Subdecadal to multidecadal cycles of Late Holocene North Atlantic climate variability preserved by estuarine fossil pigments

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ABSTRACT

The climate system in the North Atlantic region is complex and influenced by outside forcings as well as internal modes of the system. Modeling and observational work have suggested that a better understanding of the connections between ocean- and atmosphere-driven variability could lead to predictive power for North American and European weather patterns. Here we present a new millennial-length proxy record of estuarine fossil pigments and use it to investigate cyclic components of North Atlantic climate through the effects on estuarine ecosystems. The time series exhibits significant cyclic components that can be related to two of the dominant internal modes of climate variability in the region: the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO). The NAO signal is associated with internal atmospheric variability, while the AMO has been linked to previously modeled and observed changes in thermohaline circulation and meridional heatflux. In our record, the dominant periodicity of the AMO has shifted over time, in concert with Medieval Warm Period–Little Ice Age–Present Warm Period transitions. A relationship between an intermittent NAO cycle and the AMO signal suggests coupling of the ocean-atmosphere system at multidecadal time scales. Although the causal relationship is not resolved, predictive models of Northern Hemisphere interannual weather patterns and estuarine productivity may be improved by incorporating the results of this study.

Keywords: pigments, varves, climate, Holocene, thermohaline circulation, North Atlantic.

INTRODUCTION

Although recent work has greatly advanced our understanding of North Atlantic regional climate variability (Jones and Mann, 2004), its complexity has left questions unanswered regarding interactions between various forcings and internal modes of the climate system. Much of the variability in the region during boreal winter can be attributed to the atmospheric quasi-decadal North Atlantic Oscillation (NAO) (Hurrell, 1995). In addition, multidecadal oceanic fluctuations associated with the Atlantic Multidecadal Oscillation (AMO) have significant influence on the region (Delworth and Mann, 2000). Both of these internal modes affect temperature, precipitation, and atmospheric circulation around the North Atlantic Basin, and subsequently have large effects on ecosystems and society. Due to the short duration of instrumental records, preanthropogenic behavior and low-frequency climate variability are difficult to assess in observational records. Therefore, a priority in paleoclimate science is to produce high-quality proxy reconstructions of North Atlantic climate variability that preserve both decadal and multidecadal periodicities. Such records are crucial to validate general circulation models and to further our understanding of the natural dynamics present in regional climate.

In this study, we present a single-proxy reconstruction of estuarine productivity in southern New England that exhibits various cyclic components associated with North Atlantic climate fluctuations. A unique record of well-preserved photosynthetic pigments from the anoxic, annually laminated (varved) estuarine sediments of the Pettaquamscutt River Estuary, Rhode Island (Figs. 1, DR1,[1] and DR2; Table DR1) is used to produce a robustly dated, 980 yr (A.D. 1024–2004) time series with an average temporal resolution of 2 yr.

The field site is a small north-south–trending estuary immediately southwest of Narragansett Bay, Rhode Island. In the upper reaches of the estuary are two ice-block depressions formed during the retreat of the Laurentide Ice Sheet at the close of the Last Glacial Maximum (Orr and Gaines, 1973). These kettles are four to five times deeper than the rest of the estuary and produce a fjordlike circulation pattern, which isolates bottom waters in the two basins due to density-driven stratification. The isolated water is dominated by hydrogen sulfide, and as a result, no bioturbation is evident in the sediment record. We have examined pigments from the deeper of the two basins in order to minimize overturn events, which could affect the sediment record by oxygenating the bottom waters. The primary productivity in this environment is dominated by brown-green anoxygenic photobacteria residing just below the oxycline (~4 m), with lesser quantities of oxygenic green phytoplanktonic algae just above the oxycline (Sieburth and Donaghay, 1993).

We focus this study on the pigment Bacteriochlorophyll *e* (Bchle), which is produced

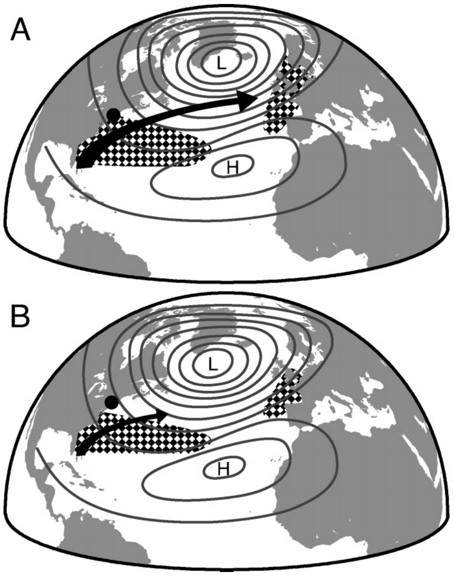

Figure 1. North Atlantic region showing locations of the Pettaquamscutt River Estuary (circle) and the regional pressure centers associated with a positive NAO during (A) increased and (B) decreased meridional oceanic heat flux (AMO). Arrow symbolizes northward heat flux via Gulf Stream and North Atlantic Current, and hatched areas symbolize zones of positive atmospheric temperature anomalies during a positive NAO. Note the southward shift of the atmospheric system coincident with reduced oceanic meridional heat flux.

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[1] GSA Data Repository item 2006109, methods, detailed locus map (Fig. DR1), age model (Fig. DR2), cross spectral plot (Fig. DR3), and radiocarbon data (Table DR1), is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

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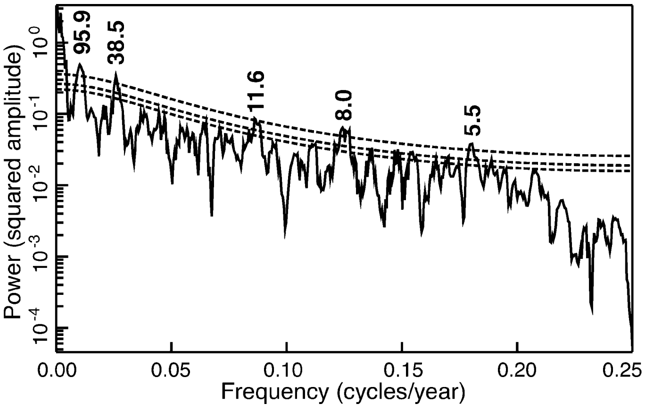

Figure 2. Multitaper spectral analysis of the Pettaquamscutt River Bchle MAR time series (A.D. 1058–2004). Dashed lines represent the 90%, 95%, and 99% confidence levels with respect to first order autoregressive [AR(1)] red noise background (Mann and Lees, 1996). All periodicities significant above 99% are labeled.

just below the oxycline of the water column by brown-green sulfur photobacteria (Chen et al., 2001; Sieburth and Donaghay, 1993). Due to the anoxic habitat of these bacteria, Bchle is an ideal pigment to use for climate studies as it avoids zooplankton grazing complications often encountered with phytoplankton productivity studies (Keller et al., 1999). Since local air and water temperatures during the growing season (winter/spring) are significantly correlated to climate fluctuations such as the NAO (Hawk, 1998), we hypothesize that productivity will be associated with regional climate. Therefore, mass accumulation rates (MARs) of Bchle can be used as a proxy for North Atlantic climate variability over the last millennium.

RESULTS AND DISCUSSION

Climate Cycles

It is apparent that the reconstructed time series of Bchle MAR exhibits variability at a number of different time scales (Figs. 2 and 3A). In order to examine this variability quantitatively, spectral analysis was performed on the portion of the time series from A.D. 1058 to A.D. 2004. This time window was chosen in order to avoid the environmental contamination of the climate signal in the early part of the record due to water column stabilization after marine inundation and potentially questionable preservation of photosynthetic pigments during this time. A log transformation of the data was performed to obtain a more normal distribution, and the multitaper method was performed. The spectral analysis exhibits five periodicities that are statistically significant at greater than 99% above the first order autoregressive [AR(1)] red noise background (Fig. 2) (Mann and Lees, 1996).

At the subdecadal end of the spectrum, there are two significant periodicities in the Bchle MAR time series. First is a strong 8.0 yr cycle, which has been shown to dominate NAO instrumental and proxy records (Cook, 2003; Hurrell, 1995; Jones et al., 1997). Further support of the NAO origin of this cycle is gained through cross spectral analysis between the Jones et al. (1997) NAO index and the overlapping segment of the Bchle MAR time series from A.D. 1824 to A.D. 1960 (Fig. DR3). This analysis demonstrates a significant coherence in the ~8 yr spectral peak between the two records prior to local cultural eutrophication of the estuary after ca. A.D. 1960 (Hubeny and King, 2003). In addition to the 8 yr cycle, there is significant power at the 5.5 yr spectral peak. Although not as commonly cited as being associated with the NAO, similar significant periodicities have been found in NAO records (Luterbacher et al., 2002).

At the quasi-decadal range, the Bchle time series has a significant spectral peak at 11.6 yr. The origin of this cycle is unknown, but there are a number of possibilities. Commonly, ~11 yr cycles in climate records are attributed to solar variability associated with the Schwabe Cycle due to coincidence in cycle length. Recent studies have demonstrated potential communication of this rather small solar forcing to the atmosphere through upper troposphere–lower stratosphere interactions (Labitzke and van Loon, 1997); however, there has not been any definitive evidence in the literature linking the Schwabe Cycle to surface climate variability. Other potential candidates for driving ~11 yr cycles have been proposed (Mann and Park, 1996) and include potentially unstable extratropical ocean-atmosphere interactions in the North Atlantic Ocean between the oceanic gyre system and atmospheric circulation through air-sea heat exchanges (Latif and Barnett, 1994).

At the multidecadal frequency ranges, significant power is observed in peaks centered at 38.5 yr and 95.9 yr. Both of these peaks can be attributed to the AMO, which has been observed both in proxy (Delworth and Mann, 2000; Gray et al., 2004) and in modeling studies (Delworth and Mann, 2000; Knight et al., 2005). Although the AMO has commonly been cited as having a periodicity of 65–80 yr, current proxy and modeling results exhibit a more complex picture with variable periodicities ranging from perhaps as low as 30–40 yr (Gray et al., 2004; Knight et al., 2005) to 100 yr and more (Delworth and Mann, 2000; Gray et al., 2004; Knight et al., 2005). Despite this lack of a definitive period associated with the AMO, there is general agreement that the phenomenon is internal and involves ocean-atmosphere coupling as well as variability in the strength of the thermohaline circulation (Delworth and Mann, 2000; Knight et al., 2005). In addition to the aforementioned AMO studies, various other proxy reconstructions of North Atlantic climate variability have found significant power in similar multidecadal spectral peaks from regional (Appenzeller et al., 1998; Proctor et al., 2002), and hemispheric (Luterbacher et al., 2002; Mann et al., 1995) proxy and instrumental records.

Variable Cycles over the Last Millennium

Examination of a wavelet transform of the Bchle MAR time series (Torrence and Compo, 1998) shows temporal variability in periodic components over the last millennium (Fig. 3B). In the low-frequency sector, there is variable dominance between the 38.5 and 95.9 yr AMO cycles. In order to accentuate this phenomenon, we have band-pass filtered the time series at the two AMO frequencies and summed the results to produce a record of total multidecadal variability in this record (Fig. 3C). It is apparent from these analyses that both frequencies are present throughout the record, but there is a preference for the lower-frequency component during the Little Ice Age compared to the Medieval or Present Warm periods. Further support for a distinct Little Ice Age in the record comes from the biologic lamination thickness associated with individual varves (Fig. 3D). The decadally smoothed thicknesses of these laminations are statistically thinner during the Little Ice Age than either of the warm periods, showing that overall productivity and runoff were lower due to dominance of cool, dry climate during this time.

The variability found in the AMO periodicity is not unique to our record. For instance, in their tree-ring-reconstructed AMO time series, Gray et al. (2004) demonstrate wide periodic dominance in the 40–128 yr band from A.D. 1567 to the late nineteenth century, after which the dominance shifted to a narrower band centered at ~40 yr. Although this may be an artifact of their technique, the timing matches our frequency transition well (Fig. 3B). Recent modeling studies provide additional support for variable AMO periodicities. It has been demonstrated using the HadCM3 climate model that the AMO can exhibit unforced variability between roughly centennial cyclicity and a higher-frequency (~40 yr) cyclic component (Knight et al., 2005).

The NAO component of the wavelet exhib-

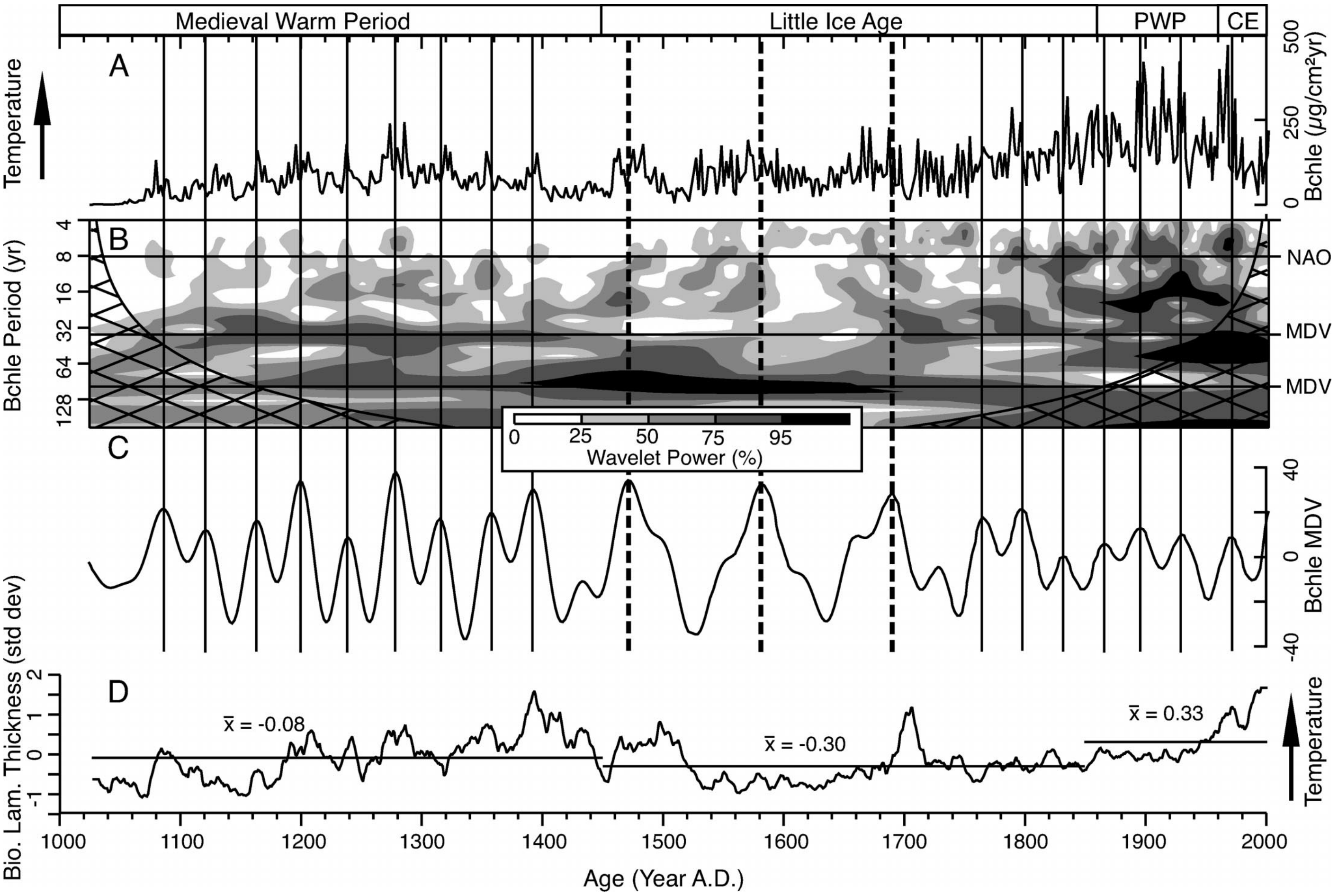

Figure 3. A: Pettaquamscutt River Bchle MAR time series along with (B) the corresponding wavelet transform (Torrence and Compo, 1998). Gray scale indicates power, which is scaled to percent total power, and hatched areas illustrate the cone of influence and hence edge effects of the transform. North Atlantic Oscillation (NAO) and multidecadal variability (MDV) periodicities are labeled. C: Sum of Bchle MAR time series band-pass filtered at 38.5 and 95.9 yr used to represent multidecadal variability. The Medieval Warm Period, Little Ice Age, Present Warm Period (PWP), and local cultural eutrophication (CE) times are labeled at the top of the figure and are supported by (D) decadally smoothed biologic lamination thicknesses (standard deviation units, "std dev"), which represent total productivity and runoff. Vertical lines indicate multidecadal amplitude peaks, which are related to the intermittent 8 yr NAO periodicity. See text for full discussion of the data.

its intermittent oscillatory behavior throughout the record (Fig. 3B). This behavior is not unlike that observed in Greenland ice records (Appenzeller et al., 1998), suggesting that it is not a unique feature to our proxy or geographic location. The intermittent nature of the NAO signal in the wavelet is related to the AMO signal in such a way that during phases of active NAO cyclicity, the AMO signal tends to be at a peak. This relationship can be seen in Figure 3 by comparing the 8 yr NAO periodicity band in the wavelet to the vertical lines drawn through peaks in the data filtered at multidecadal periods. This relationship is clearest during the Medieval Warm Period, when the amplitude of multidecadal variability is large. The amplitudes of the multidecadal variability are lower during the Present Warm Period, and the relationship between the NAO and AMO is not as apparent. During the Little Ice Age, the relationship between the AMO and the intermittent NAO behavior is similar to warmer periods, although there is a shift toward lower-frequency multidecadal variability (Fig. 3, dashed vertical lines).

The relationship between the NAO and AMO in our time series suggests a coupling between the atmosphere and ocean at multidecadal time scales (Fig. 1). The causal relationship, however, cannot be determined from these data. There is strong modeling evidence that the dominant influence on climate variability in the extratropical Northern Hemisphere is from the atmosphere, not from oceanic circulation variability (Jones and Mann, 2004). Recent modeling studies have argued for direct radiative forcing of the NAO (Shindell et al., 2001; Shindell et al., 2003). The NAO has a known effect on sea surface temperature through atmospheric wind-stress changes, which can in turn affect thermohaline circulation via associated changes in the density of seed waters (Delworth and Dixon, 2000). Therefore, if the NAO is being forced by solar variability, then the low-frequency nature of the AMO could be attributed to atmospheric changes. Observational studies support the interpretation that the NAO is forcing the Gulf Stream (and in turn thermohaline circulation) by showing that the NAO leads changes in water properties associated with Gulf Stream migration with leads of 1.5–2 yr (Rossby and Benway, 2000; Taylor and Stephens, 1998).

Although the NAO has been established as a driver for sea surface temperatures over the North Atlantic, these effects may be restricted to decadal and subdecadal time scales (Czaja et al., 2003). If this is actually the case, then the possibility remains that multidecadal oscillations in the North Atlantic region could be forced by oceanic dynamics (Kushnir, 1994). The primary suspect for this driver is variability of the thermohaline circulation, which is related to the AMO. Modeling studies have supported this hypothesis by demonstrating that sea surface temperature variability can influence North Atlantic climate at multidecadal time scales (Sutton and Hodson, 2003), and that if the deep ocean dynamics are dampened, the NAO can lose the red portion of its spectrum (Wu and Gordon, 2002). In addition, there is evidence that multidecadal variability in the NAO can be predicted with a knowledge of North Atlantic sea surface temperatures (Rodwell et al., 1999).

Either of the above scenarios is possible but cannot be ascertained from this time series. The key to the problem is to determine which aspect of the system has enough of a memory to maintain periodic fluctuations of up to 100 yr. The underlying assumptions as stated above are that the sun and/or the oceans provide this memory. Since studies suggesting atmospheric forcing of the oceans do not include dynamic oceanic processes (Shindell et al., 2001; Shindell et al., 2003), and studies suggesting oceanic forcing of the atmosphere do not incorporate dynamic stratosphere-troposphere interactions (Sutton and Hodson, 2003; Wu and Gordon, 2002), the ultimate driver of these periodicities remains unresolved.

CONCLUSIONS

In conclusion, we have utilized photosynthetic estuarine pigments to investigate North Atlantic climate dynamics over the last millennium through ecological responses. The pigments exhibit variable frequencies over the length of the time series, which can be associated with the North Atlantic Oscillation and the Atlantic Multidecadal Oscillation. The Atlantic Multidecadal Oscillation has varied in dominant frequency, and the North Atlantic Oscillation cyclicity has been intermittent throughout the record. The intermittent nature of the North Atlantic Oscillation signal is related to the Atlantic Multidecadal Oscillation, which suggests coupling between the atmosphere and ocean. The driver in this relationship, however, has not yet been determined.

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