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A low latitude paleoclimate perspective on Atlantic multidecadal variability

K. Halimeda Kilbourne [a,*], Michael A. Alexander [b], Janet A. Nye [c]

[a] University of Maryland Center for Environmental Science Chesapeake Biological Laboratory, 146 Williams St., Solomons, MD 20688, United States
[b] NOAA Earth Systems Research Laboratory, 325 Broadway, R/PSD1 Boulder, CO 80305, United States
[c] School of Marine and Atmospheric Sciences, 107 Dana Hall, Stony Brook University, Stony Brook, NY 11974-5000, United States

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ABSTRACT

Traces of environmental conditions found in natural archives can serve as proxies for direct climate measurements to extend our knowledge of past climate variability beyond the relatively short instrumental record. Such paleoclimate proxies have demonstrated significant multidecadal climate variability in the Atlantic sector since at least the mid-1700s. However, Atlantic multidecadal climate variability is primarily defined by fluctuations in sea surface temperature (SST) and the proxy evidence comes from a variety of sources, many of which are terrestrial and are not directly recording sea surface temperature. Further analysis into the causes and consequences of Atlantic multidecadal climate variability requires development of a spatial network of decadal resolution proxy SST records with both low and high latitude contributions. An initial attempt at a low latitude Atlantic SST reconstruction found only 4 sites with ≤5 year resolution data, demonstrating the paucity of appropriate data available. The 4-site average correlated significantly with instrumental average SST and the Atlantic Multidecadal Oscillation (AMO). The full record, 1360–2000 C.E., and a shortened version 1460–1850 C.E., had significant multidecadal variability centered at a 60-year period. Comparing our reconstruction with reconstructions of SST anomalies in the North Atlantic shows that there is no consensus yet on the history of Atlantic multidecadal variability.

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1. Introduction

Multidecadal-scale sea surface temperature (SST) anomalies in the North Atlantic, often called the Atlantic Multidecadal Oscillation or AMO, after the editorial article by Kerr (2000), are a subject of great research interest. The AMO has been connected to physical processes such as African rainfall (Folland et al., 1986), Atlantic sector hurricane frequency (Goldenberg et al., 2001), and precipitation in North America (Enfield et al., 2001), as well as ecological processes such as lower trophic-level productivity and fish migration patterns (Lehodey et al., 2006; Nye et al., 2014-in this issue).

The widely used AMO index by Enfield et al. (2001) defines the phenomenon as a detrended SST anomaly in the North Atlantic but a rotated EOF analysis of global SST variability shows a horseshoe pattern of correlation over a broad region of the North Atlantic (Goldenberg et al., 2001). The EOF analysis produces two centers of action for multidecadal SST variability, one in the northern North Atlantic at about 45–60°N latitude, and one in the tropical North Atlantic south of about 20°N latitude (Goldenberg et al., 2001). The mid-latitude western Atlantic (about 20–45°N) does not correlate highly with the rest of the basin on these time scales and some areas may even have negative correlation with the rest of the basin (Goldenberg et al., 2001).

Understanding the past behavior and mechanisms behind this multidecadal temperature variability in the North Atlantic contributes toward improved forecasts of the climate system and the related climatologic and ecologic processes. The leading hypothesis for the cause of the North Atlantic temperature anomalies invokes changes in ocean circulation and ocean heat transport (Delworth et al., 2007). Atlantic Meridional Overturning Circulation (AMOC), transports heat from the southern hemisphere to the northern hemisphere, driving hemispheric surface temperature anomalies (Vellinga and Wu, 2004). AMOC includes a warm, salty northward flowing surface circulation that moves along with the wind-driven surface currents, including the Gulf Stream. This surface flow replaces water at higher latitudes that cools, looses buoyancy, and sinks to depth in the North Atlantic. The cold deep water moves southward in a deep western boundary current, contributing to the net northward heat flow. AMOC is likely not the only process affecting North Atlantic sea surface temperature (SST) on these time scales, but it has the potential to be a primary driver (Zhang et al., 2007). Evidence for the link between AMOC and AMO is primarily from modeling experiments (e.g., Knight et al., 2005), because the required long-term ocean circulation observations have only begun to be collected in recent years (Johns et al., 2010; Kanzow et al., 2010). Correlations between AMO and changes in water masses thought to be associated with AMOC provide circumstantial evidence for a connection between overturning circulation and AMO during recent decades (Kilbourne et al., 2007; Zhang et al., 2011), though the

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* Corresponding author. Tel.: +1 410 326 7205; fax: +1 410 326 7341.
E-mail address: kilbourn@umces.edu (K.H. Kilbourne).

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uncertainty inherent in the analyses leaves room for alternative explanations.

A major stumbling block for exploring the causes of the AMO is the relatively short length of instrumental records compared to the time scale of the phenomenon (Johns et al., 2010). The global SST record only goes back about 160 years, representing a little over two oscillations between negative and positive phases. Direct ocean circulation observations targeting AMOC from programs such as the RAPID-MOCA observation array have only been made for a few years (Johns et al., 2010). Such short record lengths make it difficult to determine the frequency of oscillatory cycles and to fully characterize the related processes. Thus, the name Atlantic Multidecadal Oscillation may be a misnomer because there is not enough evidence that the phenomenon is oscillatory with such a short instrumental record (Vincze and Janosi, 2011). Many authors describe the phenomenon as Atlantic Multidecadal Variability (AMV) instead of AMO; though for consistency with other papers in this volume we will continue using AMO in this paper.

Natural records of climate variability, known as paleoclimate proxies can supplement existing instrument-based observations to extend our records of climate to earlier periods. This paper describes recent contributions of paleoclimate work to our understanding of the AMO and highlights open questions. An analysis of existing data demonstrates the hurdles we still need to overcome and provides guidance for future research.

2. Summary of the paleoclimate literature addressing the AMO

The scientifically diverse audience for this paper warrants a brief explanation of paleoclimate data before delving into the nature of the AMO as evidenced in paleoclimate data. Climate system processes leave traces in natural archives such as marine and lake sediments, shells of marine organisms, glacial ice, and cave deposits. Different chemical, biological, and physical variables measured in these natural archives provide many types of information including ocean and air temperature, relative precipitation amounts, and changes in ocean circulation patterns. The chemical, biological and physical variables measured in natural archives are often referred to as “proxies” because they provide information in proxy to direct measurements of climate variables.

Paleoclimate proxy data have their advantages and disadvantages, like any other kind of data. The primary reason we use paleoclimate proxies is that they give us the ability to look back in time and extend our knowledge of Earth's systems to before we were widely recording measurements. One major advantage of paleoclimate data in relatively recent samples is that the recording processes only change on evolutionary and geologic time scales, unlike instrumental data where observation methods often shift through time and can cause increased uncertainty in identifying long-term processes. A challenge of paleoclimate data is limited spatial and temporal resolution. Each archive is sensitive to specific climate variables (e.g., temperature, salinity, water mass mixing), has a specific spatial distribution (e.g., tropics, high altitudes, mid-latitudes) and has a characteristic time domain (e.g., summer only temperatures, interannual resolution, 100–300 year length), limiting the spatial and temporal resolution of some types of information. Another challenge is that paleoclimate proxies are not perfect recorders of climate variables and it is important to acknowledge and address the uncertainties in the records during interpretation.

Like direct measurements of the climate system, local synoptic variations can impact variations at any given site, but the relatively broad spatial and temporal correlation of ocean and atmospheric variations can be utilized to represent larger scale processes. Just like the atmospheric pressure difference between Tahiti and Darwin, Australia represents the Southern Oscillation in the climate system, well-placed proxy measurements can be used to reconstruct specific climate processes such as the El Niño-Southern Oscillation, or in the case of this paper, the AMO.

One of the most common methods of reconstructing past temperatures is by determining the oxygen isotopic composition in biogenic $CaCO_3$, a method that was first proposed by Harold Urey (1947). The oxygen isotopic composition of inorganic $CaCO_3$ precipitated in equilibrium is a function of both the temperature of precipitation and the isotopic composition of the water from which it precipitates. Some organisms, including sclerosponges and foraminifera (Druffel and Benavides, 1986; Erez and Luz, 1983) precipitate their skeleton at or close to isotopic equilibrium with the surrounding seawater and behave similarly to inorganic $CaCO_3$ (Druffel and Benavides, 1986; Erez and Luz, 1983). Other organisms, such as corals have an isotopic composition with a mean offset from equilibrium but the skeletal isotopic *variations* respond to temperature and water isotopic composition just like the organisms that precipitate in equilibrium with the water (Weber and Woodhead, 1972). Isotope data are reported in delta notation, which expresses the isotopic ratio ($^{18}O/^{16}O$) in a sample (R_{smp}) relative to the isotopic ratio of a standard (R_{std}). The standard for marine carbonates is Pee Dee Belemenite (PDB). Delta notation is defined by the following equation.

$$\delta^{18}O = 1000 \times \frac{R_{std} - R_{smp}}{R_{std}}$$

Empirical and experimental equations have been determined that quantify the relationship between the three variables, temperature, water isotopic composition and carbonate isotopic composition for different taxonomic groups included in this study (e.g., Erez and Luz, 1983; Leder et al., 1996; Rosenheim et al., 2009). Seawater oxygen isotopic composition is primarily determined by salinity in the tropics over recent centuries, but water mass changes and global ice volume contribute over longer time scales. Oxygen isotopic data alone provide a convolved signal of temperature and water isotopic composition that can be de-convolved with an independent measure of temperature or water oxygen isotopic composition.

An independent method of determining temperature using $CaCO_3$ involves measuring Sr/Ca or Mg/Ca ratios in biogenic carbonates. These elements tend to substitute for the Ca in $CaCO_3$, with a distribution coefficient between the water and the mineral that is a function of temperature (Beck et al., 1992; Rosenthal et al., 1997). The distribution coefficient (D) in this case is defined as the ratio of the Sr/Ca molar ratio in the aragonite (Sr/Ca_A) to the Sr/Ca molar ratio in the liquid (Sr/Ca_L):

$$D = \frac{Sr}{Ca_A} \Big/ \frac{Sr}{Ca_L}$$

after equation (1) in (Kinsman and Holland, 1969).

The concentration of the elements in seawater is also important as the above equation makes clear, but is usually assumed to be constant for conservative elements with long residence times in the open ocean such as Mg and Sr. Although this is the traditional view of Mg and Sr, some variations in seawater Sr/Ca exist (de Villiers, 1999) and this could be a source of significant error in some records. $CaCO_3$ has two common mineral forms at Earth's surface temperature and pressure, aragonite and calcite. Sr/Ca ratios are used for paleotemperature reconstructions from aragonitic corals and sclerosponges, whereas Mg/Ca ratios are used in reconstructions from calcitic foraminifera. Empirical calibration studies provide the quantitative relationships between $CaCO_3$ element/Ca ratios and temperature (e.g., Rosenheim et al., 2005; Rosenthal et al., 1997; Swart et al., 2002). The rest of this section highlights recent contributions of paleoclimate work using these proxies to our understanding of the AMO.

A major focus of recent paleoclimate work on multidecadal time scales has been to generate proxy records with enough length and time resolution to robustly capture multidecadal-scale signals and use those records to characterize past behavior of the AMO. One of the early attempts to characterize multidecadal variability in paleoclimate data was Delworth and Mann (2000). These authors used the 5th eigenvector of a multi-proxy global climate reconstruction to demonstrate

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that the climate system has a concentration of variance with a time scale of about 70 years. Furthermore, they demonstrated that the spatial patterns of the observations were similar to those found associated with thermohaline circulation variability in multiple versions of the GFDL coupled ocean–atmosphere model. Acknowledging the need for more data and improved modeling work, Delworth and Mann (2000) laid out a framework that has guided many paleoclimate studies on multidecadal climate variability in the intervening time.

One null hypothesis and two competing alternative hypotheses tend to drive the paleoclimate discussion since the Delworth and Mann (2000) paper. The null hypothesis is that multidecadal variability in the climate system is simply random low frequency behavior (red noise), likely caused by the slow response of the ocean to higher frequency atmospheric noise. The first alternative hypothesis is that the multidecadal signal in the climate system is forced by some external factor such as volcanoes, anthropogenic aerosols or changes in solar irradiance. The second alternative hypothesis is that the climate system has an inherent internal mode of variability, like the El Niño-Southern Oscillation, with a concentration of variance at a characteristic time scale of multiple decades. Either of the two alternative hypotheses indicate that there can be a mechanistic understanding of the process causing such climate fluctuations and therefore this is a predictable process.

What do the data indicate? Many high-resolution (<25 years per sample) paleoclimate studies have produced data that correlate to the modern AMO during the 20th century (e.g., Hetzinger et al., 2008; Moses et al., 2006). Fewer extend before the instrumental period, although several studies have found substantial multidecadal variability in different types of paleoclimate data from various locations back to at least 1750 (Black et al., 2007; Delworth and Mann, 2000; Gray et al., 2004; Haase-Schramm et al., 2003; Kilbourne et al., 2008; Knudsen et al., 2011; Saenger et al., 2009). An important caveat to the findings in these papers is that they explore a process that is defined as a North Atlantic sea surface temperature anomaly, whereas none of them reconstruct sea surface temperature anomalies over the entire North Atlantic. Instead, they rely on reconstructing local variables (such as temperature or precipitation) that are linked to larger scale processes such as the AMO during the recent period. Some of the studies rely heavily on tree ring records from various locations around the northern hemisphere which reflect temperature and/or precipitation over land (e.g., Delworth and Mann, 2000; Gray et al., 2004), while other records represent mostly hydrologic variability on decadal time scales (Kilbourne et al., 2008; Knudsen et al., 2011). The records with the strongest link to North Atlantic SST anomalies are paleo-SST records from locations that are spatially correlated to a broader region of the North Atlantic (Black et al., 2007; Saenger et al., 2009) but even those records have caveats about the potential for local/regional processes to influence the conclusions about North Atlantic-wide phenomena.

Recognizing that much of the existing paleoclimate data are not necessarily describing North Atlantic-wide multidecadal *SST anomalies*, one can still learn something about multidecadal-scale *climate* variability from the data. The longer records tend to see weaker multidecadal signals and stronger centennial-scale signals before 1750 (Black et al., 2007; Gray et al., 2004; Saenger et al., 2009), leading Saenger et al. (2009) to conclude that multidecadal climate variability is not a persistent feature of the climate system before about 1730 AD.

To test the persistence of strong multidecadal variability in the climate system, Knudsen et al. (2011) gathered the few existing high temporal resolution (<25 years) proxy records spanning the last 8000 years. They found a quasi-persistent 55–70 year signal in each record, concluding that the AMO is a regular, but intermittent, feature throughout most of the Holocene (the geologic period that started 10,000 years ago), consistent with the conclusion made by Saenger et al. (2009). The long lengths of the records contribute to small error bars and a compelling case. However, the fact that multiple proxies representing a variety of climate system variables and processes were used in their study keeps this from being a definitive study of Atlantic SST variability. Additionally, it is difficult to say from their analysis if the intermittent signal is real, or if the significant spectral peaks are among the 5% of spurious peaks expected for an analysis that sets a 95% confidence level. Further statistical and spectral analysis of the data could help differentiate between these possibilities.

Although these studies do not overwhelmingly support one or the other alternative hypotheses, the majority of these studies effectively conclude that the null hypothesis can be rejected; the climate system naturally has a concentration of variance at multidecadal scales that is larger than expected from a red noise background, at least since the mid 1700s. If we can reject the null hypothesis, the alternative hypotheses must be considered and authors of previous papers have argued for both alternative hypotheses.

Several studies point out the potential for external factors such as volcanic ash, anthropogenic aerosols and solar variability to have caused multidecadal SST fluctuations in the Atlantic (e.g., Booth et al., 2012; Mann and Emanuel, 2006; Ottera et al., 2010). However, the proposition that solar variations are a major contributor to multidecadal variability is not supported by long paleoclimate records (Knudsen et al., 2011). Aerosol and volcanic forcing are widely acknowledged as contributing to recent multidecadal variability, but some contribution from ocean forcing also seems likely (Ting et al., 2009; Zhang et al., 2007).

By far the most well supported alternative hypothesis is that multidecadal temperature variations are, at least in part, an intrinsic feature of the ocean–atmosphere system. Many general circulation models (GCMs) contain intrinsic North Atlantic temperature fluctuations that can be linked to AMOC (e.g., Delworth et al., 1993; Timmermann et al., 1998; Vellinga and Wu, 2004). The strongest evidence lies in studies such as Delworth and Mann (2000) and Delworth et al. (2007), which demonstrate that the observed patterns of climate variability in paleoclimate proxy data are similar to the patterns caused by AMOC perturbations in models. However, the mechanism for AMOC variation on multidecadal to centennial time scales differs between models and even versions of the same model (Danabasoglu, 2008) and the paleoclimate data to our knowledge has not yet yielded evidence in support of one particular mechanism. Future research linking paleoclimate data with proposed mechanisms based on model experiments could yield progress in our understanding of the AMO and its connections to AMOC.

3. Evidence for a link between AMOC and surface temperature

Evidence of a link between ocean circulation changes and hemispheric temperature anomalies on multidecadal time scales is still circumstantial. One area of focus has been to identify the amount of equatorial water brought into the Caribbean in the North Brazil Current (NBC) and its eddies, because the NBC is a primary conduit for surface water transport between the northern and southern hemispheres. Kilbourne et al. (2007, 2008) used coral radiocarbon as an ocean water mass tracer to document a shift in the amount of equatorial water entering the Caribbean in the 1970s that coincided with a switch from warming to cooling temperature anomalies in the AMO. More recently, five decades of NBC transport observations have been compiled from shorter physical oceanographic studies (Zhang et al., 2011). The results show a significant correlation to Labrador Sea Water thickness, thought to be related to AMOC strength, and a significant correlation (at zero lag) with the AMO index (Enfield et al., 2001), providing further observational evidence of a link between the AMO and AMOC.

Paleoclimate research has amassed significant evidence of a connection between deep ocean overturning in the northern North Atlantic and hemispheric temperature anomalies over centennial to millennial time scales (Stanford et al., 2011). Several past climate events have been blamed on a shutdown or slowdown of AMOC. The most recent event is the Little Ice Age (~1450–1850 C.E.), which was recently linked to reduced AMOC due to ice sheet expansion caused by volcanism (Miller et al., 2012; Zhong et al., 2011). According to this hypothesis,

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volcanic aerosols reduced temperatures and caused ice sheet expansion, which limited air–sea heat exchange and diminished high latitude deep ocean convection. It should be noted that this is only one hypothesis and that other mechanisms for the Little Ice Age have been proposed.

Evidence from marine sediment cores and ice cores of abrupt cooling events over the last glacial and deglacial period led to the proposition that these millennial-scale events were caused by changes in the amount of meridional overturning circulation (Broecker and Denton, 1989). This premise has held up as a cause of several events in the geologic record through much investigation and the development of new proxies for ocean circulation (Austin et al., 2011; Boyle and Keigwin, 1987; Broecker and Denton, 1989; McManus et al., 2004; Murton et al., 2010).

4. Low latitude AMO synthesis

4.1. Introduction to the synthesis

Refining our picture of past the AMO behavior requires the generation of long, high-resolution paleo-SST records that can be synthesized into a time series analogous to the modern AMO index of Enfield et al. (2001). A multi-site reconstruction with records from both high and low latitudes ensures that both centers of action are included while avoiding undue influence from local processes at any single site. Obtaining enough records for separate low and high latitude networks is key because the signals may not be forced by the same dynamics (Ting et al., 2009).

A network of records will provide the best possible reconstruction of past North Atlantic SST behavior and it is worth considering the specific characteristics required of those records for successful the AMO reconstruction. Heslop and Paul (2011) suggested that annually resolved proxies are required to achieve a high enough signal-to-noise ratio. However, they only considered signal-to-noise ratios of single records that get averaged over time, not spatial networks of records that can be averaged over both space and time. Spatial averaging similarly increases the signal-to-noise ratio and does not require records with such high temporal resolution. Paleoclimate records longer than 420 years ensure a minimum of 6 repetitions of a 70-year oscillation, enough to identify the multidecadal band robustly out of the noise in the system, but longer records are needed to explore the interaction of the AMO with centennial and longer-scale climate variability. Sample sites located in North Atlantic regions that are highly correlated with the modern-day AMO index (Enfield et al., 2001) provide reconstructions that have a high likelihood of representing the AMO-related processes. Long, annually resolved SST reconstructions from the high latitude Atlantic are still unavailable to our knowledge, though several records are being developed currently. In the meantime, it is useful to explore a low latitude perspective of the AMO where we have a few high resolution, multi-century paleoclimate data sets.

The following is an analysis of multidecadal variability in the existing high resolution, low latitude paleoclimate proxies. A focus on the low latitudes is justified for two reasons. The first is that tropical SST anomalies are critical to tropical storm frequency, with increased tropical SST associated with more tropical cyclones (Goldenberg et al., 2001). Low latitude SST is only one of many possible drivers of hurricane activity, so a tropical Atlantic SST reconstruction would be valuable for comparing to reconstructions of hurricane frequency from the Atlantic basin (e.g., Donnelly, 2005; Donnelly and Woodruff, 2007; Woodruff et al., 2008). A second reason a tropical focus is of interest is that although SST observations and reanalysis data indicate a strong the AMO signal in the tropics (see Alexander et al., 2014-in this issue), climate modeling efforts indicate that the low and high latitude North Atlantic may not be equally involved in multidecadal variability (Ting et al., 2011). It is unclear if this difference is a deficiency of the models or if it applies to the real world (Alexander et al., 2017-in this issue). Independent SST constructions from high and low latitudes could lend support to one of these perspectives.

4.2. Methods

NOAA's World Data Center for Paleoclimatology and the Pangaea databases were mined for high-resolution (≤5 years/sample) SST-related proxy data in the tropical North Atlantic (latitude 0°–22°N) that extend the instrumental record (earliest date before 1880). We chose a slightly lower resolution than the recommended annual resolution (Heslop and Paul, 2011) in order to include more data. Several high-resolution SST reconstructions in the Atlantic come from Florida, Bermuda and the Bahamas which lie north of the 22° latitude delineation. We intentionally excluded these records because the SSTs in those regions are not part of the center of action for AMO (see figure 2 in Goldenberg et al. (2001)).

Six records from four sites met the criteria (Table 1, Fig. 1): sclerosponge Sr/Ca and $\delta^{18}O$ records from just south of Jamaica (Haase-Schramm et al., 2003), a foraminiferal Mg/Ca record from the Cariaco Basin (Black et al., 2007), coral Sr/Ca and $\delta^{18}O$ records from Puerto Rico (Kilbourne et al., 2008), and a coral growth record from the Yucatan peninsula (Vásquez-Bedoya et al., 2012). The coral record from Puerto Rico is supplemented with new data from the same site from an older coral (manuscript in preparation by K. H. Kilbourne) and both data sets supersede the previously published, much shorter, paleoclimate records from this site (Watanabe et al., 2002; Winter et al., 2000).

Each geochemistry record was converted to temperature using a proxy-specific calibration, two of which were based on a local calibration with the proxy data during the instrumental period and four of which were based on species-specific calibrations done elsewhere that are independent from the proxy data used in the reconstruction. The foraminiferal Mg/Ca (Black et al., 2007) and the coral growth records (Vásquez-Bedoya et al., 2012) were converted to temperature using the authors' calibrations of the data to instrumental temperature. The calibrations for the sclerosponge came from Rosenheim et al. (2005), whereas the calibrations for the coral Sr/Ca and $\delta^{18}O$ records came from Swart et al. (2002), and Leder et al. (1996) respectively. The successful application of an independent calibration equation to another dataset demonstrates that the reconstructed climate signal is not just based on fitting the modern data, but is based on relatively well-understood, reproducible processes that cause climate information to be recorded in natural archives. Unlike many multi-proxy reconstructions, we first turned the proxy variables into temperature units, thus eliminating the need to normalize the data by the standard deviations to keep the units comparable and enabling us to treat the proxy data as if it were instrumental temperature data.

Monthly instrumental temperature anomaly data from the ERSST3b dataset (Smith et al., 2008) provided comparison for our proxy data. Data were obtained from the grid-box that contained each site.

Both the proxy and the instrumental SST records were treated essentially the same way. The temperature anomalies relative to the 20th century mean from each site were degraded to 5-year resolution by integrative interpolation where each point represents the series mean between two endpoints using the software package Analyseries (Paillard et al., 1996). The individual 5-year resolution records were averaged to create two composite Caribbean SSTA records, one proxy and one instrumental. The proxy reconstruction spans 1225 to 2000 C.E., but 1225 to 1355 C.E. consists of only one record and the reconstruction is most robust from 1470 to 1990 C.E., the period of overlap between at least three of the records.

The analysis of the proxy records differed from that of the instrumental data in the following ways. The temperature estimates from Sr/Ca and $\delta^{18}O$ in the coral and sclerosponge records were averaged into a site-specific temperature estimate because both proxies are temperature dependent and we did not want to overweight these two sites

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Table 1
Tropical Atlantic SST proxy records with ≤5 year resolution that begin before 1880 C.E. from NOAA's World Data Center for Paleoclimatology and the Pangaea open access data library.

Reference	Proxy	Location	Lat	Lon	Start date (C.E.)	End date (C.E.)	Average resolution (years)	Local SST correlation to AMO	Proxy correlation to AMO
Black et al. (2007)	Foraminiferal Mg/Ca	Cariaco Basin	10.766	295.230	1221	1990	1.4	0.44	0.26
Kilbourne et al. (in prep)	Coral $\delta^{18}O$	Puerto Rico	17.933	292.999	1469	1669	1	0.65	N/A
Kilbourne et al. (2008)	Coral $\delta^{18}O$	Puerto Rico	17.933	292.999	1751	2004	1	0.65	0.48
Haase-Schramm et al. (2003)	Sclerosponge Sr/Ca	Jamaica	18.467	282.050	1356	1990	3.1	0.69	0.68
Vásquez-Bedoya et al. (2012)	Coral growth (3-coral average)	Yucatan Peninsula	20.83–20.74	273.04–273.26	1773	2009	1	0.70	0.67

when averaging all the data together. Using $\delta^{18}O$ as a temperature proxy implicitly includes any salinity-driven $\delta^{18}O$ signal into the temperature estimate but in the tropics warmer conditions are more often than not associated with wetter conditions and the direction of the $\delta^{18}O$ anomaly is the same in both instances, so the signal from a temperature anomaly is thus magnified and the signal-to-noise ratio is improved.

For the discontinuous Puerto Rico coral record, the gap between the two corals was filled with a value equal to the average of the 10 years of data on either side of gap ($N = 20$) before the temporal resolution was reduced. The gap impacts the spectral analysis of Puerto Rico coral data alone by increasing the power at centennial scales slightly, but there is little impact on multidecadal frequencies. Filling the gap with the mean reduces the impact on multidecadal scales and the composite record is even more robust to the influence of the gap.

We iterated the primary proxy reconstruction in two ways to test the robustness of the reconstruction. First we left out the results from a single site in iterative reconstructions to test the dependence of the signal on any particular location. Next we left out individual records, for instance leaving out the coral Sr/Ca-based SST record from Puerto Rico, but leaving in the $\delta^{18}O$-based SST record from Puerto Rico to test the dependence on any particular proxy record. In this example the Puerto Rico site would be represented by only the coral $\delta^{18}O$-based record instead of the average of the Sr/Ca- and $\delta^{18}O$-based data as usual. The variance of the exercise where we left out individual records was greater than the variance where we left out particular sites, so we use the former in subsequent time series analysis.

An analysis of the 7 reconstructions (6 iterations plus one reconstruction with all the data) in frequency space illuminated the periods of significant variance over the years 1360 to 2000 C.E. (the length of the reconstruction including at least 2 records). The centennial signal had to be removed before higher frequency variability could be investigated, much as a trend must be removed from shorter time series because of the potential for contamination via spectral leakage from the low frequencies to higher frequencies inherent in spectral analysis of finite length records, especially when the time series are short relative to the frequency of interest. These data will be referred to in this text as the detrended data. The first principal component of a Singular Spectral Analysis (SSA, (Ghil et al., 2002)) of the SST anomaly reconstruction provided an estimate of the long-term variations to be removed and was subtracted from the original reconstruction. SSA is a method of decomposing a time series into its primary modes of variability, in mathematically the same way that a spatial data set is decomposed into spatial Empirical Orthogonal Functions (EOFs).

Next, a multi-taper method (MTM) spectral analysis was performed on all 7 reconstruction iterations using the software Spectra (Ghil et al., 2002) with a bandwidth parameter of 2 ($p = 2$) and 3 tapers

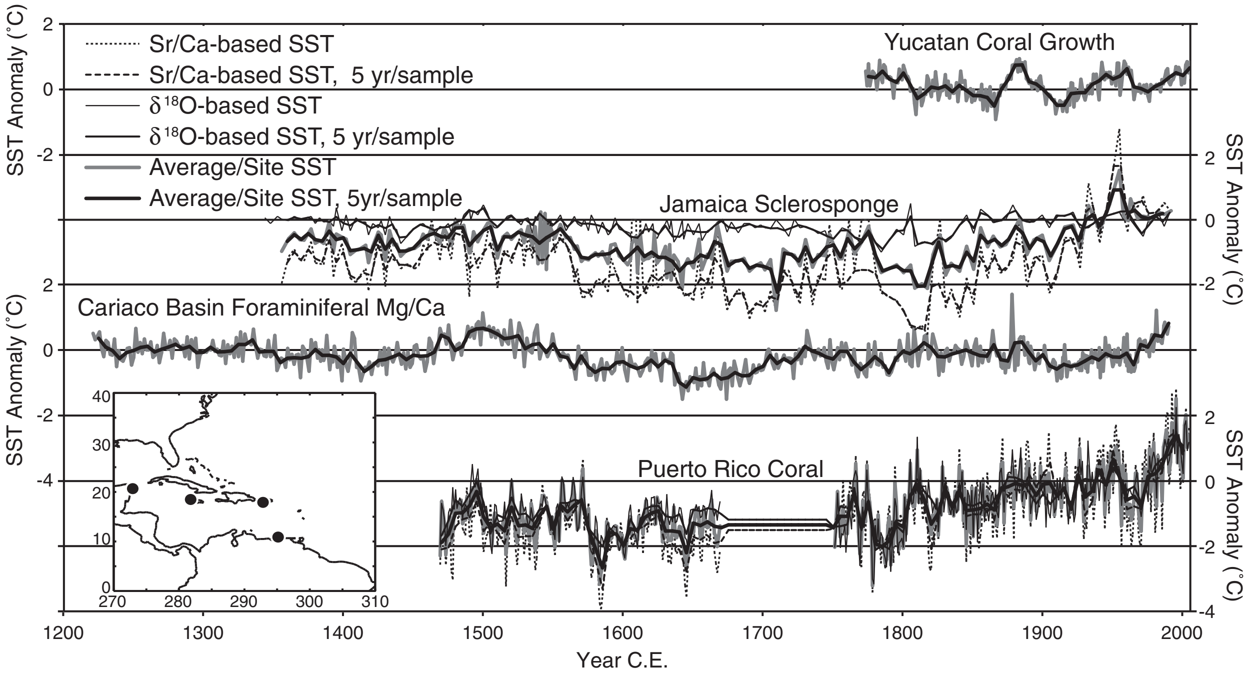

Fig. 1. Raw paleoclimate data used in the Caribbean SST reconstruction. B) Sclerosponge Sr/Ca-based and $\delta^{18}O$-based temperature anomalies from Jamaica (Haase-Schramm et al., 2003) using the calibration equation of Rosenheim et al. (2004). C) Cariaco basin foraminiferal Mg/Ca-based temperature reconstruction (Black et al., 2007). D) Puerto Rico coral $\delta^{18}O$-based and Sr/Ca-based temperature reconstructions, data from (Kilbourne et al., 2008) and Kilbourne un-published data. The $\delta^{18}O$ records from both the sclerosponge and coral may include significant contribution from regional salinity variability.

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(tapers $= K = 2 * p - 1$). Three tapers reduce the variance of the spectral estimate (the error bars on the spectrum) at a specific frequency by 3 fold compared a traditional Blackman Tukey analysis (Ghil et al., 2002) and the bandwidth parameter chosen here results in a spectral resolution of ±0.003 cycles/year. In other words, the spectral power at 0.016 cycles/year (59.9 years/cycle) averages the power between 0.019 cycles/year and 0.013 cycles/year (52.6 and 76.9 year periods). Changing the p and k parameters would impact the error bars on both power and frequency, but do not change the general results of the spectral peaks.

In order to test the robustness of the significant peaks from the first MTM analysis, a new SSA was calculated on the detrended primary reconstruction with all of the proxy data and the first 8 principal components were used to reconstruct a new time series that contains most of the variance from the original data. A second, similar MTM analysis was conducted on the reconstructed series (again $p = 2$, $K = 3$). This SSA–MTM process is a good check that the peaks found in the original MTM analysis are valid because the reconstructed series has a different noise spectrum and therefore different spurious peaks (Penland et al., 1991). All spectral analyses were tested against a first autoregressive (AR-1) red noise model.

Repeating the MTM analysis on the primary reconstruction for the years 1460 to 1850 C.E. provided a test of dependence of the results on the strong multidecadal variability during the 20th century.

5. Results

The Caribbean proxy SST anomaly record reproduces the modern regional SST anomaly over the years 1860 to 2000 C.E. with a standard error of ±0.34 °C. The decadal-scale variability of SST in this region as measured by the standard deviation of the 5-year average instrumental SST anomaly data used in the calibration is 0.44 °C. The two series are significantly correlated ($r = 0.66$, $p < 0.05$ for effective degrees of freedom $N = 9$ to 27) and the proxy data visually matches the regional SST composite over the period of overlap with a few years of exception (Fig. 2). The reconstruction is also correlated ($r = 0.66$) to the AMO index of Enfield et al. (2001), explaining 44% of the variance in that record, which is comparable to the correlation between the AMO and the regional SST composite ($r = 0.76$, 58% variance explained). The correlation of the detrended proxy and detrended AMO index gives a measure of the ability of the proxy reconstruction to reproduce Atlantic multidecadal signals alone and that correlation is strong as well ($r = 0.55$, 30% variance explained). These correlation coefficient values are comparable to good tree ring reconstructions, with the proxy reconstruction capturing 30–44% of the variance in the instrumental record, depending on which data are being compared.

A strong centennial-scale signal is visible in the SST anomaly reconstruction associated with the Medieval Climate Anomaly, Little Ice Age and modern warming trend (Fig. 3). The warmest temperatures during the earliest period (1225–1355 C.E.) should not be considered representative of the Caribbean as a whole because the data are purely from the Cariaco Basin, a location which saw a lower magnitude of centennial variability compared with the northern Caribbean records. The latter are consistent with centennial variability in subtropical records from the Gulf of Mexico (Richey et al., 2007).

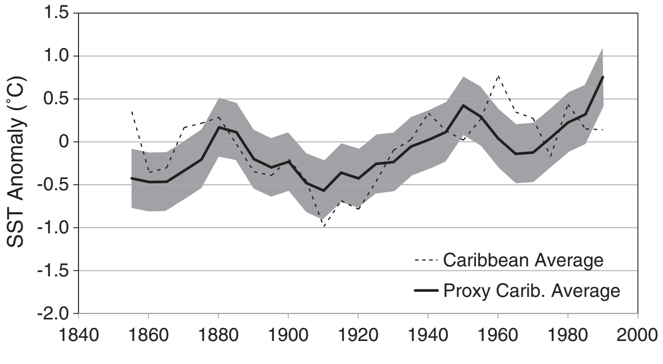

Fig. 2. Comparison of reconstructed temperature as an average of the SST proxies from the Caribbean (Proxy Carib average, bold line) with averaged instrumental temperature (Caribbean average, dashed line) from grid boxes nearest the proxy sample sites.

Spectral analysis of the detrended Caribbean SST anomaly reconstruction contained 3 significant peaks that were above a 95% confidence level relative to a red noise background (Fig. 4). The results were similar for all of the reconstruction iterations, and for the pre-20th century reconstruction. Similar peaks were found in MTM analyses using the un-altered temperature reconstruction and the detrended temperature reconstruction (Table 2). The only peak that exceeded the 95% confidence limit in both the MTM and the SSA–MTM analyses on the detrended data is centered at a period of 60 years, indicating that the Caribbean climate system has had a concentration of variance in the multidecadal band since at least 1360 C.E.

6. Discussion

The 520-year, multi-proxy record is sufficient to have good confidence in the identification of a 60-year period signal. These results are exciting because we demonstrate significant multidecadal SST variability over many centuries using a regional composite record from six different proxy types in four different locations with independent proxy-specific calibrations. Unlike results from studies that are dependent on a single location and a single proxy, using a network of marine proxies theoretically reduces the non-climatic and local climate noise inherent in individual records and gives us much more confidence in the results compared to single-record reconstructions. Additionally, these results are from marine temperature proxies being used to reconstruct ocean temperature, located in a region that directly responds to the AMO, unlike some studies that have used non-marine archives to attempt to reconstruct the AMO.

Comparison of our Caribbean SST results with other reconstructions of the AMO illustrates that much more work is needed before we have a consensus view of the past behavior of the AMO. Only two AMO reconstructions are available for comparison at National Ocean and Atmospheric Administration's World Data Center for Paleoclimate database (Gray et al., 2004; Mann et al., 2009). Both the AMO reconstructions rely heavily on mid-latitude tree ring data and neither has a focus on marine temperature proxies, the obvious choice if one is trying to reconstruct ocean temperature variability. Both the Gray et al. (2004) and Caribbean SST records are significantly correlated to the AMO index over the instrumental period, though they are not significantly correlated to each other (Table 3). It is impossible to compare the Mann et al. (2009) AMO reconstruction with these records during the instrumental period because the authors chose to provide a reconstruction only pre-1850. However the climate field reconstruction from which this record is derived has significant skill over much of the North Atlantic (Mann et al., 2009).

Despite the similarities during the instrumental period, all three records are quite different during the pre-instrumental era (Table 4, Fig. 5). Why might this be? The most likely culprit is the lack of available well-dated, high-resolution marine proxy temperature records. The Gray et al. (2004) dataset includes no marine records and although SSTs do influence continental temperatures, it is possible that much of the signal in that record represents substantial influence of other climate processes. The climate field reconstruction of Mann et al. (2009) is limited by the number and spatial location of data sets available, which makes the number of spatial degrees of freedom low and artificially makes the AMO and PDO reconstructions similar (Mann et al., 2009). The Caribbean SST reconstruction presented here is only representative of one region within the whole North Atlantic and thus misses the mid- and high latitude component of the Atlantic SST signal. Each of the records has their own strengths and weaknesses but none are likely

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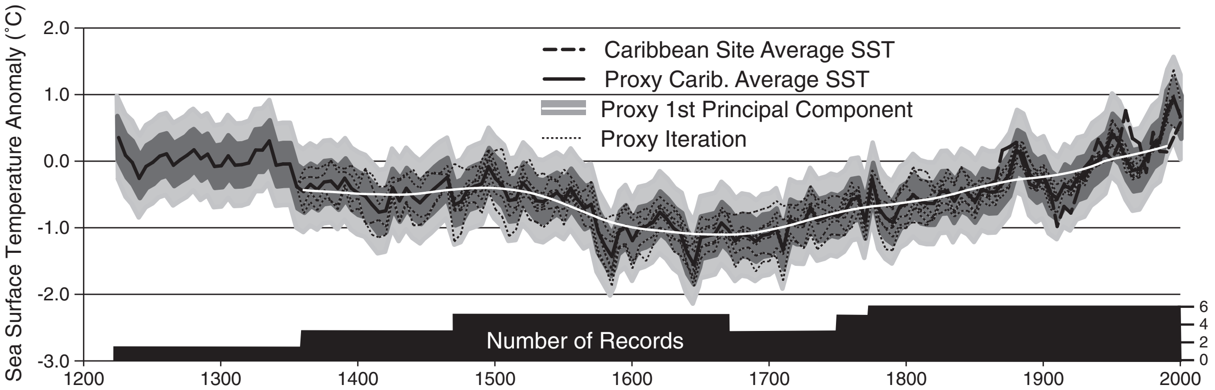

Fig. 3. Caribbean SST anomaly reconstructions from the proxy records in Fig. 1. First (dark gray) and second (light gray) standard error envelope is based on the standard error of regression between the reconstructed SST (black line) and instrumental SST (dashed line) during the most recent era. The first principal component (white line) is used to de-trend the data for time series analysis. The leave-one-out proxy reconstruction iterations from both the site-specific test and the record-specific test are shown (dotted gray lines). The instrumental Caribbean average dataset is the average of the ERSST data (Smith et al., 2008) from the grid boxes nearest the proxy sites, (68°W, 18°N; 80°W, 18°N; 65°W, 12°N).

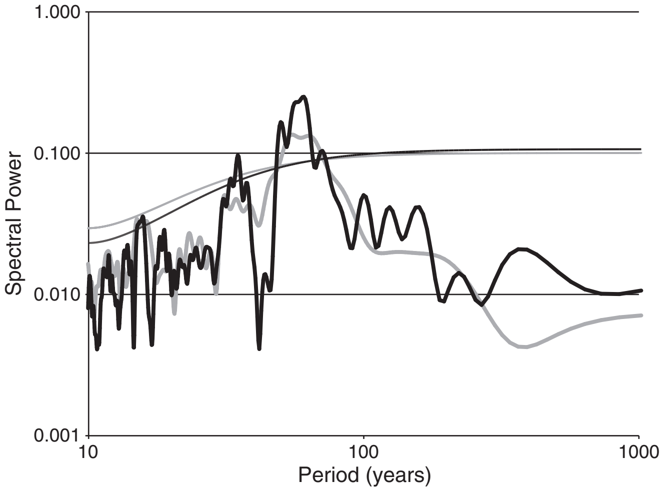

Fig. 4. Multi-taper method power spectra of the detrended reconstructed Caribbean SST based on sclerosponge, foraminifera and coral proxies for the periods 1360–2000 C.E. (black) and 1460–1850 C.E. (gray). The thin curves in black and gray indicate the 95% confidence level based on an AR-1 red noise model for each spectrum respectively. Note the variance conserving log–log plot has the feature that equal areas under the curve represent equal amounts of variance. The strongest peaks are centered at a ~60 year period for each time period.

to represent the actual history of the North Atlantic SST anomalies that are often used to define the AMO. However, the present analysis provides a tropical perspective that can be compared with regional perspectives from mid to high latitude Atlantic records to provide greater insight into multidecadal temperature variability in the Atlantic and thus AMO. A concerted effort to increase the number of high-resolution SST proxies available will enable future studies to make more robust estimates of the AMO past behavior.

Future work must expand the Caribbean SST reconstruction both temporally and spatially into a truly North Atlantic-wide SST reconstruction. Long records are usually lower resolution, but longer records can also give better spectral resolution because the Fourier Frequency (1/T,

Table 2
Periods associated with significant spectral peaks in the Caribbean reconstructed SST record. Associated confidence level exceeded is noted in parentheses.

1360–2000 Reconstructed temperature MTM	1360–2000 Detrended reconstructed temperature MTM	1360–2000 Detrended reconstructed temperature SSA–MTM	1470–1850 Detrended reconstructed temperature MTM
322 years (99%)		97 years (99%)	
56 years (99%)	61 years (99%)	57 years (99%)	55 years (99%)
35 years (95%)	35 years (95%)	42 years (99%)	15 years (90%)
16 years (95%)	16 years (95%)		
12 years (90%)			

Table 3
Pearson's correlation coefficients (r), between variables representing multidecadal SST signals during the instrumental era (1990–1860). Significant r-values are in bold as tested against 1 independent data point per decade of data.

	Proxy Caribbean average SSTA	Instrumental Caribbean average SSTA	AMO Index (Enfield et al., 2001)
Proxy AMO (Gray et al., 2004)	0.43	**0.60**	**0.81**
Proxy Caribbean avg.	1.00	**0.63**	**0.66**
Instrumental Caribbean avg		1.00	**0.77**

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Table 4
Pearson's correlation coefficients (r), between variables representing multidecadal SST signals during the pre-instrumental era (1855–1570). Significant r-values are in bold as tested against 1 independent data point per decade of data.

	Proxy AMO (Mann et al., 2009)	Proxy Caribbean Average SSTA
Proxy AMO (Gray et al., 2004)	0.04	**−0.50**
Proxy AMO (Mann et al., 2009)	1.00	**0.45**

where T = record length) is smaller and there are more repetitions of a cycle, so that one can confidently identify frequencies closer to the Nyquist frequency (1/2Δt, where Δt is the time resolution of the record). A novel method of increasing the length and resolution of reconstructed SST data is proxy-to-proxy calibration that quantifies the relationship between a direct, but usually time consuming and expensive SST proxy (such as alkenone unsaturation index U^{K}_{37}) and a less expensive, higher resolution data type such as x-ray fluorescence scans or in-situ reflectance spectroscopy (von Gunten et al., 2012). Networks of decadal-scale data (not multidecadal, because that is too close to the Nyquist frequency) spanning a few thousand years could be very valuable to complement the higher resolution data, as long as we are careful to use only SST proxies to reconstruct an SST-related phenomenon.

The modern AMO index is defined as a sea surface temperature signal integrated over the North Atlantic basin, so it is appropriate to similarly combine proxy records from a spatial network into one time series to get a reconstruction of the AMO (Mann et al., 2009). Examples of ocean paleotemperature proxies with consistently high temporal resolution include foraminiferal geochemistry from laminated sediments and growth rates or geochemistry from corals (Jones et al., 2009), long-lived pelecypods (Wanamaker et al., 2008), and coralline algae (Halfar et al., 2009). These proxies provide opportunity to create a multi-proxy marine network with a wide latitudinal distribution because massive reef-building corals are found at low latitudes whereas long-lived pelecypods and massive coralline algae tend to be found at higher latitudes and sediment cores can be taken at all latitudes. Focusing only on marine temperature proxies will generate data that directly reconstruct the process of interest (SST variability), steering clear of signals from other climate variables and the teleconnections that may have changed over time.

Once a North Atlantic SST history is established, spatial reconstructions such as Evans et al. (2002) and Mann et al. (2009) will be important to explore the coherence of high and low latitude signals and to help diagnose the processes involved in the real-world variability. Higher resolution spatial and temporal reconstructions paired with other key paleoceanographic and paleoclimatic data will help us eventually diagnose which of the many proposed model-based processes dominate the actual driving factors of multidecadal variability in the Atlantic.

7. Conclusions

Two main conclusions can be drawn from the literature reviewed and the data presented. The first is that multidecadal climate variability observed in paleoclimate data from many studies at least sporadically exceeds a red noise background. Secondly, the data are sparse but the data available are in the Caribbean and indicate a concentration of variance centered on a 60-year period that exceeds the red noise background since the mid-1300s C.E. A synthesis of existing ocean temperature reconstructions is needed in the future with both high and low latitude records to establish the common low and high latitude North Atlantic SST signals.

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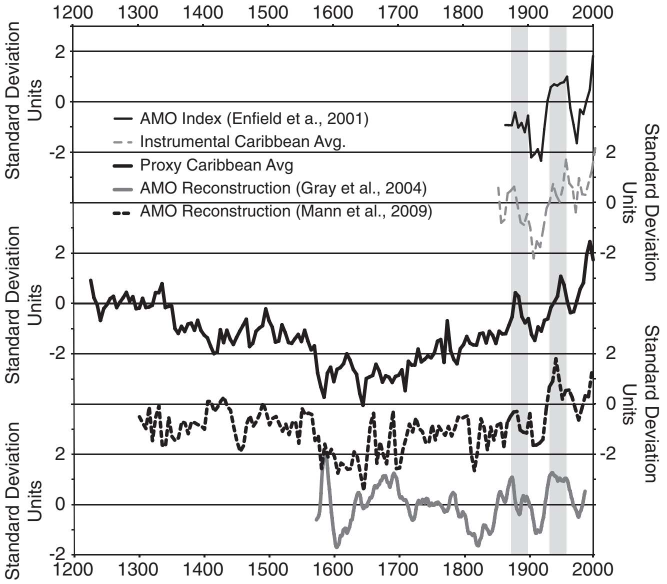

Fig. 5. Proxy reconstructions of Atlantic multidecadal variability correlate to instrumental records of SST anomalies during the modern period, but do not show coherent multidecadal-scale variability during the pre-instrumental period. All data sets were normalized by their z-scores and are in standard deviation units. The instrumental Caribbean average dataset is the average of the ERSST data (Smith et al., 2008) from the grid boxes nearest the proxy sites, (68°W, 18°N; 80°W, 18°N; 65°W, and 12°N). The gray bars represent eras of warm Atlantic SST as determined by the AMO index of Enfield et al. (2001).

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