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Surface-temperature trends and variability in the low-latitude North Atlantic since 1552

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Sea surface temperatures in the North Atlantic Ocean recorded since the 1900s have been ascribed to a natural multidecadal oscillation superimposed on a background warming trend[1–6]. It has been suggested that the multidecadal variability may be a persistent feature[6–8], raising the possibility that the associated climate impacts may be predictable[9]. However, our understanding of the multidecadal ocean variability before the instrumental record is based on interpretations of terrestrial-based proxy records[7,8]. Here we present an absolutely dated and annually resolved record of sea surface temperature from the Bahamas, based on a 439-year time series of coral growth rates. The reconstruction indicates that temperatures were as warm as today from about 1552 to 1570, then cooled by about 1 °C from 1650 to 1730 before warming until the present. Our estimates of background variability suggest that much of the warming since 1900 was driven by anthropogenic forcing. Interdecadal variability with a period of 15–25 years is superimposed on most of the record, but multidecadal variability becomes significant only after 1730. We conclude that the multidecadal variability in sea surface temperatures in the low-latitude western Atlantic Ocean is not persistent, potentially making accurate decadal climate forecasts more difficult to achieve.

Fluctuations of North Atlantic sea surface temperature (SST) on decadal–multidecadal timescales can influence hemispheric temperature and precipitation patterns[3,5], tropical Atlantic hurricane behaviour[4,5] and may mask or augment warming due to anthropogenic causes[9]. The multidecadal portion of this SST variability, commonly referred to as the Atlantic Multidecadal Oscillation (AMO), is thought to reflect, at least partially, natural internal variations in the Atlantic Meridional Overturning Circulation[6,10,11] (MOC). In contrast, the lower-frequency background component of SST variability is considered to be externally forced by variations in solar activity, volcanism, greenhouse gases and tropospheric aerosols[2,12].

Model simulations[5,6,10,11] suggest that the AMO is a persistent mode of internal ocean variability, the climatic impacts of which may be predicted decades in advance once externally forced background SST variability is removed[9]. However, neither the AMO nor long-term changes in the background SST are well characterized in the brief (~150 year) observational record. Attempts to extend the instrumental record using proxy reconstructions have relied heavily on high-latitude tree-ring records[7,8], but these non-marine proxies do not respond directly to SST variability and may have significant biases at centennial timescales[13]. So far, reconstructions of Atlantic SST variability based strictly on oceanographic proxies lack either the age control[14–16] or the length[17–19] needed to separate the AMO from changes in externally forced background SST (see Supplementary Fig. S1).

Here we present the first continuous, absolutely dated and annually resolved proxy record of Atlantic SST spanning many centuries. Using computed axial tomography (CAT) imaging, we quantified temperature-dependent variations in the annual growth of a massive *Siderastrea siderea* coral collected from the Bahamas (25.84° N, 78.62° W) in 1991. We first established the growth–SST relationship for this coral over the full instrumental record (1857–1991), and then verified this calibration by applying it to an *S. siderea* colony from Belize (17.50° N, 87.76° W). Robust correlations between coral growth and SST in several other species[17,18,20–22] have yielded valuable palaeotemperature records[17,20], but these techniques have not been applied to *S. siderea*. In this and previous studies[20], CAT imaging is especially useful because unlike conventional two-dimensional X-ray techniques, three-dimensional CAT scans can be rotated electronically during data processing to ensure analyses are carried out along a coral's axis of maximum growth.

Greyscale analyses of CAT scan images revealed 439 (±1) annual high-density bands spanning 1552–1991 in the Bahamas coral and 66 bands spanning 1936–2001 in the Belize specimen (see Supplementary Fig. S2). We used the distance between successive high-density bands to calculate the annual upward growth of each coral. Annual growth rates, which ranged from 0.11 to 0.38 cm yr^{-1} in the Bahamas coral and 0.19–0.36 cm yr^{-1} in the Belize specimen, showed an inverse correlation with instrumental SST (Fig. 1a–c)[23]. Coral growth and observed annual average SST anomalies were significantly coherent (95%) at periods longer than ~6 years (see Supplementary Fig. S3). We calibrated coral growth rate anomalies against observed 1857–1991 Bahamas SST anomalies ($r = -0.67$, $p = 0.024$, $N_{effective} = 25$; Fig. 1a, see the Methods section). SST explains 45% of the variance in coral growth on 6-year timescales, and 78% of the variance on multidecadal (>30 year) timescales ($r = -0.88$, $p < 0.001$, $N_{effective} = 16$). Although it is well established that environmental parameters other than SST influence coral growth, we find SST to be the dominant forcing on the timescales of interest to this study, consistent with ref. 21. Furthermore, Belize SST anomalies reconstructed using our Bahamas coral calibration also correspond well with observations ($r = 0.70$, $p = 0.002$, $N_{effective} = 36$), capturing both the timing and amplitude of major SST excursions (Fig. 1c)[23].

Coral-based Bahamas SST anomalies show mild conditions from 1870–1900 and 1940–1960 separated by two decades of cooler SSTs from 1900–1920 (Fig. 1c). These multidecadal trends are significantly coherent (95%) with instrumental SST and the AMO index at periods longer than 6 years (Fig. 1d, see Supplementary Figs S3, S4). However, Bahamas SST anomalies did not cool markedly during the

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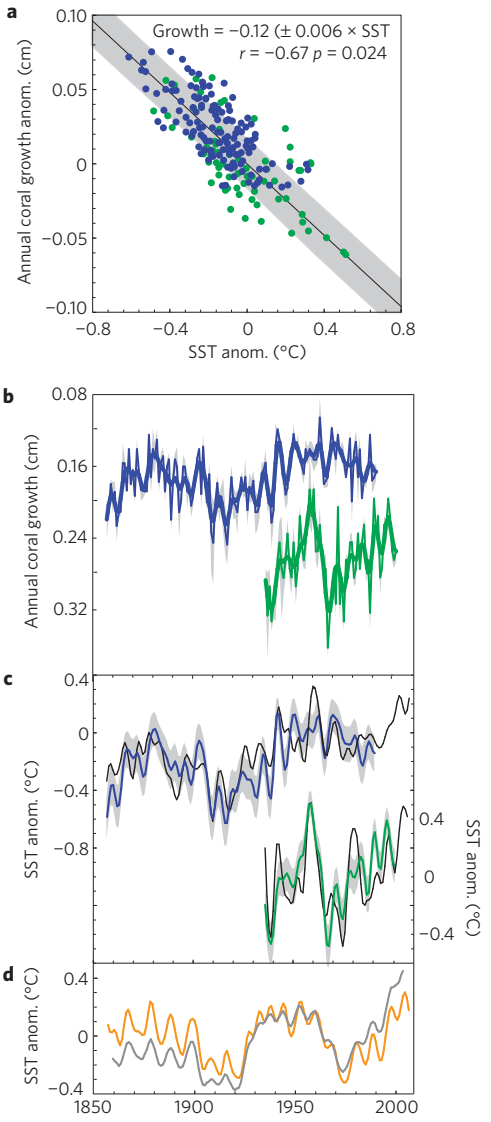

Figure 1 | Calibration and verification of the coral-based SST proxy. **a**, 1857–1991 Bahamas SST anomalies[23] regressed against Bahamas coral growth anomalies (blue). Belize coral growth anomalies and their equivalent SST anomalies (green) do not contribute to the calibration. **b**, Annual unfiltered (fine) and filtered (bold) coral growth measured from CAT scans of Bahamas (blue) and Belize (green) specimens. **c**, Coral-based SST anomalies reconstructed from Bahamas (blue) and Belize (green) corals compared with observed 1857–2008 filtered instrumental SST anomalies (black). The shading in **a**–**c** indicates 1σ standard error. **d**, The mean (grey) and linearly detrended mean (AMO; orange) SST anomaly from 0–75° N, 10–75° W.

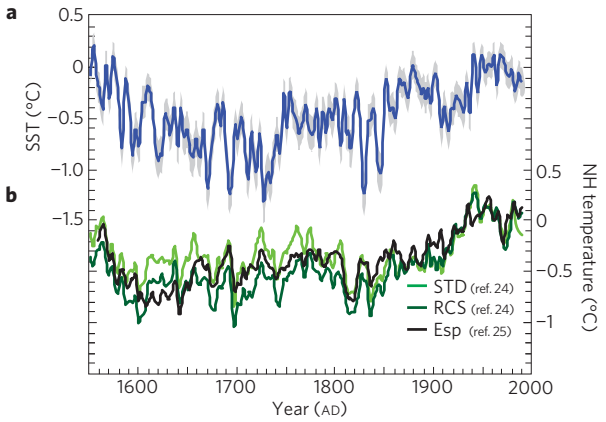

Figure 2 | Northern Hemisphere and Atlantic temperature variability since 1550. **a**, Bahamas coral-based SST anomaly and 1σ standard error (shading), estimated by applying the calibration in Fig. 1a to filtered annual coral growth rates (blue). **b**, Filtered hemispheric surface temperature anomalies from extratropical tree rings using regional curve standardization (RCS) and standard curve fitting (STD; refs 24, 25) methods.

recent negative AMO phase, indicating that regional-scale processes also influence low-latitude western Atlantic SST.

We applied our calibration to the entire record of Bahamas coral growth rate measurements to generate a continuous 439-year reconstruction of SST anomalies (Fig. 2a). Over this time period, which includes much of the Little Ice Age, Bahamas SST anomalies generally fluctuated within ~1 °C of the twentieth century mean. Our record suggests that SSTs were as warm as present from 1552 to 1570, but cooled steadily throughout the seventeenth century. Maximum cooling occurred from 1650 to 1730, and was punctuated by especially cool periods near 1672, 1694 and 1729. An ~70 year period of relatively stable warmth from ~1750 to 1830 ended with two abrupt cooling events between 1830 and 1850. A general warming trend after 1850 follows the instrumental record against which our SST reconstruction is calibrated.

Low-frequency variability in our Bahamas coral-based SST reconstruction is similar to that observed in annually resolved extratropical tree-ring-based estimates of Northern Hemisphere temperature variability (Fig. 2b)[24,25]. The major features of these hemispheric temperature reconstructions can be explained by variations in solar radiation, volcanic eruptions and the combined anthropogenic influence of greenhouse gases and tropospheric aerosols[12]. The similarities with our Bahamas record suggest the same forcings also influence low-latitude western Atlantic SST. Of note are two abrupt cold episodes in our record near 1830 and 1850 that occur ~15 years after similar volcanically driven hemispheric cool events. Although this relatively long delay suggests hemispheric and Bahamas cool episodes are unlikely to be responses to common volcanic forcings, similar abrupt events in a coral Sr/Ca record from Bermuda (see Supplementary Fig. S1c) are nearly synchronous with our reconstruction, suggesting that the cold excursions we observe are real features of low-latitude western Atlantic variability.

We estimate the externally forced background signal in our SST reconstruction using a multiple regression approach. To estimate the influence of individual radiative forcings, we simultaneously regressed an energy balance model's temperature response to solar, volcanic and anthropogenic variability[12] against Bahamas SST (Fig. 3a). Significant uncertainties are associated with radiative forcing estimates[26] and with applying the multiple regression approach to our single proxy record. However, because Bahamas SST is strongly correlated with low-latitude SST in other regions (see Supplementary Fig. S5), we consider this method to provide a useful approximation of externally forced SST variability across a broad region.

The results of our multiple regression approach suggest externally forced SST cooled by ~0.2 °C from ~1552 to 1600, remained cool from ~1600 to 1800 and warmed by ~0.8 °C after ~1800 (Fig. 3a). This trend, which accounts for 35% of the variance in our Bahamas SST reconstruction, is similar to lower-resolution SST reconstructions in the region that suggest a ~1 °C cooling from ~1600 to 1700 was the largest SST anomaly of the past few centuries[15,16]. Although it has been speculated that this cooling may reflect an oceanic response to reduced solar activity, a robust link has not been established owing to the relatively large chronological uncertainties inherent in lower-resolution sedimentary records[15]. Using our absolutely dated record, we could not distinguish the

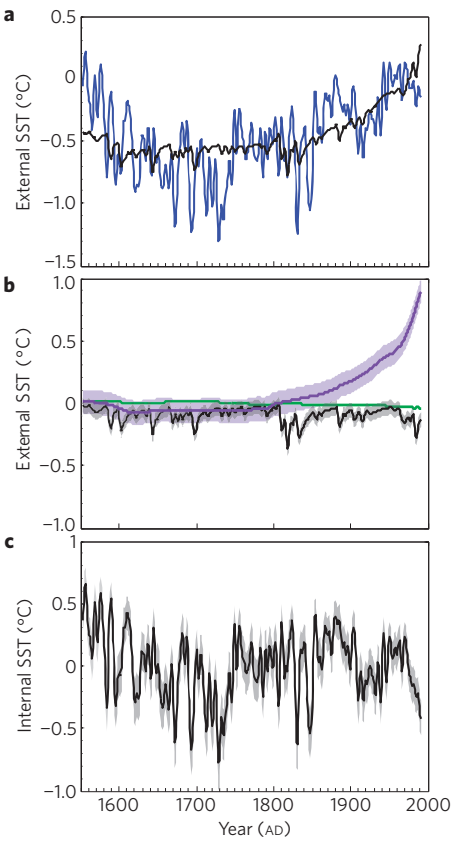

Figure 3 | Externally and internally forced SST variability a, Coral-based SST anomalies (blue) and estimated externally forced SST anomalies (black). **b**, SST variability and 1σ standard error attributed to volcanic (black), solar (green) and anthropogenic (purple) external forcings (see the Methods section). **c**, Internal SST variability (grey) and standard error (1σ) calculated by subtracting the curves in **a**.

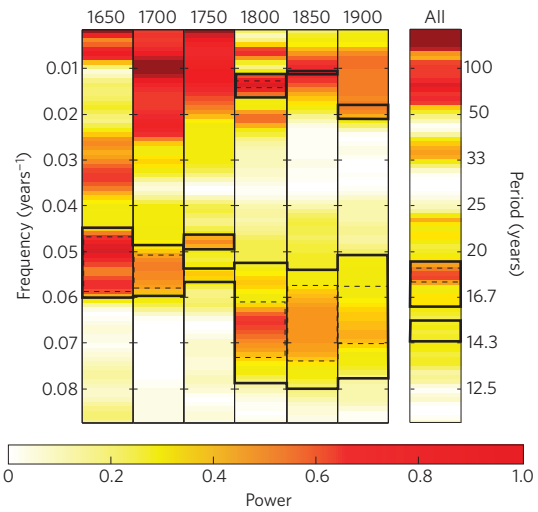

Figure 4 | Spectral analysis of internal SST variability. Spectral signature of internally driven SST variability from Fig. 3c. Spectra were calculated using the multitaper method[27] for the entire record (All) and in ~200-year bins spanning the periods 1552–1750, 1600–1800, 1650–1850, 1700–1900, 1750–1950 and 1800–1991. The centre year of each bin is shown (top). Gradients indicate the relative power at a given frequency (left *y* axis) and period (right *y* axis). Bounding boxes identify frequencies with significant power above red noise at 90% (bold) and 95% (dashed) confidence levels.

effect of solar forcing from natural internal ocean variability, suggesting that it may not have been a dominant SST forcing on these timescales (Fig. 3b, c). In contrast, we did detect a significant SST response to volcanic and anthropogenic signals, the latter of which accounts for most of the warming in our coral-based SST record since ~1900.

Internal SST variations show clear multidecadal oscillations, but only back to ~1730 (Fig. 3c). In addition to the two AMO cycles inferred from the instrumental record, a third multidecadal cycle occurs from ~1740 to 1840 that is consistent with proxy evidence suggesting the AMO predates the instrumental record[7,8]. However, the longer period (100 years) and extended warm phase (70 years) of this extra cycle suggests that any multidecadal low-latitude western Atlantic SST variability is at best quasi-periodic. Before ~1730, there is little evidence for extra AMO-like oscillations, implying that multidecadal variability may not have been a persistent feature of low-latitude western Atlantic SST.

To characterize changes in the dominant periodicities of internal SST variability, we carried out multitaper method spectral analysis[27] in six overlapping ~200-year bins (Fig. 4). Bins centred on 1800, 1850 and 1900 show significant (90%) multidecadal power similar to the AMO, whereas no significant multidecadal power is evident in bins centred on 1650, 1700 and 1750. Although the absence of multidecadal variability before ~1730 may be caused by the same processes responsible for the recent divergence of observed Bahamas SST from the AMO (Fig. 1c, d), it may also reflect broad changes in multidecadal Atlantic SST variability. To the degree to which our record represents the larger North Atlantic, it suggests that if the AMO is a natural mode of internal ocean variability, it may be less persistent than previously suggested[6–8]. In contrast, interdecadal (15–25 year) internal variability is significant (>90%) throughout our record, hinting that variations on these timescales may be a more persistent feature of Atlantic SST.

Control runs of the HadCM3 coupled ocean–atmosphere global climate model show natural interdecadal to multidecadal MOC oscillations that may help explain the variability in our reconstructed SST. In the model, multidecadal oscillations are part of a coupled ocean–atmosphere process in which phase reversals rely on oceanic transport of density anomalies[10]. The model's interdecadal variability is not coupled however, but rather seems to arise from atmospherically driven oscillations of salt and heat advection into the subpolar Atlantic and Arctic oceans[11]. If the mechanisms of HadCM3 are accurate, the absence of multidecadal variability in the earliest centuries of our record may be related to a 15–25% reduction in northward Gulf Stream transport before ~1750 (ref. 28) and with a possible weakening of the MOC. We speculate that such a reduction may have diminished the effectiveness of the negative feedback responsible for multidecadal oscillations by increasing the time needed to transport low-latitude ocean density anomalies from the tropics to the subpolar Atlantic. The persistent interdecadal power in our record suggests that the atmospheric forcing potentially responsible for 15–25 year SST variability was not significantly changed by the weaker MOC. However, the mechanisms responsible for interdecadal–multidecadal SST oscillations remain poorly understood[29], and a link with multicentennial MOC vigour must be considered to be one of many possible explanations for the apparent lack of multidecadal variability before ~1730.

Methods

CAT scanning. A 9-cm-diameter coral core was split lengthwise, and one half was imaged using a Siemens Volume Zoom Spiral Computerized Tomography Scanner at the Woods Hole Oceanographic Institution. A 0.8-cm-thick by 5-cm-wide coral slab from Belize was scanned using the same method. Scans were conducted at 400 mA s and 120 kV using a 0.5 mm slice that was reconstructed at 0.2 mm. Siemens CT and eFilm software were used to identify the plane orthogonal to the coral's axis of maximum growth. We used ImageJ software to measure greyscale variations in a 10-pixel-wide transect along parallel corallites in each image (see Supplementary

Fig. S2). The lightest value of each sinusoidal annual cycle represented the location of each high-density band. The annual extension rate of each corallite was averaged for each year and is reported as a mean and standard error (1σ). Coral high-density band formation typically occurs during maximum SST and we assume annual extension represents growth between successive Augusts. Thus, data represents September (year -1) to August (year 0) of the date plotted.

Filtering. A second-order Butterworth low-pass filter with a cutoff frequency equivalent to 6 years was used to generate filtered data. This cutoff frequency was chosen on the basis of the coherence between coral extension and instrumental SST (see Supplementary Fig. S3).

Calibration and verification. Six-year filtered annual SST anomalies[23] in the $5° \times 5°$ gridbox centred on 22.5° N, 77.5° W were regressed against similarly filtered Bahamas coral growth rate anomalies for the period 1857–1991 and forced through the origin (Fig. 1a). Anomalies were calculated relative to the 1951–1980 mean, consistent with ref. 23. The effective number of samples in filtered data ($N_{\text{effective}}$) was estimated following the method of ref. 30 (pp. 261–263). Other reasonable choices for the filter cutoff frequency had a small influence on the calibration slope and do not affect our results with respect to frequency. A calibration based on SSTs in an adjacent $5° \times 5°$ gridbox centred on 27.5° N, 77.5° W yielded nearly identical results. Estimates of Belize SST anomalies were calculated by applying the calibration regression to 6-year filtered Belize coral growth anomalies. Statistical correlations of coral-based Belize SST anomalies are based on regression against 6-year filtered annual SST anomalies[23] in the $5° \times 5°$ gridbox centred on 17.5° N, 87.5° W.

Detection and attribution. Six-year filtered solar, volcanic and the sum of greenhouse gas and tropospheric aerosol radiative forcings (anthropogenic)[12] were simultaneously regressed against 6-year filtered coral-based Bahamas SST anomalies. Best-fit regression coefficients were multiplied by the original radiative forcings to estimate the SST contribution from solar, volcanic and anthropogenic influences (Fig. 3b).

The standard error (1σ) of each forcing's SST response was estimated using a Monte Carlo approach. Each year of our coral-based SST reconstruction was randomly sampled from its probability distribution. This was repeated 1,000 times to generate 1,000 SST estimates, each 440 years long. SST estimates were regressed against radiative forcings following the method above to estimate three series of SST responses to solar, volcanic and anthropogenic variability. Standard errors (1σ) were then calculated from these three series after accounting for reduced degrees of freedom[30].

The best estimate of externally forced SST was subtracted from the full Bahamas SST record (Fig. 3a) to estimate internal SST variability (Fig. 3c). We considered external signals (Fig. 3b) that were significantly different from internal variability at 95% based on a one-tailed t-test to be detectable.

Spectral analysis. The multitaper method ($p = 2$, $K = 2$; ref. 27) was applied to our estimate of internal SST variability (Fig. 3c) over the frequency range from 0 to 0.15 cycles yr^{-1}. Confidence levels were determined relative to a red noise AR(1) background.

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Author contributions

C.S., A.L.C. and D.W.O. designed the experiment. C.S. collected and analysed the data, and wrote the paper. C.S., A.L.C. and D.W.O. interpreted the data, discussed their implications and contributed to the manuscript. R.B.H. and J.E.C. provided sample material and manuscript comments.

Additional information

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