [2009] showed that annual growth rates of the Atlantic massive coral *Siderastrea siderea* from Belize and Bahamas are strongly, inversely correlated with average annual SST, and captured multidecadal variability at each site over the period of the instrumental record. Application of a growth rate-based coral thermometer to a 450-year old coral from the Bahamas revealed that multidecadal variability consistent with AMO was dominant from 2009 to 1750 AD at this site, but prior to this time, was replaced by higher-frequency variability, notably during the coolest period of the Little Ice Age. These results suggest the AMO may not be a persistent or predictable feature of Atlantic variability, contrary to reconstructions based largely on tree rings [*Gray et al.*, 2004; *Mann et al.*, 2008]. However, while instrumental data indicate that SST at the Bahamas site is strongly correlated to Atlantic SST on multidecadal time scales during the instrumental era, it is on the northern margin of the AWP. If the AWP contracted during the LIA, then the Bahamas coral site may have been outside of the AWP region having strong multidecadal SST variability.

[9] Here, we expand on this original study, using multiple long-lived colonies of *S. siderea* collected live at two sites on the Yucatan Peninsula, Mexican Caribbean, located in the heart of the AWP. Our goals were to (1) confirm that growth rate chronologies of multiple *S. siderea* colonies from the same region yield similar signals, (2) to confirm that growth rates of *S. siderea* from these sites also record SST on decadal time scales, and (3) to extend the instrumental SST record at a site where SSTs covary with the basin-wide SSTs on multidecadal time scales. Yucatan is geographically well placed to capture AMO variability: instrument-based SST reconstructions from a grid box containing our core site show a strong positive correlation with the AMO Index ($r = 0.68$) over the last 150 years (Figure 1). We demonstrate that the annual growth rates of all three coral colonies are significantly inversely correlated with these instrumental SSTs on both annual and decadal timescales. We apply the coral thermometer to extend the record of Yucatan SSTs back through 1775 AD and interpret multidecadal SST variability over this time period. Finally, we compare our marine-based record of multidecadal variability with other SST reconstructions from the AWP spanning the last several hundred years, and with paleo-AMO reconstructions based largely on terrestrial proxies. Our results present strong motivation for extending proxy records of Atlantic SST

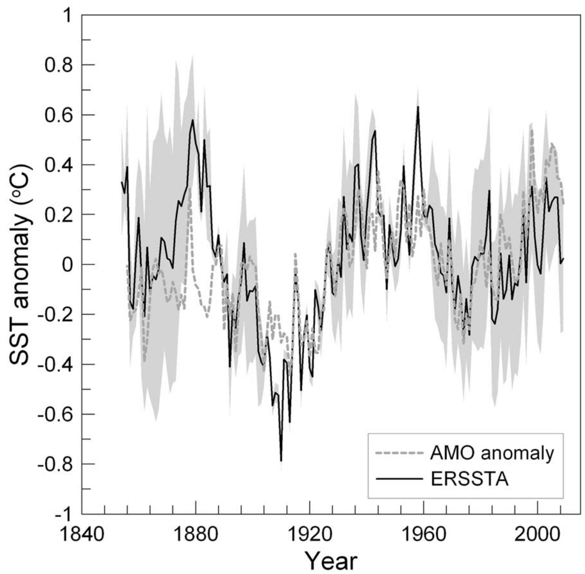

Figure 1. Annual average sea surface temperature anomalies (SSTA) calculated from NOAA Extended Reconstructed SSTV3b in a 2 × 2° grid box centered on 20N, 86W (solid black line) versus the unsmoothed, undetrended AMO SST anomaly (0 to 70N) calculated from the Kaplan EXT SST V2 (http://www.esrl.noaa.gov/psd/data/timeseries/AMO/) (dashed gray line). ERSST anomalies were calculated relative to the average annual mean SST from 1880 to 2008 AD. The gray shading is the estimated error on the analyzed ERSST.

further back in time using a combination of longer-lived *S. siderea* at select locations.

2. Methods

2.1. Study Site

[10] The coasts of Puerto Morelos and Punta Maroma, Yucatan Peninsula, are fringed by reefs that stretch several kilometers along the shore, creating relatively shallow (3–4 m depth) lagoons, each connected to the open ocean via two or more inlets. A single core was drilled from each of 3 live colonies of the massive Atlantic coral *Siderastrea siderea* [*Ellis and Solander*, 1786] on scuba, using a submersible underwater hydraulic drill and targeting the axis of maximum growth of each coral. A 110 cm-long core, JardinA, was removed in August 2009 from a colony living at ~3.1 m depth in the Puerto Morelos Reef Park (20.83N, 86.74W). Cores MarA and MarB were 95 cm and 75 cm long respectively and removed in August 2010 from colonies living at 5.3 and 2.7 m depth in Punta Maroma (20.74N, 86.95W and 20.74N, 86.96W resp.).

2.2. CAT Scanning, Image Analyses and Calibration of Coral Growth to SST

[11] The 7-cm-diameter coral cores were split lengthwise, and one half was imaged using a Siemens Volume Zoom Spiral Computerized Tomography Scanner at the Woods Hole Oceanographic Institution. Scans were conducted at 400 mAs and 120 kV and 0.2 mm resolution. The corals were scanned along a transaxial (shorter cross-section) plane and reconstructed using an ultra-high bone algorithm (u90u) at 0.1 mm increments. Three-dimensional reconstructions from Dicom files and virtual image manipulation, including rotation and slicing, were completed using Visage Imaging Inc. software [*Cantin et al.*, 2010]. From each 3-D image, a 2.5 mm-thick “virtual” 2-D slice was cut and from which we quantified annual gray scale variations. Using a 10-pixel wide line probe in ImageJ, we constructed density profiles down the axis of maximum growth of each core. The number of high and low density peaks in the density profiles matched the number of high and low density growth bands visible in the CT image. From the density profiles, the annual linear extension was calculated as the distance in millimeters between successive high-density peaks. This was repeated along 3 parallel tracks. The extension for each coral in each year was calculated by averaging the linear extension estimate from three tracks. We use the NOAA NCDC extended reconstructed global sea surface temperature data (ERSST3b) [*Smith et al.*, 2008] from a 2 × 2° grid centered on 20°N, 86°W and the annually resolved coral growth record generated here, to construct the coral growth-SST calibration. In situ SSTs are not available, but as our goal is to reconstruct regional SST variability, rather than variability of SST at the reef itself, calibrating against SST in a 2 × 2° grid is reasonable. The correlation coefficient (r) between IGOSS nmc Reyn_SmithOIv2 (1 × 1°) [*Reynolds and Smith*, 1995] and ERSST (2 × 2°) at this site is 0.97 for the overlapping time period (1982–2008).

3. Results

[12] The CAT scan images revealed 235 annual low-density bands spanning 1773–2008 in the coral JardinA, 255 bands spanning 1784–2009 in MarA and 135 annual low-density bands spanning 1874–2009 in MarB. Annual growth rates of the individual colonies ranged from 2.02 to 6.02, 1.65 to 5.54 and 2.20 to 6.18 mm yr^{-1} respectively, over this time period. Their records of annual growth (skeletal extension, mm/yr) are shown in Figures 2a–2c. In each figure, the solid dark line represents the average annual extension calculated from analysis of three parallel profiles i.e., triplicate analyses, along the axis of maximum growth in the 2-D slice. The shaded area represents the maximum and minimum value obtained from the triplicate analyses of each annual band. We compared the annual growth record from each coral with average annual ERSSTs over the corresponding time period and found a significant inverse correlation, consistent with that reported by *Saenger et al.* [2009]. Over the period 1860 to 2008 AD, the linear correlation coefficient “r” between skeletal extension and SST on annual timescales is −0.57 ($p < 0.01$), −0.46 ($p < 0.01$), and −0.58 ($p < 0.01$), for JardinA, MarA and MarB respectively. The correlation with SST is strongest for the data set created by combining annual growth rates of all three corals: r = −0.66 ($p < 0.01$).

[13] A coral growth-SST calibration equation was derived by regressing the average annual skeletal growth anomaly (EXTA) against the average annual ERSST anomaly (SSTA) for the period 1900–1960 AD, selected to contain periods with both maximum and minimum SSTs (Figure 3).

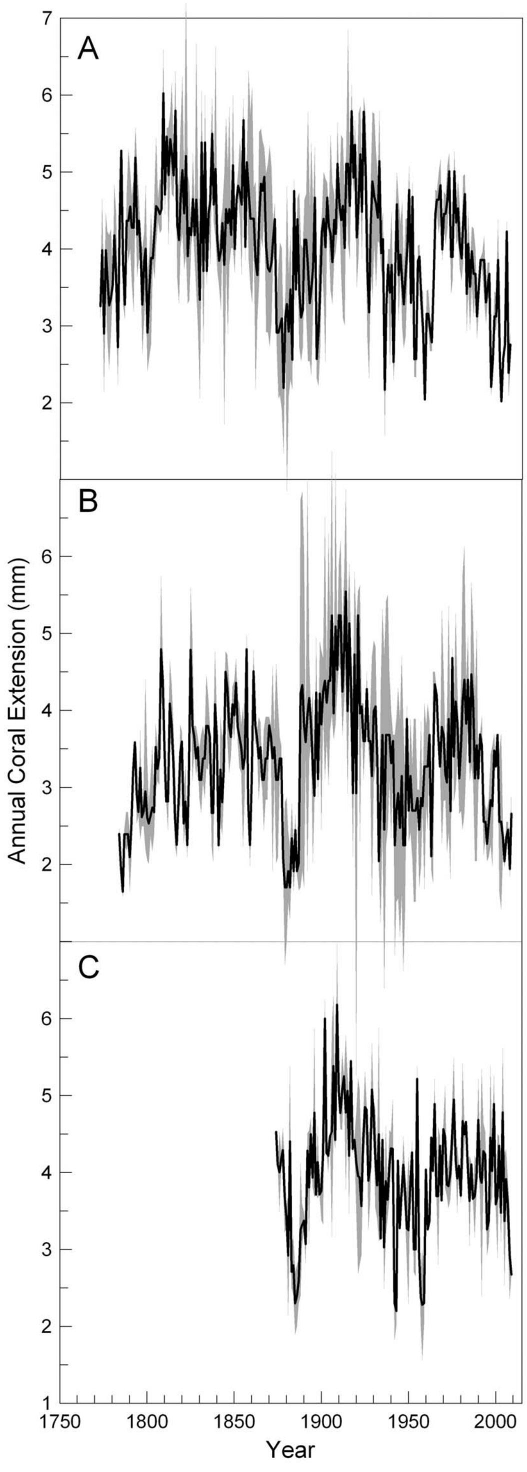

Figure 2. Average annual linear extension (in millimeters) measured from CAT scan images of each coral core. The 3-D images are sliced virtually to ensure exposure of the axis of maximum growth of each coral colony. The annual linear extension is the distance between consecutive high density bands measured directly on the 2-D slice, and the average annual linear extension is calculated from measurements along three parallel tracks. The gray shading in each plot represents the maximum and minimum extension rate measured each year from triplicate tracks. The growth records from (a) Jardin A, (b) Marum A and (c) Marum B.

For both the growth and the SST data sets, anomalies were calculated relative to 1880–2008 AD mean. The calibration is:

$$\mathrm{EXTA(mm)} = -1.62(\pm 0.17) \times [\mathrm{SSTA}(^\circ\mathrm{C})] + 0.18(\pm 0.06),$$
$$(\mathrm{r} = -0.77; \mathrm{p} < 0.05). \quad (1)$$

[14] The calibration was verified against data generated for the periods 1860–1900 and 1961–2008 AD respectively. The correlation between coral-derived SSTA and ERSSTA for the verification periods are: $r = 0.56$, $p < 0.01$ and $r = 0.55$, $p < 0.01$ respectively. The continuous 235-year-long record of annual SST anomalies derived from the average coral growth record using equation (1) is shown in Figure 4. The correlation (r) between derived and instrumental SSTA (shown in gray) for the full period of overlap (1860–2008 AD) is 0.66; $p < 0.01$.

4. Discussion

[15] Two of the coral colonies analyzed in this study each grew continuously for 235 and 225 years respectively, together spanning the time period 1773 to 2009 AD. This enabled us to extend the instrumental record of annually resolved SST by 85 years. Our coral-based reconstruction captures the multidecadal variability evident in the instrumental record as well as the amplitude of SST variability

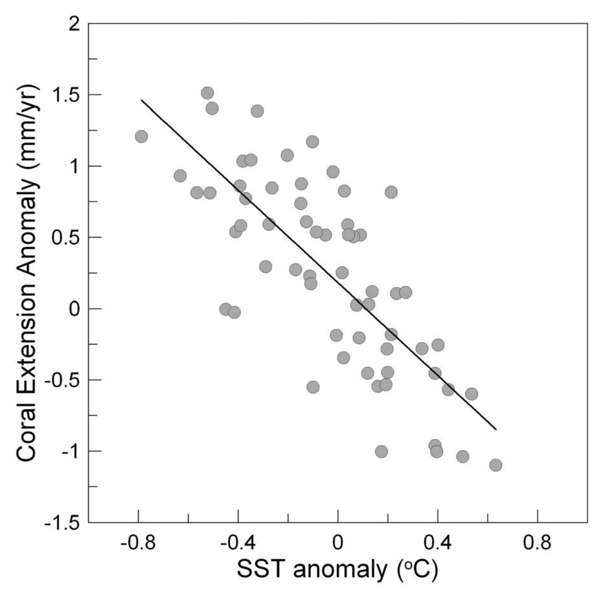

Figure 3. The relationship between annual coral growth (linear extension) and SST at Yucatan for the calibration period 1900 to 1960 AD; r = −0.66 (p < 0.01). The annual linear extension rates of all three colonies were combined to produce a single growth record spanning 1773 to 2008 AD. The linear extension anomaly was then calculated relative to the mean growth rate for the period 1880–2008 AD. Similarly, the annual average sea surface temperature anomaly (SSTA) was calculated relative to the average SST for the period 1880–2008 AD (using NOAA Extended Reconstructed SSTV3b in a 2 × 2° grid box centered on 20N, 86W).

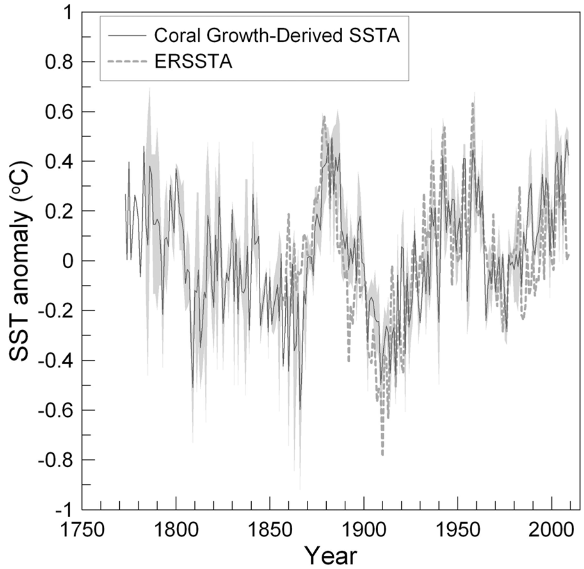

Figure 4. Yucatan sea surface temperature anomalies spanning the period 1773–2008 AD, reconstructed from the coral growth record using the growth-SST relationship established in Figure 3 (solid black line) compared with the instrumental record of annual sea surface temperature anomalies from 1860 to 2008 AD (NOAA Extended Reconstructed SSTV3b in a 2 × 2° grid box centered on 20N, 86W) (broken gray line). The correlation (r) between coral derived SSTA and ERSSTA for the overlapping time period is 0.66; $p < 0.01$.

before and after the calibration period. Further, the reconstructed SSTAs closely follow the mean ERSSTA for the period 1860–1880 AD even though the estimated error on the instrumental SST during this time is large: ±0.43°C.

[16] The reconstructed SST record suggests that SSTs remained within error of modern values through the late Little Ice Age. However, our record reveals a multidecade-long cool period at this time, ~1810–1850 AD. This pre-instrumental cool period was preceded by a warming that lasted at least 30 years. Thus, our data suggests that multidecadal variability, with approximately the same cycle length (~75 years) and amplitude observed in the instrumental record was a significant feature of the pre-instrumented Atlantic Ocean, at least since 1775 AD. This observation is in agreement with a previous coral growth rate based SST reconstruction from the Bahamas [*Saenger et al.*, 2009].

[17] Our annually resolved coral based SST record is compared with the undetrended, unsmoothed AMO SST Index in Figure 5. On annual timescales, the correlation (r) between derived SST and AMO Index is 0.56. We applied a 10-year low-pass Butterworth filter to the coral-derived SSTs and compared the filtered record with the 10-year filtered undetrended AMO Index (http://www.esrl.noaa.gov/psd/data/timeseries/AMO). The correlation between the coral-derived SST and the AMO Index on decadal timescales is $r = 0.70$; $p < 0.05$. In Figures 6a and 6b, we compare our SST reconstruction with the *Mann et al.* [2009] multiproxy AMO reconstruction and the *Gray et al.* [2004] tree ring-based AMO Index, respectively. The timing of variability is consistent between our marine record and the two terrestrial proxy records, for the overlapping time period. The amplitude of SST variability on AMO timescales, which is ~0.6°C in the instrumental record, is accurately captured by our coral-based record and the *Mann et al.* [2009] reconstruction. We cannot make a direct amplitude comparison with the *Gray et al.* [2004] reconstruction because their data are reported in standard deviation units.

[18] Our results and those of *Saenger et al.* [2009] show that annual growth rates of *S. siderea* at Yucatan, Bahamas and Belize (i.e., the sites studied to date) track multidecadal SST variability. Similarly, *Cantin et al.* [2010] reported a strong inverse correlation between annual linear extension and calcification of the massive Indo-Pacific species *Diploastraea heliopora* and SST. However, the observed relationship between coral skeletal growth rates and temperature is not always inverse nor is it always as tightly correlated as it is in these studies. For example, multiple laboratory experiments and field observations show that coral growth and calcification rates increase with increasing SST, at least until a critical threshold temperature is reached, after which skeletal growth rates decline [*Clausen and Roth*, 1975; *Lough and Barnes*, 2000; *Bessat and Buigues*, 2001; *Marshall and Clode*, 2004; *Carilli et al.*, 2009]. A downcore extension rate compilation from Flower Gardens, Gulf of Mexico [*Slowey and Crowley*, 1995] shows a decline in coral growth attributed to Pacific climate variability. This decline in growth also coincides with a sharp drop in SST, suggesting that linear extension rates of the coral *Montastraea annularis* are positively correlated with SST at this location. Conversely, *Carricart-Ganivet* [2004] reported a strong inverse

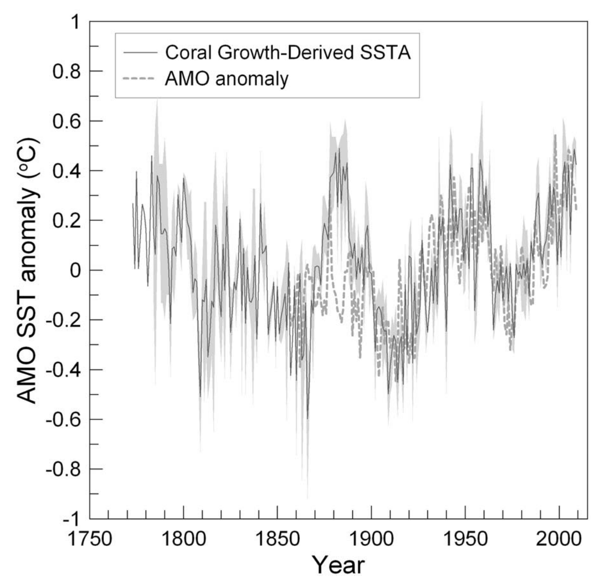

Figure 5. Yucatan sea surface temperature anomalies spanning the period 1773–2008 AD, reconstructed from the coral growth record using the growth-SST relationship established in Figure 3 (solid black line) compared with the unsmoothed, undetrended AMO SST anomaly (0 to 70N) calculated from the Kaplan EXT SST V2 (http://www.esrl.noaa.gov/psd/data/timeseries/AMO/) (dashed gray line). The correlation (r) between coral derived SSTA and the AMO SST anomaly for the overlapping time period is 0.56; $p < 0.01$ on annual timescales, and 0.70; $p < 0.05$ on decadal timescales.

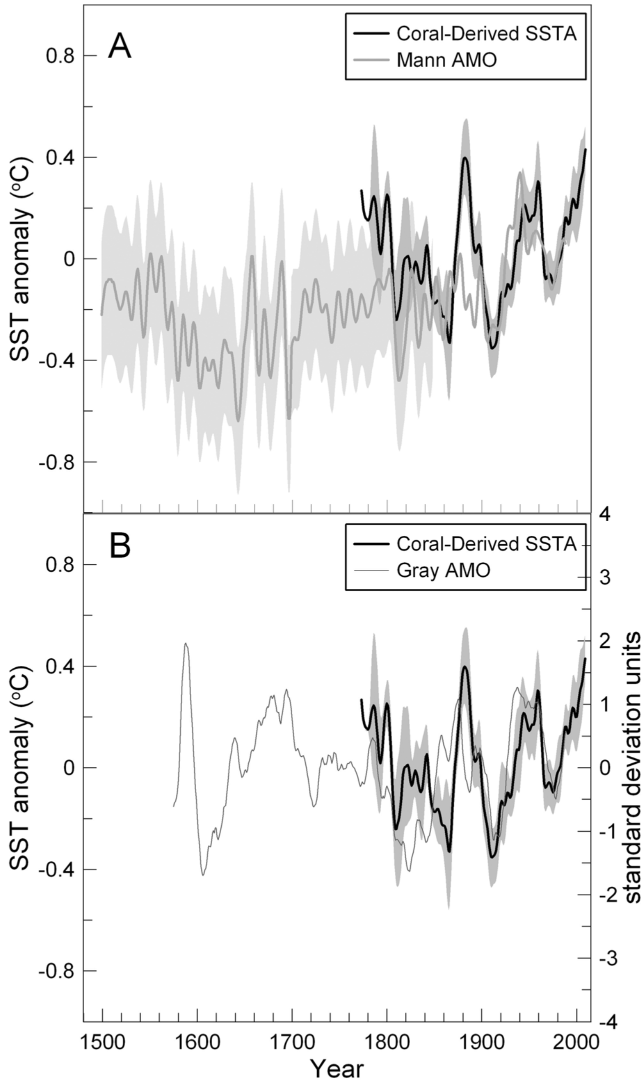

Figure 6. Sea surface temperature anomalies derived from our coral growth record compared against other proxy records of Atlantic multidecadal variability. (a) Decadally filtered coral derived SSTAs for the Yucatan (this study) shown against the decadal sea surface temperature reconstruction for the North Atlantic AMO region by *Mann et al.* [2008]. The error estimates on both proxy reconstructions are indicated by the gray shading. (b) Decadally filtered coral derived SSTAs for the Yucatan (this study) shown against the northern hemisphere tree ring based AMO reconstruction of *Gray et al.* [2004], also decadally filtered. Note in Figure 6b, units are different for each record. The coral proxy data are reported as SST anomalies whereas the Gray AMO data are reported in standard deviation units.

correlation between skeletal extension and SST for the Atlantic coral *Montastrea annularis* in the Gulf of Mexico, but this was based on a spatial rather than temporal correlation.

[19] Multiple factors, in addition to temperature, are known to influence coral growth rates, including light [*Barnes and Chalker*, 1990], flow [*Scoffin et al.*, 1992], heterotrophic feeding [*Ferrier-Pagès et al.*, 2011] and the aragonite saturation state of seawater [*Langdon et al.*, 2000]. It is possible that SST dominates over these other variables in driving coral growth at Yucatan, Bahamas and Belize, but it is also possible that in other regions or in less exposed parts of reefs, these other factors could dominate over SST. It is also possible that the strong inverse correlations between coral linear extension rate and SST that we observe at Yucatan, Bahamas, and Belize, and that others have observed elsewhere, is mediated through another mechanism. Ultimately, a better understanding of the factors that control coral growth rates is desirable, as such an understanding will improve our ability to use these records to reconstruct past oceanographic conditions. Thus, as with all paleo-temperature proxies, careful calibration is needed before growth rates are applied to reconstruct past SST.

[20] The amplitude of Yucatan SST variability implied by the coral-based SST reconstruction is similar to that inferred from Mg/Ca of planktonic foraminifera from a Cariaco Basin sediment core, where the authors calibrated downcore Mg/Ca variations against the instrumental SST record [*Black et al.* 2007] (Figure 7). This approach was not possible in several lower resolution records from the Gulf of Mexico [*Richey et al.*, 2009] and northern Caribbean Sea [*Lund and Curry*, 2006] where instead, published core top (spatial) calibrations were applied. Records from the northern Caribbean [*Lund and Curry*, 2006], and one Gulf of Mexico site (Garrison Basin) [*Richey et al.*, 2009] exhibit similar amplitude of variability to our coral-growth based reconstructions and the Cariaco Mg/Ca record. Conversely, another foraminifer-based Mg/Ca record from the northern Gulf of Mexico (Fisk Basin) suggests a 2–3°C warming since the LIA [*Richey et al.*, 2009], greater than implied by the other foraminifer-based Mg/Ca and coral growth records

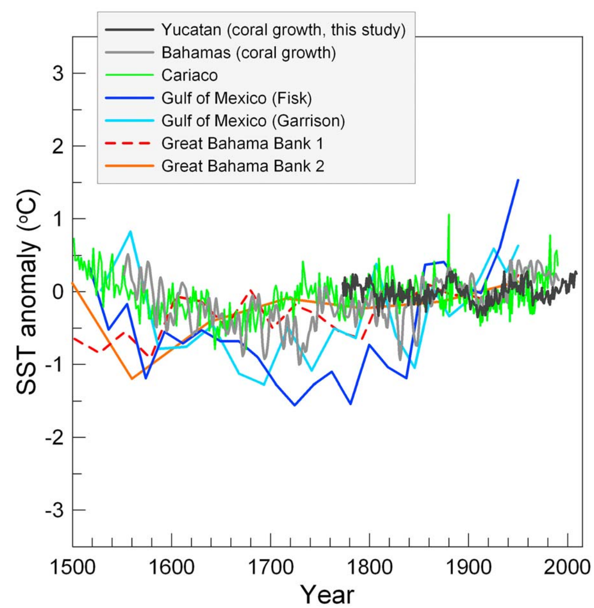

Figure 7. Coral-growth rate SST reconstructions in thick gray (this study) and black [*Saenger et al.*, 2009] compared to SST foraminifer Mg/Ca-based SST reconstructions from the Caribbean [*Black et al.*, 2007; *Lund and Curry*, 2006] and Gulf of Mexico [*Richey et al.* 2009]. All records are normalized to their 1800–2000 A.D. mean.

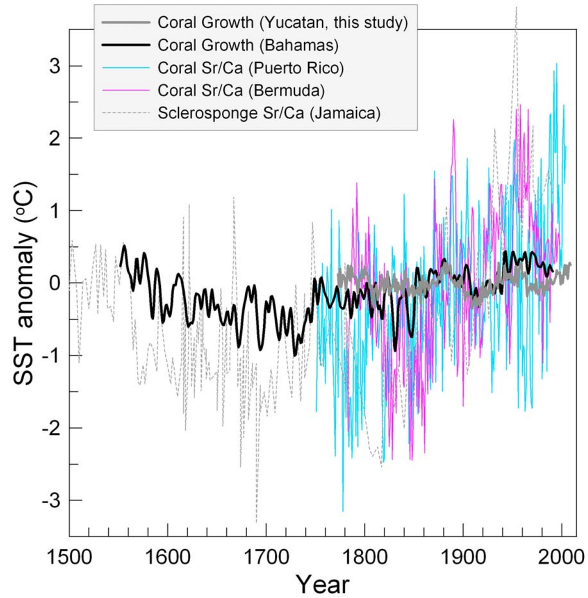

Figure 8. Coral-growth rate SST reconstructions in thick gray (this study) and black [*Saenger et al.*, 2009] compared to coral Sr/Ca-based SST reconstructions from Puerto Rico (blue [*Kilbourne et al.*, 2008]) and Bermuda (pink [*Goodkin et al.*, 2008]), and to a sclerosponge (20 m water depth) Sr/Ca-based temperature reconstruction from Jamaica (dotted gray line [*Haase-Schramm et al.*, 2003]).

(Figure 7). However, the amplitude of mean annual SST variations over the instrumental period is overestimated by the Fisk Basin Mg/Ca record, suggesting that this record may overestimate past regional SST variability.

[21] While the amplitude of SST variability implied by our Yucatan and Bahamas coral growth-based reconstructions is consistent, at least within error, with that implied by most tropical Atlantic Mg/Ca records, it is inconsistent with that implied by SST reconstructions based on coral and sclerosponge geochemistry (Figure 8). Recently, a >250-year-long Sr/Ca record was generated from a *Montastraea faveolata* coral core from Puerto Rico [*Kilbourne et al.*, 2008, 2010]. Applying a Sr/Ca-SST calibration developed previously for *M. faveolata* based on seasonal Sr/Ca cycles [*Swart et al.*, 2002] would suggest a >2°C warming at this site since 1750 AD compared with the ~0.5°C warming between 1750 and 1990 AD implied by the coral growth records. Taken at face value, Sr/Ca ratios from a second, older core imply an almost 4°C warming since ~1670 AD compared with ~1°C since 1670 AD implied by the coral growth records. However, *Kilbourne et al.*, [2010] attribute this exaggerated warming to difficulties with the interpretation of coral Sr/Ca ratios. Specifically, they propose that inter-coral variability in baseline (mean) Sr/Ca ratios, which can differ significantly between colonies of the same species, growing at the same site [*Goodkin et al.*, 2005; *Saenger et al.*, 2008], could explain at least part of the exaggerated signal. In addition, coral Sr/Ca ratios can be contaminated by the presence of secondary aragonite, which has a higher Sr content, yielding cooler SST estimates [*Cohen and Hart*, 2004; *Sayani et al.*, 2011]. However, in this instance, *Kilbourne et al.*, [2010] were careful to avoid diagenetically altered regions of the cores. A Sr/Ca-based SST reconstruction from a *Diploria labyrinthiformis* coral core from Bermuda also implies much larger changes in SST than both the Yucatan and Bahamas records over the corresponding time period [*Goodkin et al.*, 2008]. Applying a Sr/Ca-SST calibration that is corrected for growth-rate effects on coral

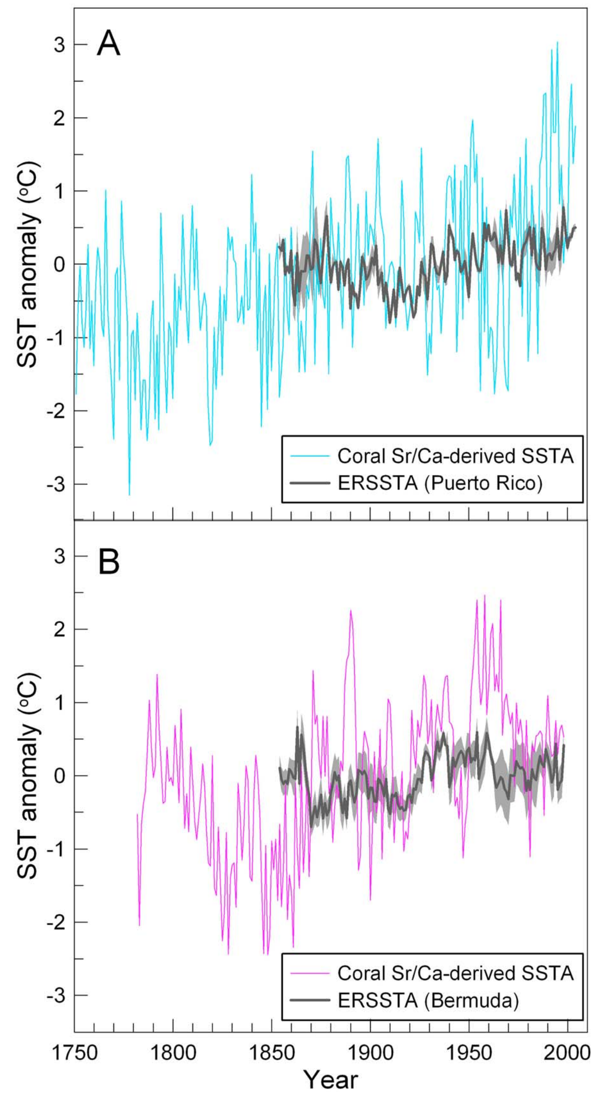

Figure 9. Annually resolved sea surface temperature anomalies for two Atlantic sites reconstructed from the skeletal geochemistry of long-lived corals. (a) An SST anomaly reconstruction for Puerto Rico based on coral Sr/Ca ratios [*Kilbourne et al.*, 2008, 2010] using the Sr/Ca-SST calibration equation derived by *Swart et al.* [2002] (light gray line) compared with the instrumental record of sea surface temperature (NOAA Extended Reconstructed SSTV3b in a 2 × 2° grid box centered on 18N, 68W) (dark gray line). (b) An SST anomaly reconstruction for Puerto Rico based on coral Sr/Ca ratios [*Goodkin et al.*, 2008] (light gray line) compared with the instrumental record of sea surface temperature (NOAA Extended Reconstructed SSTV3b in a 2 × 2° grid box centered on 32N, 64W) (dark gray line). In both panels, the gray shading on the instrumental SST is the estimated error on the analyzed ERSST.

Sr/Ca ratios [*Goodkin et al.*, 2005] implies that average annual SSTs at Bermuda were more than 4°C cooler during the late Little Ice Age than they were during the mid-1900s (Figure 8). Finally, we compare the temperature reconstruction based on Sr/Ca from a sclersoponge collected from 20 m water depth, in Montego Bay, Jamaica [*Haase-Schramm et al.*, 2003]. Following the authors, we assume a sensitivity of 0.1 mmol/mol/°C. This reconstruction implies similarly large SST excursions during the late Little Ice Age as implied by the coral Sr/Ca reconstructions. Using a more recent calibration [*Rosenheim et al.*, 2004], would increase the amplitude of temperature variability. As noted by the authors, this record greatly overestimates the amplitude of SST variability over the instrumental period, and they thus suggest that the record reflects thermocline temperature variability.

[22] In Figure 9, we compare the annually resolved Sr/Ca-based SST anomalies at Puerto Rico and Bermuda with the 150-year-long instrumental record of SST for a 2 × 2° grid centered on both study sites. The blue (Figure 9a) and pink lines (Figure 9b) represents the Sr/Ca SST anomaly reconstructions at Puerto Rico and Bermuda respectively, and the bold gray lines represent the ERSST anomalies; the ERSST errors are shown by shaded area. In both cases, the Sr/Ca-based SST reconstructions significantly overestimate the amplitude of the SST variability and trends over the period of the instrumental record. Thus, it is likely that SST variability prior to the start of the instrumental record is exaggerated in these records.

5. Conclusions

[23] Our conclusions can be summarized in five main points.

[24] 1. Three colonies of the massive coral *Siderastrea siderea* from eastern Yucatan exhibit similar annual growth rate chronologies over their interval of overlap.

[25] 2. Annual growth rates of all colonies are significantly, inversely correlated to regional SST.

[26] 3. Extending the record of instrumental SST using coral-proxy data shows an additional multidecadal SST cycle prior to instrumental record. This suggests that AWP multidecadal variability, and likely AMO variability, persisted since at least 1775 AD with an amplitude comparable to that of the instrumental era. Additional SST reconstructions are needed to confirm similar amplitudes before and after the industrial era.

[27] 4. Our data imply that tropical Atlantic SSTs remained within 1°C of modern values during the past 225 years, consistent with a previous reconstruction based on coral growth rates and most Mg/Ca-based sediment estimates.

[28] 5. Our results are inconsistent with Atlantic Warm Pool SSTs derived from coral Sr/Ca ratios as well as a foraminifera Mg/Ca-based reconstruction from one northern Gulf of Mexico site, all of which imply larger amplitude changes (>2°C) over the corresponding time period.

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