

**INVESTIGATING LATE HOLOCENE NORTH ATLANTIC CLIMATE
VARIABILITY THROUGH SPELEOTHEM PALEOPROXY
AND HISTORICAL WEATHER DATA FROM BERMUDA**

INTRODUCTION

Recent trends in hurricane frequency and intensity, a continually growing coastal population, and the presence of wide-reaching climatic patterns all underscore the importance of understanding changes in North Atlantic climate. Numerous paleoclimate studies have identified the North Atlantic as a region of importance in regulating global climate through meridional overturning circulation and other processes. The study proposed herein is focused on using stable isotope data from Bermuda speleothem calcium carbonate to help reconstruct dominant low-frequency modes of North Atlantic climate variability through the mid-Holocene (the last several thousand years). This period is replete with climate changes, from the warm hypsithermal peak of ~6000 years ago, followed by the slow overall cooling of the neoglacial, punctuated by rapid change “events” and century-scale periods like the Medieval Warm Period and Little Ice Age. Recent warming from the start of the 20th century to the present has been attributed largely to the build-up of atmospheric greenhouse gases (Mann et al., 1998, 1999) and may herald the beginning of a possibly rapid transition to a new, warmer climate regime. The more we learn about the natural workings of the climate system on time scales of decades to centuries, which are of particular relevance as they are on the scale of a human lifetime, the better prepared we can be for warming-induced changes, some of which may already be afoot, such as the possibility that warmer ocean temperatures are increasing hurricane frequency (Goldenberg et al., 2001; Knight et al., 2006) or intensity (Knutson and Tuleya, 2004). Because instrumental records of climate are only ~150 years long, we must turn toward paleoclimate records contained in paleoproxy indicators such as glacial ice, marine and freshwater sediments, tree rings, and as in the case of this prospectus, speleothems (cave formations), to gain a longer-term perspective. Such a perspective is essential in evaluating past, recent, and future climate changes in the North Atlantic region.

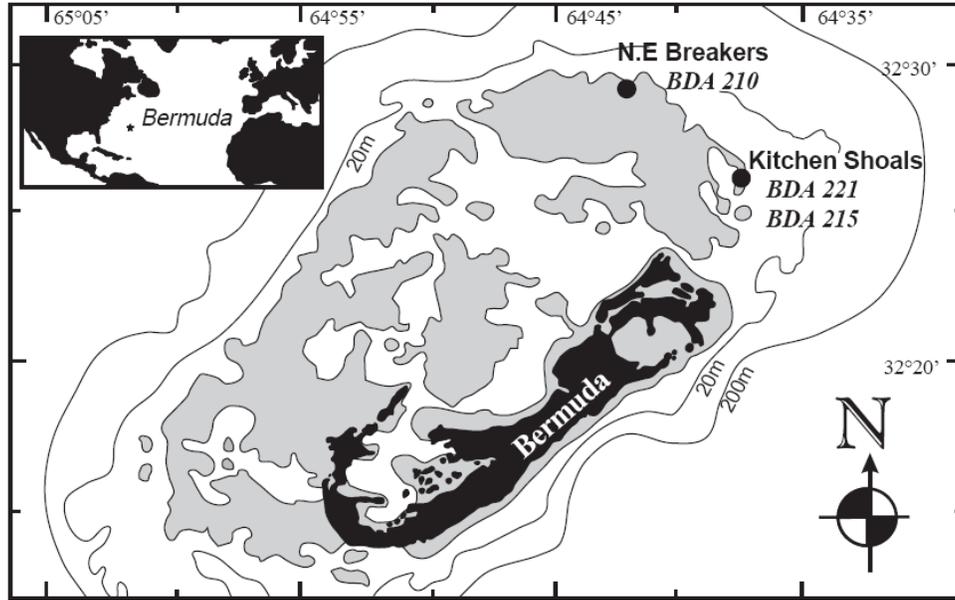


Figure 1. Map of Bermuda, showing oceanic location (inset), geographic position, and emergent portion of carbonate cap. (from Draschba et al., 2000)

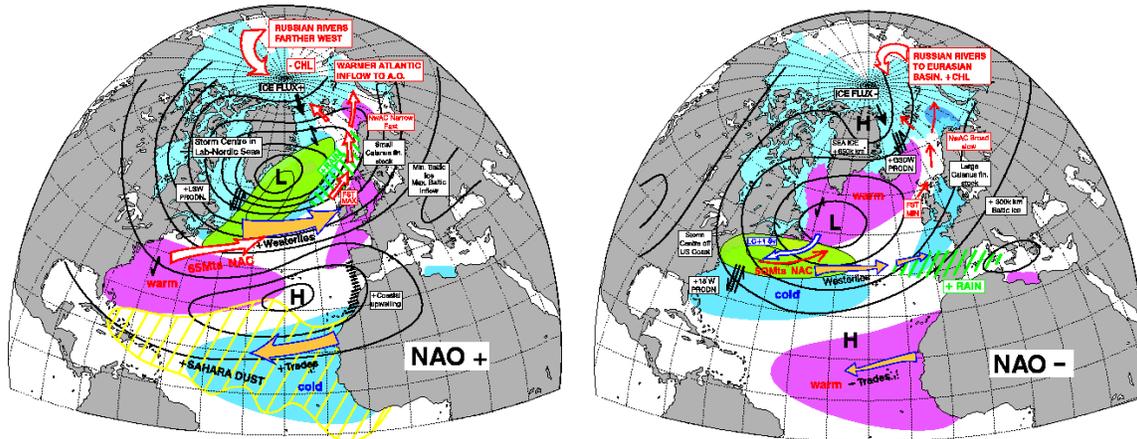
There is perhaps no more logical place to look for North Atlantic climate change than the interior of the North Atlantic Ocean itself, making the island of Bermuda (at 32°20'N, 64°45'W) a good place to start (see Figure 1). Owing to its subtropical latitude and oceanic setting, Bermuda has only a small range of seasonal temperature variability and essentially no appreciable seasonal cycle in precipitation. The most pronounced seasonal change in Bermuda is that of wind speed and direction - strong westerlies in the winter months, strong southerlies in the summer months, and relatively calm conditions in spring and fall. Seasonal movement of the subtropical high pressure cell accounts for this. Geologically speaking, Bermuda is a unique environmental laboratory, consisting of a long-extinct volcanic seamount with an emergent limestone cap that formed during the Pleistocene Epoch. During glacial times of low sea level, limestone caves began to form in the consolidated carbonate cap, probably starting about one million years ago (Ilfie, 2003), as acidic groundwater rich in CO₂ from interior marshes dissolved large voids in the carbonate over time (Myroie et al., 1995). More than 150 caves dot the tiny landscape of Bermuda, concentrated in Hamilton Parish, the northeast section of the main island. Actively growing, thin stalagmites from deep within a Bermuda cave, where humidity is high and evaporation potential low, would serve well for this proposed study.

BACKGROUND

The overarching question I plan to investigate in my research is, “What is the dominant mode, or modes, of climate variability in the North Atlantic region over the Holocene, on decadal-to-millennial time scales?” Paleoproxy data from Bermuda speleothems, together with observational data and isotope tracer modeling, can help answer this question. The North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO) are the two leading predominant modes of North Atlantic climate variability (Hurrell et al., 2003; Wang et al., 2008). There is little current knowledge of the nature of decadal variability in the North Atlantic prior to the industrial period, making it difficult to assess or predict the response of this area to global warming. Bermuda speleothems can be used in conjunction with other paleoproxy archive data to extend the climate record of these modes back in time through the mid-Holocene, thereby providing a past-as-the-key-to-the-future connection. A brief background on each of these climate modes, or indices, is given below.

NAO: On annual-to-decadal time scales, the NAO is the predominant mode of climate variability in the region of the northern hemisphere Atlantic Ocean (Hurrell et al., 2003). The NAO is a quasi-periodic oscillation in the winter season atmospheric pressure difference in the North Atlantic region, between the mid-latitude atmospheric high (the “Bermuda” or “Azores” high) and the subpolar low (the “Icelandic” low). In the positive NAO phase, this pressure difference is high, mid-latitude winds are stronger than normal, the northwest Atlantic regions receive cold Canadian winds, and trans-Atlantic storms tend toward northern Europe as they make landfall; in the negative NAO phase, the pressure difference is less, and reverse conditions occur (see Figure 2). The NAO has detectable effects on atmospheric circulation, rainfall patterns, storm tracks, and ocean circulation in most of the North Atlantic region (Hurrell et al., 2003; Visbeck et al., 2003). The NAO also has a well-known strong correlation to SST’s in the North Atlantic, displaying a pattern that has been characterized as an “SST tripole,” with cold lobes in the subarctic and tropical-to-subtropical N. Atlantic, and a warm lobe in the western subtropical-to-mid-latitude N. Atlantic, during a positive phase of the NAO (Visbeck et al., 2001; see Figure 2A).

A)



B)

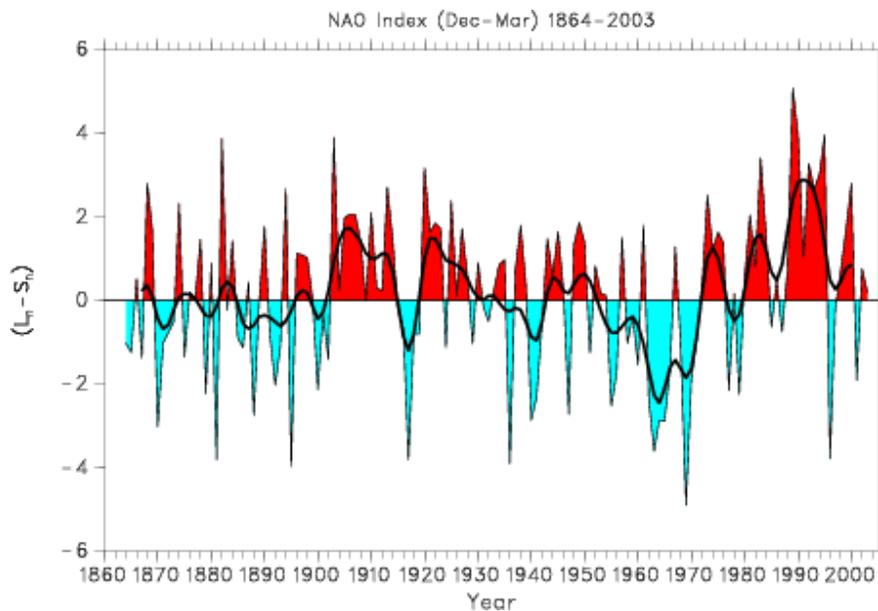


Figure 2. A) Schematic representations of environmental conditions during the positive (NAO+) and negative (NAO-) phases of the NAO (from Stephenson, 2005). B) Observational time series of NAO index (from Hurrell, 2005).

Using European observation-based reconstructions back to the mid-16th century, along with a spatially diverse set of paleoproxy data from Greenland ice cores and tree rings from western Europe and eastern North America, Cook (2003) reconstructed the annual-to-decadal cycles of the winter NAO back to about 1400 CE. One indicator that was left out of this study but holds potential promise in this regard is the geochemical or morphological analysis of speleothems. Speleothems can be reliably dated by Uranium decay-series analysis, and their growth often occurs at such rapid rates that decadal-to-

annual, or sometimes even subannual, time scales can be resolved (e.g., Baldini et al., 2002; Burns et al., 2002; Frappier et al., 2002; Mangini et al., 2005). The ability to understand the past behavior of the NAO and make educated predictions about its future would be invaluable to climate science and to society as a whole.

AMO: The Atlantic Multidecadal Oscillation (AMO) is a relatively newly identified climate index based on a multi-decadal oscillation in North Atlantic sea surface temperature (SST), first recognized by Schlesinger and Ramankutty (1994). It is thought to be closely tied to ocean thermohaline circulation (THC) (Kerr, 2000; Delworth and Mann, 2000; Sutton and Hodson, 2005). When detrended and smoothed with a ten-year running average over the last ~150 years, observational annual mean basin-averaged North Atlantic SST data appear to have undergone a statistically significant warm-cold oscillation (see Figure 3), with overall warm periods in the late 19th century, from 1931 to 1960, and 1991 to the present, and overall cold periods from 1905 to 1925 and 1965 to 1990 (Sutton and Hodson, 2005; Enfield et al., 2001). The record of the AMO has been extended to the mid-16th century by tree-ring reconstruction, using samples from eastern North America, Europe, Scandinavia, and the Middle East, with thirteen total warm and cold regimes (Gray et al., 2004), and Caribbean corals show promise for AMO reconstruction as well (Hetzinger et al., 2008), but other high-resolution climate proxies (e.g., speleothems) are needed to enhance and compare with this record. The AMO seems to have effects on North American rainfall patterns, notably in the eastern Mississippi basin and the Southeast USA, with warm AMO periods corresponding to less rainfall in these areas (Enfield et al., 2001). It is theorized that the SST fluctuations associated with the AMO affect atmospheric climate (and perhaps the NAO) by way of evaporation/precipitation and air-sea heat fluxes (Gray et al., 2004). Recent modeling studies suggest that the AMO exerts multidecadal control over some farther afield climate patterns, including atmosphere-ocean circulation in the tropical and extratropical North Pacific (Zhang and Delworth, 2007; Sutton and Hodson, 2007), as well as precipitation in the Sahel region and in India (Zhang and Delworth, 2006). Notably, there is current debate about the role that the AMO plays in the recent rise of Atlantic hurricane frequency and intensity. Several studies have suggested a causative link (Wang et al., 2008; Knight et al., 2006; Molinari and Mestas-Nunez, 2003; Goldenberg et al., 2001),

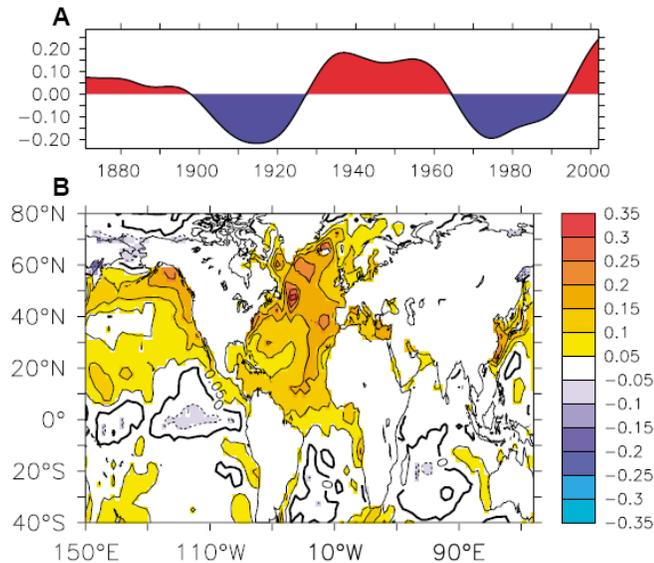


Figure 3. **A)** AMO index time series, calculated as low-pass filtered, smoothed annual mean SST anomalies (in °C) for observational data from the North Atlantic Ocean (0°-60°N, 75°-7.5°W). **B)** Spatial pattern of variability (regression coefficients in °C per unit standard deviation) corresponding to the time series in A; note the lack of correspondence in regions other than the North Atlantic. (from Sutton and Hodson, 2005)

whereas others have attributed the recent increase in hurricane activity to anthropogenic global warming (Webster et al., 2005; Mann and Emmanuel, 2006). These lines of evidence underscore the importance of understanding the AMO better.

The AMO varies on multi-decadal scales, with most analyses revealing a 50-70 year periodicity (Schlesinger and Ramankutty, 1994; Delworth and Mann, 2000). Marshall et al. (2001) and Sutton and Hodson (2003) proposed that decadal-scale variability in the winter NAO signal (Hurrell, 1995) results from a modulating effect of oceanic circulation on the NAO. Model studies have suggested a NAO-forced response in North Atlantic surface circulation (Eden and Jung, 2001), and there is empirical evidence for the AMO having a modulating effect on the NAO (Goswami et al., 2006). Taylor et al. (1998) established a statistical relationship between the latitudinal position of the Gulf Stream's north wall, which is tied to THC and the AMO, and NAO index; high values of NAO index tend to correspond to more northerly positions of the Gulf Stream after a lag of about two years. These studies provide evidence for a connection between the AMO and the NAO.

Investigating modes of North Atlantic climate variability has been the focus of multiple previous studies, some of which (e.g., Gray et al., 2004; Bradbury et al., 2002, 2003; Rittenour et al., 2000; Taylor et al., 1998) have suggested that Pacific patterns such as the El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and the Pacific North American (PNA) indices display, or at times have displayed, teleconnections in the extratropical North Atlantic region. Changes in variability, linked with the 11-year sunspot cycle, the 22-year Hale magnetic reversal cycle, the 88-year Gleisberg sunspot cycle, and the 206-year solar activity cycle, have also been proposed to play a potentially significant role in Northern Hemisphere climate (e.g., Neff et al., 2001; Burns et al., 2002; Berger et al., 2002; Fleitmann et al., 2003; Mangini et al., 2005), though the response of the climate system is disproportionate to the magnitude of solar forcing (Rind, 2002), suggesting solar-induced feedback processes.

Based on emerging evidence of the influence of the AMO and possible ocean-atmosphere coupling associated with the NAO, it seems most likely that at present, North Atlantic climate is principally controlled by these processes that have been identified in the North Atlantic region itself rather than by more distant modes through teleconnections. Hence, this prospectus is focused on the North Atlantic indices.

Holocene climate: The Holocene Epoch, the current interglacial period, has been a period of relative stability in global and regional temperature (Denton and Broecker, 2008; Visbeck, 2002), but it should be noted that studies of hydrological conditions in Africa indicate substantial variability in precipitation over the last millennium on decadal time scales (Oldfield, 2000; Verschuren et al., 2000). During the Holocene there have been some periods during which sustained warm or cold conditions prevailed for several centuries, identified in paleoproxy data. The earliest is the 8200-year BP cooling event, or the 8.2ka event, which appears as a centuries-long negative excursion in oxygen isotope data around 8200 years BP from Greenland and Canadian Arctic island ice cores (Alley and Augustdottir, 2005; Fisher and Koerner, 2003); however the scope of this study does not go back that far in time. Another, though less pronounced, cool and dry event occurred about 4200 years ago, which would be included in this study, in the midlatitude northern hemisphere and is thought to be responsible for the downfall of the Akkadian Empire in the Middle East (Weiss et al., 1993; deMenocal, 2001; Booth et al.,

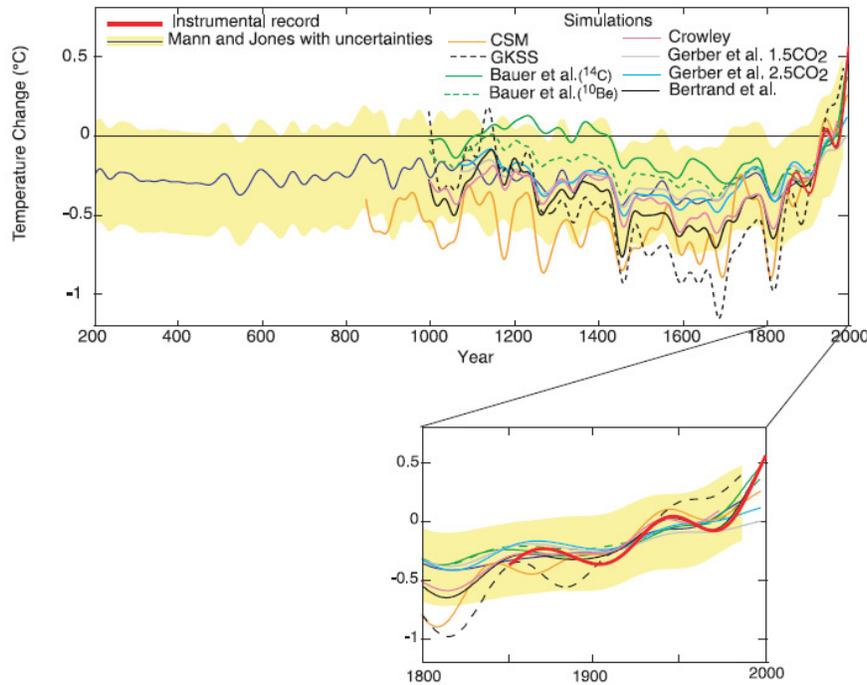


Figure 4. The proxy-based estimate of Mann and Jones (2003) with a 95% confidence interval, along with several model-based estimates of NH temperature variations over the past two millennia. Also shown is the instrumental NH record (1856–2003). The expansion provides a view of the changes over the past two centuries. (from Jones and Mann, 2004)

2005). This event corresponds in time to Bond event #3, part of a ~1500-year cycle in ice-rafted debris in high latitude North Atlantic sediments (Bond et al., 1997; Wang et al., 2005). Around 536 A.D., a pronounced cool event occurred, associated with a high concentration of atmospheric dust and consequent dimming of sunlight. This event was documented as a cool, dry period by ancient peoples in the Mediterranean and Middle East (Stothers, 1984; Rigby et al., 2004). There is current debate about the source of this dust, between those who implicate explosive volcanic activity (Stothers, 1984; Larsen et al., 2008) and those who point to a comet or asteroid impact, perhaps occurring in the southwest Pacific (Rigby et al., 2004; Abbott et al., 2008). A more recent, and seemingly anomalous, period in Holocene climate in the North Atlantic region involves the so-called “Medieval Warm Period,” a relatively warm spell seen in paleoproxy data from some areas during the 10th to 13th centuries (see Figure 4) (Jones and Mann, 2004); even the warmest reconstructed temperatures during this time, however, do not match the rapid

warming recorded in the late 20th century (Mann et al., 1999; Jones et al., 2001; Mann et al., 2003; Bradley et al., 2003a). Even more recently, the so-called “Little Ice Age” represents a period of colder temperatures in the North Atlantic region indicated in the paleoproxy records, spanning the 14th to 19th centuries (see Figure 4) (Jones and Mann, 2004). These episodes have apparently caused signals in Bermuda Rise foram-rich sediments (Keigwin, 1996a) and a stalagmite from the Italian Alps (Mangini et al., 2005); perhaps stalagmites from Bermuda would record these as well.

Speleothem data: Holocene climate proxy records can be derived from a variety of sources, including oxygen and hydrogen isotopes in ice cores (e.g., Fisher and Koerner, 2003), oxygen isotopes and band thickness of coral skeletons (e.g., Cole, 2003; Cohen et al., 2004), oxygen isotopes and species assemblages of marine plankton shells in ocean sediments (e.g., Maslin et al., 2003), pollen and lake biota preserved in lacustrine sediments (e.g., Fritz, 2003), thickness and character of tree rings (e.g., Baillie and Brown, 2003), and of course, stable isotopes of oxygen and carbon in calcium carbonate of limestone cave formations known as speleothems (Lauritzen, 2003). Speleothems are particularly useful among these in that they can be independently and reliably dated by high-precision techniques involving radioactive Uranium decay series analysis, that they can resolve changes on high-frequency time scales (often annual-to-decadal or finer; e.g., Fleitmann et al., 2004; Frappier, 2002), and that the stable isotopes within them record changes in the meteoric water cycle, a key component of regional climate (Lauritzen, 2003).

Speleothems are a product of precipitation of calcium carbonate (CaCO_3) dissolved in water that has percolated through the CO_2 -rich soil above the cave ceiling (White, 2004). The CaCO_3 of speleothems captures changes in stable isotopes of oxygen and carbon, namely oxygen-18 (^{18}O) and carbon-13 (^{13}C), of the percolating groundwater that carries the isotopic signatures of the rainfall from which it was derived (White, 2004). Changes in $\delta^{13}\text{C}$ of speleothems generally indicate changes in above-cave surface vegetation between C3 and C4 types (Harmon et al., 2004), which is not likely to be a major factor in Holocene climate change in Bermuda. However, there is a possibility that early deforestation by original settlers of the island in the 1600’s and/or the effects of a non-native insect-induced cedar blight in the late 1940’s (Rueger and Wallmenich, 1996)

might cause a significant signal (positive excursion) in $\delta^{13}\text{C}$, which could provide a measure of age control on modern sections of stalagmites.

The inherent challenge in speleothem analysis is to determine the exact cause of the stable isotope changes. Oxygen isotopes in speleothem CaCO_3 change in response to several factors, but these can be categorized into two main groups: fractionation effects and water effects (Harmon et al., 2004). In the first case, the thermodynamic fractionation factor, which expresses the difference in $\delta^{18}\text{O}$ between speleothem CaCO_3 and the dripwater from which it precipitated, decreases as cave temperature increases (Harmon et al., 2004; Lauritzen, 2003). The water effects, on the other hand, refer to the changes in $\delta^{18}\text{O}$ that result from various factors, including the temperature and original $\delta^{18}\text{O}$ of the source seawater at time of evaporation, the air temperature at time of condensation over the cave site, the amount of “rainout” of vapor that occurs during transport from source to site, and the moisture evaporation and mixing within the soil and epikarst zone above the cave (Harmon et al., 2004). In general, higher temperatures correlate with heavier $\delta^{18}\text{O}$ values in precipitation, dripwater, and speleothem CaCO_3 (Harmon et al., 2004); higher rainfall generally causes lighter $\delta^{18}\text{O}$ values in the same (Lauritzen, 2003). Assuming that the CaCO_3 deposition occurred in conditions of isotopic equilibrium between the dripwater and the CaCO_3 (i.e., that the CaCO_3 precipitated as a result of slow outgassing of CO_2 from the water rather than rapid outgassing or evaporation), competing influences of the fractionation effects and the water effects ultimately determine the magnitude and direction of the change in speleothem $\delta^{18}\text{O}$ with climate (Harmon et al., 2004; Lauritzen, 2003). In some cases, the speleothem oxygen isotope outcome is dominated by changes in precipitation amount (e.g., Burns et al., 2002), whereas in others, temperature and/or source effects dominate (e.g., Mangini et al., 2005).

APPROACH

This dissertation project is proposed as an attempt to extend the record of the NAO and AMO and to help answer the much larger question of how and why North Atlantic climate has varied, over the latter half of the Holocene Epoch. In addition to extending the temporal and spatial record of the NAO and AMO, this study will also

facilitate investigation of the role, if any, that the Sargasso Sea region plays in regulating North Atlantic regional climate.

The overall approach to this project involves four main steps. 1) Historical weather data from Bermuda, including hand-written records from as far back as 1852 from the British Naval Air Station, will be analyzed to establish modern conditions and provide a basis for calibration and comparison. 2) A small number of actively growing stalagmites will be collected from Bermuda caves, dated by the Uranium decay series method, and analyzed for $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, and trace elements. The results from the modern section of the stalagmites will be calibrated and verified against the observational data to establish a speleothem isotope-climate relationship, and this will be combined with other proxy data from the Sargasso Sea region and other sites around the North Atlantic that are likely to be affected by the NAO or AMO. 3) A cave dripwater study will be carried out in Bermuda to establish a relationship between precipitation and dripwater $\delta^{18}\text{O}$ and to help interpret the stalagmite $\delta^{18}\text{O}$ results. 4) Isotope tracer modeling will be employed to strengthen the isotope-climate relationship, to analyze interannual climate variability, and to investigate future scenarios. These steps are discussed in more detail below.

1) Historical weather data: Since speleothem $\delta^{18}\text{O}$ data records changes in temperature and/or precipitation-related climatic processes over time, it is important to understand the modern meteorology of the area from which speleothems are collected. Climatological data from Bermuda show annual variation in rainfall of about 80 mm (May) to 160 mm (September) and temperature variation of about 17°C (February) to 27°C (August). Prevailing winds are characterized by strong westerlies during winter, southwesterlies during spring, strong southerlies and southwesterlies during summer, and weak easterlies during fall, a consequence of seasonal movement of the subtropical high (Bermuda Weather Service, 2005).

A 155-year record of historical weather data from Bermuda was kindly provided by the Bermuda Weather Service and exists in two sets: the modern set which is a digitized record that extends back to 1941, and the earlier set which consists of digital photographs of handwritten records, compiled by the British Navy, covering the period from 1853 to 1953. The latter set has been digitized in the form of monthly averages of air temperature, precipitation, atmospheric pressure, and wind speed and direction

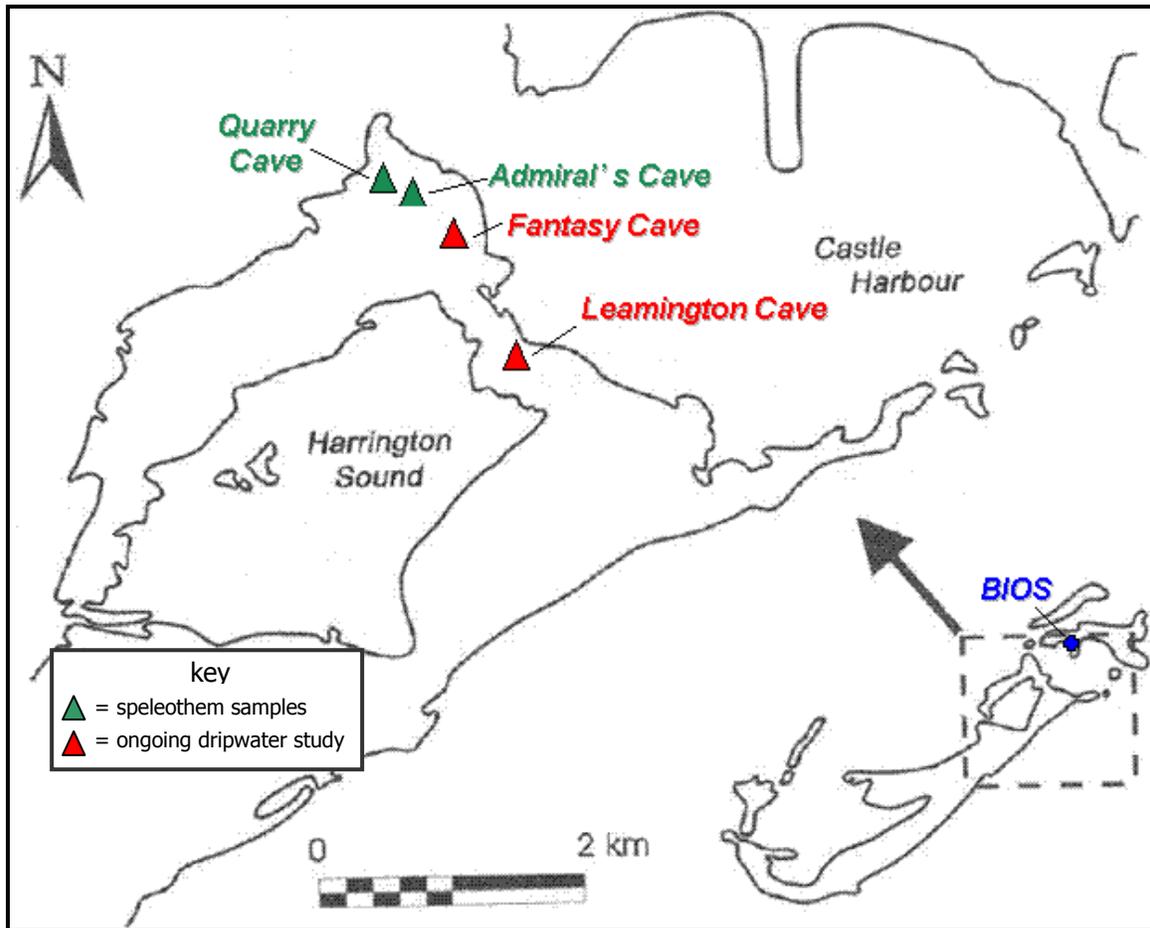


Figure 5. Location map showing caves where stalagmites were collected and those where ongoing dripwater collection is being performed. Also shown (on inset) is the location of Bermuda Institute for Ocean Sciences. (modified from Iliffe, 2003)

(results shown in “Initial Results” section below). The two sets overlap from 1941-1953, which allows validation of the older set. The goal of this stage of the project is to establish a connection between the NAO and AMO modes and Bermuda rainfall/temperature through the course of the observational period.

2) Stalagmite collection and analysis: Several stalagmites have been collected from two caves in the Hamilton Parish section of Bermuda (see Figure 5). These have been dated by U-Th technique at the University of Minnesota, but only two have yielded useful age results. One of these, B05-01, spans a period from 4840-2590 years BP and has been sampled at approximately 5-7 year resolution for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ by mass

spectrometry in S. Burns's Stable Isotope Laboratory at UMass (results shown in "Initial Results" section below). The other, B08-08, dates from modern at the top to ~1500 years BP at the bottom, though it has yet to be analyzed for stable isotopes. In addition to stable isotopes, trace element concentrations can be determined by microprobe (Baldini et al., 2002) or excimer laser ablation techniques (Treble et al., 2003). The stable isotope time series from the modern speleothem will be compared and contrasted with the observational climate data discussed in step 1, and the pre-historical sections of both speleothems will be compared with other paleoclimate proxies from the North Atlantic region. In particular, other Holocene paleoproxy data from the Bermuda/Sargasso Sea region will be utilized, including Bermuda coral $\delta^{18}\text{O}$ and skeletal density (Draschba et al., 2000; Cohen et al., 2004; Goodkin et al., 2005, 2008), Bermuda Rise marine sediment $\delta^{18}\text{O}$ from foraminifera (Keigwin, 1996a,b; see Figure 10 below), and pollen from Bermuda pond and marsh sediments (Rueger, 2003). In addition to other paleodata proximal to Bermuda, other speleothem studies from the North Atlantic region will be included in this statistical analysis. Of particular note are studies by Baldini et al. (2002), McDermott et al. (2001), and Fairchild et al. (2006) on stable isotope and trace element analysis of a Holocene-age stalagmite from Ireland, and Mangini et al. (2005) on a strong correlation between Sargasso Sea temperatures and stable isotope data from a stalagmite collected in the European Alps.

Rigorous statistical processes will be employed to check for coherence between Bermuda speleothem stable isotope data and other datasets. First, the modern section of the $\delta^{18}\text{O}$ data from the stalagmites will be detrended and low-pass filtered to preserve low-frequency (decadal to centennial) cycles of variability. The 20th century portion of the proxy $\delta^{18}\text{O}$ record will then be compared to the latter portion of the detrended and filtered observational record to calibrate the $\delta^{18}\text{O}$ -temperature and $\delta^{18}\text{O}$ -rainfall relationship, and the 19th century portion will be validated against the earlier observational data. Spectral and wavelet analysis will be performed to determine the dominant frequencies of cyclic variability in the Bermuda speleothem data. For example, a peak in the 50-70 year periodicity range would be encouraging, though not deterministic, in terms of identifying an AMO signal in the data. Also, the speleothem time series data will be compared to the principal component (PC) time series

corresponding to the rotated empirical orthogonal functions (EOF) spatial patterns representing the NAO, AMO, and other dominant modes of North Atlantic climate variability (e.g., see Delworth and Mann, 2000). More in-depth investigation will include cross-spectral analysis (e.g., Burns et al., 2002; Cohen et al., 2004) and “semblance” analysis (Cooper and Cowan, 2008), to reveal coherency patterns at different time scales between speleothem data and other datasets.

Building on the small-to-large scale approach introduced in the previous section, from the perspective of a climate-precipitation connection, there are four main processes that could change $\delta^{18}\text{O}$ in precipitation and, eventually, speleothem calcite. These include a change in the temperature of the source water for evaporation; a change in atmospheric circulation producing changes in source areas, pathways, and amount of precipitation; changes in the global or regional ocean $\delta^{18}\text{O}$ levels; and changes in the seasonality of precipitation (Darling et al., 2006). Of these, the first two are likely more important for a subtropical speleothem study of decadal-to-millennial patterns in Holocene climate change. An essential consideration, therefore, is whether or not Bermuda is situated in a location where changes in precipitation $\delta^{18}\text{O}$ will respond to changes in climatic parameters associated with the NAO and AMO. This question is more complicated than it may seem. Further discussion on this can be found in the Expected Results section below.

3) Dripwater analysis: A useful way to approach a paleoproxy study is to consider the problem starting from small-scale and working up to a large-scale perspective (Darling et al., 2006). In this study’s case, we could start from the speleothem, considering what changes might occur from the cave dripwater falling from the ceiling to the point where new calcite is deposited on the growing stalagmite. An important question is whether or not this process takes place in isotopic equilibrium; kinetic effects during calcite precipitation, often indicated by close correlation between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, can render speleothems unusable for paleoclimate analysis (Hendy, 1971). According to a comprehensive summary of modern speleothem analysis studies by McDermott et al. (2006), however, speleothems usually grow sufficiently close to equilibrium with cave dripwater to enable their use as recorders of the stable isotopes of meteoric waters. As part of this study, cave dripwater collection and analysis is currently

being performed in two Bermuda caves within two kilometers of the caves from which the speleothems were collected (see Figure 5).

This step involves measuring stable isotopes of oxygen (^{18}O) in the dripwater. Precipitation on Bermuda is being collected and archived by Dr. Peter Sedwick and colleagues at the Bermuda Institute for Ocean Sciences (BIOS); this will likewise be analyzed. Because dripwater is derived from meteoric water, in this way a relationship can be determined between rainwater $\delta^{18}\text{O}$ and dripwater $\delta^{18}\text{O}$, which can then be correlated to the $\delta^{18}\text{O}$ of the speleothem calcite (Cruz et al., 2005). So far, dripwater samples from April 2006 to March 2008 have been sampled, including the effects of the passage of Hurricane Florence in September 2006 (results shown in “Initial Results” section below).

4) Isotope tracer modeling: The next step will be to employ an isotope tracer model to investigate past changes in climate. Isotope tracer modeling is a paleoclimate analysis tool pioneered in the early 1980's by Sylvie Joussaume (Jouzel, 1991). The idea is to track changes in ^{18}O and D in water throughout the hydrologic cycle in an atmospheric general circulation model (AGCM). An isotope tracer model operates in each grid box of the AGCM, tracking sources and sinks of the isotopes, which are a function of isotopic fractionation during evaporation at the air/sea interface and condensation above (Jouzel, 1991; Mathieu et al., 2002). Using stable isotope data from analysis of paleoclimate indicators, such as speleothems, for comparison to model results, an isotope tracer model incorporated into an AGCM can be used to determine past patterns of atmospheric circulation and precipitation source in a particular region (like the North Atlantic), which can be correlated to changes in climatic factors such as air circulation and sea surface temperature (Joussaume et al., 1984; Jouzel, 1991; Juillet-Leclerc et al., 1997; Jouzel et al., 2000). Levels of D in a speleothem can be measured in fluid inclusions (Lauritzen, 2003), which are common in speleothems (McDermott et al., 2006) and should exist in those collected for this study.

Mathieu et al. (2002) incorporated an isotope tracer model into the GENESIS (Global ENvironmental and Ecological Simulation of Interactive Systems) model (Pollard and Thompson, 1995) AGCM. This model is readily available for use on servers in R. DeConto's lab at UMass and will therefore be used in this proposed study. The

first goal of the modeling component will be to help analyze the climate index-precipitation $\delta^{18}\text{O}$ relationship, by prescribing model SST patterns associated with high and low phases of the NAO and AMO and tracking the resulting range of $\delta^{18}\text{O}$ values in the precipitation falling on Bermuda in the model. Another goal is to analyze interannual variability in the model North Atlantic to see how well it compares to interannual variability in observational and proxy data. Time permitting, I also hope to perform at least some measure of predictive modeling to make an attempt at forecasting how North Atlantic climate might change with the persistence of global warming. One example of this idea is to try and answer the questions of what magnitude SST changes would be necessary to force the model climate into different dominant modes of North Atlantic climate variability, and whether or not these changes would be realistic in a global warming scenario.

EXPECTED RESULTS

Bermuda is situated on the eastern edge of the western Atlantic subtropical-to-midlatitude SST lobe in correlation plots of the NAO vs. winter SST (see Figure 2a); for this to affect rainfall on Bermuda, the vapor source would have to be close by and the Sargasso Sea region SST difference between high and low phases of the NAO would have to be of sufficient magnitude to produce a detectable change in $\delta^{18}\text{O}$ of the precipitation. Not surprisingly, the primary source of moisture for Bermuda rainfall is the nearby ocean, specifically the western subtropical North Atlantic, or Sargasso Sea region (Miller and Harris, 1985). SST differences in the Sargasso Sea region between the high and low phases of the NAO vary on the order of 0.25°C (Visbeck et al., 2003), which could produce a difference in the $\delta^{18}\text{O}$ of vapor/precipitation of about 0.075‰ (Rozanski et al., 1993; Darling et al., 2006), within the error limit of $\delta^{18}\text{O}$ mass spectrometry analysis (Harmon et al., 2004). On the other hand, Figure 6 shows results from the ECHAM model, part of the Stable water isotope intercomparison group (SWING) project, which suggest that the NAO might have a more pronounced effect, on the order of 1-2 ‰, on the $\delta^{18}\text{O}$ of Bermuda rainfall, so perhaps the NAO excites SST-driven feedbacks in the climate system that lead to higher variability in precipitation $\delta^{18}\text{O}$. The AMO has not been as extensively analyzed as the NAO in terms of its effects

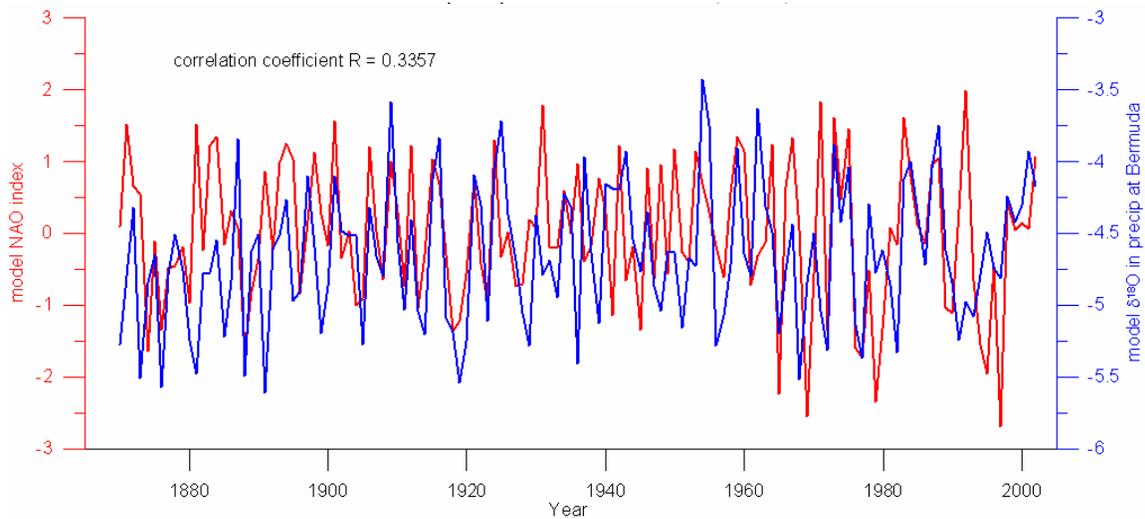


Figure 6. ECHAM model output correlation (1870-2003): NAO index (normalized sea level pressure difference between Azores and Iceland, DJFM) vs. $\delta^{18}\text{O}$ in precipitation at Bermuda (DJFM).

on climatic parameters, but maximum average SST variability associated with the AMO is on the order of 0.45°C for the North Atlantic as a whole (Knight et al., 2005), which could cause a change in $\delta^{18}\text{O}$ of 0.135‰ in the vapor (Darling et al., 2006). Changes in the Sargasso Sea region may be as little as half this magnitude, as suggested by the loading pattern for the AMO (see Figure 2).

It is possible that changes in precipitation amount would have pronounced effects on the $\delta^{18}\text{O}$ signal in Bermuda rainfall, via the “amount effect” (Dansgaard, 1964). A negative correlation has been found between evaporation-minus-precipitation (E-P) in the Bermuda area and the NAO index, which results in about 1 mm/day more net rainfall on Bermuda during a high NAO index (Hurrell et al., 2003). Converting to mm/month gives about 30 mm/month, which would translate to a 0.6‰ change in rainfall $\delta^{18}\text{O}$ (Dansgaard, 1964). As for the AMO, Enfield et al. (2001) linked it to continental USA rainfall, and model results (Knight et al., 2006) suggest a warm AMO causes about 0.5 mm/day more rainfall near Bermuda, or half the effect of the NAO. Interannual changes in Bermuda rainfall amount are on the order of ~ 100 mm/month, which would translate to about 2‰ difference in rainfall $\delta^{18}\text{O}$ (Dansgaard, 1964) from one year to the next. Clearly this would dwarf the temperature effects mentioned above, but only a fraction,

say 25% at most, of this variability could be attributed to climate indices such as the NAO (Hurrell et al., 2003; Visbeck et al., 2003), which would similarly mean about a 0.5‰ change in rainfall $\delta^{18}\text{O}$. Based on this reasoning, it might be fair to expect that the amount effect would tend to overpower the source temperature effect, in rainfall at Bermuda. However, it should be noted that $\delta^{18}\text{O}$ in Bermuda rainfall measured by the International Atomic Energy Agency (IAEA) from 1962-1965 suggest a lack of an amount effect at Bermuda; IAEA data from a similar setting (Midway Island) in the Pacific Ocean span a longer period, 1962-1991, and show a similar absence of an amount effect. The amount effect is most pronounced at tropical settings (Dansgaard, 1964), so this is perhaps not surprising.

A third possible influence on changes in rainfall $\delta^{18}\text{O}$ is that of changes in precipitation pathway associated with these modes, which would be associated with changes in wind patterns. Wind patterns over the North Atlantic change considerably with the phase of the NAO, as the subtropical high moves northward and intensifies during a high phase, bringing stronger westerlies across the ocean at midlatitudes. The AMO's effects on atmospheric circulation/wind over the oceans is not as clear but a modeling study by Knight et al. (2006) suggests that a high AMO causes a southerly wind anomaly in the North Atlantic. Most Bermuda precipitation derives from nearby oceanic sources (Miller and Harris, 1985). A look at Figure 7 shows that ocean water $\delta^{18}\text{O}$ around Bermuda varies by about 1‰, at most, within about a 100km radius, with the strongest gradient farther away to the northwest, next to New England and Nova Scotia. Wind anomalies associated with the NAO in the region of Bermuda tend to be directed from the west but not from the north, and the modeled southerly wind anomaly possibly associated with the AMO is likewise in the wrong direction for causing a significant change in precipitation $\delta^{18}\text{O}$ due to a change in source region. The water-vapor fractionation factor decreases with higher temperatures (Clark and Fritz, 1997), which would tend to dampen the effect of changes in source water $\delta^{18}\text{O}$ for Bermuda's warm-water sources. While it is difficult to quantify the effects of the NAO and AMO on changes in the location and $\delta^{18}\text{O}$ of the vapor source, it is likely that the effect would amount to considerably less than 1‰.

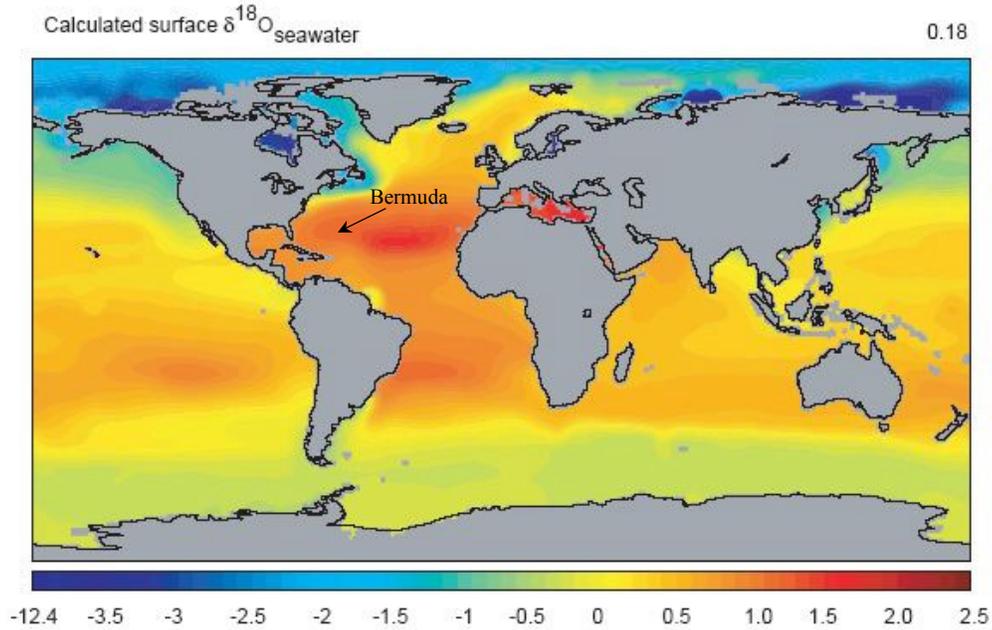


Figure 7. Gridded data set of ocean surface $\delta^{18}\text{O}$, calculated from the values available in the Global Seawater Oxygen-18 Database at NASA/GISS. This dataset uses regional $\delta^{18}\text{O}$ - salinity relationships and PO_4^* to define water mass boundaries. (from Schmidt et al., 1999 at <http://data.giss.nasa.gov/o18data/>)

It seems reasonable to expect a good degree of correlation between Bermuda speleothem $\delta^{18}\text{O}$ results and results from other nearby climate proxy indicators. There are a number of previous paleoclimate studies involving ocean sediments, corals, and marsh pollen samples from or near Bermuda. Keigwin (1996a) analyzed foraminifera shells in ocean sediments from the Bermuda Rise and found oscillations corresponding to the Medieval Warm Period and Little Ice Age, estimating the SST's to have been about 1°C warmer and cooler, respectively, than today. Rueger (2004) found wet and dry periods roughly corresponding to Keigwin's cool and warm periods, respectively, in pollen sequences from a sediment core taken in Devonshire Marsh, Bermuda. Good agreement of Bermuda stalagmite stable isotopes and/or trace elements with these data would support a connection between the Sargasso Sea region and some of the longer term changes in Holocene climate, like Bond cycles, the Medieval Warm Period, and the Little Ice Age. Most other paleoclimate studies from the Bermuda area involve corals. Berger et al. (2002) claimed to have found climate cycles related to sunspot activity-induced wind changes in the growth bands of an 800-year-long Bermuda coral. Draschba et al.

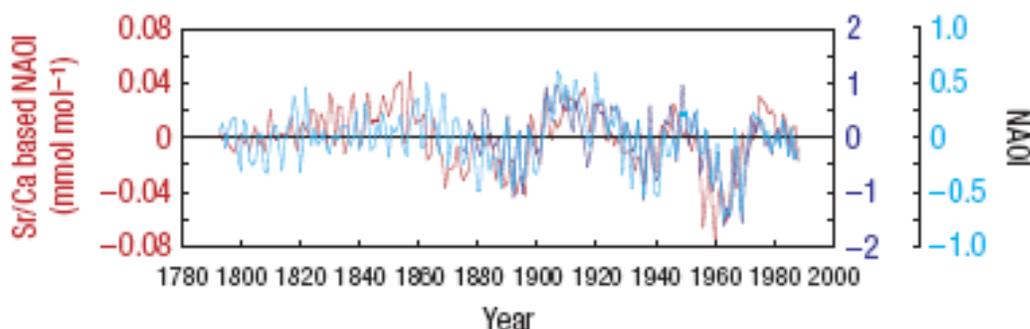


Figure 8. Bermuda coral Sr/Ca-based NAO reconstruction. (from Goodkin et al., 2008)

(2000) employed stable isotope analysis of Bermuda corals to establish a $\delta^{18}\text{O}$ -SST anomaly relationship and created a record through the middle of the 16th century, showing temperature variations during the Little Ice Age comparable in scale to modern variability. Similarly, Cohen et al. (2004) and Goodkin et al. (2005) established a Bermuda coral Sr/Ca ratio-derived SST proxy and reconstructed SST's from the Little Ice Age in a Bermuda coral record through the late 1700's, finding they were about 1.5°C cooler than modern SST's. In a follow-up paper by Goodkin et al. (2008), very applicable to the proposed stalagmite research herein, monthly-resolution Sr/Ca results from Bermuda corals are used to reconstruct past behavior of the NAO from 1781-1999 (see Figure 8). A good correlation of stalagmite $\delta^{18}\text{O}$ with these data would lend confidence to the utility of speleothems in reconstructing the NAO as well as SST changes near Bermuda, which are closely associated with the AMO.

There would hopefully also be a good degree of correlation between the Bermuda stalagmite data and that of several other speleothem-oriented studies from around the North Atlantic. Using growth rate-inferred precipitation and temperature data from a set of Scotland stalagmites, Proctor et al. (2000, 2002) found precipitation variability corresponding to the NAO and multidecadal variability, which they attribute to SST changes, on the scale to the AMO. In fact, a recent study by Trouet et al. (2009) uses these stalagmite data as part of a multi-proxy reconstruction of the NAO to more than 1000 years ago, showing a persistent positive phase during the Medieval Warm Period. In another notable example, Mangini et al. (2005) show a direct comparison between

$\Delta^{14}\text{C}$ from tree rings and $\delta^{18}\text{O}$ from a European Alps stalagmite and argue that solar variability drives changes in temperature that determine their speleothem $\delta^{18}\text{O}$; they also compare their $\delta^{18}\text{O}$ to Sargasso Sea temperature reconstructions from Bermuda Rise sediment cores and find strong correlation. If the results from Bermuda speleothems fit nicely with these datasets as well, this would shed light on the role of freshwater forcing and solar variability in North Atlantic climate. This study will be instrumental in extending and enhancing the paleo record of several key components of North Atlantic climate variability.

INITIAL RESULTS

At this point, results have been generated in all steps of the project except the stable isotope modeling (step 4). Some of the raw data collected so far are presented here, with limited analysis. These initial results suggest great potential for the project.

Weather data: As mentioned, the historical weather data provided by the Bermuda Weather Service have been digitized in the form of monthly averages of air temperature, precipitation amount, and average wind direction; monthly sea level pressure was included in the digitization as well, but there is a suspicious shift in the data that needs further investigation before it is presented. Figure 9A shows winter (DJFM)-averaged weather data plotted with the station-based winter (DJFM) NAO, and Figure 9B shows annual-averaged weather data plotted with the annually averaged, unsmoothed AMO value. Note that air temperature seems to follow both the AMO (in a broad sense) and the NAO (on finer scales). This suggests that Bermuda temperature is affected by these climate patterns. By contrast, no such clear relationship is seen between total rainfall or average wind direction and either the AMO or NAO. Further analysis will explore potential relationships in more detail. At least, it should be true that wind direction is affected by the NAO in some way, since the phase of the NAO partially determines the position of the subtropical high (Hurrell et al., 2003).

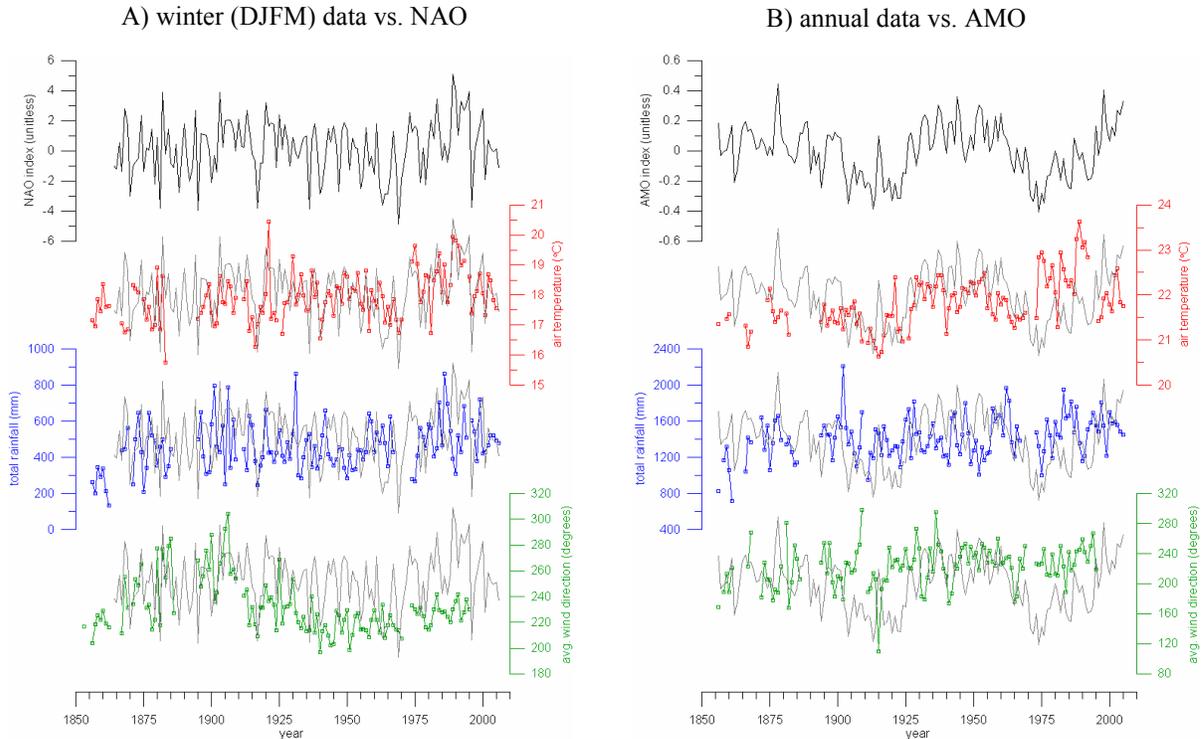


Figure 9. Observational weather data – air temperature, rainfall amount, average wind direction – vs. **A.** winter NAO (station-based) and **B.** annual AMO (unsmoothed)

Speleothem data: Figure 10 shows stable isotope results ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) from the entire section of stalagmite B05-01, sampled at approximately 5-7 year intervals; overlaid on the $\delta^{18}\text{O}$ curve is Lloyd Keigwin's (1996b) Bermuda Rise sediment core $\delta^{18}\text{O}$ data from *G. ruber* shells. There is some similarity between the B05-01 data and the Bermuda Rise data, though it is hard to discern how closely they match due to the difference in sampling resolution. Clearly the magnitude of variability in the $\delta^{18}\text{O}$ record of B05-01 is greater than that suggested by the potential influences of changes induced by the NAO and AMO as discussed above, so other processes must be at work here; perhaps the variability is driven mostly by changes in source water $\delta^{18}\text{O}$. The significant drop in the stable isotopes at close to 4000 years ago may be aligned with a hemisphere-wide drought (Booth et al., 2005) at ~4200 year ago. The obvious trend toward less depleted values from the beginning of the record to ~ 3000 years ago may be the result of neoglacial cooling; Mangini et al. (2005) found a negative relationship between temperature and stalagmite $\delta^{18}\text{O}$, which they attribute to mixing of heavier summer and

lighter winter precipitation. The significant drop in stable isotopes at the end of the record from 3000-2600 years ago might signify a change in regional circulation, though it should be noted that there is a dark layer in the stalagmite at about 2660 years ago, that corresponds to spikes in both $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ and might represent a growth hiatus; further age dating must be done to determine this. Some studies have found a link between stalagmite $\delta^{18}\text{O}$ and solar variability as measured by $\Delta^{14}\text{C}$ (e.g., Neff et al., 2001; Mangini et al., 2005; Zhang et al., 2008), but preliminary investigation suggests no such link in these data.

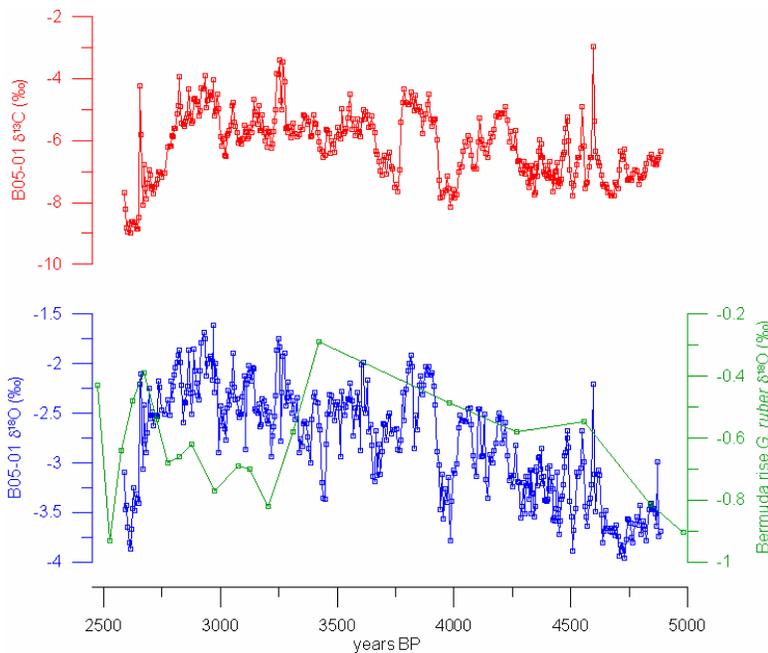


Figure 10. Stable isotope results from stalagmite B05-01. $\delta^{13}\text{C}$ shown in red; $\delta^{18}\text{O}$ shown in blue, compared with Keigwin's (1996b) $\delta^{18}\text{O}$ data from Bermuda Rise *G. ruber* shells, shown in green.

Cave dripwater: Since April 2006, we have been collecting dripwater from three active drips in two Bermuda Caves (see Figure 5), Fantasy Cave and Leamington Cave. There is also a drip counter currently installed in Fantasy Cave, to track the response of the limestone “plumbing” system above the cave to significant rainfall events. Fortunately for us, Hurricane Florence passed over Bermuda in September 2006; dripwater samples from a few days after the storm show a significant positive spike in $\delta^{18}\text{O}$ (see Figure 11). This was opposite to our expectations but could be explained by

either a change in moisture source or a flux of sea spray caused by the hurricane-force winds. Seawater ion analysis performed on the dripwater samples shows no appreciable increase in ions associated with this spike in $\delta^{18}\text{O}$, suggesting that sea spray is an unlikely explanation for it. Instead, a change in source water resulting from the atypical (east-to-west) direction of vapor transport during the hurricane was probably responsible. At present we have no explanation for the sharp drop in $\delta^{18}\text{O}$ in summer of 2007; it is not associated with anomalous temperatures or exceptionally high rainfall. Another hurricane, Bertha, passed very close by Bermuda in July 2008; dripwater samples were collected after this event as well, but stable isotope analysis has not yet been performed on these samples. Hopefully they will show a similar signal.

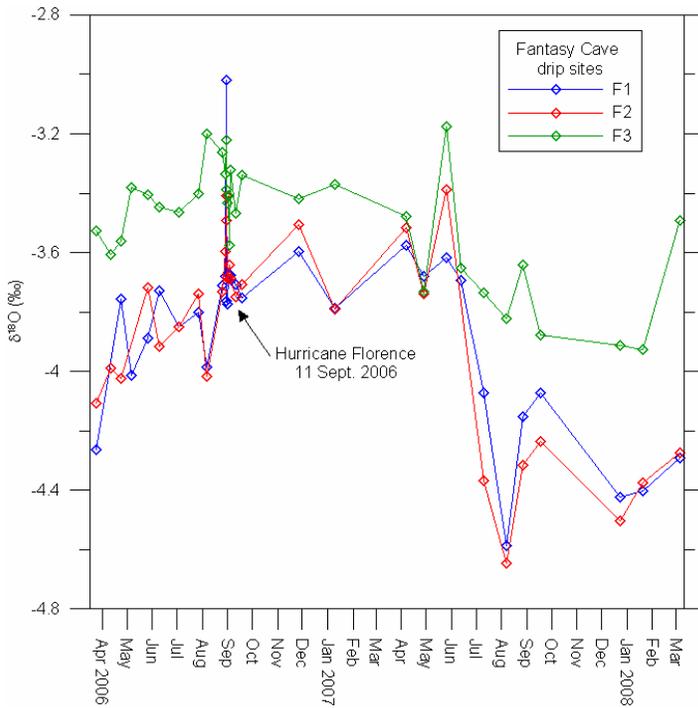


Figure 11. oxygen isotope results from Fantasy Cave dripwater, April 2006 – March 2008.

SUMMARY

The North Atlantic region is thought to be important in driving and regulating global climate change, and it is the site of increasingly destructive hurricane activity in recent years, so it is clearly an area worthy of continuing scientific investigation. The overall approach to this project involves four main steps: 1) analysis of historical weather data from 1852 to present, 2) stable isotope and trace element analysis of two geochemically unaltered speleothems, 3) a >3-year stable isotope study of modern cave dripwaters, and 4) isotope tracer modeling. This approach will enable reconstruction of the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO), the two most important modes of Holocene North Atlantic climate variability, and investigation the role of the Sargasso Sea region in responding or contributing to pronounced rapid climate change events and periods of the late Holocene. The AMO is of particular note in this prospectus, as it is a relatively newly identified pattern of SST variability specific to the North Atlantic Ocean. More high-resolution climate proxy data are needed to resolve past changes in the AMO, possibly an essential missing piece of the puzzle that is North Atlantic climate variability, and all these data from Bermuda represent a potential gold mine of information to fill that very need. Changes on timescales associated with the NAO and AMO are of concern to human populations on the order of human lifetimes. Since these are likely to play at least a significant, if not dominant, role in weather and climate variability over the North Atlantic region, it is vitally important to try to understand how they have operated in the past under different climate regimes of the Holocene, and by extension, how we might expect them to operate under climate changes predicted for the future.

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