Geophysical Research Letters

Observational and Model Evidence for an Important Role for Volcanic Forcing Driving Atlantic Multidecadal Variability Over the Last 600 Years

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Abstract The modern history of North Atlantic sea surface temperature shows variability coinciding with changes in air temperature and rainfall over the Northern Hemisphere. There is a debate about this variability and, in particular, whether it is internal to the ocean-atmosphere system or is forced by external factors (natural and anthropogenic). Here we present a temperature record, obtained using the Sr/Ca ratio measured in a skeleton of a sclerosponge, that shows agreement with the instrumental record over the past 150 years as well as multidecadal temperature variability over the last 600 years. Comparison with climate simulations of the last millennium shows that large cooling events recorded, in the sclerosponge, are consistent with natural (primarily volcanic activity) and anthropogenic forcings. There are, however, multidecadal periods not connected to current estimates of external forcing over the last millennium allowing for alternative explanations, such as internally driven changes in ocean and atmospheric circulation.

1. Introduction

Sea surface temperature (SST) variations in the Atlantic Ocean show strong multidecadal variability over the past 150 years (Enfield & Mayer, 1997), which we will refer to here as Atlantic Multidecadal Variability (AMV). However, there is debate as to the causes of this variability. Previous studies have argued a role for changes internal to the climate system such as the Atlantic Meridional Overturning Circulation (AMOC) (Frajka-Williams et al., 2017; Smeed et al., 2018; Zhang et al., 2019), or changes in atmospheric circulation (Clement et al., 2015), while others support external forcing (greenhouse gases, aerosols, solar forcing, and volcanic eruptions) (Bellomo et al., 2018; Bellucci et al., 2017; Birkel et al., 2018; Booth et al., 2012; Haustein et al., 2019; Mann et al., 2020; Murphy et al., 2017; Watanabe & Tatebe, 2019). It is difficult to resolve these issues since the instrumental record only contains a few multidecadal cycles over which the strength of these forcings vary considerably. Attempts to reconstruct the AMV over longer time periods have utilized the analyses of proxy archives such as tree rings (Gray et al., 2004; Mann et al., 2009; Wang et al., 2017), bivalves (Butler et al., 2011; Reynolds et al., 2013; Wanamaker et al., 2012), corals (Goodkin et al., 2008; Hetzinger et al., 2008; Kilbourne et al., 2008; Moses et al., 2006; Saenger et al., 2009), lake sediments (Burn et al., 2016; Hodell et al., 2005), ocean sediments and foraminifera (Cunningham et al., 2013; McGregor et al., 2015; Moffa-Sanchez, Born, et al., 2014; Moffa-Sanchez, Hall, et al., 2014; Moffa-Sanchez et al., 2019), and speleothems (Fensterer et al., 2010; Mann et al., 2009; Winter et al., 2011). Of these, tree ring records offer the potential to extend the record back in time with optimal temporal resolution, with the caveat that they do not directly represent measurements of SST. For example, the studies that used tree ring records and corals showed reasonable agreement with the instrumental record between the mid-19th century and present day; however, the records disagree prior to the instrumental period.

One proxy archive which has only been sparingly applied to the reconstruction of water temperature are sclerosponges. Sclerosponges have aragonitic skeletons, slow growth rates (100 to 300 μm/year) (Druffel & Benavides, 1986; Rosenheim et al., 2005; Swart et al., 2002; Willenz & Hartman, 1993), and are long-lived with some specimens in excess of 1,000 years old. Inhabiting vertical walls and caves between 20- and 400-m water depth, sclerosponges allow the study of oceanographic conditions outside of the range of

typical paleoclimate indicators. In the Atlantic Ocean, studies have focused on the species *Ceratoporella nicholsoni* which is typically found between 20- and 150-m water depth. As sclerosponges form their skeletons close to what is considered to be C and O isotopic equilibrium (Böhm et al., 2000), they act as recorders of both ambient temperatures and the $\delta^{18}O$ and $\delta^{13}C$ values of ambient H_2O and dissolved inorganic carbonate. The $\delta^{13}C$ values of sclerosponge skeletons have been shown to reflect the "$\delta^{13}C$ Suess Effect" resulting from increased CO_2 inputs to the atmosphere (and ocean) post industrialization (Böhm et al., 1996; Lazareth et al., 2000; Swart et al., 2010; Wörheide, 1998). Oxygen isotope values measured from sclerosponge skeletons of *Ceratoporella nicholsoni* (Atlantic) and *Astrosclera willeyana* (Indo-Pacific) are consistent with anticipated equilibrium values for local mean temperatures and water conditions (Böhm et al., 2000; Druffel & Benavides, 1986; Moore et al., 2000). The Sr/Ca ratio of sclerosponges has been shown to be temperature dependent and in some instances the Sr/Ca ratios and $\delta^{18}O$ values demonstrate seasonal variability (Haase-Schramm et al., 2003; Rosenheim et al., 2004; Swart et al., 2002; Waite et al., 2018). Using the Sr/Ca ratio as an indicator of temperature and the skeletal $\delta^{18}O_c$ value (which is dependent on both temperature and the $\delta^{18}O$ of the water [$\delta^{18}O_w$]), it is possible to determine the $\delta^{18}O_w$ value and, with knowledge of the relationship between $\delta^{18}O_w$ and salinity (Ganssen & Kroon, 2000), reconstruct past variations in salinity in the Atlantic. This approach has demonstrated that the salinity increase in the Atlantic recorded by Curry et al. (2003) between 1960 and 2000 was not part of a long-term increase, but rather related to increased evaporation driven by increases in temperature, related to the AMV, and winds associated with the North Atlantic Oscillation (NAO) (Rosenheim et al., 2005). In this study, we have extended the record of seawater temperature by using a sclerosponge specimen of *Ceratoporella nicholsoni* (LSI-4) collected live in 1993 off Lee Stocking Island (LSI) in Exuma Sound (76.0795°W, 23.7651°N), The Bahamas from a water depth of 133 m (Figure 1).

2. Methods

2.1. Age Dating

The ~11 cm in diameter sclerosponge specimen was sliced into a 2-cm-thick slab (Figure 1b). The slab was subsampled at seven locations in the skeleton by removing intact skeleton parallel to the growth bands with a diamond band saw or a diamond drill and the aragonite was cleaned following the procedures of previous studies (Chen et al., 1986; Edwards et al., 1986). Element separation procedure was based on Eichrom-UTEVA resin. Calculation of geochronological data and activity ratios use the decay constants of Cheng et al. (2000). The U-Th isotope measurements were performed on representative aliquots (approximately one third of original subsample) using a VG Elemental AXIOM MC-ICP-MS or a Thermo Neptune at GEOMAR applying the multistatic MIC-ICP-MS (multi-ion counting-inductively coupled plasma-mass spectrometry) approach after Fietzke et al. (2005). Further details are included in the supporting information.

2.2. Strontium/Calcium

Sampling was carried out using a computer controlled micro sampler (New Wave Research) with each sample located 0.1 mm apart and ~0.1 mg in size. A total of 1,088 samples were collected translating to ~1.8 samples/year. Of these 12 samples were discarded as a result of low yield. Further details of the sampling and analytical procedures are included in the supporting information and in Waite (2011) and Waite et al. (2018). Replicate analyses of an internal laboratory standard provide a precision of 0.01 mmol/mol at the 95% confidence limits. The total error including analysis and the conversion of the Sr/Ca ratio to temperature approximates to ~1°C (Waite et al., 2018).

2.3. Definition of the AMV

We define the AMV index as the spatially weighted averaged SST over the North Atlantic basin (0–60°N, 80°E to 0). This definition mimics the Enfield et al. (2001) index. We use a band-pass filter because detrending over both the preindustrial and industrial periods induces a spurious signal.

2.4. Statistics

Data were interpolated to yearly values using a rectangular interpolation method (Davis, 1973). In order to examine the multidecadal timescales, the data were filtered using a Butterworth band-pass filter to remove periods longer than ~90 years and shorter than ~20 years.
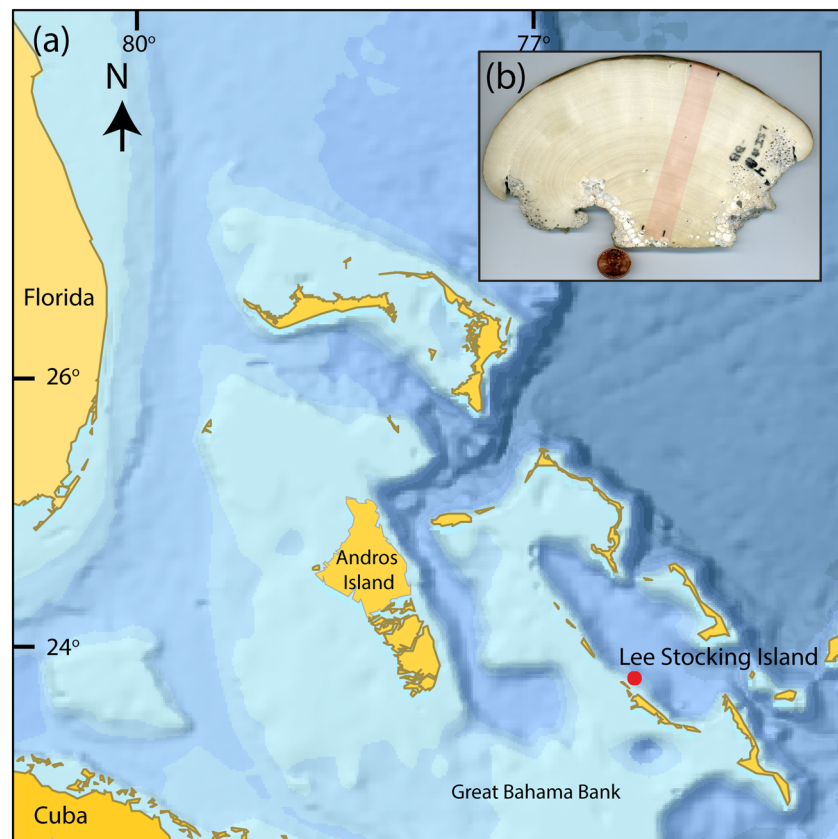
Figure 1. (a) Collection location of the sclerosponge specimen LSI-4 (Lee Stocking Island, The Bahamas). (b) Slab of the sclerosponge analyzed with the shaded region indicating the location of the sampled transect.

3. Results

3.1. Age Dating

The seven U/Th ages show a uniform growth rate for the LSI-4 specimen and (Figure S1.1) yield a maximum age of ~615 years ($R^2 = 0.9984$) at a depth of 10.9 cm below the oral surface. The samples were dated during three sessions between 2005 and 2019. Data from all three sessions and the associated error are included in the supporting information together with the relevant concentration data (^{238}U, ^{232}Th, and ^{230}Th) and ratios (^{234}U/^{238}U) for sessions in 2009 and 2019. Elemental concentrations and ratios are not available for the 2005 session. In order to assess the impact on the exclusion of the 2005 data upon the age model, a Monte Carlo approach was used following the methods of Anderson (1976) and Sohn and Menke (2002) to compare the age model with and without the 2005 data. This comparison found that there was no statistically significant difference between the models using all the data and the model in which the 2005 data had been removed and this is outlined in the supporting information. The specimen used in this study, consistent with other sclerosponge samples collected in The Bahamas, exhibits a nonzero age for the surface of the samples. This is a result of the incorporation of a small quantity of initial ^{230}Th into the skeleton which for this sample provides a surface age of ~54 years in the future. Explanations for this incorporation are discussed by Rosenheim et al. (2006). Correcting for this effect provides a skeletal record between 1378 and 1993 and a growth rate of 178 μm year^{-1}, in excellent agreement with other sclerosponges collected from the same locality (Rosenheim et al., 2006) that show a depth dependent growth rate (Figure S1.1). The 95% confidence error based on the regression alone is ~ ±8 years, an uncertainty approximately equal to the 95% uncertainty in the age estimate of the individual data points. All data and age uncertainties are provided in the supporting information.

3.2. Strontium/Calcium

The mean Sr/Ca ratio of the LSI-4 sclerosponge is 10.29 mmol/mol ($n = 1,076$) and ranges between 9.98 and 10.55 mmol/mol. Interpolated data are included in the supporting information. The Sr/Ca ratios of the sclerosponge were converted to water temperature using the equation proposed by Waite et al. (2018) (Equation 1) (Figure 2a).

$$Sr/Ca = 13.7 - 0.147 * T \qquad (1)$$

This translates to a range in annual temperature (1385–1993) between 21°C and 25°C ($m = 23°C$). The error on this equation is discussed in section 4.1.

## 4. Discussion

4.1. Variations in Temperature

The temperature record calculated from the LSI-4 sclerosponge can be separated into two portions, the first between 1385 and 1800, during which there is no long-term change in temperature ($m = 23$, $\sigma = 0.5$), and the second, from 1800 to 1993, during which there is an increase of between 1.5°C and 2.0°C related to anthropogenic warming ($m = 23.96$, $\sigma = 0.3$) (Figure 2a). This latter change is greater than the mean estimate of 1.0°C presented by the IPCC (2013) but nevertheless consistent with increases in temperature calculated using scleractinian corals from Puerto Rico (Kilbourne et al., 2008). The increase is also not an unreasonable change considering that this sclerosponge inhabited a water depth of 133 m and is therefore ideally located to detect a thickening of the thermocline caused by a warming of the surface oceans (Haase-Schramm et al., 2003). Between 1856 and 1993, the period of the instrumental record, the temperatures reconstructed from the sclerosponge show similar decadal deviations from the detrended mean to those observed in the AMV and from the SST record from the nearest 1° × 1° grid square to the sclerosponge (Figures 2b–2d).

While the range of temperatures are significantly greater in both the sclerosponge record (Figure 2b) and in the local SST data (Figure 2c), when compared to the AMV (Figure 2d), the local SST shows strong correlation with the AMV (Figure 2e), indicating that variations at this site reflect the basin-wide changes. The larger amplitude temperature variations (compared to the AMV), both in the local SST and in the sclerosponge, are not unexpected considering that the AMV represents the mean of temperature readings taken over a large region of the North Atlantic while the waters surrounding The Bahamas are influenced by local heating and cooling of the shallow water on Great Bahama Bank. These waters affect the adjacent open ocean and during the winter and summer high-density bank top plume waters cascade into adjacent deeper water (Hickey et al., 2000) thus affecting their temperature. The mean water temperature calculated from the Sr/Ca ratio between 1856 and 1993 (23.9°C) is statistically identical to the estimate (23.8°C) at this depth calculated from the in situ water temperature data collected at 104 and 146 m at Lee Stocking Island between 1987 and 1995 (Swart et al., 1998). On multidecadal timescales, the correlation coefficients between the temperature reconstructed from the sclerosponge record and various estimates of surface water temperature in this region are +0.55 (Extended Reconstructed SST) (Huang et al., 2017) and +0.45 (Hadley Center SST) (Kennedy et al., 2011), all statistically significant ($p < 0.02$). Hence, while the error based on the correlation between water temperature and the Sr/Ca ratio is ~1°C (Waite et al., 2018), the agreement of the temperature estimated from the sclerosponge with the observed data suggests that this calibration related error is an over estimate and that the temperature calculated from the sclerosponge Sr/Ca ratios accurately reflects both the absolute and range of temperatures observed in the area.

While some other proxy reconstructions of temperature show good agreement with the AMV (Hetzinger et al., 2008), others depict multidecadal variability that is asynchronous with the AMV (DeLong et al., 2014; Goodkin et al., 2008; Kilbourne et al., 2008; Vásquez-Bedoya et al., 2012). These discrepancies can result from a combination of factors and may relate to the fact that coastal corals often are subject to high frequency local signals (e.g., runoff and winds) that may mask the AMV signal. In contrast, a temperature record based on variations in growth rate of a coral from The Bahamas (Saenger et al., 2009) shows many similar characteristics to the LSI-4 sclerosponge and tree ring reconstructions (Gray et al., 2004; Mann et al., 2009; Wang et al., 2017). Other proxy records obtained from lake sediments (Hodell et al., 2005),
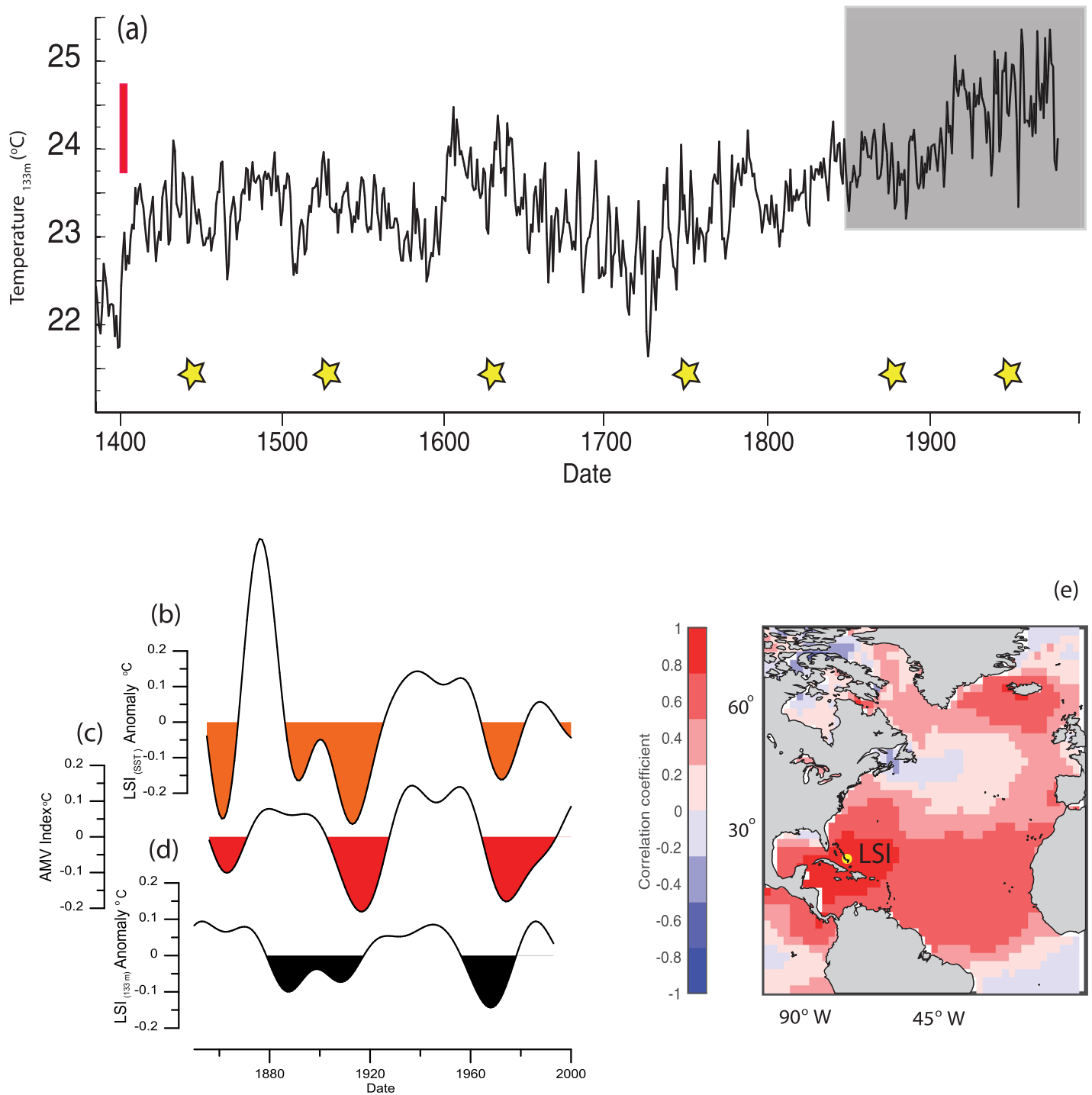
Figure 2. (a) The temperature calculated from the Sr/Ca ratios measured in the LSI-4 sclerosponge; the red rectangle represents the error based on the calibration between the Sr/Ca ratios and temperature (Waite et al., 2018) and the stars the locations of samples taken to date the sample. The gray box indicates the period of instrumental data and the band-pass filtered signal for the nearest 1° × 1° square to the location of the sclerosponge (Huang et al., 2017), (c) the AMV signal, and the temperature signal calculated from the Sr/Ca ratios of the sclerosponge and shown in (b), (c), and (d). (e) The correlation between sea surface temperature (Huang et al., 2017) and the AMV index. The LSI grid square (yellow dot) shows one of the highest correlation coefficients with the AMV index.
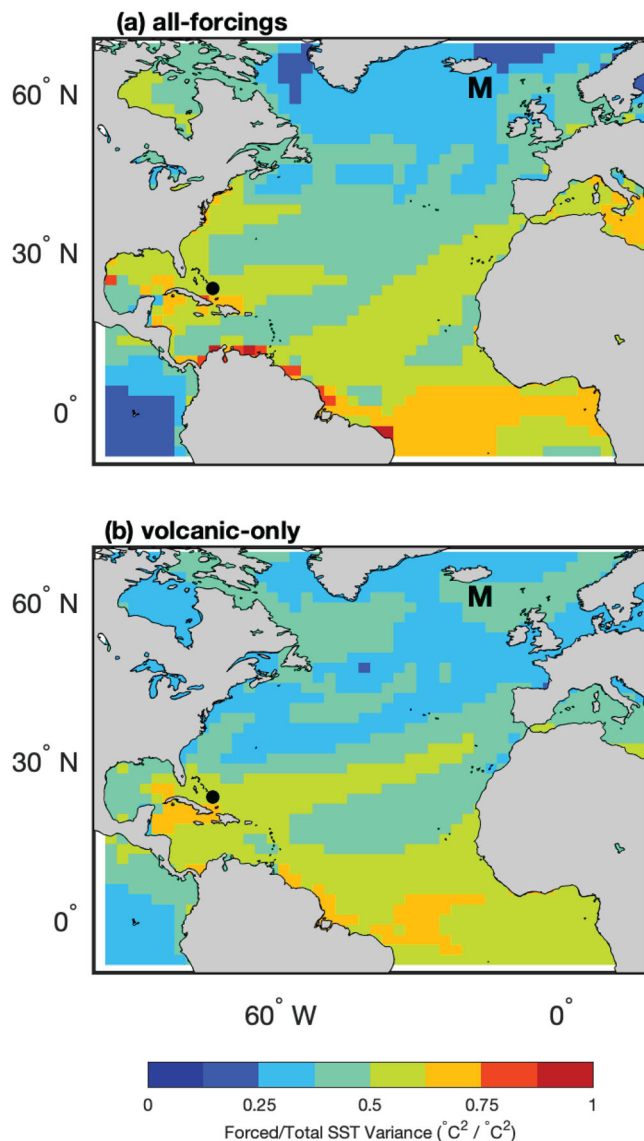
Figure 3. The relative role of external forcing in CESM-LME between 1385 and 1993. (a) A map of the ratio of annual average ensemble mean SST variance to the average total SST variance across the ensemble for the "all-forcings" runs. (b) As in (a), but for the "volcanic-only" ensemble. The "M" denotes the site discussed by Moffra-Sanchez et al. (2019).
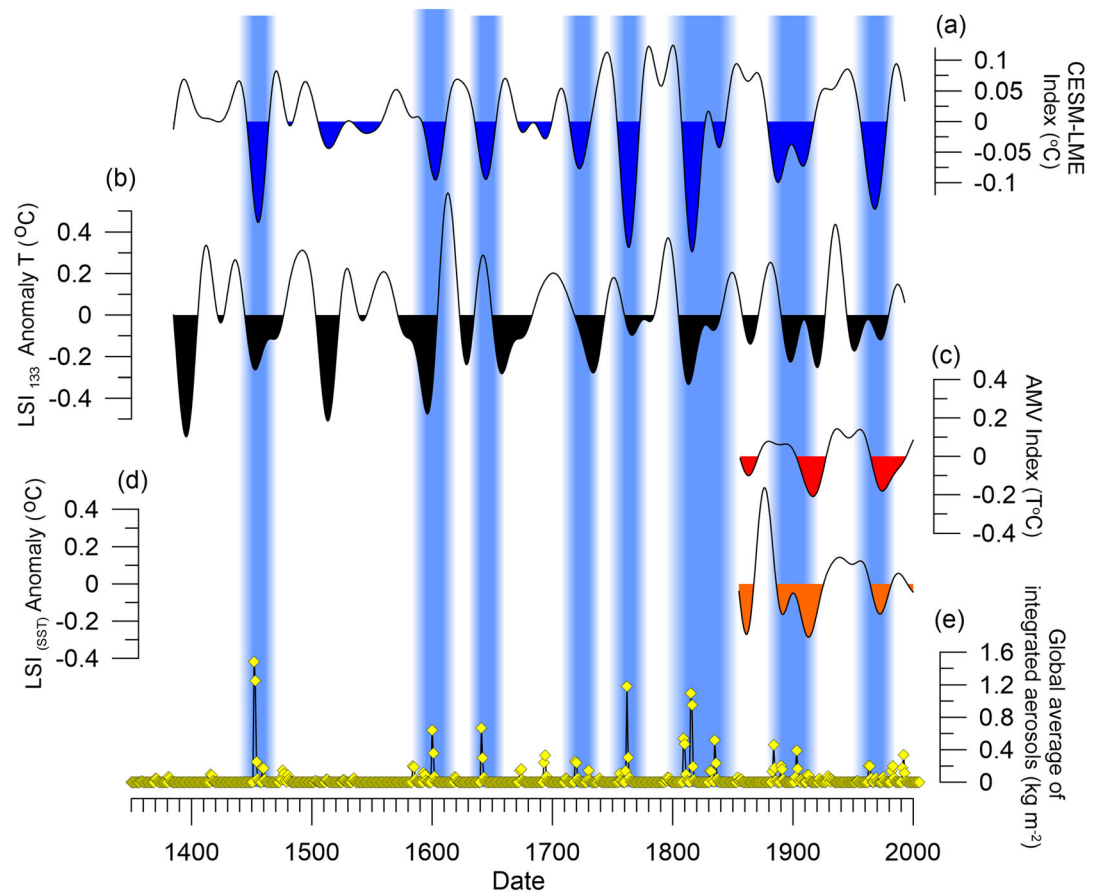
marine sediments (Black et al., 2007), and speleothem records (Winter et al., 2011) also show some AMV type characteristics but are hampered by low sampling resolution and possible dating uncertainties.

4.2. Internally Generated or Externally Forced Variability?

In order to address whether variations in the AMV are controlled by internally generated changes in oceanic or atmospheric circulation or by changes in external forcing, we examined the Community Earth System Model-Last Millennium Ensemble (CESM-LME) (Otto-Bliesner et al., 2016). This 13-member ensemble is run from 850–2005. Each member is branched from a long control simulation (constant year 850 forcing) and initialized with minute perturbations in the initial atmospheric temperature field. These small changes in initial conditions result in unique and uncorrelated time history of internal variability in each individual ensemble member. The total variability in each ensemble member will be the combination of this internal variability with the model's response to external forcing. All ensemble members are forced by identical boundary conditions: CMIP5 reconstructions of historical external forcing from greenhouse gases, volcanic aerosols, solar variability, and others (Hurrell et al., 2013; Otto-Bliesner et al., 2016). Because the internal variability is uncorrelated, averaging across all 13 members yields an estimate of the model's response to the prescribed external forcing, which we call the ensemble mean SST. With $N = 13$ ensemble members, we expect an 8% error $(1/N)$ in our estimate of the forced response. We call this ensemble "all-forcings."

The Bahamas, and LSI in particular, are reasonable localities to record a forced signal in the AMV. In observations, the correlation between the LSI SST and AMV is +0.44. The ensemble mean SST at LSI is more strongly correlated with the ensemble mean AMV ($r = +0.88$), indicating an important role for forcing at this site, consistent with previous studies using CESM (Bellomo et al., 2018). At this location, as well as over much of the tropical Atlantic, forced SST variability explains the majority of the multidecadal variance (Figures 3a and 3b). Conversely, other records, like those at higher latitudes, may capture more internal variability. For example, Figure 3 shows the site (south of Iceland) discussed by Moffa-Sanchez et al. (2019) which has much more internal than forced variability.

The ensemble mean AMV shows strong coherence with both the instrumental data and the LSI sclerosponge (Figure 4) and, prior to the industrial era, multidecadal variability is present. The correlation between the model simulated AMV and the sclerosponge reconstruction is larger for the ensemble mean than it is for an individual ensemble, which we would expect if it were strongly forced (Murphy et al., 2017). The correlation value between the sclerosponge and the ensemble mean LSI SST and AMV is +0.27 and +0.21, respectively (p < <.001). However, correlations with paleoclimate records are plagued by dating uncertainties (Hu et al., 2017), which complicates the interpretation of the observed variance. There are eight instances where the smoothed temperature calculated from the ensemble mean falls at least 0.05°C below the mean (and four which fall below 0.1°C) for periods of between approximately 5 and 20 years. In seven of these, a decrease is also noted in the LSI-4 record indicating the sclerosponge can capture and record large, externally forced variations in ocean temperature. This decrease is in all instances larger in magnitude than that observed from the CESM-LME ensemble mean. A majority of pre-1850 externally forced variance can be attributed to volcanic forcing alone: total AMV variance and externally forced variance from the volcanic eruptions only single-forcing ensemble are remarkably similar to the "all-forcings" ensemble (Table S1; see also O'Reilly et al., 2019).

Figure 4. Comparison of temperature anomalies from the (a) ensemble record with the (b) LSI-4 sclerosponge record, (c) the AMV index, (d) the temperature record from the grid square closest to Lee Stocking Island (Huang et al., 2017), and (e) the global average of column-integrated aerosols (Schmidt et al., 2011). All data have been filtered using a Butterworth band-pass filter to remove frequencies higher than 100 years and less than 5 years. The blue shaded bars represent periods of lower temperature greater than 0.05°C as estimated from the ensemble record. A 10-year transition zone is located on either side of the shading and is centered on the transition from a positive to negative temperature anomaly. Periods of lower temperature indicated by the LSI-4 record generally correspond with periods of lower temperature predicted by the ensemble mean. The period between 1620 and 1700 represents the time of poorest agreement between the two records, although this could be resolved by slight changes in the growth rate during this interval.

In summary, these results indicate that (1) the LSI locality is particularly sensitive to forcing (relative to other parts of the Atlantic), (2) that there is good correlation between this site and the AMV as a whole, and (3) that many of the major negative excursions recorded in the LSI-4 record coincide in time with volcanic forcing. Of course, this does not mean that forcing describes everything that the sclerosponge records—which is evident in the presence of cooling events around 1500 and 1700 CE that are absent from the ensemble mean, nor does this mean that what is recorded at LSI perfectly captures the Atlantic as a whole, leaving room for regional oceanic and atmospheric processes to influence records at other sites.

In the model, volcanic events appear more influential on the phasing of the LSI-4 record prior to 1700. This is consistent with Figure 4, which shows that all of the large volcanic eruptions in the record occur prior to 1850. This concurs with O'Reilly et al. (2019) who show that volcanic forcing is a key component in the pre-1855 AMV in CESM-LME. After 1850, anthropogenic forcing replaces natural forcing as the key contributor to multidecadal North Atlantic SST variability (Bellomo et al., 2018; Undorf et al., 2018; Watanabe & Tatebe, 2019). Incidentally, volcanic eruptions have been smaller during this period.

There is also the question of magnitude: The magnitude of temperature change recorded by the sclerosponge is larger than that in the model throughout the studied interval and the variability in the sclerosponge reconstruction is more prominent prior to 1700 while the model depicts weaker variability. There are several

possibilities for this. One is that the sclerosponge records not only the temperature, but also changes in the mixed layer depth. Some support for this comes from the fact that twentieth century variations are larger in the LSI sclerosponge than in observed SST (Figure 4). The second possibility is that the model underestimates the magnitude of forcing and/or the response to forcing (Murphy et al., 2017). The AMV may also be produced by a nonstationary process or set of processes as has been shown in the Pacific for the mid-Holocene (Friddell et al., 2003).

Internally generated climate variability from both the atmosphere and ocean certainly contributes to any discrepancies between the CESM-LME ensemble mean and the LSI-4 record. By design, the ensemble mean minimizes the signal from internal variability. However, numerous studies have argued that internally generated AMOC variability influences North Atlantic SST (Zhang et al., 2019). We believe that the LSI site is less susceptible to the influence of internal variability. For example, the so-called "AMOC fingerprint" is centered in the subpolar gyre with a limited signature in the western Atlantic Basin (Frankignoul et al., 2017; Wills et al., 2019). Likewise, multidecadal variability in the large-scale atmospheric circulation (often described by the NAO index) can intermittently drive North Atlantic SSTs (Polyakova et al., 2006). However, the LSI site is in the out-of-phase portion of the SST tripole associated with the NAO (i.e., the western subtropical Atlantic is warm for the positive NAO phase when the subpolar gyre and tropical Atlantic are cool). If the sclerosponge was recording a strong contemporaneous NAO signal, it would not explain the fact that in the modern part of the record, the temperature variations are positively correlated with the basin-wide changes. Some studies argue that the Atlantic warms about a decade after an NAO positive event (Delworth et al., 2017; O'Reilly et al., 2016); however, there is no consistent, statistically significant SST signal in the subtropics as part of a lag response to the NAO (Klavans et al., 2019). Nevertheless, there remains the possibility of an indirect route of NAO influence at this site at depth through changes in the subtropical ocean response to the NAO, as suggested by Rosenheim et al. (2005) and Zhang et al. (2013), which could explain differences between the ensemble mean and the sclerosponge reconstruction.

5. Conclusions

A temperature record derived from Sr/Ca ratios measured in a sclerosponge is one of the few continuous, well-resolved, direct measurements of multidecadal temperature variability in the Atlantic. The reconstruction shows agreement with temperature records based on proxies such as tree rings and some corals throughout the period of instrumental record. Although comparison of the sclerosponge reconstruction to last millennium climate simulations suggests large preindustrial volcanic forcing plays an important role in generating AMV and that, in the twentieth century, volcanoes plus anthropogenic forcing are also important drivers, other drivers, such as variations in atmospheric circulation or AMOC, may also play a role in AMV.

Data Availability Statement

Data will be available through the NOAA paleoclimate website (https://www.ncdc.noaa.gov/data-access/paleoclimatology-data).

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