SEA SURFACE TEMPERATURE VARIABILITY OVER THE LAST 2000 YEARS IN THE
NORTH ATLANTIC OCEAN AND ITS IMPLICATIONS FOR SEA LEVEL CHANGE

A Thesis in
Meteorology
by
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for the Degree of

Master of Science

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Spatial and temporal patterns of sea surface temperature (SST) are analyzed over the past 2000 years throughout the North Atlantic using twenty-four proxy records of ocean temperature along with instrumental SST data from the 20th century. Spatial patterns of SST are generated by calculating correlation length scales using instrumental SST at each proxy location. Temporal patterns of the ocean temperature proxies are examined using multi-taper method spectral analysis. Finally, the relationship of instrumental SST and regional instrumental sea level (SL) using tide gauge data are examined to identify possible dynamic processes driving SST and SL changes. The proxies are broken up by location into four regions: polar/subpolar, north-central, western, and tropical North Atlantic. The spatial correlations were high between polar/subpolar locations and tropical sites, while the north-central North Atlantic proxy sites only correlated significantly within their own region. This is due to isolation of the north-central region caused by the Subpolar Gyre. Temporally, many of the higher resolution temperature proxies exhibit periodicities in the 60 to 80 year range and/or 20 to 40 year range, corresponding well with variability determined by model reconstructions of the North Atlantic Ocean. The SST-SL correlations are positive in the polar/subpolar region, negative in the north-central region, and mostly negative in the tropics. This result may reflect the influence of internal ocean dynamics on regional SST and SL as shown in previous studies.
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Chapter 1

INTRODUCTION

1.1 – North Atlantic Ocean Dynamics

The oceans and their dynamics play a dominant role on the Earth’s climate system and is a primary driver of sea surface temperature (SST) as well as regional sea level (SL). In order to understand the temporal and spatial patterns of SST and SL in the time before instrumental records were kept, a general understanding of how ocean dynamics affects these properties must be established. Observations of the ocean gives some insight to the dynamics taking place, but due to the size and time scale on which processes occur, modeling of the ocean-atmosphere system is also necessary to get a solid understanding of ocean dynamics.

Frankcombe et al. (2010) discuss the many features of the oceanic system that exhibit cyclical patterns. They investigate observations of SST, Sea Surface Salinity, ice extent, and others for dominating time scales. Two time scales emerge over the Atlantic: a 20-30 year cycle, and a 50-70 year cycle. Frankcombe et al. state that the shorter cycles, while exhibited at all latitudes in the North Atlantic, are regional and thus not in phase basin-wide. The driver for the shorter mode is the atmosphere, whereas the longer cycle is possibly an excitation of the shorter cycle, or is driven by water exchanged from the Arctic and North Atlantic.

1.1.1 - The AMOC and Regional Climate

The Atlantic Meridional Overturning Circulation (AMOC) is a basin-wide dynamical process that transports warm, salty water northward above a southward transport of cold, fresh water [Lozier et al. 2010]. It is responsible for the major surface currents in the North Atlantic as well as the formation of North Atlantic Deep Water (NADW) in the Labrador and Greenland Seas [Miettinen et
The AMOC has a large effect on the climate throughout the northern hemisphere especially northwest Europe and northeast North America. The amount of freshwater entering the North Atlantic from Arctic sources determines the strength of the AMOC [Miettinen et al. 2012]. A large amount of freshwater can decrease or stop NADW formation, which will slow down the AMOC and transport less heat to the northern North Atlantic.

Many studies have focused on the effects that the AMOC has on regional climate. Vellinga and Wu (2004) discovered that a stronger AMOC causes the Intertropical Convergence Zone (ITCZ) to move northward due to the temperature gradient it creates. Sicre et al. (2008) find that northward displacement of the ITCZ caused increased warmth throughout the northern Atlantic basin during the Medieval Climate Anomaly. Opposite this mechanism, a decline in the AMOC causes the ITCZ to move south and in turn cools down the northern Atlantic basin.

1.1.2 - North Atlantic SST and SL Variability

This study focuses mainly on proxy-derived historical SST but also extends to examine historical SL based on SST-SL relationships. Lozier et al. (2010) described the relationship between ocean dynamics, SST, and SL. They analyzed the regional variability of changes in SL by taking observed temperature and salinity data over two twenty-year periods (1950-1970 and 1980-2000) and subtracting the earlier time from the later time. The time periods chosen represent a time of high amplitude NAO (1950-1970) and low amplitude NAO (1980-2000). Lozier et al. found that regional SL changes depended on temperature and salinity changes. In general, north of 45°N, both temperature and salinity declined from the 1950-1970 period to the 1980-2000 period. Temperature affected density more than salinity in general north of ~55°N, and thus SL declined with the temperature. South of here, salinity changes on ocean density trumped temperature and SL increased as the water freshened.

In the mid-latitude North Atlantic, Lozier et al. (2010) showed that ocean temperature has risen, while salinity remained generally unchanged. This results in a lower density mid-latitude ocean and thus higher SL. In the tropical North Atlantic, again the temperature has risen in the later period, and so has the salinity. This is where the most variability can be found. In some locations, the salinity increase outweighs the temperature increase thus decreasing SL, while in other locations the temperature increase outweighs the salinity increase thus increasing SL. There are more regions where salinity trumps temperature in the tropics. Density changes from the earlier to later period are...
shown to vary from -0.1 kgm$^{-3}$ to 0.1 kgm$^{-3}$ over only hundreds of km, leading to complex regional to sub-regional patterns of SL change.

Lozier et al. found that in general, ocean temperature and SL should be positively correlated on average in the polar and subpolar regions of the North Atlantic, and on average slightly negatively correlated in the tropical regions. This paper examines the relationship between instrumental SST and SL using tide gauges near proxy locations to see if they match Lozier et al. (2010). If shown to be consistent, the SST-SL relationship can be extended to the ocean temperature proxies so as to gain insight to past regional SL along with ocean temperature.

1.2 – Ocean temperature Proxies

Most instrumental records of SST and SL throughout the world’s oceans only go back as far as the late 19th century. To investigate variability over longer time scales, proxy methods for SST reconstructions from sediment cores and coral skeletons have been used extensively. In this study, twenty-four published SST proxy records from seventeen different locations throughout the North Atlantic were examined to investigate paleoceanographic variability over the last 2000 years and to evaluate instrumental trends in SST and SL.

Many of these proxies are evaluated using the proxy data that overlaps instrumental SST data. Cronin et al. (2010) found that their Chesapeake Bay Mg/Ca temperature proxy compared well to nearby instrumental SST data throughout the 20th century. Their proxy shows the same general temperature oscillations seen in the instrumental SST data. Black et al. (2004) evaluate their $\delta^{18}\text{O}$ proxy in the Caribbean by correlating it with instrumental SST data throughout the entire North Atlantic. This provides not only a measure of how the proxy performed, but also the correlation length scale of the proxy. This method is applied to each of the proxies used in this paper as a way to understand the regional dynamics of the ocean near the proxies.

1.3 – Trends, Transitions and Oscillations

The temperature records produced from the proxies are broken into trends, transitional periods, and oscillations. The trend aspect of the proxy represents the temperature trends on a multi-
centennial time frame or longer. Many of the proxies dating over 1000 years old show a cooling trend from the mid Holocene up until the 20th century [Andersson, 2010; Black et al. 2004; Bendle, 2007]. Transitional periods are multi-decadal to centennial oscillations. A few examples of these periods are the Medieval Climate Anomaly (MCA) which shows up in the records in some regions of the North Atlantic from ~800 to 1400 CE, and the Little Ice Age (LIA) spanning from ~1400 to 1850 CE. Superimposed onto the trends and transitions are temperature oscillations. These oscillations are noted in many of the papers used in this study. The oscillations vary from millennial scale, caused by glacial formation [Bendle, 2007], to decadal oscillations, caused by atmospheric or even solar forcings [Sicre et al. 2008; Black et al. 2004].

The trends and transitional periods of proxy-based ocean temperature are analyzed for each proxy. One goal of this study is to examine if or when certain proxies show evidence of a MCA and LIA. The oscillations within the temperature reconstructions will be found by performing a multi-taper method power spectrum to each time series. For each proxy, the power spectrum will show how many statistically significant oscillations are superimposed onto the time series, as well as the period of each oscillation.
Chapter 2

METHODS

2.1– Materials

2.1.1 – Ocean Temperature Proxy Data

Twenty-four ocean temperature proxy records for seventeen locations across the North Atlantic were the basis of this investigation. There are more proxies than proxy locations because some locations contain more than one proxy method. Table 2-1 (proxy metadata) shows the principle investigator, location, and method of each proxy record used. The proxy locations were broken into three main regions of the North Atlantic: polar/subpolar, north-central, and tropical. A fourth region, the western North Atlantic, is not rigorously examined as its own region and is grouped in with the north-central proxies for some regional analyses. For this paper, the proxy location (PL) was most important so each proxy was assigned a number based on latitude going north to south. Multiple proxies at the same PL were assigned letters, in addition to their location, for easier identification (ex: proxies 1a, 1b, 1c, and 1d all are located at PL 1). Figure 2-1 shows the PL of all the proxies along with the four regions described above.

Each proxy record used in this analysis came from either a sediment core of a drilling project or a coral skeleton in certain tropical locations. Within each core, there are the calcium carbonate (CaCO$_3$) shells of planktonic foraminifers that lived in surface or shallow subsurface ocean layers. The isotopic composition of CaCO$_3$ contains information about the oceanic environment in which it was formed. One widely used proxy is known as $\delta^{18}$O which uses the ratio of heavy oxygen ($^{18}$O) to the more common isotope oxygen ($^{16}$O), which is governed by temperature and regional hydrology and, over longer timescales, by global ice volume. The ratio found in the shell therefore often depends on the temperature of the water at the time of calcification, as well as background oceanic $\delta^{18}$O, which is itself dependent on local hydrology (Black et al. 2004).
The use of $\delta^{18}O$ alone may not be enough to create an accurate analysis of oceanic temperature because it has two dependencies. To solve this, another geochemical attribute of the shell is used to eliminate one of the unknown contributors. The ratio of magnesium to calcium in the shell also depends on the temperature of calcification. The combined use of $\delta^{18}O$ and Mg/Ca ratios creates a proxy for ocean temperature. The relationship between these ratios and ocean temperature has been calibrated to minimize errors. Many of the studies in this analysis used a combined $\delta^{18}O$ and Mg/Ca ratio as the basis of their temperature reconstruction [Richey, 2007; Thornally, 2009; Kilbourne, 2008; Black et al. 2004].

Several investigations used alkenones as a proxy for ocean temperature. Alkenones are organic compounds found in sediment cores and come from the remains of small organisms. The unsaturation index of a particular type of alkenone has been calibrated with ocean temperature and is widely accepted as a useable proxy [Sicre et al. 2008].

There are other methods of reconstructing ocean temperature from sediment cores. The species assemblages of foraminifera or diatoms relates to the oceanic conditions at that time [Spielhagen, 2011; Jiang, 2007]. The temperature analyses in some tropical locations used the strontium/calcium ratio found in coral [Saenger, 2008; Kilbourne, 2008]. Many of the seventeen investigators examined their site using multiple proxy methods for their analyses to avoid overconfidence and/or ensure consistency.

In this study, it is assumed that the original authors performed rigorous error analyses and calibration with the current instrumental SST record. It is also implied that all of the proxies have been properly converted from proxy form (raw $\delta^{18}O$, alkenone values, etc.) to temperatures or temperature anomalies. Only proxies that represent the temperature at or near the ocean surface were used. Some proxies represented a warm or cold season temperature. The effect of this was removed when looking at temperature anomalies instead of raw proxy temperature.
Figure 2-1 A map of the locations of proxies and the regions they are placed in. Proxy locations are indicated by white numbers. Refer to Table 2-1 to see which proxies the numbers represent. Some locations are close together at this scale. Locations 3, 4, and 5 are all north of Iceland. Locations 11 and 12 are in the Gulf of Mexico. Locations 15 and 16 are near Puerto Rico.
Table 2-1 Proxy metadata. Lettered proxies represent proxies at the same location.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Proxy #</th>
<th>Lat</th>
<th>Lon</th>
<th>Proxy Method</th>
<th>Start date (CE)</th>
<th>End Date</th>
<th># Data points</th>
<th>Notes/Season</th>
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<td>1a</td>
<td>78.92</td>
<td>6.77</td>
<td>Relative abundance of foraminifers</td>
<td>-94</td>
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<td>2007</td>
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<td>Dinocyst abundance</td>
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<td>1943</td>
<td>51</td>
<td>Winter</td>
</tr>
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<td>Bonnett et al. 2010</td>
<td>1d</td>
<td>78.92</td>
<td>6.77</td>
<td>Dinocyst abundance</td>
<td>-492</td>
<td>1943</td>
<td>51</td>
<td>Summer</td>
</tr>
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<td>2000</td>
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<td>Mg/Ca ratio, relative abundance</td>
<td>-9922</td>
<td>1862</td>
<td>110</td>
<td>Summer</td>
</tr>
<tr>
<td>deMenocal</td>
<td>14b</td>
<td>20.75</td>
<td>-18.6</td>
<td>Mg/Ca ratio, relative abundance</td>
<td>-9922</td>
<td>1862</td>
<td>110</td>
<td>Winter</td>
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<td>2004</td>
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<td>566</td>
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2.1.2 – Instrumental SST data

Three sets of instrumental North Atlantic SST data were used in this study. The ERSST data set contains monthly mean SST data on a 2° by 2° grid from January 1854 through 2012 [Smith et al. 2004]. The Kaplan data set contains monthly averaged SST anomaly data from January 1856 through
2012 on a 5° by 5° grid [Kaplan et al. 1998]. Finally, the HadISST1 data set shows mean monthly SST anomalies from January 1870 through 2012 on a 1° by 1° grid [Rayner et al. 2003]. All three instrumental SST data sets use an optimized interpolation scheme to fill in data gaps. Since the proxies represent one point, instrumental data was chosen to represent the point at the grid square that contained the PL (ex: Kaplan SST was a 5° by 5° average SST containing the location of the proxy, while HadISST1 was a 1° by 1° average SST containing the location of the proxy. If no instrumental SST grid squares encompassed the exact PL, the nearest grid square was used).

2.1.3 – Sea Level Data

Sea level data from tide gauges came from the Permanent Service for Mean Sea Level [Woodworth and Player, 2003; PSMSL, 2013]. One tide gauge was chosen to represent a given PL. The gauge chosen was the closest gauge to the proxy where instrumental SST and tide gauge data overlap for at least 40 years. Table 2-2 lists the tide gauges and relevant data.

<table>
<thead>
<tr>
<th>Proxy Location (PL)</th>
<th>Geographic Location</th>
<th>Location of Tide Gauge</th>
<th>Duration of data overlap</th>
<th>Dist from proxy to tide gauge (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Fram Strait</td>
<td>BARENTSBURG</td>
<td></td>
<td>1949 to 2000</td>
<td>196</td>
</tr>
<tr>
<td>2 Norwegian Sea</td>
<td>BODO</td>
<td></td>
<td>1950 to 2000</td>
<td>291</td>
</tr>
<tr>
<td>3 North of Iceland</td>
<td>REYKJAVIK</td>
<td></td>
<td>1957 to 2000</td>
<td>344</td>
</tr>
<tr>
<td>4 North of Iceland</td>
<td>REYKJAVIK</td>
<td></td>
<td>1957 to 2000</td>
<td>336</td>
</tr>
<tr>
<td>5 North of Iceland</td>
<td>REYKJAVIK</td>
<td></td>
<td>1957 to 2000</td>
<td>286</td>
</tr>
<tr>
<td>6 North Atlantic</td>
<td>REYKJAVIK</td>
<td></td>
<td>1957 to 2000</td>
<td>303</td>
</tr>
<tr>
<td>7 North Central NA</td>
<td>REYKJAVIK</td>
<td></td>
<td>1957 to 2000</td>
<td>797</td>
</tr>
<tr>
<td>8 Gulf of Maine</td>
<td>PORTLAND (MAINE)</td>
<td></td>
<td>1913 to 2000</td>
<td>36</td>
</tr>
<tr>
<td>9 Chesapeake Bay</td>
<td>ANNAPOLIS (NAVAL ACADEMY)</td>
<td></td>
<td>1929 to 2000</td>
<td>32</td>
</tr>
<tr>
<td>10 NW Africa</td>
<td>SANTA CRUZ DE TENERIFE I</td>
<td></td>
<td>1929 to 1990</td>
<td>653</td>
</tr>
<tr>
<td>11 Gulf of Mexico</td>
<td>GRAND ISLE</td>
<td></td>
<td>1948 to 2000</td>
<td>289</td>
</tr>
<tr>
<td>12 Gulf of Mexico</td>
<td>GRAND ISLE</td>
<td></td>
<td>1948 to 2000</td>
<td>270</td>
</tr>
<tr>
<td>13 Bahamas</td>
<td>MIAMI BEACH</td>
<td></td>
<td>1932 to 1981</td>
<td>153</td>
</tr>
<tr>
<td>14 Eastern NA</td>
<td>SANTA CRUZ DE TENERIFE</td>
<td></td>
<td>1928 to 1990</td>
<td>888</td>
</tr>
<tr>
<td>15 Puerto Rico</td>
<td>MAGUEYES ISLAND</td>
<td></td>
<td>1956 to 2000</td>
<td>7</td>
</tr>
<tr>
<td>16 Puerto Rico</td>
<td>MAGUEYES ISLAND</td>
<td></td>
<td>1956 to 2000</td>
<td>48</td>
</tr>
<tr>
<td>17 Cariaco Basin</td>
<td>MAGUEYES ISLAND</td>
<td></td>
<td>1956 to 2000</td>
<td>838</td>
</tr>
</tbody>
</table>
2.2 – Methods

2.2.1 – Spatial Analysis of Proxies

Spatial patterns of SST were created based on the temperature proxies and instrumental SST records. In order to spatially expand a point proxy, a correlation length-scale was calculated. The 140 years of ERSST data in the form of 9-year running means were used for this calculation. Nine years was the chosen time scale because this study investigates trends and cycles on the decadal scale and longer and to calculate a running mean of annual temperature, an odd number of years must be used. Each proxy site was represented by the nearest 2° by 2° grid square of ERSST data. This time series was correlated with each 2° by 2° grid square time series of ERSST data throughout the North Atlantic. Any grid square with a p-value under 0.05 was considered significant and thus the proxy’s temperature influence extended there. This style of spatial SST analysis was performed by Black et al. (2004) when they correlated their proxy of foraminiferal δ¹⁸O to the HadISST data set. Expanding the spatial relationship found with the instrumental SSTs onto the locations of the ocean temperature proxies, the proxy data can be expanded to represent a two-dimensional region of temperature in the North Atlantic instead of just a point.

2.2.2 – Temporal Analysis of Proxies

To analyze the proxy records themselves for periodicity, a power spectrum was created for each proxy using the Multi-Taper Method (MTM) toolkit. For each proxy, frequencies were tested against red noise for statistical significance levels above 90%. If a frequency peak was above the significance threshold, it was considered to have an oscillation with a period of 1/frequency.

To find out if each proxy experienced temperature anomalies during the MCA and/or LIA, the annually interpolated proxy temperature anomalies were first low-pass filtered at a 100-year time scale. Whenever the filtered time series was colder than one standard deviation below its own mean temperature, it was considered to be a cold period. Likewise, whenever the filtered proxy was warmer than one standard deviation above its mean, this was noted as a warm period.

Long-term time series were created by averaging the proxy SST. Proxies that had continuous data from 0 CE to 1900 were considered long-term proxies. 1800-1899 was used as the reference
period for each proxy. Anomalies were created for each proxy with respect to the reference period. These anomaly time series were averaged together from 0 to 1900 to form a long-term record average temperature anomaly. This method was performed on medium-term proxy records (1500-1900) and short-term proxy records (1800-2000) in the same fashion using the same 1800-1899 reference period.

A similar technique was applied to find temperature trends by location. Three sections were examined: polar/subpolar North Atlantic, north-central and western North Atlantic, and the tropical North Atlantic. Temperature anomalies from the 1800-1899 reference period were created for each proxy and then all proxy time series in each zone were averaged together. These time series cover temperatures from 1250 to 1950 CE.

2.2.3 – Instrumental SST and SL Correlation

In order to examine relationships between SST and regional SL, the instrumental SST record representing a given proxy was correlated with the nearest tide gauge time series record. To properly correlate the SST with the SL, all data were converted to a common format. The monthly SST values were averaged over a year, and then a 9-year running mean was calculated using these annual means. Running mean anomalies were calculated for all three instrumental SST data sets. The raw tide gauge time series were also monthly means, so to properly compare the SL to the SST, a 9-year running annual mean anomaly was calculated for each tide gauge.

For all seventeen PLs, the tide gauge time series was correlated to each of the three corresponding instrumental SST time series for the time period when the data overlapped (Table 2-2).
Chapter 3

RESULTS

3.1 – Spatial SST Patterns

3.1.1 – Polar/subpolar Region

Spatial correlations of instrumental SST time series in the polar/subpolar region are plotted in Figure 3-1. Temperature trends have the strongest relationship throughout the polar/subpolar North Atlantic, with a secondary area south of 40˚N excluding the Gulf of Mexico. The instrumental record shows that there is no significant correlation between polar/subpolar SSTs and the north-central SSTs to the southwest.

Figure 3-1 Spatial correlation patterns using ERSST data for proxy locations 1 (left) and 2 (right) located in the polar/subpolar region. For each figure, the ERSST time series data at the proxy location (represented by the number on the map) was correlated with the ERSST time series data at each 2˚ by 2˚ grid square on the map. Grid squares in the ocean that are not statistically correlated are colored deep blue.
3.1.2 – North-Central Regions

Spatial patterns in the north-central North Atlantic show that this region only correlates significantly in its own area. Figure 3-2 shows that significant correlations extend out over 1000 km in every direction from PL 7. PL 6, located closer to some of the polar/subpolar sites shows an extension of significant correspondence along the eastern boundary of the North Atlantic.

Figure 3-2 Spatial correlation patterns using ERSST data for proxy locations 6 (left) and 7 (right) located in the north-central region. These maps were created the same way as Figure 3-1.
3.1.3 – Tropical Regions

Spatial patterns in the tropical region (Figure 3-3) show that a large majority of the ERSST data in this area recorded similar SST trends and patterns. For PL 16, high positive correlations extend all the way across the Atlantic basin at that latitude. The SST records in tropical locations correlated least with SST records in the north-central and polar/subpolar regions.

![Correlation coefficient for proxy location 13 (ERSST)](image1)
![Correlation coefficient for proxy location 16 (ERSST)](image2)

Figure 3-3 Spatial correlation patterns using ERSST data for proxy locations 13 (left) and 16 (right) located in the Tropical region. These maps were created the same way as Figure 3-1.

3.2 – Temporal Patterns

The MTM spectral analysis performed for each proxy revealed time scales of statistically-significant periodicities in SST, although as expected, the resulting spectra depended highly on the resolution of the proxy. In order to resolve periodicity of \( n \) years, a proxy must have a resolution of \( n/2 \) years or less. For example, the power spectrum for proxy 8 (annual resolution), shown in Figure 3-4, has several significant periodicities. The MTM toolkit calculated peak frequency signals at \( f = 0.0479, 0.0381, 0.0254 \) and \( 0.0021 \text{ yr}^{-1} \) corresponding to periods of 21, 26, 39 and 485 years respectively. For the purposes of this study, any periodicities shorter than 20 years were disregarded despite proxy resolution.
This same calculation carried out over all proxies yields Figures 3-5 and 3-6. Figure 3-5 shows these time scales for each proxy for periods between 20 and 100 years. Of the thirteen proxies with a resolution of 50 years or less, all but three exhibit sub-centennial periodicity. There are two peaks of periodicity at this scale: 20 to 40 years, and 60 to 80 years. Lower-resolution proxies do show significant signals of periodicity, but at periods of centuries or longer. Figure 3-6 shows significant periodicities between 20 and 500 years for all proxies. At this longer time scale, secondary peaks in periodicity appear around 200 and 400 years, but it is clear that most SST oscillations occur with sub-centennial periods.
Figure 3-5 Significant periodicity for all proxies from 20 to 100 years. After performing the spectral analysis for each proxy, all significant spectral peaks are recorded here in terms of 1/frequency. All signals are significant at the 90% level or higher. Grey regions represent time scales that are not resolvable for a given proxy record.

Figure 3-6 Significant periodicity for all proxies from 20 to 500 years. Same as Figure 3-5, but over a longer time interval.

Another temporal aspect of the proxies investigated was the transitional periods: times that were notably cooler or warmer than the proxy mean. Figure 3-7 shows the relative warm and cool periods for all seventeen PLs over the past 2000 years. The period between 1600 and 1800 is dominated by lower than normal temperatures in the proxies. This coincides well with the timing of at least part of the Little Ice Age. During the period from around 600 to 900, a large portion of the
proxies with data recorded warmer than normal temperatures. This coincides with part of the Medieval Warm Period.

Figure 3-7 Times of relative cold and warm ocean conditions for each proxy. All proxies were low-passed with a 100 year filter. One standard deviation below normal was considered below normal and was plotted as a blue circle (each circle represents 1 year). A red circle was plotted when the temperature exceeded one standard deviation above the normal. Grey sections represent no data for that proxy at that time. The bottom plot is a sum of cold proxies and warm proxies by year.
The final aspect of temporal patterns is the long-term trends of the proxies. Figure 3-8 shows a reconstruction of North Atlantic temperature using only proxy data. The proxies are broken into three time scales: long-term (0-1900), medium-term (1500-1900) and short-term (1800-1990). Each proxy anomaly was based on the common reference period (1800-1899 mean). Each category had the same continuous proxies throughout the time period (thirteen long-term, nineteen medium-term, and nine short-term proxies). The mean temperature was plotted for each time period, as well as a lowpass filter of each mean for smoothing purposes (100 years for long-term, 25 years for medium-term, 10 years for short-term). A 95% confidence interval was calculated by bootstrapping the mean proxy temperature anomaly at each year 1000 times, taking the range of the middle 950 means. Figure 3-8 shows a long-term cooling up until around 1900, followed by multi-decadal oscillations resolved by the higher resolution proxies.

Figure 3-8 Mean ocean temperature anomaly derived ocean proxies over various time scales. The thin red line is the mean proxy temperature anomaly for all proxies with continuous data from year 0 to 1900. The smooth, thick red line is a 100-year lowpass filter of the long term proxy mean. The translucent red shading is a 95% confidence interval for the mean temperature. The blue section is the medium length time scale, representing proxies with data from 1500 to 1900. The black section is short term, high resolution proxies from 1800 to 1990. Temperatures are anomalies from the 1800-1899 reference period.
Figure 3-9 is a closer look at recent proxy records with instrumental SST plotted on top. There is good agreement between the proxy-based average North Atlantic temperature and the average instrumental North Atlantic SST records at the same locations as the proxies. The nine short-term proxies comprising the mean correctly capture the multi-decadal oscillations apparent in the instrumental record.

Figure 3-9 Temperature anomaly time series of short-term proxies from Figure 3-8 overlaid with three instrumental SST records. Data are 9-year running means. The proxy time series is the average (and uncertainty in the average) of nine proxies, ending in 1990. The three instrumental records are the average temperature anomaly at these nine locations and extend from 1870 to 2000. Note: 9-year running means cut off 4 years of data from beginning and end times.
Figure 3-10 examines the mean temperature anomaly time series in three different locations throughout the North Atlantic: the polar/subpolar region, the north-central and western regions, and the tropical region. In the polar/subpolar region, there appears to be a slight cooling over the 1250-1950 CE period. The north-central and western areas exhibited gradual warming over the same 700 years. The tropical section does not have a clear temperature trend.

Figure 3-10 Temperature time series by region. The top plot in blue shows the average temperature anomaly for all proxies in the polar/subpolar region from 1250 to 1950. The green time series is mean temperature for all proxies in the north-central and western Atlantic regions. The red time series is all proxies in the tropical region. The reference period is 1800 through 1899 for all proxies. Shaded areas are 95% confidence for mean temperature anomaly.
3.3 – Temperature Reconstruction

Using the temperature anomalies derived from the ocean proxies, along with the spatial patterns of SST arising from the instrumental data, a basic temperature reconstruction for the proxy period can be created. For each grid square in the North Atlantic, ocean temperature was calculated based on the weighted mean of the correlation coefficients of any statistically significant proxies. This was calculated for each 2° by 2° grid square throughout the North Atlantic every year from 0 to 2000. The resulting SST anomaly time series was averaged by century and mapped. These figures assume that the same spatial SST relationships hold throughout the 2000 year period, and that the proxies are without error. The centennial resolution is shown to dampen error and to provide a general idea as to what SST throughout the North Atlantic may have looked like and how it evolved.
Figure 3-11 Century-averaged SST anomaly (K) reconstruction based on ocean temperature proxies and SST patterns derived from instrumental data.
These reconstructed ocean temperature maps show that North Atlantic was warmest during the 8th century and coolest around the 16th and 17th centuries. There is the most variability in regions that have the most proxies with significant spatial correlation i.e. the tropics and Canary Current. The least variability is in the subtropical gyre of the North Atlantic where there is almost no data to use for this reconstruction. The area surrounding PL 1 way up north appears out of touch with the surrounding basin because that region is only influenced by one proxy, and will therefore be subject to more erratic SST changes instead of the gradual changes seen when averaging several proxies. Figure 3-12 shows the range of temperature for each grid square across the 20 maps. It is also an indicator of how many proxies are influencing a particular grid square. The accuracy of these reconstruction maps can be vastly improved with increased proxy coverage.

Figure 3-12 Range of temperatures for each grid square across all 20 centuries.
It is important to compare this reconstructed analysis to the instrumental record to determine performance and to find areas that need improved coverage. To do this, the mean SST for the decade spanning from 1991 to 2000 was mapped for the proxy-derived reanalysis (Figure 3-13a), the ERSST data set (Figure 3-13b), and finally the difference in of temperature between the two maps (Figure 3-13c).

As expected, the proxy reconstruction fared well only in the areas where there was good proxy coverage. The proxies accurately captured the cool area surrounding the southeast US coast and the warming in the East Atlantic as well as some of the polar areas. The region under the influence of the Subtropical Gyre was a very poor area for the proxy reconstruction. The proxies depicted a near-zero SST anomaly where in reality, the ERSST dataset shows this is where the most significant warming in the entire North Atlantic basin occurred.

### 3.4 – SST and SL Relations

Table 3-1 shows the correlation coefficients of the tide gauge record to each instrumental SST record for each PL. In general, the relationship between SL and instrumental SST was positive in the polar/subpolar region of the North Atlantic, and negative in the tropical region. Below is a closer examination of these relationships in the three main regions of the North Atlantic (polar/subpolar, north-central, and tropical).
Table 3-1 Correlation between SL recorded at nearby tide gauges and instrumental SST at each proxy location. Statistically significant correlations are highlighted (green for positive, red for negative). NaN indicates that a correlation could not be computed.

<table>
<thead>
<tr>
<th>PL</th>
<th>Region</th>
<th>ERSST</th>
<th>Kaplan</th>
<th>HadISST1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>polar/subpolar</td>
<td>0.15</td>
<td>NaN</td>
<td>0.14</td>
</tr>
<tr>
<td>2</td>
<td>polar/subpolar</td>
<td>0.53</td>
<td>0.80</td>
<td>0.66</td>
</tr>
<tr>
<td>3</td>
<td>polar/subpolar</td>
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<td>0.20</td>
<td>0.27</td>
</tr>
<tr>
<td>4</td>
<td>polar/subpolar</td>
<td>NaN</td>
<td>0.20</td>
<td>0.27</td>
</tr>
<tr>
<td>5</td>
<td>polar/subpolar</td>
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<td>0.59</td>
<td>0.77</td>
</tr>
<tr>
<td>6</td>
<td>North-central</td>
<td>-0.46</td>
<td>-0.35</td>
<td>-0.59</td>
</tr>
<tr>
<td>7</td>
<td>North-central</td>
<td>-0.52</td>
<td>-0.71</td>
<td>NaN</td>
</tr>
<tr>
<td>8</td>
<td>Western</td>
<td>0.09</td>
<td>0.59</td>
<td>NaN</td>
</tr>
<tr>
<td>9</td>
<td>Western</td>
<td>-0.33</td>
<td>0.01</td>
<td>NaN</td>
</tr>
<tr>
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<td>Tropical</td>
<td>-0.69</td>
<td>0.13</td>
<td>0.40</td>
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<td>-0.16</td>
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<tr>
<td>17</td>
<td>Tropical</td>
<td>NaN</td>
<td>-0.89</td>
<td>-0.76</td>
</tr>
</tbody>
</table>
3.4.1 – Polar/subpolar Region

In the polar/subpolar region, the instrumental SST, SL correlation is positive. Figure 3-14 plots the results of two of the locations tested. The plots show all available SST records and tide gauge records in the format described in the methods section. From these plots, it can be seen that SL and SST are well correlated. In addition to the positive correlation, the SST time series displays some cyclic patterns. There is a local maximum in temperature in the 1890s, a local minimum in the 1910s, another higher amplitude maximum around the 1950s, and a second minimum around 1980. The time between peak SSTs is around 60 years, which coincides with the multidecadal oscillations seen in modeling studies described above. The amplitude of these SST cycles average around 0.5 to 1 K.

![Figure 3-14 Time series of polar/subpolar region 9-year running mean instrumental SSTs (solid lines) and nearby SL from tide gauge (dotted line). Plotted above are the data from PLs 2 (left) and 5 (right). All time series are detrended.](image)
3.4.2 – North-Central Region

In the north-central region (south of 65°N), there are only two PLs. The calculations in Table 3-1 show both locations have negative correlations between SST and SL. Figure 3-15 shows the SST and SL time series for each location. Both PLs use the Reykjavik tide gauge due to the scarcity of tide gauges in the region. The Reykjavik tide gauge has data going back to 1957. During the first 30 years, the record shows a rise in SL with a sharp decrease after around 1990. For both locations, the instrumental SST declined during the 1960-1980 time period, leveled off, and began rising through the 1980s and 1990s.

As was observed in the polar/subpolar locations, there appears to be about one-and-a-half oscillations of SST from 1880-1996. The first maximum occurs around 1890, with a minimum 30 years later in 1920 followed by a maximum in the 1950s and a minimum in the 1980s. Again the amplitude of the temperature cycles is on the order of 1 K.

![Figure 3-15 Time series of north-central region 9-year running mean instrumental SSTs (solid lines) and nearby SL from tide gauge (dotted line). Plotted above are the data from PLs 6 (left) and 7 (right). All time series are detrended.](image-url)
3.4.3 – Tropical Region

In the tropical region of the North Atlantic, the SST-SL relationships show mostly negative correlations. This is not uniform, however, as there are locations with a positive SST-SL relationship (Table 3-1). Figure 3-16 shows plots of SST and SL near Puerto Rico and in the Gulf of Mexico where SST and SL were negatively correlated.

At the Puerto Rico location, the Magueyes Island tide gauge is used. In the 1960s, instrumental records indicated SST was beginning a steep decline from a maximum, yet the tide gauge indicated a rise in SL. In the 1970s, SST began to rebound while SL continued to rise but slower. So here, SST and SL started out with opposite signals but later exhibited similar trends. The tide gauge used in the Gulf of Mexico (Grand Isle gauge) began records in the early 1950s. Instrumental SST began to decline from the 1950s through the end of the period, while the tide gauge shows a concurrent increase in SL. These two locations did not show clear temperature cycles like the polar/subpolar and north-central regions did. There are oscillations, but they do not have regular frequencies or amplitudes.

Figure 3-16 9-year running mean instrumental SSTs (solid lines) and nearby SL from tide gauge (dotted line) for the tropical region. Plotted above are the data from PLs 15 (left) and 11 (right). All time series are detrended.
Chapter 4

DISCUSSION

4.1 – Spatial Patterns

The calculations of length scale provided a glimpse into the process driving regional SST patterns at and around the PLs. Figure 4-1 shows the surface ocean currents of the North Atlantic basin. The currents explain the patterns of SST seen in the spatial correlation maps in section 3.1 above. In the polar/subpolar section, PL 2 had significant SST relations extend southward through the Canary current and into the tropics. PL 1, which is further north, had no spatial extension southward since the current in that region flows north. The north-central North Atlantic spatial figures (Figure 3-2) showed that common SST trends for PL 7 only hold true within the Subpolar Gyre where the proxy itself lies. PL 6 has a reach that is closer to PL 2 because of its proximity to the Canary Current. In the easterly-dominated tropical regions, there is a more uniform SST trend. This is why locations in tropical regions such as PL 16 display a relatively large area of significant temperature correlations. PL 13 in the Gulf of Mexico is more isolated from the Atlantic surface currents and thus has a smaller area of relatable temperature trends.

Figure 4-1 Ocean currents in the North Atlantic (Godfrey and Tomczak, 2003)
These surface currents allow for the examination of a time series at only one point to be extrapolated over a much larger area. The best area to use this technique is in the tropical Atlantic outside of the Gulf of Mexico where surface currents are dominated by the large-scale easterly Trade winds. A more difficult region to apply this 2-D expansion is to the polar North Atlantic where the North Atlantic Current branches off into smaller, more complex currents. In this study, the area where ocean temperature history is least known is within the subtropical Gyre. This is the case for two reasons: no proxy records in this study are available near this area, and no proxies from outside the gyre have significant SST relationships to grid squares inside the gyre.

To apply this areal expansion to proxies in order to gauge regional SST back beyond the instrumental record, it must be assumed that the ocean currents have not altered much from the present. A study about the changes in North Atlantic currents would be necessary to extrapolate proxy SST records in space with reasonable accuracy.

4.2 – Temporal Patterns

Analysis of the proxy-derived temperature time series shows many consistencies with both modern day observations and other pre-instrumental temperature reconstructions. The long-term trend over most of the last two millennia is a slight cooling of around 0.5 K. The cooling is most pronounced in the high-latitude proxies (see Figure 3-10). This trend is consistent with Andersson et al. (2010) who mention that much of the high and middle latitudes of the northern hemisphere experienced a period of warmth relative to the early Holocene (the Early to mid-Holocene optimum) followed by a progressive (in some regions stepwise) cooling. In the shorter-term high resolution temperature proxies, multi-decadal oscillations relating to the Atlantic Multidecadal Oscillation (AMO) can be seen over the last 100 years.

The temperature proxy records suggest that while each region experienced cooler and warmer periods, their timings differed. The results from the proxy analysis performed above shows that of the two tropical basin proxies with data going back before 1000 AD, both exhibit warm anomalies in the 800 to 1000 CE time frame (Figure 3-7). Moving towards 1200 AD, the majority of high-latitude proxies show warm anomalies, while the tropical proxies are cool. This discrepancy in timing of cold and warm SST anomalies throughout different regions in the North Atlantic infers that even at the centennial and multi-centennial time scales, temperature trends do not occur in synch basin-wide.
Even at the nearly millennial time scale, the northern-latitude proxies and mid-latitude proxies had opposing temperature trends (Figure 3-10).

The temperature oscillations found in the proxies may also reveal ocean dynamical processes. Six out of the twelve proxies with sufficiently high resolution have a significant temperature cycle with a period between 60 and 80 years. The second highest occurring periodicity for the higher-resolution proxies is 20 to 40 years. These time scales for periodicity correspond nearly perfectly with the time scales of North Atlantic variability found in the 500-year IPCC model simulation mentioned in Frankcombe et al. (2010).

According to Frankcombe et al. (2010), the mechanism behind the shorter cycle is a complex internal ocean mode which propagates subsurface temperature anomalies westward. The 50 to 70 year cycle may be an excitation of the shorter cycle, or it may also be due to interaction from the atmosphere including multidecadal NAO variability [Frankcombe et al. 2010]. The agreement between the proxies and the IPCC model is encouraging. It shows that the dominant time scales of SST periodicity found in the proxies are backed up by physical mechanisms found by complex modeling of internal ocean dynamics.

4.3 – SST and SL Relationship

As a whole, the correlations calculated between the instrumental SSTs at the PLs and the nearest tide gauge SL matched the expected signs based on the study of Lozier et al. (2010). In the polar/subpolar region, temperature effects overcame salinity effects to give temperature change and density change the same sign. PLs 6 and 7 in the north-central region had negative correlations. Even though the north-central and polar/subpolar regions are close to each other, the Subpolar Gyre surrounding the north-central region effectively separates the two regions from behaving in the same way. In the tropics, salinity effects overcame temperature effects to give temperature change and density change opposing signs. This is due to the small scale of variability in the temperature and salinity changes. In these regions, salinity changes may have been more important than temperature changes, which led to the observed anti-correlation between SST and SL. Overall, this study shows that the locations of most of the proxies do represent the bigger picture of ocean temperature, SL relationship.
There are some pitfalls to the approach of using SST and Tide Gauge records to evaluate SST-SL relationships. First, the tide gauge picked to represent a PL may not be the best match. Some of these gauges were several hundred km away from the SST record, leading to a sizeable source of possible error in correlation calculation, especially considering many tide gauges were on the coast and not necessarily indicative of open water SL. Second, the temperatures that Lozier et al. (2010) uses to determine SL change is the entire ocean column from 0-750 m while instrumental data sets used in the current study are strictly sea surface temperatures. Additionally, the correlation was performed with no time lag. It is possible that the SL response to temperature changes requires some time. In future studies it would be important to do a partial auto-correlation investigation to further understand the SST-SL relationship. If both past SST as well as the sign of the relationship between SST and SL are known, then a rudimentary history of regional thermosteric SL can be created.
Chapter 5

CONCLUSION

Records of past ocean temperature from within corals and sediment cores, when combined with vast instrumental SST coverage, allow for an understanding of historical ocean temperature patterns and evolution through time. To analyze temperature trends through space, instrumental SST data substituted proxy data at the proxy’s location and were compared to instrumental SST throughout the Atlantic. The spatial patterns returned by this analysis show that SST patterns are consistent with surface currents as might be expected. With this information, and assuming that the spatial relationship between instrumental SST holds true back through the proxy era, the proxies are able to accurately represent SST over an entire section of the North Atlantic basin instead of just one point.

The proxies themselves give insight to temporal SST trends, transitions, and oscillations throughout the last few thousand years. By averaging all proxy data together, it is shown that there was very slight cooling of the North Atlantic from 0 CE through around 1900. After this, proxy data shows a multidecadal oscillation in temperature. Many of the seventeen locations experienced a Little Ice Age cool down lasting on average a few centuries. This cooling centered around 1600 to 1800, and coincides well with the generally accepted LIA time period. The MCA shows up in the proxy data at different times for different regions, ranging from as early as 600 in the tropics, to 1300 in the polar North Atlantic. Using the Multispectral Taper Method power distribution, periods of temperature oscillation within the proxy records were found. The most common frequency of statistically significant periodicity was 60 to 80 years, corresponding well with the multidecadal periodicity of the AMOC.

Comparing instrumental temperatures to nearby tide gauges created a relationship between SST and regional SL. The calculations showed that in the polar and subpolar North Atlantic, SST and SL trended together, in the nearby north-central region they trended opposite, and in the tropics they trended mostly opposite too. These regional relationships depend on the change in density of the ocean water, which itself depends on both SST and salinity. In the polar North Atlantic, SST changes dominate salinity changes, while in the other regions salinity changes dominate SST changes. The SST and salinity changes in a given region are predominantly determined by the ocean currents.
Extending this instrumental SST-SL relationship back to the proxy records, a large-scale picture of historic sea level emerges.

It is clear that the AMOC and other internal dynamics may be driving SST and regional SL in some regions of the North Atlantic. Further understanding of these processes would benefit this type of study. An increased number of long-term ocean temperature proxies can only help to solidify the understanding of regional SST patterns before instrumental records. Extending this study to other ocean basins would be necessary to get global coverage. Finally, a more detailed quantitative analysis of the proxies themselves (errors, biases, etc…) would help in creating a more accurate reconstruction of pre-instrumental SST.

Understanding long term historic SST patterns, and what drives them, can go a long way to understanding what the future may hold for regional ocean temperatures and sea level.
WORKS CITED


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