

Sea surface temperatures in the North Atlantic

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Abstract

Paleo and recent sea surface temperature (SST) measurements at six locations spanning the North Atlantic, from the northeastern North Atlantic off the British Isles to the Dry Tortugas in the southwest, were examined in order to determine whether a period of cooling was responsible for the die-off of elkhorn corals (*Acropora palmata*) on the reef off Broward County around six thousand years ago (6 Kya) and whether warming sea temperatures might contribute to their recovery. The paleo data show indications of a warm period between 13 Kya and 7 Kya, followed by cooling, probably due to orbital forcing arising from the coincidence of insolation maxima in the Milankovitch obliquity and axial precession cycles in the Northern hemisphere at that time, but the lack of paleo data in the immediate proximity of the reef makes it difficult to draw firm conclusions regarding the die-off of the corals. However, the marine SST data obtained from ships and buoys since 1870 raise questions about the presumed recent global warming. Annual average sea surface temperatures in the North Atlantic show remarkable stability and consistency with little or no change over the 146 years between 1870 and 2015, despite large seasonal and latitudinal variation in response to differences in solar irradiance.

1. Introduction

This research originated after reading a paper describing a report of a 1973 survey of the coral reef off Hillsboro Inlet, Broward County, Florida, at the time when this was exposed by the construction of a ditch to accommodate an offshore sewage outfall pipeline (Lighty, 1977). A copy of this typewritten paper was kindly provided to the author, following a conversation at a restaurant in Fort Lauderdale in December 2015, by consulting engineer Dane Hancock, who had been involved in the 1973 construction of the sewage pipeline. As this was a unique opportunity, a PhD student in the Geology Department at Duke University, Robin Lighty, was brought in to survey the reef before the trench was refilled. This survey, titled “Relict shelf-edge Holocene coral reef: southeast coast of Florida”, concluded that no elkhorn coral (*Acropora palmata*) was found living on the reef at the time of the survey and that the part of the reef exposed by the ditch was a relict coral reef which had accumulated between 10 Kya and 6 Kya and was subsequently inactive despite being shallow enough in 1973 for vigorous coral growth. It also noted the lack of any significant reef-framework accumulation since 6 Kya. This was attributed to cooler water temperatures off southeast Florida during this period.

In a subsequent paper, Lighty et al. (1978) notes a rapid accumulation of the *A. palmata* framework in response to rapidly rising sea levels from around 9.4 Kya, and radiocarbon dating indicating that reef growth terminated around 7 Kya, which coincided with extensive flooding of the continental shelf by rising seas of the Holocene transgression. It also notes that unusually cold bottom waters in the shallow waters off south-east Florida, caused by seasonal atmospheric cooling and by northerly winds producing an offshore Ekman transport of surface waters, resulting in the advection of cooler waters on the shelf, were effectively preventing reef growth north of Miami.

A similar date range was obtained by radiocarbon dating of a fossil elkhorn coral community discovered on the Flower Garden Banks (FGB) on the shelf-margin off the Texas coast in the Gulf of Mexico, which indicated a date range from 10.1 to 6.8 Kya (Precht et al., 2014). This was seen to correspond to a time interval of warmer than present sea surface temperatures (SST) during the Holocene thermal maximum. The subsequent demise of the coral was attributed to the inability of the shallowest reef facies to keep pace with rising sea levels possibly coupled with decreasing SSTs.

In addition, a severe cold-water event in January 2010, associated with extremely negative values of the North Atlantic Oscillation that produced northerly surface wind anomalies and the southward advection of the cold Arctic air, resulted in significant and rapid coral mortality further south on the Florida Reef Tract at the inshore habitats at the Upper and Middle Keys. The water temperature fell to 9.5°C and 10.6°C respectively, and was below 16°C, the temperature that is stressful to most species, for 140 and 110 hours respectively (Lirman et al., 2011).

I was interested in testing this hypothesis and in seeing whether the recent increase in surface temperatures might lead to renewed reef accumulation. The temperatures most relevant to these corals are the monthly and annual average sea surface temperatures at the reef. Paleo sea surface temperature (SST) time series obtained from ocean drilling cores and based on analysis of oxygen isotopes in the calcite and Mg/Ca in particular species of foraminifera were obtained from the US National Oceanic and Atmospheric Administration (NOAA) website for five locations in the North Atlantic, from the northeastern North Atlantic northwest of the British Isles to the Dry Tortugas in the southwest. These provided time series for SST ranging from four million years ago (4 Mya) to 20 Kya to the present. Unfortunately, the closest ocean core data to the Broward reef were a limited series for the Great Bahama Bank (24.76°N 79.29°W), which ran from 590 AD (1360 BP) to the present (1950 AD or 0 BP), where time before present (BP) is measured from 1950 AD, and a longer series from 20 Kya (including the period from 10 Kya to 7 Kya) for the Dry Tortugas (24.3°N 83.3°W).

The part of the reef of interest was at 26°15'15"N, 80°03' 52" W, so the marine (ship and buoy) SST data of most interest were the UK Met Office's Hadley Centre Global Sea Ice and Sea

Surface Temperature (HadISST1.1) dataset, which is available on a 1 degree grid. This includes SST data from 1870 to the present. This is not easy to access, partly on account of the size of the dataset and the need for a software utility to extract monthly series from a 360 degree by 360 degree grid, a significant part of which covers dry land. However, a researcher at the Research Data Archive (RDA) in the Computational Information Systems Laboratory (CISL) at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, kindly provided csv files for a grid square off the Broward reef, where the survey was conducted, and for the five other locations spanning the North Atlantic for which I had been able to obtain paleo SST time series. Blended time series were created for the six locations and graphs generated from the available data using Excel.

Even though there are no paleo SST data covering the period from 10 Kya to the present sufficiently close to the Broward reef, there is some evidence at other locations of a warm period between 13 Kya and 7 Kya. Unfortunately, the available evidence is insufficient to indicate whether low sea surface temperatures at the Broward reef were responsible for the die off of the *A. palmata*. So this line of inquiry reached a dead-end, at least at the present time.

However, the graphs of marine (ship and buoy) SST data were surprising. There were significant and consistent latitudinal variation of annual average SST from 10.8°C in the northeastern North Atlantic to 26.9°C in the Dry Tortugas, with similar large seasonal (monthly average) ranges between 5.0°C and 8.0°C. But there is no evidence from this sea surface temperature data that there has been any measurable increase in sea surface temperatures in the North Atlantic during the past 146 years, and, where data are available, current sea surface temperatures are still well below those prior to the Last Glacial Maximum around 20 Kya.

Most surprising, was the remarkable stability of sea surface temperatures over the last 146 years (with virtually identical seasonal variation). Although the sea would be expected to dampen the variation, it would also be expected to reflect any warming trend in air temperatures, if such a trend existed, as the seasonal and latitudinal variations are very significant. There is a suggestion of a recent relatively modest (around a quarter of a degree) of warming in the Tropics, but this is possibly caused by the reduction in smoke pollution in the atmosphere (which mostly affects areas with longer hours of exposure to the sun).

2. Paleo sea surface temperatures in the North Atlantic

The paleo SST data reported in this paper were obtained from “Sea Surface Temperature - Reconstructions” published on the NOAA (previously National Climatic Data Center) website.

Most methods for measuring paleo SST rely on some aspect of the fossilized hard parts of marine organisms, including assemblages of calcareous microplankton, such as foraminifera and

coccoliths, or of siliceous plankton, such as radiolarian and diatoms, and chemical methods based on isotopic and trace element signatures. These generally require the skeletal material to be well preserved. In contrast, the alkenone method, which is based on individual molecules, and assumes that the ratio of biomarkers measured were actively regulated by the producing organism in life according to the temperature of the water in which they grew, does not rely on good preservation.

The measurement of paleo SST at the sites analyzed in this paper used the following methods:

(i) Alkenone method:

Alkenones are long-chain unsaturated methyl and ethyl n-ketones produced by a few phytoplankton species in the class *Prymnesiophyceae*, which may differ in the number of double bonds (unsaturation) in the chain and in the structure of the terminal ketone group (terminal carbon in the chain bonded to either a methyl or ethyl group). The alkenone organic biomarker proxy for historical SST, the $U^{k'}_{37}$ index, which measures the relative degree of unsaturation, is defined as $C_{37.2}/(C_{37.2} + C_{37.3})$, where $C_{37.2}$ represents the quantity of the di-saturated ketone and $C_{37.3}$ represents the quantity of the tri-saturated form. The C_{37} alkenones used in the $U^{k'}_{37}$ index are methyl ketones (Herbert, 2003).

The alkenones are produced by calcareous algae and the saturation ratio is actively regulated by the producing organisms during their life according to the temperature of the water in which they grew. At higher temperatures a greater relative proportion of less unsaturated alkenones is produced, so SST is positively related to the $U^{k'}_{37}$ index. This index can then be used to estimate SST based on an empirical relationship based on core-top calibrations. The most commonly used calibration is that of Muller et al. (1998), $U^{k'}_{37} = 0.033 T(^{\circ}\text{C}) + 0.044$.

The alkenones in Miocene through Pleistocene age marine sediments have been linked to a certain species of extant haptophyte (coccolithophorid) algae and in modern sediments to *Emiliania huxleyi* and *Gephyrocapsa oceanica* (Conte et al., 1994; Volkman et al., 1995). These organisms require sunlight and generally prefer the upper photic zone so the information contained in their molecular fossils provides a specific estimate of near-surface ocean temperatures and does not require good preservation of the skeletal material.

(ii) $\delta^{18}\text{O}$ method:

$\delta^{18}\text{O}$ is a measure of the ratio of stable isotopes oxygen-18 (^{18}O) and oxygen-16 (^{16}O). In the paleosciences, this ratio in corals, in planktonic foraminifera, and in ice cores is used as a proxy for temperature due to the preferential evaporation of the lighter ^{16}O from seawater, although this complicated by ^{16}O enrichment of freshwater input from rainwater, by the preferential

condensation of the heavier ^{18}O molecules, variations in rainwater precipitation, salinity and ice volume change. Assuming that the $\delta^{18}\text{O}$ signal is attributable to the SST alone, and ignoring the effects of salinity and ice volume change, Epstein et al. (1953), estimated that a 0.22% increase in $\delta^{18}\text{O}$ is equivalent to a cooling of 1°C , or more precisely, $t\ (^{\circ}\text{C}) = 16.5 - 4.3\ \delta^{18}\text{O} + 0.14\ (\delta^{18}\text{O})^2$, where t is the temperature in $^{\circ}\text{C}$, based on a least-squares fit between 9°C and 29°C .

Foraminifera shells are composed of calcium carbonate (CaCO_3) so the $\delta^{18}\text{O}$ ratio can be used to indirectly determine the temperature of the surrounding water at the time the shell was formed. However, many assemblages of planktonic foraminifera live well below the surface mixed layer and there are potential problems demonstrating that the temperature sensitivity of the foraminiferal material is retained from their chamber formation through the development of gametogenic calcite and crust, through dissolution, to residence at the sea bed.

(iii) Mg/Ca method:

The Mg/Ca ratio method of estimating paleo SST is derived from the inorganic thermodynamic dependency of Mg incorporation in the foraminiferal calcite lattice on the temperature of the water from which it is being precipitated. As noted above for $\delta^{18}\text{O}$ SST estimation many assemblages of planktonic foraminifera live well below the surface mixed layer, with *N. pachyderma* and the globigerinids generally following SST, whilst the globorotalids (*Globorotalia hirsute*, *Globorotalia inflata* and *Globorotalia truncatulinoides*) follow the temperature at water depths of 300m-400m (Elderfield & Ganssen, 2000). The best fit for eight species of planktonic foraminifera resulted in $\text{Mg/Ca} = 0.52\ \exp\ 0.10t(^{\circ}\text{C})$, where t is the temperature in $^{\circ}\text{C}$. The Mg levels in foraminifera shells decrease steadily through dissolution but this can be adjusted for using a flow-through leaching procedure to extract the initial calcification temperatures (Benway et al., 2003).

3. Marine observations of sea surface temperatures from 1870 AD to the present

Sea surface temperatures have been measured and recorded since the Brussels Maritime Conference of 1853 when representatives of several seafaring nations agreed the standardization of meteorological and oceanographic observations from ships at sea. Until around 1963 this was achieved by dipping a thermometer into a bucket of water manually drawn from the sea, after which it was automated by measuring the temperature of the water in the intake port of large ships. Moored weather buoys have been used since 1951 and drifting buoys since 1979. Buoys, which measure the SST at a depth of one meter, have become the dominant source of in situ SST data since 1970 as ships routes have changed and the number of reporting ships has declined. Although measurement of SST by weather satellites has supplemented this data since 1982 they

face difficulties as they only measure the top “skin” of the ocean and suffer from a cool bias in cloudy areas.

The marine SST data used for this analysis are the monthly mean SST in degrees Centigrade from the UK Met Office’s Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST1.1) dataset for the period from January 1870 through December 2015. It was chosen primarily because of its availability on a 1-degree grid, enabling a more precise measurement of SST at the Broward Coral Reef. It also provides absolute temperatures rather than anomalies. This is a globally complete SST database of individual observations and dataset of monthly mean SST on a 1-degree grid from 1870 to the present, maintained by the UK Met Office Hadley Centre.

HadISST1.1 consists of two datasets; HadISST1.1_SST, a set of SST data in monthly 1° area grids; and HadISST1.1_ICE, monthly 1° grids of ice coverage, both from 1870. HadISST1.1 replaced the Hadley Centre’s earlier Global Sea Ice and Sea Surface Temperature (GISST) dataset. The data are based primarily on the U.K.’s Met Office Marine Data Bank (MOMMDB) SST data from 1871, but, where there are no data in the MOMMDB, monthly median SSTs from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) are used. Folland and Parker (1995) “bucket” adjustments were applied to the SST data to correct for biases resulting from the changing use of semi-insulated wooden buckets, uninsulated canvas buckets and insulated rubber buckets to lift sea water onto the decks of ships. No adjustments were applied after 1941 (Rayner et al., 2003; Met Office, 2016).

4. Sea Surface Temperatures in the North Atlantic

The locations chosen for analysis were based on the availability of paleo SST data series. These ranged from the northeastern North Atlantic, northwest of the British Isles, at 57.5°N 15.9°W, to the southwestern North Atlantic at the Dry Tortugas, at 24.3°N 83.3°W, to provide a wide range of climatic conditions, whilst avoiding the equatorial and polar extremes.

The graphs of paleo and marine SST data are shown on the same temperature scale for each time period and location to demonstrate the comparative annual variation, and, for the marine data, the monthly variation throughout each year. In particular, this highlights the extremely low annual variation between 1870 and 2015 compared with significant seasonal variation and latitudinal variation over the same period, indicating the over-riding influence of solar irradiance. The vertical blue lines in the graph of marine data between 1870 and 2015 show the monthly SST variation during each year; and the black trend line is the 12 month moving average.

(i) Northeastern North Atlantic (57.5°N 15.9°W) 4 Mya to present

The paleo SST data for the northeastern North Atlantic (57.5°N 15.9°W) are provided by a single SST reconstruction covering the period from 4 Mya BP to the present based on the analysis of the sediments from the Ocean Drilling Program Site 982 for their alkenone unsaturation index (Lawrence et al., 2009).

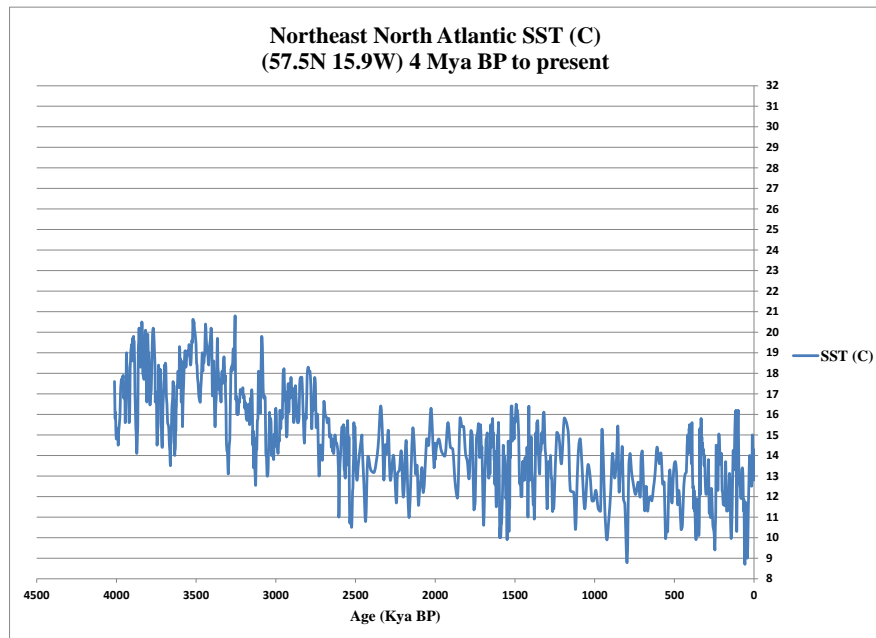


Figure 1. Paleo SST data for northeastern North Atlantic (57.5°N 15.9°W) from 4 Mya to present.

The graph in Figure 1 shows that SST were significantly warmer (around 6°C) than present day SST, with sustained cooling (around 4.5°C) occurring between 3.5 to 2.5 Mya followed by an interval of more modest cooling (an additional 1.5°C) from 2.5 Mya to the present. Reconstructed SSTs in the northeastern North Atlantic were virtually unchanged at about 13°C between 19.02 Kya, at the Last Glacial Maximum, and 13.35 Kya, and then increased by 2.0-2.5°C to 15°C between at 13.35 Kya and 11.26 Kya. This was followed by a modest cooling to 13.7°C between 11.26 Kya and 7.93 Kya, a recovery to 14.3°C at 3.78 Kya, and a further cooling to 12.8°C at 1.01 Kya.

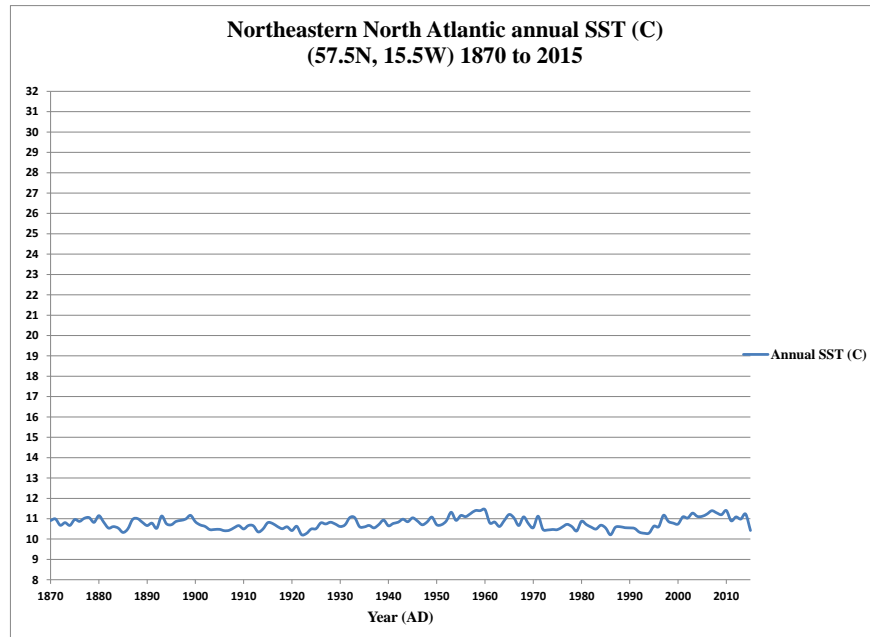


Figure 2. Annual average SST for northeastern North Atlantic (57.5°N 15.5°W) between 1870 and 2015.

Figure 2 shows an average annual marine SST of 10.8°C for the northeastern North Atlantic (57.5°N 15.5°W), with no significant change during the 146 years between 1870 and 2015. The lowest annual SST of 10.2°C was recorded in 1922 and 1986, and the highest annual SST of 11.4 C was recorded in 1958/60, 2007 and 2010.

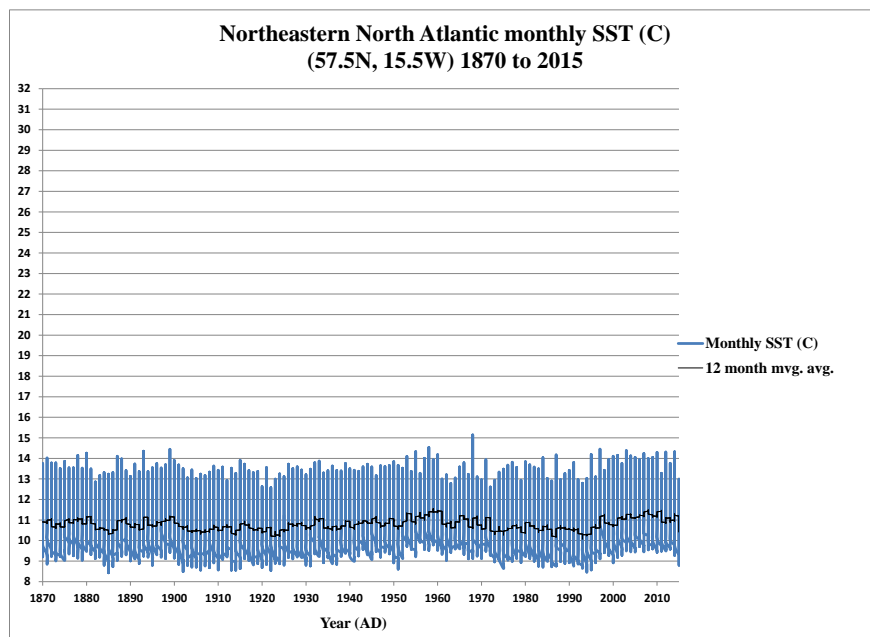


Figure 3. Monthly SST data for northeastern North Atlantic (57.5°N 15.5°W) between 1870 and 2015.

The monthly marine SST data for the northeastern North Atlantic (57.5°N 15.5°W) in Figure 3 show that the seasonal variation (blue line) is remarkable constant between 9°C in winter to 14°C in summer. The black line shows the 12 month moving average. The lowest 10-year moving average SST of 10.5°C was recorded in 1922/27 and 1991/96, and the highest 10-year moving average SST of 11.2°C was recorded in 1960/62 and 2009/14, resulting in an increase of 0.24°C between 1870/9 and 2006/15.

There is a single overlapping data point between the paleo SST and marine SST data in 1950 for which the paleo SST is 13.4 °C, 2°C above the HadISST1.1 marine annual average SST. This corresponds to the marine observations for July/August of that year and is in agreement with the observation in Lawrence et al. (2009) of a bias toward a summer season for alkenone production at this site in the late Pleistocene. Even after adjusting the paleo data downwards by 2°C, the recent annual average SST of around 11°C is significantly lower than the 21°C to 15°C experienced in the northeastern North Atlantic between 4 and 2.5 Mya.

(ii) Central North Atlantic (Bermuda Rise; 33.7°N 57.6°W) from 61 Kya to 570 BP

The Bermuda Rise is a sediment drift deposit in the northwest Sargasso Sea, northeast of Bermuda. The paleo SST data in Figure 4 are provided by two SST reconstructions at the same geographical location, respectively covering the periods from 61.2 Kya BP to 31.75 Kya BP (Sachs & Lehman, 1999) and 19.9 Kya BP to 570 BP (Carlson et al., 2008).

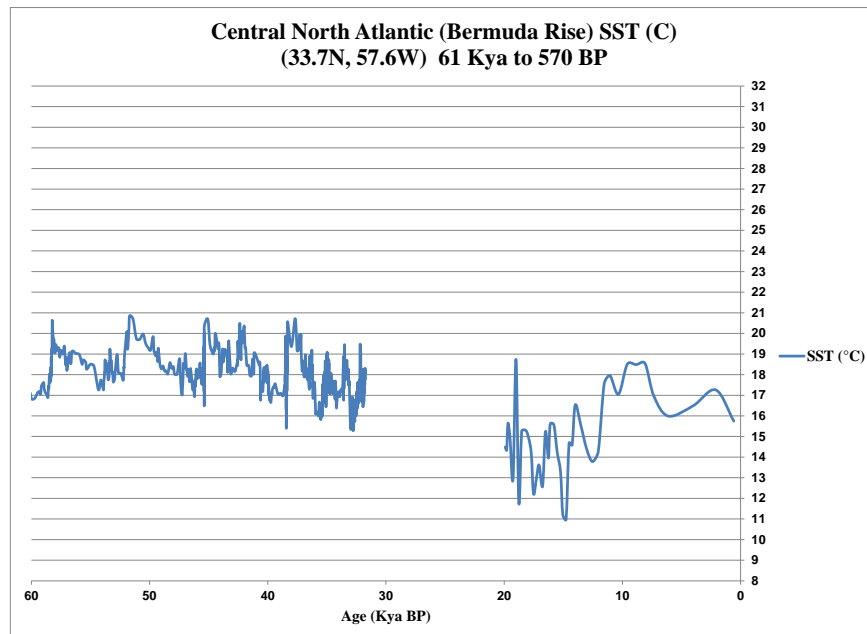


Figure 4. Paleo SST data for central North Atlantic (33.7°N 57.6°W) from 61 Kya to 570 BP.

The Sachs and Lehman (1999) SST estimates were derived from sediments from the Bermuda Rise core MD95-2036 based on the alkenone unsaturation index and the dates from visually aligning features of the alkenone SSTs to Greenland GISP ice $^{18}\text{O}/^{16}\text{O}$ variations. Reconstructed SSTs ranged from 21°C to 15.5°C during MIS 3 (57–29 Kya), with lows at Heinrich Event 5 (45 Kya) and Heinrich Event 4 (38 Kya) with stadial minimum SST falling from 17.3°C to 15.3°C.

The Carlson et al. (2008) SST estimates derived from sediments from the Bermuda Rise core OCE326-GGC5 were based on $\delta^{18}\text{O}_{\text{calcite}}$ and Mg/Ca of the planktonic foraminifera *Globorotalia inflata* for the core top, Holocene and deglacial sections of the core. After converting Mg/Ca to calcification temperature (CT), the $\delta^{18}\text{O}$ ratio was corrected for changes in CT and continental ice volume to reconstruct $\delta^{18}\text{O}_{\text{sw}}$. Reconstructed SSTs at the Bermuda Rise were virtually unchanged at about 14.5°C between 19.9 Kya, at the Last Glacial Maximum, and 12.04 Kya, and then increased by 3°C to 17.5°C by 11.54 Kya and 18.5°C in 8.08 Kya, before falling by 2.5°C to 17.0°C in 7.33 Kya and 16.0°C in 6.11 Kya. After a partial recovery of a little over 1°C, SST fell again to 15.75°C in 570 BP (1380 AD). This unusually low temperature may reflect the cooling that took place during the Little Ice Age, between 1300-1850 AD, when the Atlantic ice pack extended southwards, following a period of warming during the Medieval Climate Optimum, or Medieval Warm Period, between 900-1300 AD.

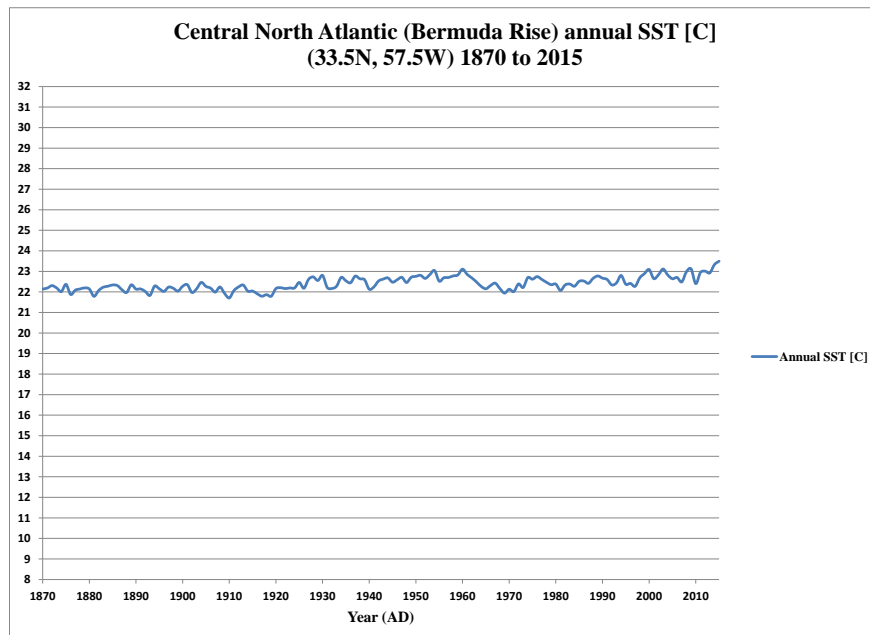


Figure 5. Annual average SST for central North Atlantic (33.5°N 57.5°W) between 1870 and 2015.

Figure 5 shows an average annual marine SST for the Bermuda Rise (33.5°N 57.5°W) of 22.4°C between 1870 and 2015, with two step increases in annual SST, of around 0.5°C in 1927 and a

further 0.4°C in 1999/2000. The lowest annual SST of 21.7°C was recorded in 1910, and SSTs over 23.0°C were recorded in 1954, 1960, 2000, 2003, 2009 and 2012. The highest annual SST of 23.3 and 23.5°C, respectively, occurred in 2014 and 2015.

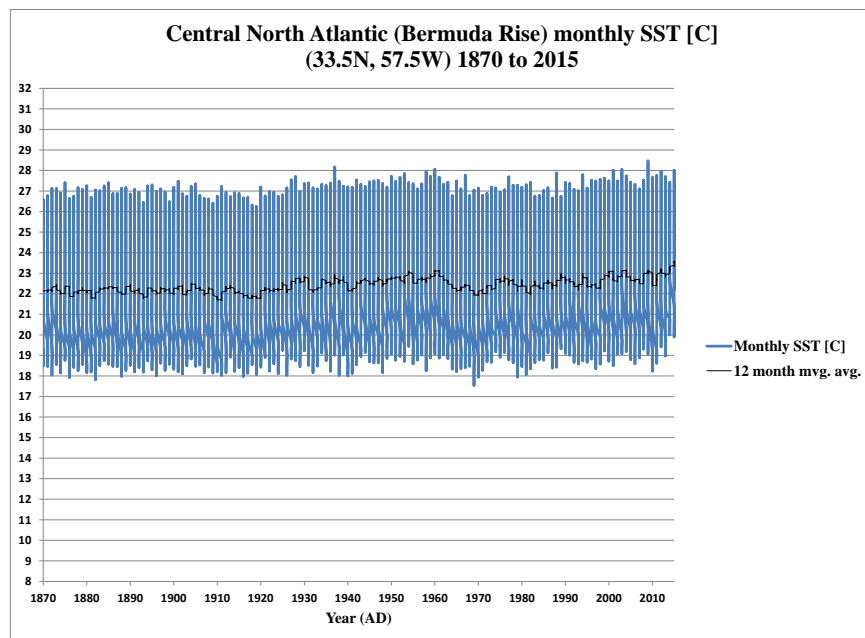


Figure 6. Monthly SST data for central North Atlantic (33.5°N 57.5°W) between 1870 and 2015.

The monthly marine SST data for the Bermuda Rise (33.5°N 57.5°W) in Figure 6 show that the seasonal variation remained remarkably constant at around 8°C (between around 19.5°C in winter to 27.5°C in summer) despite the changes in the annual average. The lowest 10-year moving average SST of 22.0°C was recorded between 1917 and 1924, and the highest 10-year moving average SST of 22.8/9°C was recorded between 1958/63 and between 2006/15. This resulted in an increase of 0.79°C between 1870/9 and 2006/15, significantly larger than elsewhere in the North Atlantic.

The marine SST data suggest that there has been a significant recovery in SST at the Bermuda Rise from the Carlson et al. (2008) SST estimate of 15.75°C in 570 BP (1380 AD) to a level above the peak SSTs between 60 Kya and 30 Kya.

(iii) Western North Atlantic (Blake Outer Ridge, 30.8-32.8°N 74.5-76.3°W) 59 Kya to present

The Blake Outer Ridge is near the present-day position of the northward flowing Gulf Stream, in the southwest Sargasso Sea. The paleo SST data in Figure 7 are provided by three SST reconstructions at different locations on the Blake Outer Ridge, respectively covering the periods

from 59.21 Kya BP to 45.88 Kya BP (Schmidt et al., 2006); from 25.12 Kya BP to 7.76 Kya BP (Carlson et al., 2008); and from 1.70 Kya BP until 100 BP (Saenger et al., 2011).

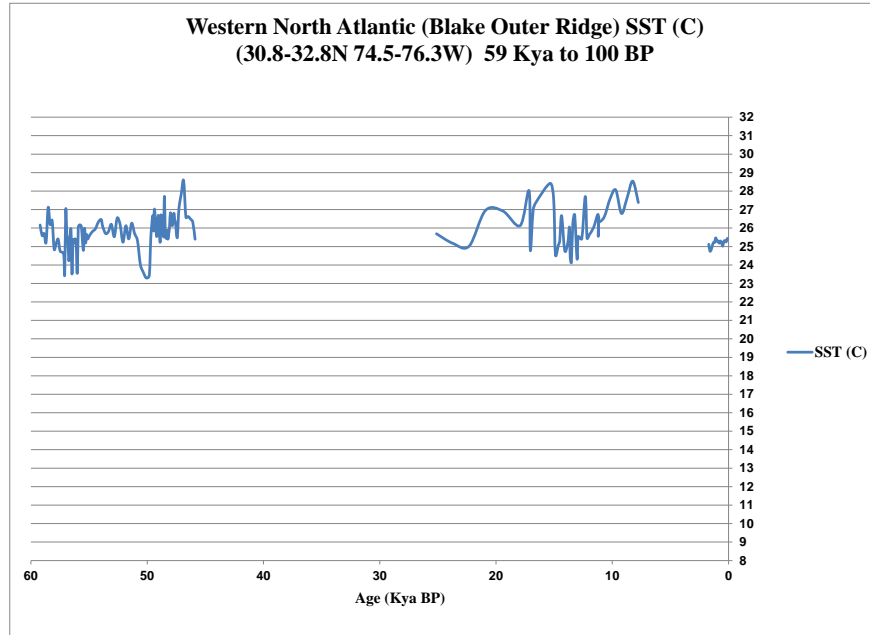


Figure 7. Paleo SST data for western North Atlantic (30.8-32.8°N 74.5-76.3°W) 59 Kya to present.

The Schmidt et al. (2006) SST estimates were derived from sediments from the Ocean Drilling Program (ODP) site 1060 (core ODP1060) at 30.8°N 74.5°W based on $\delta^{18}\text{O}_{\text{calcite}}$ and Mg/Ca of the planktonic foraminifera *Globigerinoides ruber* (white variety). Mg/Ca ratios in *G. ruber* were converted to SST using a species-specific depth correlated relationship for the Atlantic (Dekens et al., 2002). The observation that Mg/Ca SST reconstructions are similar to August faunal SST estimates at site 1060 suggests that *G. ruber* inhabited the water column above this site during the warmest summer months of MIS 3 (57–29 Kya).

The Carlson et al. (2008) SST estimates were derived from sediments from the Blake Outer Ridge core KNR140-51GGC at 32.78°N 76.28°W, 2 degrees to the northwest, based on $\delta^{18}\text{O}_{\text{calcite}}$ and Mg/Ca of the planktonic foraminifera *Globigerinoides ruber* (white variety) for the core top and deglacial sections of the core. After converting Mg/Ca to calcification temperature (CT), the $\delta^{18}\text{O}$ ratio was corrected for changes in CT and continental ice volume to reconstruct $\delta^{18}\text{O}_{\text{sw}}$. Reconstructed SSTs at the Blake Outer Ridge were virtually unchanged at 26.5-27.0°C between 19.42 Kya, at the Last Glacial Maximum, and 10.67 Kya, and then increased by 1.5°C to 28.0-28.5°C at about 9.70 Kya through to the end of the record at 7.76 Kya.

The Saenger et al. (2011) SST estimates were derived from sediments from the multicore CH07-98-MC22 at 32.784°N 76.276°W on the Carolina Slope near the southern flank of the Gulf

Stream, based on $\delta^{18}\text{O}_{\text{calcite}}$ and Mg/Ca of the planktonic foraminifera *Globigerinoides ruber* (white variety). SST was estimated using a Mg/Ca-SST calibration based on Sargasso Sea *G. ruber*, $\text{Mg/Ca (mmol/mol)} = 0.34\exp(0.104 \times \text{SST}(\text{°C}))$ (Anand et al., 2003). The chronology was based on several planktic foraminiferal radiocarbon ages, calibrated using Fairbanks et al. (2005). The Saenger et al. (2011) estimates indicate a 3°C cooling between the end date of the Carlson et al. (2008) estimates at around 8 Kya and Saenger et al. (2011)'s start date at 1.7 Kya.

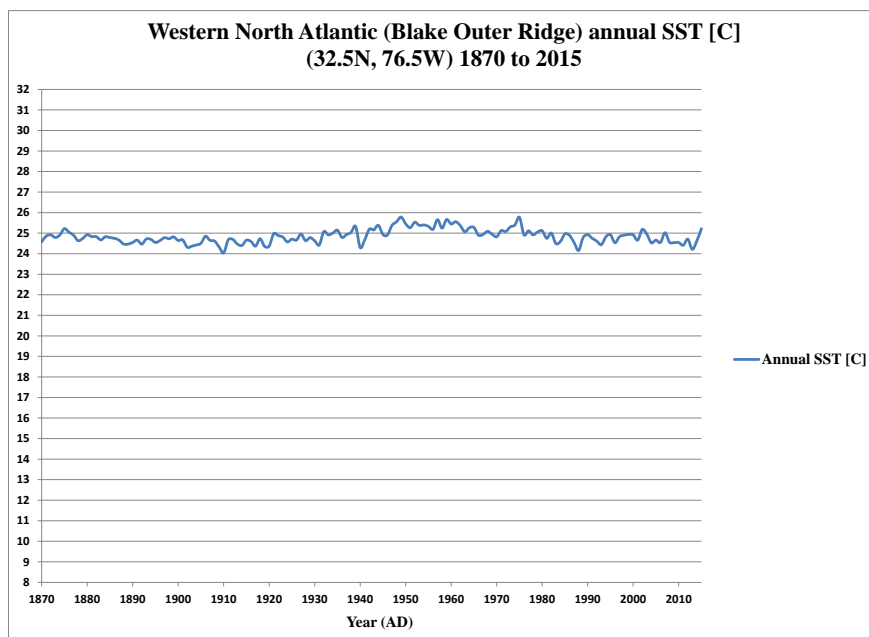


Figure 8. Annual average SST for western North Atlantic (32.5°N 76.5°W) between 1870 and 2015.

Figure 8 shows an average annual marine SST for the Blake Outer Ridge (32.5°N 76.5°W) of 24.85°C between 1870 and 2015, with slight warming (less than 0.5°C) between 1921 and 1949 followed by a similar degree of cooling between 1950 and 2013, followed by the warming effect of the strong El Nino in late 2015. The lowest annual SST of 24.0°C was recorded in 1910, followed by 24.15°C in 1988, and the highest SST of 25.8°C was recorded in 1949 and 1975.

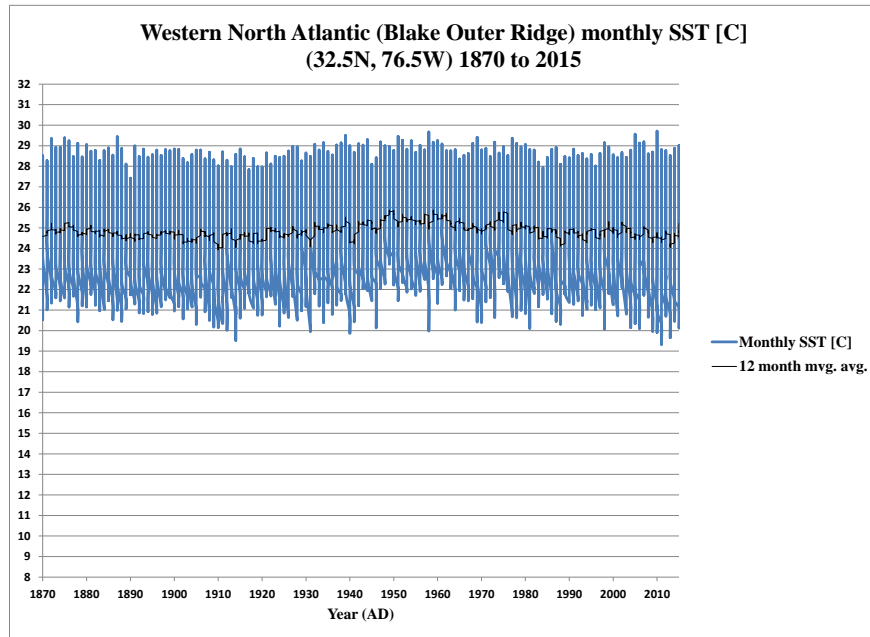


Figure 9. Monthly SST data for western North Atlantic (32.5°N 76.5°W) between 1870 and 2015.

The monthly marine SST data for the Blake Outer Ridge (32.5°N 76.5°W) in Figure 9 show a constant seasonal variation of the monthly medians of around 8°C (between 20°C in winter and 28°C in summer). The 10-year moving average fell to a low of around 24.5 C between 1909 and 1920, increased to a high of 25.4°C between 1953 and 1965, then fell back to 24.6°C between 2013 and 2015, despite the strong El Nino in 2015. This resulted in a decrease of 0.22°C between 1870/9 and 2006/15.

The closest overlap is between the paleo SST of 25.44°C in 100 BP (1850 AD) and the marine SST of between 20.0°C and 28.3°C in 80 BP (1870 AD), which are reasonably consistent, bearing in mind that the paleo SST is likely to represent the SST during the warmer part of the year. Even after adjusting the paleo SST downwards by 2°C, the recent annual average SST of around 24.6°C at the Blake Outer Ridge is well below the maximum temperatures of 28.5°C at this location around 47 Kya and around 8 Kya.

(iv) Southwestern North Atlantic (Broward Coral Reef, 26.25°N 80.06°W) 1870 AD to present

There are no sediment cores close to the Broward Coral Reef that show SST between 10 Kya and the present. The cores on the Blake Outer Ridge in the southwest Sargasso Sea cover 59 Kya to the present, but KNR140-51GGC and CH07-98-MC22 at 32.78°N 76.28°W on the Carolina Slope near the southern flank of the Gulf Stream, and ODP1060 at 30.8°N 74.5°W, lie between 4-6 degrees to the north and 4-6 degrees to the east. The cores on the western margin of the Florida Straits near the Dry Tortugas cover 20 Kya to the present, but KNR166-2-26JPC and W167-

79GGC at 24.3N 83.3W lie 2 degrees to the south and 3 degrees to the west. The closest is the core KNR166-2-125MC-D at 24.76N 79.29W on the Great Bahama Bank, which lies 1.5 degrees to the south and 0.75 degrees to the east, but this only covers the period from 1360 BP to the present.

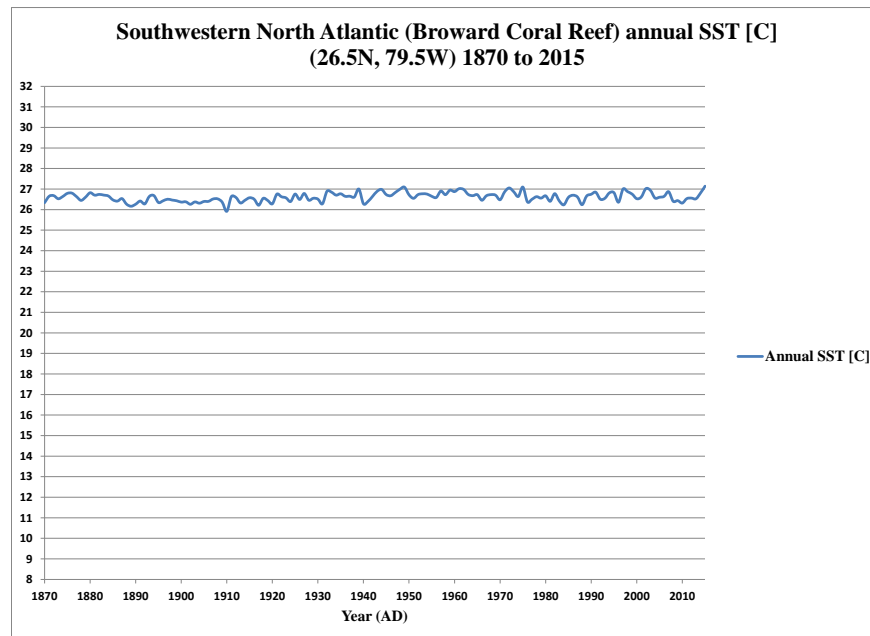


Figure 10. Annual average SST for Broward Coral Reef (26.25°N 80.06°W) between 1870 and 2015.

Figure 10 shows an average annual marine SST for the Broward Coral Reef (26.25°N 80.06°W) of 26.6°C between 1870 and 2015, with very little change during this period and temperatures ranging between 26°C and 27°C. The lowest annual SST of 25.9°C was recorded in 1910, as for the Blake Outer Ridge, Great Bahama Bank, and Dry Tortugas, and the highest SST of 27.1°C was recorded in 1949 and 1975, and in 2015 in response to the strong El Nino.

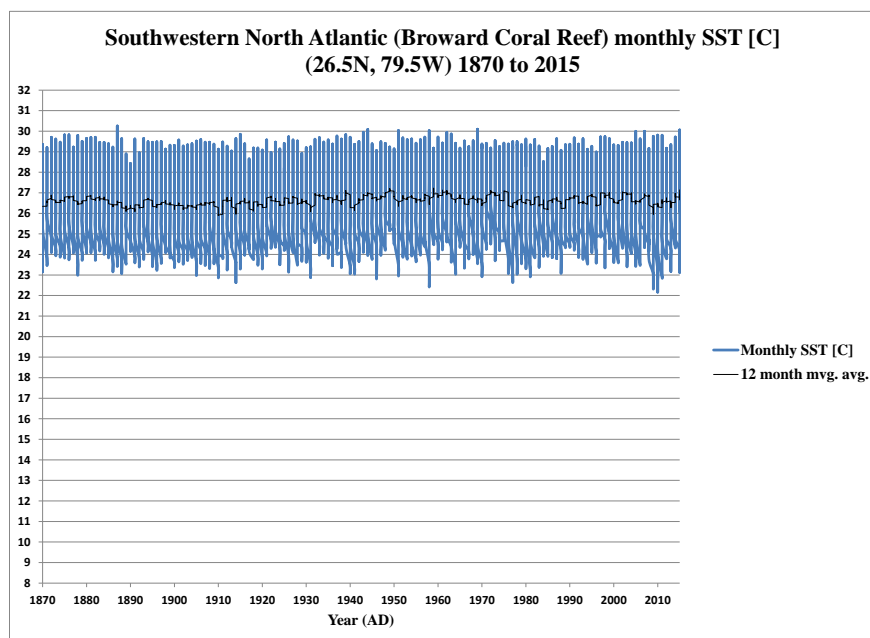


Figure 11. Monthly SST data for Broward Coral Reef (26.25°N 80.06°W) between 1870 and 2015.

The monthly marine SST data for the Broward Reef (26.5°N, 79.5°W) in Figure 11 show a constant seasonal variation of the monthly medians of between 5-6°C (between 24.0°C in winter to 29.5°C in summer). The 10-year moving average recorded a low of around 26.3°C in 1910, and a high of 26.8 C between 1949-69, 1975-76, and 2003-06. There was an increase of 0.01°C in the 10-year moving average SST between 1870/9 and 2006/15.

(v) Southwestern North Atlantic (Great Bahama Bank, 24.76°N 79.29°W) 1360 BP to present

The SST data in Figure 12 are provided by a single SST reconstruction covering the period from 1360 BP (590 AD) to the present (1950 AD) based on the analysis of the sediments from core KNR166-2-125MC-D at 24.76°N 79.29°W on the Great Bahama Bank on the eastern edge of the Florida Current in the Florida Straits based on $\delta^{18}\text{O}_{\text{calcite}}$ and Mg/Ca of the planktonic foraminifera *Globigerinoides ruber* (white variety) (Lund & Curry, 2006).

Mg/Ca values were converted to SST using the general calibration equation of Anand et al. (2003). This generates a core top SST of about 28.5°C, about 1.5°C warmer than observed median SSTs, but falls well within the warmer months' SSTs. Using Anand et al.'s calibration for *G. ruber*, $\text{Mg/Ca (mmol/mol)} = 0.34 \exp(0.104 \times \text{SST(C)})$ the SST are two degrees cooler and agree with the present-day marine observations. Down core age control was based on multiple planktonic foraminiferal radiocarbon dates which were converted to calendar ages using

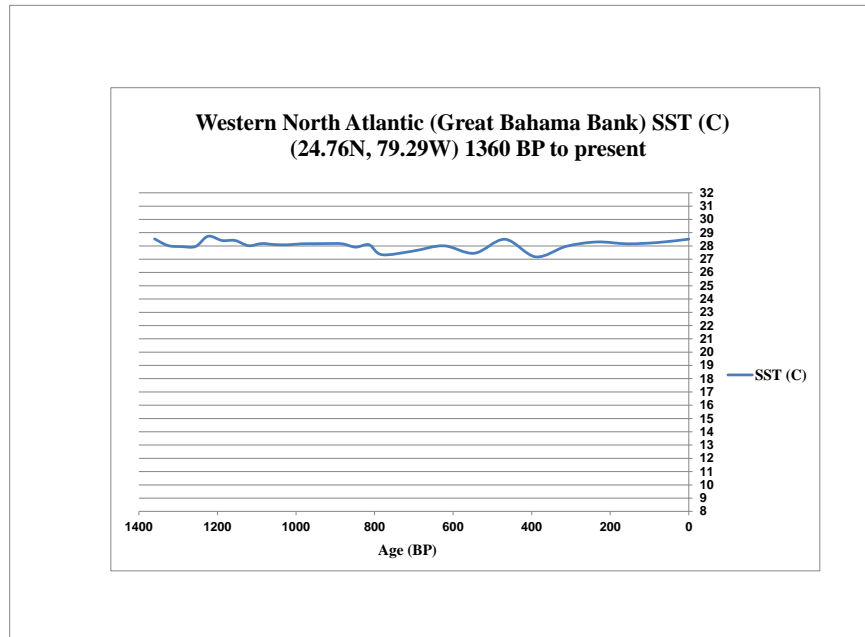


Figure 12. Reconstructed SST data for Great Bahama Bank (24.76°N 79.29°W) 1360 BP to present.

CALIB 4.3 (Stuiver et al 1998). The reconstructed SST was effectively unchanged at about 28.5°C between 1360 BP (590 AD) and the present (1950 AD), apart from a 1.5°C cooling followed by a recovery around 400 BP (1550 AD).

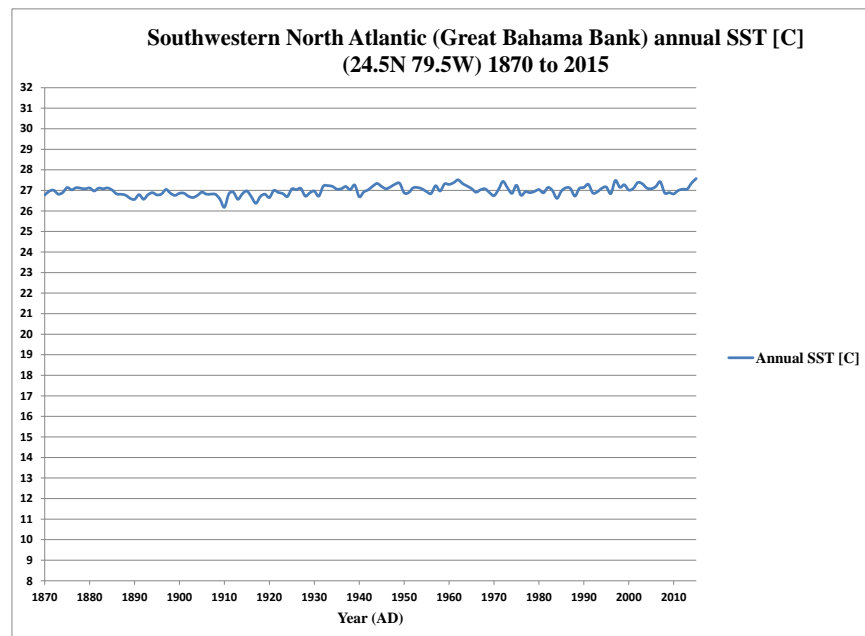


Figure 13. Annual average SST for Great Bahama Bank (24.5°N 79.5°W) between 1870 and 2015.

Figure 13 shows an average annual marine SST for the Great Bahama Bank (24.5°N 79.5°W) of 27.0°C between 1870 and 2015, with very little change during this period apart from an increase of about 0.2°C due to the strong El Nino in late 2015. The lowest annual SST of 26.2°C was recorded in 1910, as for the Blake Outer Ridge, and the highest SST of 27.5/6°C was recorded in 1962 and 2015.

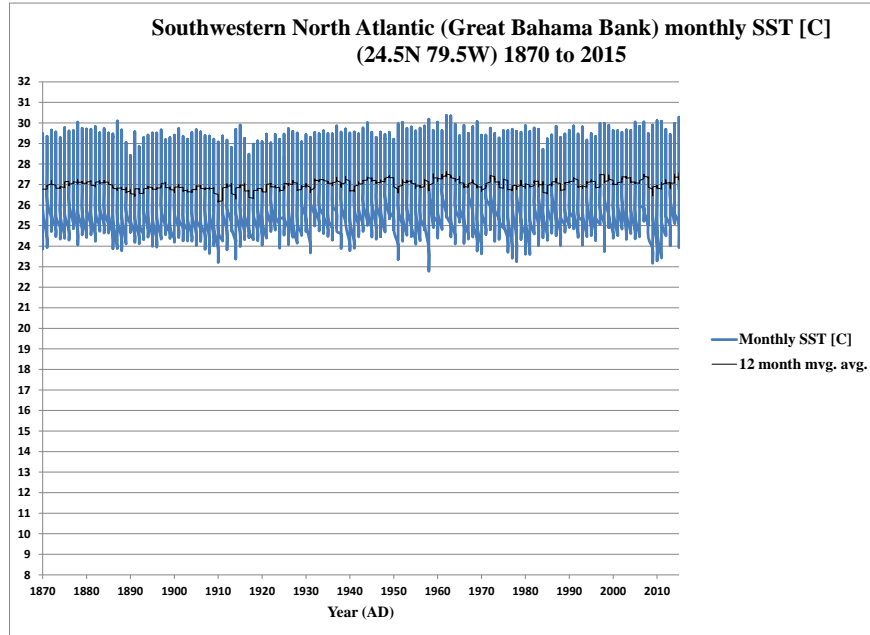


Figure 14. Monthly SST data for Great Bahama Bank (24.5°N 79.5°W) between 1870 and 2015.

The monthly marine SST data for the Great Bahama Bank (24.5°N 79.5°W) in Figure 14 show a constant seasonal variation of the monthly medians of between 5-6°C (between 24.0°C in winter to 29.5°C in summer). The 10-year moving average recorded a low of around 26.7°C between 1910 and 1920, and a high of 27.2 C between 1962-69 and 2003-2008. This resulted in an increase of 0.13°C between 1870/9 and 2006/15.

The Lund & Curry (2006) reconstructed SST data overlap and agree with the marine SST data at around 27°F, after allowing for the adjustment to an annual mean temperature.

(vi) Southwestern North Atlantic (Dry Tortugas, 24.3°N 83.3°W) 20 Kya to present

The paleo SST data in Figure 15 are provided by two SST reconstructions at the same geographical location, respectively covering the overlapping periods from 19.98 Kya BP to 640 BP (Schmidt & Lynch-Stieglitz, 2011) and from 1.29 Kya BP to 1 BP (1949 AD) (Lund & Curry, 2006).

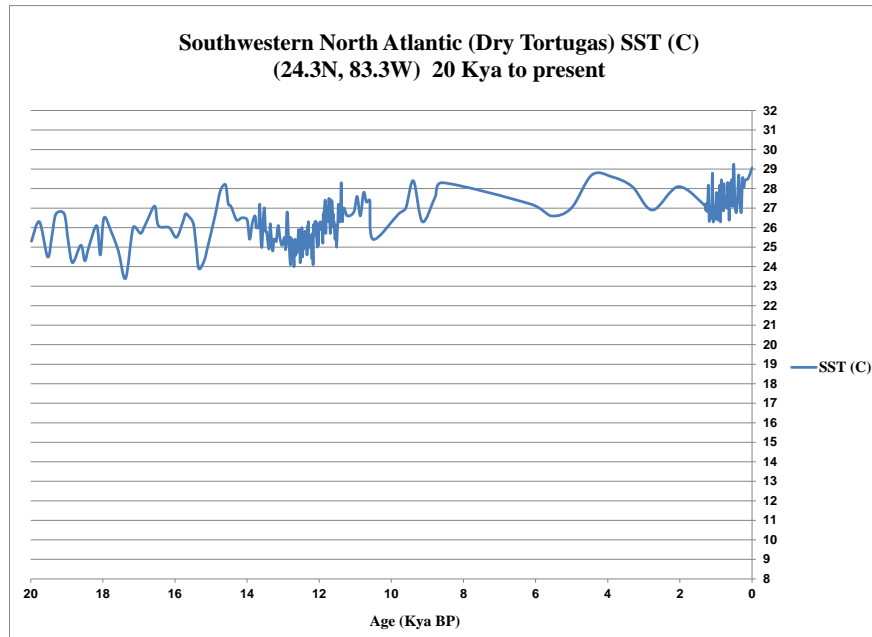


Figure 15. Paleo SST data for Dry Tortugas (24.3°N 83.3°W) 20 Kya to present.

The Schmidt and Lynch-Stieglitz (2011) SST estimates were derived from sediments from core KNR166-2-26JPC at 24.3°N 83.3°W on the western margin of the Florida Straits near the Dry Tortugas based on $\delta^{18}\text{O}_{\text{calcite}}$ and Mg/Ca of the planktonic foraminifera *Globigerinoides ruber* (white variety). Mg/Ca ratios in *G. ruber* were converted to SST using the all-species planktonic relationship based on the Sargasso Sea, $\text{Mg/Ca (mmol/mol)} = 0.38\exp(0.09 \times \text{SST}(\text{C}))$ (Anand et al., 2003). Reconstructed SST were virtually unchanged near the Dry Tortugas at 24.5–26.5°C between 19.98 Kya, at the Last Glacial Maximum, and 11.87 Kya, and then increased by 1.0°C to 26.5–28.5°C through to the end of the record, resulting in a core top SST of 27.6°C at 640 BP, which is well within the present-day annual range of 24.5°C to 30.5°C.

The Lund and Curry (2006) SST estimates were derived from sediments from core W167-79GGC at 24.4°N 83.3°W on the northwestern edge of the Florida Current in the Florida Straits near the Dry Tortugas based on $\delta^{18}\text{O}_{\text{calcite}}$ and Mg/Ca of the planktonic foraminifera *Globigerinoides ruber* (white variety). Mg/Ca values were converted to SST using the general calibration equation of Anand et al. (2003). This covers a period of rising SST from 1.29 Kya BP to 1 BP and generates a core top SST of 29°C, about 2°C warmer than observed median SSTs, but agrees with the warmer months' SSTs. (Using Anand et al.'s calibration for *G. ruber*, $\text{Mg/Ca (mmol/mol)} = 0.34\exp(0.104 \times \text{SST}(\text{C}))$ the SST are two degrees cooler and agree with the present-day marine observations.) Down core age control was based on multiple planktonic foraminiferal radiocarbon dates which were converted to calendar ages using CALIB 4.3 (Stuiver et al., 1998).

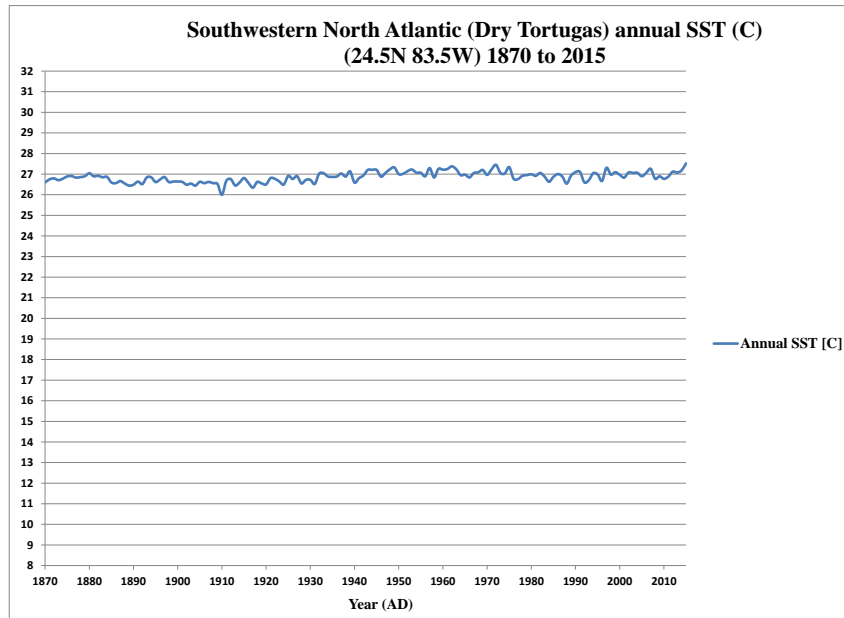


Figure 16. Annual average SST for Dry Tortugas (24.5°N 83.5°W) between 1870 and 2015.

Figure 16 shows an average annual marine SST for the Dry Tortugas (24.5°N 83.5°W) of 26.9°C between 1870 and 2015, with very little change during this period apart from a slight dip around 1910, and a slight increase around 1972, and in 2015 due to the strong El Nino in late 2015. The lowest annual SST of 26.0°C was recorded in 1910, as for the Blake Outer Ridge and Great Bahama Bank, and the highest SST of 27.5°C was recorded in 1972 and 2015.

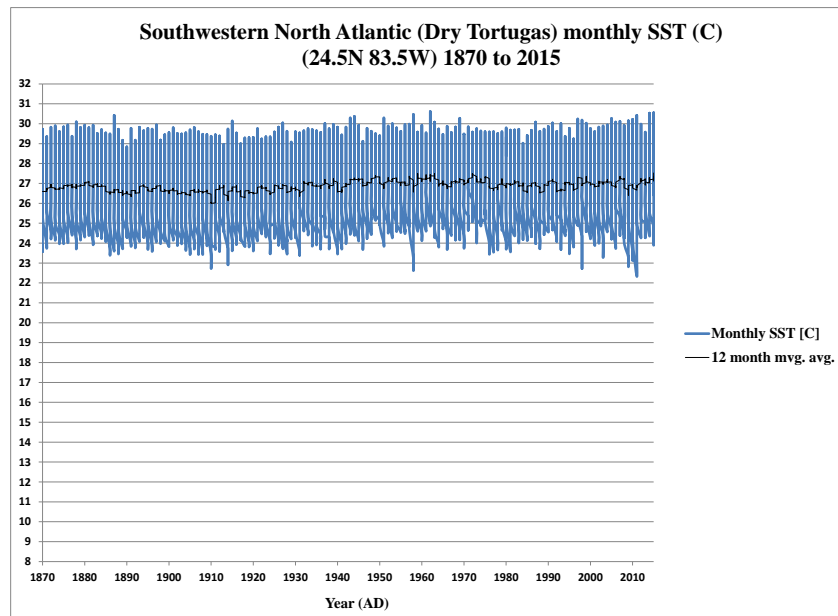


Figure 17. Monthly SST data for Dry Tortugas (24.5°N 83.5°W) between 1870 and 2015.

The monthly marine SST data for the Dry Tortugas (24.5°N 83.5°W) in Figure 17 show a constant seasonal variation of the monthly medians of between 5-6°C (between 24.5°C in winter to 30.0°C in summer). The 10-year moving average recorded a low of around 26.5°C between 1910 and 1914, and a high of 27.15°C between 1962 and 1963. There was an increase of 0.25°C in the 10-year moving average SST between 1870/9 and 2006/15.

The Lund and Curry (2006) paleo SST data overlap with the marine SST at around 27°F, after allowing for the adjustment to an annual mean temperature. After adjusting the paleo SST downwards by 2°C, SST at the Dry Tortugas show a modest recovery since the Last Glacial Maximum.

5. Summary of changes in paleo SST in the North Atlantic since the Last Glacial Maximum

Reconstructed SSTs in the northeastern North Atlantic were virtually unchanged at about 13°C between 19.02 Kya and 13.35 Kya, and then increased by 2.0-2.5°C to 15°C between at 13.35 Kya and 11.26 Kya. This was followed by a modest cooling to 13.7°C between 11.26 Kya and 7.93 Kya, a recovery to 14.3°C at 3.78 Kya, and a further cooling to 12.8°C at 1.01 Kya.

Reconstructed SSTs at the Bermuda Rise were virtually unchanged at about 14.5°C between 19.9 Kya and 12.04 Kya, and then increased by 3°C to 17.5°C by 11.54 Kya and 18.5°C in 8.08 Kya, before falling by 2.5°C to 17.0°C in 7.33 Kya and 16.0°C in 6.11 Kya. After a partial recovery of a little over 1°C, SST fell again to 15.75°C in 570 BP (1380 AD).

Reconstructed SSTs at the Blake Outer Ridge were virtually unchanged at 26.5-27.0°C between 19.42 Kya and 10.67 Kya, and then increased by 1.5°C to 28.0-28.5°C at around 9.70 Kya through to the end of the record at 7.76 Kya.

Reconstructed SSTs near the Dry Tortugas were virtually unchanged at 24.5-26.5°C between 19.98 Kya and 11.87 Kya, and then increased by 1.0°C to 26.5-28.5°C through to the end of the record, resulting in a core top SST of 27.6°C at 640 BP, which is well within the present-day annual range of around 24.5°C to 30.5°C.

The warming from 13 Kya through 7 Kya, and the subsequent cooling, provides evidence for the impact of orbital forcing on SST in the North Atlantic. The Milankovitch 41 Ky obliquity (axial tilt) cycle was at its maximum and the 19-23 Ky axial precession cycle was at its minimum at around 10 Kya, when both contributed the maximum solar forcing in the Northern hemisphere (Berger & Loutre, 1991). Based on the mid-month insolation values for July provided in Berger and Loutre (1999) for 65°N this would have provided about 40 W/m² more solar radiation at that

time. 13 Kya to 7 Kya is the period when insolation values due to orbital forcing were more than 30 W/m² higher than their long-term average. However, the lack of paleo SST data in the proximity of the Broward reef makes it uncertain whether this was sufficient to explain the death of the elkhorn corals around 7 Kya.

6. Summary of marine SST data in the North Atlantic between 1870 and 2015

The marine SST data in Table 1, spanning a large area of the North Atlantic, from the northeast North Atlantic, northwest of the British Isles, to the Dry Tortugas in the southwestern North Atlantic, show a significant and consistent latitudinal variation of average SST from 10.8°C in the northeastern North Atlantic to 26.9°C in the Dry Tortugas, with similar large seasonal ranges between 5.0°C and 8.0°C.

Average SST and seasonal range in North Atlantic based on HadISST1.1					
Region	Lat.	Long.	Average SST (°C)	Seasonal range (°C)	Range SST (°C)
Northeastern North Atlantic	57.5N	15.5W	10.8	9 - 14	5
Bermuda Rise	33.5N	57.5W	22.4	19.5 - 27.5	8
Blake Outer Ridge	32.5N	76.5W	24.85	20 - 28	8
Broward Coral Reef	26.5N	79.5W	26.6	24 - 29.5	5.5
Great Bahama Bank	24.5N	79.5W	27.0	24 - 29.5	5.5
<u>Dry Tortugas</u>	24.5N	83.5W	<u>26.9</u>	24.5 - 30	<u>5.5</u>
North Atlantic average			23.1		6.3

Table 1. Average SST and seasonal range in North Atlantic based on HadSST1.1.

In contrast, Table 2 shows very little, if any, change in the annual average sea surface temperatures (SST) in the North Atlantic over a period of 146 years from 1870 to 2015. Even with a strong El Nino starting in late 2015, the change in the 10-year moving average SST between 1870-79 and 2006-15 is only 0.20°C. This is almost certainly less than the error margin in the temperature measurements and the adjustments to them.

Change in 10-year moving average SST in North Atlantic based on HadISST1.1					
Region	Lat.	Long.	Start date	End date	Change in 10-yr mvg av SST (°C)
Northeastern North Atlantic	57.5N	15.5W	1870	2015	0.24
Bermuda Rise	33.5N	57.5W	1870	2015	0.79
Blake Outer Ridge	32.5N	76.5W	1870	2015	-0.22
Broward Coral Reef	26.5N	79.5W	1870	2015	0.01
Great Bahama Bank	24.5N	79.5W	1870	2015	0.13
<u>Dry Tortugas</u>	24.5N	83.5W	1870	2015	<u>0.25</u>
North Atlantic average			1870	2015	0.20

Table 2. Summary of changes in SST between 1870 and 2015 in North Atlantic based on HadSST1.1.

7. Conclusions

The paleo SST data provide evidence of an increase in sea surface temperatures in the North Atlantic between 13 Kya and 7 Kya, and subsequent cooling, which is consistent with the period when insolation values due to orbital forcing resulting from the coincidence of maximum solar forcing from the Milankovitch obliquity and axial precession cycles were more than 30 W/m² higher than their long-term average in the Northern hemisphere. However, the lack of paleo SST data in the proximity of the Broward reef makes it uncertain whether this was sufficient to explain the death of the elkhorn corals around 7 Kya.

The annual average sea surface temperature (marine SST) in the North Atlantic shows very little change between 1870 and 2015, despite large seasonal and latitudinal variation in response to differences in solar irradiance. Most surprising, was the remarkable stability and consistency of sea surface temperatures over the last 146 years. Although the sea would be expected to dampen the variation, it would also be expected to reflect any global warming trend, if such a trend existed, as the seasonal and latitudinal variations are very significant.

Acknowledgements

The author would like to thank Dane Hancock, who provided a copy of Robin Lighty's paper, which stimulated this research, and Chi-Fan Shih, from the Research Data Archive (RDA) at the National Center for Atmospheric Research (NCAR), Boulder, Co., who kindly provided the monthly mean SST from the Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST1.1) 1-degree grid database for the period from January 1870 through December 2015.

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