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Sensitive moisture response to Holocene millennial-scale climate variations in the Mid-Atlantic region, USA

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Abstract: Millennial-scale climate variability has been increasingly recognized as one of the most prominent features of the Holocene. However, regional responses, especially in terms of moisture conditions, are poorly documented and understood. Here we present lithologic and magnetic evidence from White Lake in northern New Jersey, USA, to show that low lake levels occurred at about 1.3, 3.0, 4.4 and 6.1 ka (1 ka = 1000 cal. yr BP). The low lake levels are indicated by heterogeneous coarse calcareous sediment layers showing strong magnetic intensities. These detrital layers were likely formed during low stands when shallow-water marls were exposed, oxidized, transported and redeposited. This model is supported by laboratory experiments showing that oxidation of marls can enhance magnetic intensities. The dry periods inferred from the low lake levels of White Lake appear to occur concurrently with the cold periods recorded in the North Atlantic sediments. The correlation between millennial-scale dry/wet cycles inferred from lake-level fluctuations of White Lake and cold/warm cycles in North Atlantic sediments suggests sensitive moisture responses to Holocene millennial-scale climate variability. The dry-cold (or wet-warm) association is supported by instrumental records of the last century showing that the Mid-Atlantic region was dominated by wet conditions, while most parts of the conterminous USA experienced droughts, when the North Atlantic Ocean was warm. The consistent moisture responses of the Mid-Atlantic region to temperature changes of the North Atlantic Ocean may have persisted for the past 6000 years.

Key words: Lake-level fluctuations, millennial scale, climate cycles, northeastern USA, Holocene, environmental magnetism.

Introduction

Holocene climate change has attracted increased attention over the past decade, and accumulated records have greatly improved our understanding of interglacial climate variability (Alley *et al.*, 2003). However, because the magnitude of the oscillations is much attenuated compared with that of the preceding glacial period (Broecker, 1994), various modes of Holocene climate variability have been proposed from a variety of proxy records (eg, O'Brien *et al.*, 1995; Bond *et al.*, 1997, 2001; Nedebragt and Thurow, 2005). For example, a quasi-periodic variation, which we will refer to as a 'cycle' in this paper, of 2600 years was found to dominate the glaciochemical time series of the Greenland ice core, suggesting cyclic atmospheric circulation at high latitudes (O'Brien *et al.*, 1995). An approximately 1000-yr cycle has been revealed by proxy records from North Atlantic sediments (Chapman and Shackleton, 2000), Greenland ice core (Schulz and Paul, 2002) and varved sediments from the Santa Barbara Basin (Nedebragt and Thurow, 2005). In northern New England, records for flood frequency from small lakes indicate a recurrence interval of about 3000 years of storm-related flood events (Noren *et al.*, 2002).

Also, a ~1500-yr climate cycle has been shown to characterize Holocene climate variability. Bond *et al.* (2001) used ice-rafted debris from northeastern North Atlantic deep-sea cores as a proxy for cooling events and identified nine cold/warm cycles spaced ~1500 years apart in the Holocene. Similar cyclicity has also been shown in other parts of the North Atlantic Ocean (Bianchi and McCave, 1999; deMenocal *et al.*, 2000). Beyond the North Atlantic Ocean, Holocene millennial-scale climate oscillations have been documented in other climate systems from regions including sub-arctic Alaska (Hu *et al.*, 2003), western Canada (Yu *et al.*, 2003), North America (Viau *et al.*, 2002; Willard *et al.*, 2005), western Europe (Niggemmann *et al.*, 2003), equatorial Africa (Russell and Johnson, 2005) and monsoonal Asia (eg, Gupta *et al.*, 2003; Hong *et al.*, 2003; Wang *et al.*, 2005) (Figure 1). These

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Figure 1 Locations of selected study sites where the millennial-scale climate variability during the Holocene is documented. 1, Hu *et al.* (2003); 2, Yu *et al.* (2003); 3, North American pollen data analysed by Viau *et al.* (2002) (see Shuman *et al.*, 2005 for different interpretations); 4, this study; 5, Bond *et al.* (2001); 6, Niggemann *et al.* (2003); 7, Gupta *et al.* (2003); 8, Hong *et al.* (2003); 9, Wang *et al.* (2005); 10, Russell and Johnson (2005)

millennial-scale climate oscillations have generally been correlated with the ~1500-yr cycles recorded in the North Atlantic Ocean sediments. Collectively these records suggest a common forcing mechanism, and solar forcing has been proposed (eg, Bond *et al.*, 2001; Hu *et al.*, 2003).

In the North Atlantic region, more high-resolution records from *continental* areas, particularly northeastern North America, are needed to constrain the geographic extent of millennial-scale climate variations. Here we present a lake-level record based on lithologic and mineral magnetic data from the Holocene sediments of White Lake, New Jersey, USA to demonstrate the sensitive response of the moisture conditions to Holocene millennial-scale climate variability. The emerging spatial patterns from our new record and other regional records would help improve our understanding of regional climate response in continental regions to large-scale climate forcing.

Study site and methods

White Lake (41°N, 74.8°W) is a hardwater lake located in New Jersey, northeastern USA (Figure 1). The lake owes its hardwater nature to the underlying limestone bedrock. It is believed that the White Lake basin originated from a preglacial karst valley (Witte, 2001). The lake has a small ephemeral inlet and one outlet, and is recharged primarily by groundwater. A marl bench, a band of unconsolidated calcareous sediments, appears around most parts of the lake shore (Figure 2A).

Two cores were extracted in 2003: WL03-1 from under 12.3 m water and WL03-2 from under 13.7 m water (Figure 2A). Five AMS ^{14}C dates on terrestrial macrofossils, including leaf fragments, plant needles and seeds, from each core were obtained. The chronology of the cores was derived by linear interpolation of the calibrated ages together with the surface age (2003 AD = −53 cal. yr BP) (Figure 3). The complete cores go back to ~14 ka (Li *et al.*, 2006). This paper focuses on the Holocene part of the record and discusses implications for millennial-scale Holocene climate variability. Loss-on-ignition was measured to estimate the organic matter and carbonate contents. Samples for mineral magnetic measurements were taken at 4-cm intervals with cubic plastic boxes. Low-field magnetic susceptibility was measured to estimate the concentration of magnetic minerals in the lake sediments. Isothermal remanent magnetization (IRM), normalized by dry mass, was used to measure the concentration of magnetic grains capable of carrying magnetic remanence (King and Channell, 1991). The IRM of a sample is acquired by exposing the sample to a 1.0 T field using an ASC impulse magnetizer. The detailed magnetic measurements of the lake sediments can be found in Li (2005).

Sediment lithologic and magnetic evidence for low lake levels

The Holocene sediments of both cores are composed primarily of gyttja, organic-rich lake sediments, but display strikingly different depositional features. The Holocene sediments in WL03-1 are characterized by a number of light yellowish marl layers punctuating the dark brownish gyttja sediments; whereas the Holocene sediments in WL03-2 are predominately gyttja with no visually distinct marl layers. The yellowish marl layers in WL03-1 comprise mainly coarse-grained marl sediments that are intermixed with gyttja sediments. Overall, the yellowish marl layers exhibit a heterogeneous texture (Figure 2B).

The Holocene sediments are generally characterized by weak magnetism. All samples yield negative magnetic susceptibility values, indicating low concentrations of para- and ferro-magnetic minerals in the sediments (Li *et al.*, 2006). The IRM measurements from the Holocene sediments display interesting patterns (Figure 4A). In WL03-1, the IRM intensity is high in the light yellowish marl layers and low in the intervening gyttja layers (Figure 4A). Overall, the IRM values from WL03-2 are weaker than those from WL03-1 except at ~1.3 ka and ~4.4 ka. Similar peaks at those times support intra-lake correlation between the two cores (Figure 4A).

The most prominent feature of the Holocene sediments is that the strong IRMs occur at the yellowish marl layers. The IRM peaks probably indicate periods of low lake levels, for the following reasons. Authigenic precipitation of marl in White Lake is largely induced by photosynthesis of the algae *Chara,* which is abundant in the present-day shallow water around the lake and is preserved as encrustations in the sediments. Marl precipitation is unlikely to cause magnetic mineral production. The marl layers contain coarse calcareous grains and display a heterogeneous texture, suggesting that marl layers were likely detrital in origin. Thus, the strong magnetization may result from marl detritus that have been transported from elsewhere. Since marl precipitation often occurs near shore, as evidenced by the presence of the marl bench around the lake (Figure 2A), precipitated (primary) marls can be exposed and could then be oxidized, eroded, transported and redeposited in relatively deeper parts of the lake when lake level drops. As a result, detrital (secondary) marls occur as distinct yellowish marl layers exhibiting a heterogeneous texture. Oxidation of primary marls may have caused the strong magnetization. Laboratory experiments of heating and air-exposure of precipitated marls, emulating natural oxidation of primary marls, show that the oxidized samples display increases in magnetic intensity (Li *et al.*, 2006). If the strong magnetism of the Holocene marl layers indicates low lake levels, WL03-1 would record low lake levels at ~1.3, 3.0, 4.4 and 6.1 ka, exhibiting a quasi-periodicity of ~1500 years of lake-level fluctuations. The reason why WL03-2 records low lake levels only at ~1.3 and 4.4 ka is probably because WL03-2 is located in the deeper part of the lake which has less extensive marl benches (Figure 2A). Therefore, this coring site should be less sensitive to lake-level changes.

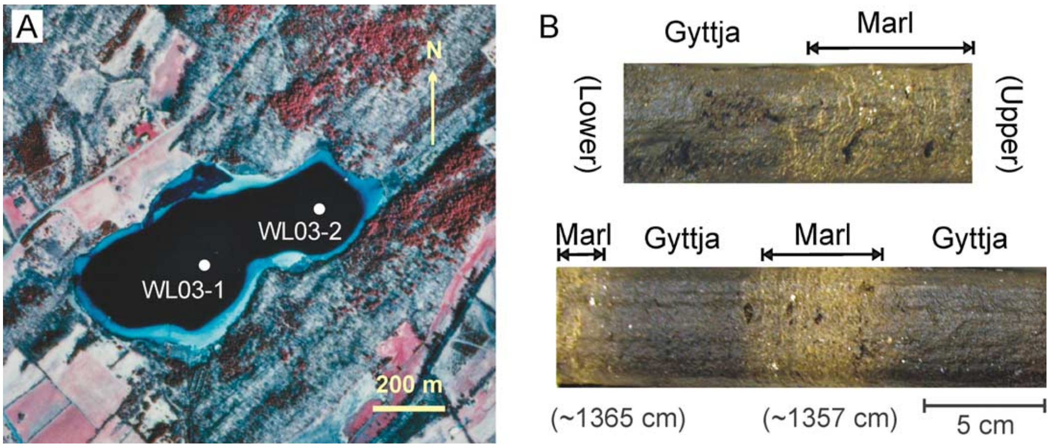

Figure 2 (A) Air photo of White Lake (NAPP #3004-36, taken on 13 April 1992) showing coring sites and the marl bench (light-coloured band) around the lake. (B) Marl layers at ~1278–1284 cm (top), and at ~1357 cm (~1354–1359 cm) and ~1365 cm (bottom) in the gyttja-dominated sediments of core WL03-1, showing a heterogeneous texture

Palaeoclimatic significance of low lake levels

The millennial-scale lake-level fluctuations of White Lake were probably caused by regional climate change. White Lake has only one ephemeral low-flow inlet on its northeastern shore, so surface inflow is only a negligible part of the lake's water budget and the lake has been fed primarily by groundwater. Lake-level fluctuations of White Lake would thus be controlled predominantly by variations in the groundwater level, which is in turn regulated by climate-controlled moisture abundance.

Moisture conditions in northeastern North America during the Holocene have been inferred in a number of studies. Harrison (1989) showed that lake levels of most lakes in eastern North America were low between 9 and 3 ka, and the lowest lake-level period centred around 6 ka. Reconstruction of the moisture balance of the northeastern USA suggests that the early Holocene was drier than other times and the moisture minimum occurred ~9 ka (Webb *et al.*, 1993). Stratigraphic data from Owasco Lake, one of the Finger Lakes in New York, indicate two highstands, one at 10.5 ka and the other at 6.9 ka, and an intervening lowstand at 9 ka (Dwyer *et al.*, 1996). Lake-level data from southeastern Massachusetts show two dry periods, one at ~10–8 ka and the other at 5.3–3.2 ka (Newby *et al.*, 2000; Shuman *et al.*, 2001). In southeastern Canada, Yu *et al.* (1997) show that low lake levels occurred from ~5 to 2 ka at Crawford Lake, Ontario. Lavoie and Richard (2000) show that the lake level of a small lake in southern Québec was lowered between 6.1 and 4.4 ka. Muller *et al.* (2003) documented three low lake-level periods: prior to 8 ka, 7.6–6.6 ka, and 4.8–3.4 ka in southern Québec. These records appear to suggest that dry conditions occurred in the early and middle Holocene in many parts of northeastern North America; however, the temporal resolution of the inferred moisture conditions is limited.

A recent study of Fayetteville Green Lake in New York, ~240 km northwest of White Lake, showed millennial-scale lake-level fluctuations with low lake levels at ~9.5, 8.3, 6.4, 5.0 and 2.1 ka (Mullins *et al.*, 2003), which are apparently not

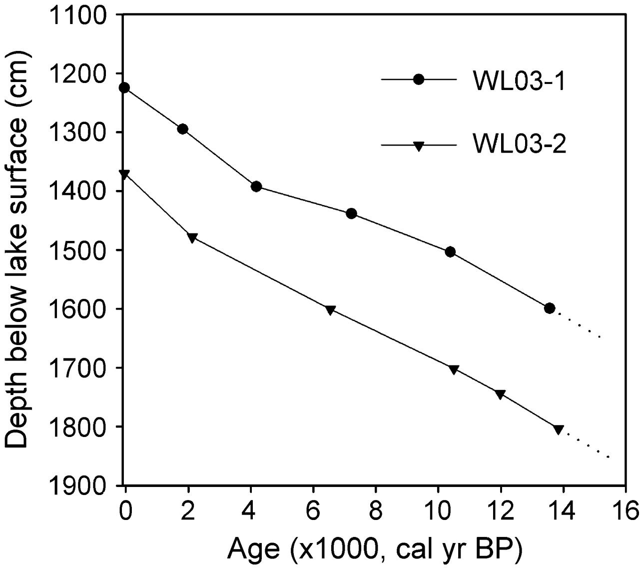

Figure 3 Age–depth models for cores WL03-1 and WL03-2 (from Li *et al.*, 2006), derived by linear interpolations of five calibrated ages and surface age (AD 2003) for each core. Cal. yr BP = calibrated age before present (AD 1950)

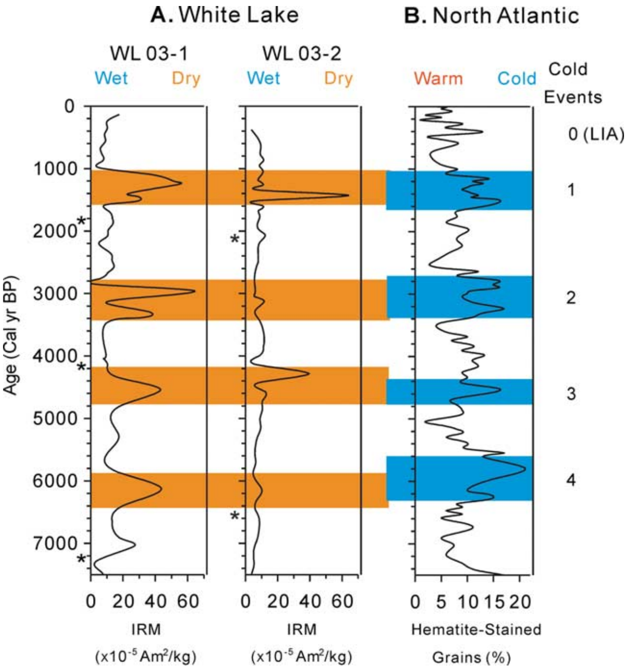

Figure 4 Correlations between magnetic parameters from two cores at White Lake and climate records from the North Atlantic Ocean (Bond *et al.*, 2001). LIA, 'Little Ice Age'; IRM, Isothermal Remanent Magnetization. Asterisks indicate levels where radiocarbon dates were obtained

synchronous with the White Lake low lake levels. The discrepancy in the timing of low lake levels at White and Green lakes could be due to the combined uncertainties of AMS dates from the two records. However, comparison of White Lake lake-level records and the drift-ice records from the North Atlantic Ocean indicates a striking correspondence (Figure 4). The low lake levels at ~ 1.3, 3.0, 4.4 and 6.1 ka correlate well with cold events 1, 2, 3 and 4 of Bond *et al.* (2001). Slight age offsets between these two records are probably within the uncertainties of radiocarbon dating in both records. The two low lake levels at ~ 8.3 and 9.5 ka documented in Green Lake during the early Holocene are well correlated with Bond *et al.*'s (2001) cold events 5 and 6 in the North Atlantic Ocean. In addition, another recent study of the Holocene pollen record from Chesapeake Bay sediments shows that *Pinus* pollen minimums occurred every ~ 1400 years and each lasted for ~ 300–500 years (Willard *et al.*, 2005). The decrease in *Pinus* pollen abundance has been interpreted to indicate cool intervals in eastern North America (Willard *et al.*, 2005). The cool intervals at ~ 3.1, 4.4 and 5.9 ka occurred almost synchronously with low lake levels at White Lake. Despite the inherent age uncertainties of each record, collectively, the records from White Lake, Green Lake and Chesapeake Bay sediments appear to suggest a temporally coherent pattern of climate variations at a quasi-1500 yr periodicity at least in the Mid-Atlantic region, if not the entire northeastern USA. In essence, the Holocene ~ 1500 yr lake-level fluctuations of White Lake are probably a manifestation of regional millennial-scale climate change rather than local perturbations.

Another interesting feature of the White Lake record is the low lake level at ~ 4.4 ka. This dry period occurred in the middle of a postulated storminess minimum from ~ 5.0 to ~ 3.5 ka, a period of low frequency of storm-related floods indicated by terrigenous inwash layers from 13 lakes in northern New England (Noren *et al.*, 2002). This dry period also coincides with the middle of the low lake-level periods from ~ 5.3 to ~ 3.2 ka documented in southern Massachusetts (Newby *et al.*, 2000; Shuman *et al.*, 2001). The apparent synchroneity of dry conditions in these areas implies the widespread nature of the ~ 4.4 ka drought in the northeastern USA. A drought at ~ 4.2 ka has been documented in mid-continental North America (Booth *et al.*, 2004) and other regions in the mid-latitude Northern Hemisphere (see review by Booth *et al.*, 2005). The ~ 4.2 ka drought has also been described as a very severe climate event in the Holocene (Booth *et al.*, 2005), which might have caused the collapse of ancient civilizations elsewhere (eg, Drysdale *et al.*, 2006). The recognition of a ~ 4.4 ka dry period in the northeastern USA, thus, lends support to the argument that the ~ 4.2 ka drought was probably severe and widespread.

Moisture responses to Holocene millennial-scale climate variability

Perhaps, the most intriguing feature of the White Lake records is the close correlation between low lake-level (dry) periods in White Lake and cold events in the North Atlantic Ocean (Figure 4). Based on the age models developed for White Lake cores and North Atlantic ice-rafting records, low lake levels occurred during cold phases of the cold/warm cycles in the North Atlantic Ocean. This correlation suggests that moisture conditions in the Mid-Atlantic region were sensitive to millennial-scale fluctuations of temperature in the North Atlantic.

Moisture variations in the northeastern USA and the temperature fluctuations in the North Atlantic Ocean were probably controlled by large-scale atmospheric circulation in the North Atlantic region. The variation of atmospheric pressure in the middle and high latitudes of the Northern Hemisphere is best described by the Arctic Oscillation (AO) (Thompson and Wallace, 1998), also known as the Northern Hemisphere Annular Mode (NAM) (Thompson and Wallace, 2001). The North Atlantic sector of the NAM is the North Atlantic Oscillation (NAO), which is characterized by an oscillation of atmospheric mass between the Arctic and subtropical Atlantic (Hurrell *et al.*, 2001). Variations in the pressure gradient between the subtropical high and polar low yield two NAO phases: a positive phase occurs when the pressure gradient is increased and a negative phase emerges when the pressure gradient is reduced. During its positive phase, stronger-than-normal westerly winds occur across the Atlantic on a more northerly track (Hurrell, 2003). The observed dry White Lake–cold North Atlantic correlation resembles the negative phase of the contemporary NAO, when decreased precipitation occurs in eastern North America and relatively cooler conditions dominate the northeastern North Atlantic where Bond *et al.*'s (2001) North Atlantic records were obtained. Although the NAO is often considered to be a mode of multidecadal atmospheric variability, it may have been modulated on longer timescales, probably by solar forcing (eg, Shindell *et al.*, 2001). Variations in solar irradiance can produce thermal anomalies in the stratosphere, which could then be propagated down to the troposphere and thus modulate tropospheric climate patterns such as the AO/NAO (eg, Baldwin and Dunkerton, 1999). The sun–climate link on millennial timescales has also been demonstrated in several records (eg, Bond *et al.*, 2001; Hu *et al.*, 2003; Niggemann *et al.*, 2003), supporting solar forcing as a plausible mechanism for modulating the AO/NAO at millennial timescales.

Our interpretation of a causal link between moisture conditions in the Mid-Atlantic region and temperature regimes in the North Atlantic Ocean is supported by instrumental records of the last century showing that drought extent and frequency in the continental USA are related to temperature fluctuations in the North Atlantic Ocean (McCabe *et al.*, 2004). Instrumental analysis and proxy-based multicentury records show that variations in the sea surface temperatures (SST) of the North Atlantic Ocean are characterized by a mode with a ~ 60–80 yr fluctuation (Delworth and Mann, 2000), known as the Atlantic Multidecadal Oscillation (AMO) (Kerr, 2000). Comparison of SST data from the North Atlantic Ocean and rainfall records from the continental USA over the past ~ 100–150 years indicates that the majority of the USA experienced dry conditions during warm AMO phases (Enfield *et al.*, 2001; McCabe *et al.*, 2004). However, there are exceptions in some regions, including the Mid-Atlantic, where wet conditions prevailed during warm AMO phases (McCabe *et al.*, 2004: Figure 2E). As conditions for cool AMO phases are generally opposite to those for warm AMO phases, the Mid-Atlantic region would experience *dry* conditions during *cool* AMO phases. This relationship is consistent with the dry White Lake–cold North Atlantic correlation at a millennial timescale observed in this study (Figure 4), suggesting that this dry-cold (or wet-warm) association may have persisted for the past 6000 years. Future palaeoclimate research should focus on collecting high-resolution records over broad regions of eastern North America to elucidate the geographic extent and temporal evolution of the linkage at different timescales between moisture conditions and ocean temperatures.

Conclusions

(1) The lithologic and magnetic data of Holocene sediments at White Lake indicate low lake levels at ~ 1.3, 3.0, 4.4 and 6.1 ka. The lake-level fluctuations likely represent wet-dry moisture response to approximately 1500-yr millennial-scale climate variations during the Holocene. The ~ 4.4 ka drought appears to be widespread in North America from the Midwest to New England.

(2) Inferred dry intervals at White Lake correlate with cold periods in the North Atlantic Ocean on millennial timescales, suggesting a sensitive moisture response to North Atlantic temperature in the Mid-Atlantic region. The dry–cold correlation reported here resembles the modern observed relationship between moisture conditions in eastern North America and the North Atlantic Oscillation (NAO), but operates at millennial timescales, possibly through modulation of atmospheric dynamics by solar forcing.

(3) The consistency in the dry–cold (or wet–warm) association on different timescales suggests that responses of moisture conditions in the Mid-Atlantic region to temperature regimes of the North Atlantic Ocean may have persisted for the past 6000 years.

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