Lacustrine isotopic evidence for multidecadal natural climate variability related to the circumpolar vortex over the northeast United States during the past millennium

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ABSTRACT

A pervasive 20–30 yr periodicity is observed in stable oxygen isotope values over the past 1000 yr from varved lacustrine calcite obtained from Fayetteville Green Lake, New York. Correlation analysis between historical oxygen isotope values and winter vortex latitude shows an inverse relationship wherein an expanded vortex is associated with high $\delta^{18}O_{calcite}$ values, and vice versa. An expansion of the vortex favors advection of cyclones from the Gulf of Mexico and the Atlantic regions characterized by high $\delta^{18}O_{precipitation}$ values, whereas a contracted vortex favors the development of cross-continental storms originating in the Pacific, which preferentially rain out ^{18}O as they propagate eastward. We hypothesize that changes in the size of the winter vortex every 20–30 yr over the past 1000 yr modify the primary source regions for meteoric precipitation. We propose two possible climate forcings to explain our hypothesis: an external forcing related to solar variability and an internal forcing related to ocean-atmosphere links.

Keywords: lacustrine, isotopes, atmosphere, precipitation, circulation.

INTRODUCTION

The climate system is influenced by a myriad of complex internal and external forcing mechanisms functioning on a variety of time scales (Mann et al., 1995). Proposed decadal- to century-scale forcing mechanisms include atmospheric trace-gas variability, volcanic aerosols, ocean-atmosphere links, solar variability, and random behavior (Rind and Overpeck, 1993). Our research indicates that a pervasive 20–30 yr periodicity in the winter climate has prevailed over the northeastern United States during the past 1000 yr. We present two possible climate-forcing mechanisms to explain our results: (1) an external mechanism, solar variability, and (2) an internal mechanism, ocean-atmosphere links. Although we accept the viewpoint that the injection of atmospheric trace gases through anthropogenic activities may be the dominant mechanism moderating Earth's present climate system (Overpeck et al., 1997), we propose that the observed 20–30 yr periodicity presented here provides evidence that the climate over the past 1000 yr has responded regularly to a forcing mechanism natural to Earth's climate system.

BACKGROUND AND SETTING

To better understand natural climate variability, there is a need to develop high-resolution climate proxy data sets from populated, mid-latitude regions of the world where global climate change may have profound societal, environmental, and economical effects. Fayetteville Green Lake, located 15 km east of Syracuse, New York, in the heavily populated and economically important northeastern United States, has been the focus of limnological research for many decades (Fig. 1A) (for review, see Hilfinger and Mullins, 1997). Our research focuses on paleoclimatic information stored in the calcite of varved lake sediments from Fayetteville Green Lake over the past 1000 yr.

Fayetteville Green Lake meets the criteria for developing high-resolution paleoclimate proxy data for several reasons. Foremost, it is topographically isolated and has a small drainage basin (4.33 km^2), thereby reducing complexities associated with vast hydrologic pathways. Furthermore, Fayetteville Green Lake is meromictic (i.e., permanently stratified) because of the inflow of saline-rich, dense groundwater at ~18 m water depth (Takahashi et al., 1968). Thus, bottom waters are permanently anoxic, yielding conditions favorable for preservation of annually deposited varves (Ludlam, 1969). Seasonal precipitation of biologically mediated calcite between the months of May and August by the cyanobacterium *Synechococcus* accounts for >80% of the summer part of the varves (Thompson et al., 1997). The short water residence time (1–2 yr; Takahashi et al., 1968) in the mixolimnion (upper 18 m where waters mix seasonally and calcite precipitates) assures that $\delta^{18}O_{calcite}$ values record high-resolution (<2 yr) variability.

Lacustrine $\delta^{18}O_{calcite}$ values vary as a function of water temperature and $\delta^{18}O_{lake\ water}$ (Stuiver, 1970). Research by Hilfinger et al. (2001) indicates that $\delta^{18}O_{lake\ water}$ is the dominant signal recorded by calcite in Fayetteville

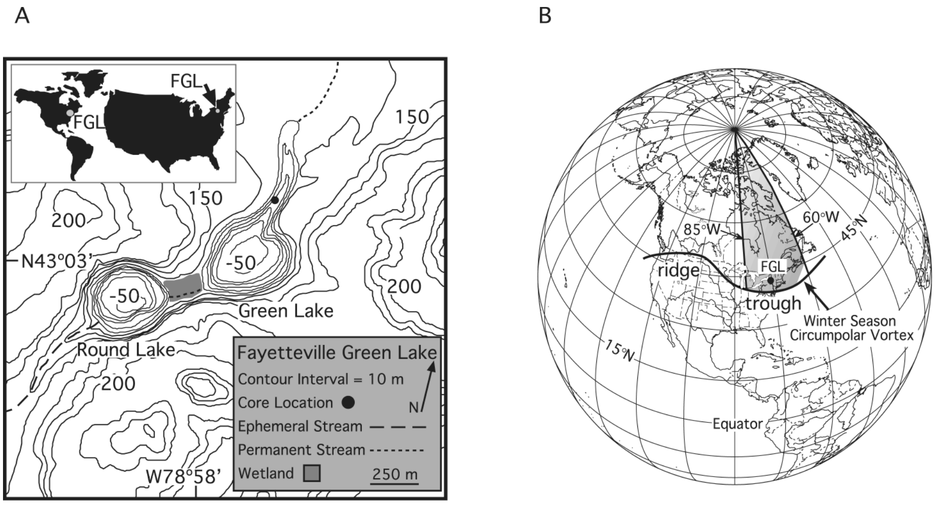

Figure 1. A: Study site map showing core location. B: Winter vortex at 500 mbar geopotential height field. Shaded area is longitudinal width used for this study. FGL—Fayetteville Green Lake.

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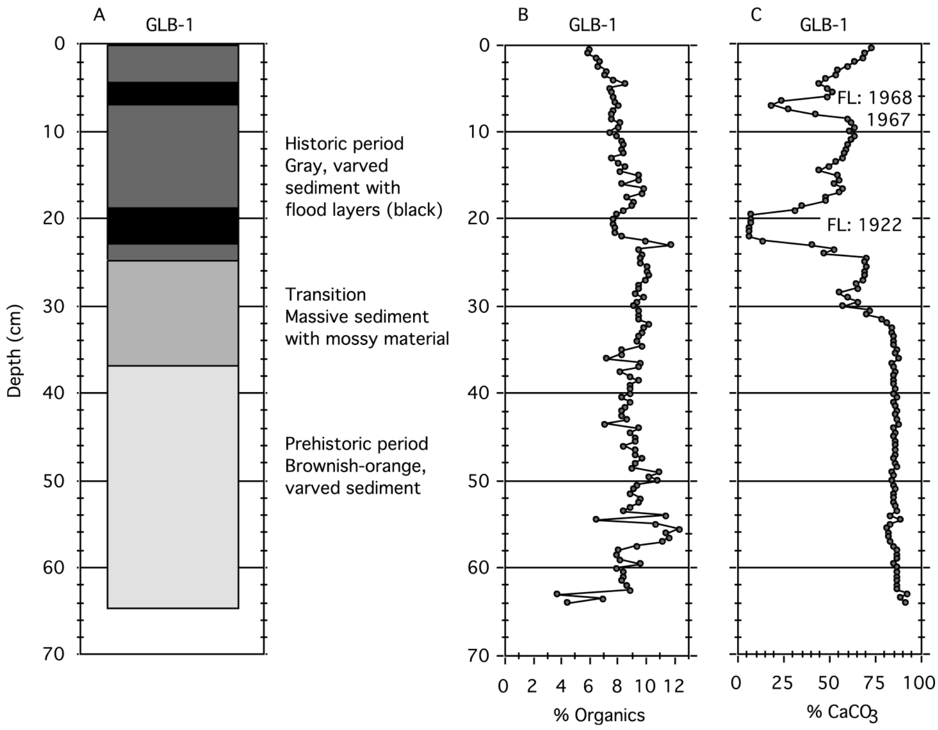

Figure 2. A: Core lithology. B: Weight percent total organics. C: Weight percent total carbonate.

Green Lake. Studies of regional hydrologic budgets show that >75% of annual water inflow is contributed by winter precipitation in the form of spring meltwater (Michel and Kraemer, 1995). Consequently, $\delta^{18}O_{calcite}$ from the lake should reflect winter meteoric precipitation at 1–2 yr resolution.

Balling and Lawson (1982) showed that the winter climate of the northeastern United States is sensitive to changes in atmospheric circulation aloft. Circulation over Fayetteville Green Lake, as with other mid-latitude locations, is associated with the circumpolar westerlies. The core of the westerlies (i.e., polar front jet stream) is characterized by the region of strongest north-south (meridional) temperature gradient. Because of the circumpolar nature of the westerlies and the polar front jet stream, this flow is often referred to as the circumpolar vortex. The mean annual position of the winter vortex over North America is just south of Fayetteville Green Lake (Fig. 1B; Yarnal and Leathers, 1988). As can be seen in Figure 1B, the vortex over North America does not have a simple east-west (zonal) flow, but rather reflects a wave pattern, typically with trough formation (meridional, expanded) over eastern North America. Variations in the position and amplitude of this trough are important in driving air-mass transport, storm development, and storm tracks. As such, the vortex plays a critical role in winter surface climate of the northeastern United States. Ultimately, the size and shape of the circumpolar vortex are driven by hemispheric energy distribution, and can be used to monitor and understand climate change (Angell, 1992).

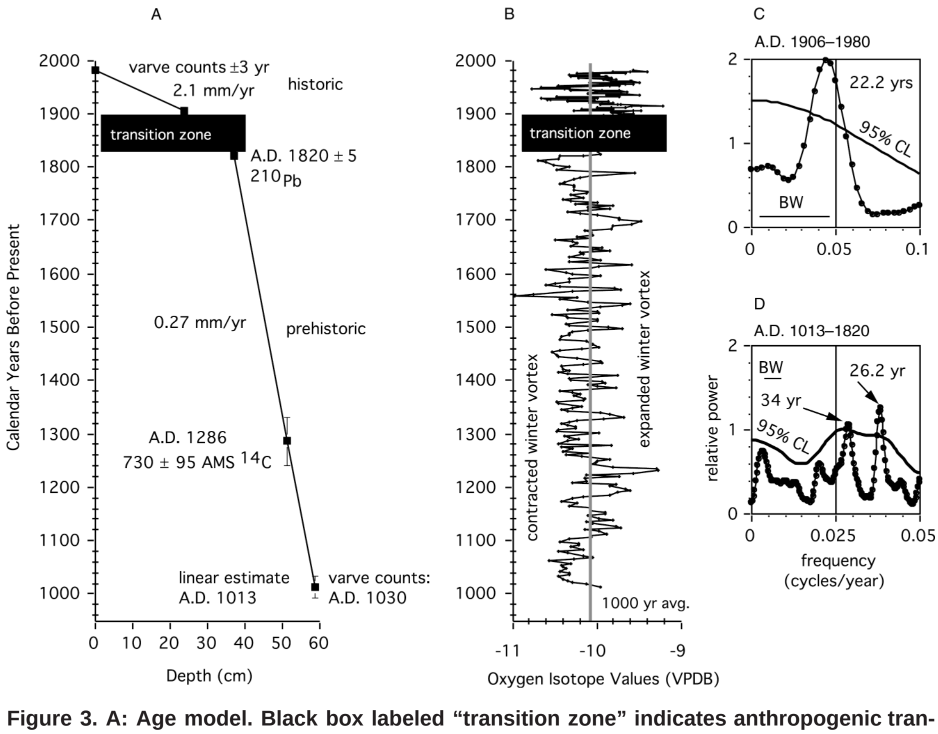

Figure 3. A: Age model. Black box labeled "transition zone" indicates anthropogenic transition zone (Hilfinger et al., 2001). B: Stable oxygen isotopic values for historic period and prehistoric period. VDPB is Vienna Peedee belemnite. C and D: Blackman-Tukey spectral analysis of oxygen isotope data for historic (*n* = 75; bandwidth [BW] = 0.04; lags = 37; degrees of freedom = 6) and prehistoric (*n* = 162; bandwidth = 0.0037; lags = 81; degrees of freedom = 6) periods. Data used to compute spectra are shown in B. CL is confidence level.

METHODS

Box-core GLB-1 was collected at 22 m water depth from the neck of Fayetteville Green Lake (Fig. 1A). The core was split and visually described (Fig. 2A). Weight percent total organic matter and total carbonate content were determined by loss on ignition at 550 °C and 1000 °C at 0.5 cm intervals, respectively (Fig. 2, B and C; Dean, 1974). Calcite $\delta^{18}O$ values were determined for the historic period (A.D. 1906–1980) on the summer part of individual varves ($n = 74$). Calcite $\delta^{18}O$ values for the prehistoric period (A.D. 1000–1820) were determined at ~1 mm intervals equaling ~3–4 yr per sample ($n = 225$). Prior to analysis, all samples were roasted in vacuo at 200 °C to remove volatile organic components and water. All isotope analyses were performed on a Finnigan MAT 252 gas ratio mass spectrometer directly coupled to a Kiel III carbonate preparation device. All samples were corrected for acid-water fractionation effects, ^{17}O contribution, and temperature fractionation. Samples are reported in standard delta notation relative to Vienna Peedee belemnite (VPDB); NBS-18 and NBS-19 standards as well as an in-house standard were used. Precision is better than ±0.1‰ for both carbon and oxygen isotope values.

The historic part of the core was dated using multiple varve counts ($n = 74$; standard error = ±3 yr), index varves (Ludlam, 1969), and a flood unit (e.g., 1922 flood layer; Figs. 2C and 3A). The prehistoric part of the core was dated by accelerator mass spectrometry ^{14}C converted to calendar years A.D. (Stuiver and Reimer, 1993; Hilfinger et al., 2001), geochemical correlation of a previously ^{210}Pb-dated horizon, and varve counts (Wahlen and Lewis, 1980), as well as primary historical references (Knapp, 1989; Fig. 3A). A linear sediment accumulation rate (0.27 mm/yr) is assumed for the prehistoric part of the core between dates. Varve counts (Wahlen and Lewis, 1980) match ($\pm$20 yr) our linear age estimate of ca. 1000 yr ago.

Spectral analysis was performed separately on both the historic and prehistoric isotope time series. The Blackman-Tukey method from the AnalySeries 1.2 program was used for spectral analysis (Paillard et al., 1996). A confidence level of 95% was set for each analysis. Prehistoric isotope data were prewhitened by 0.5 to remove low-frequency dominance. Tests of prewhitening on resultant spectra did not indicate a significant change in our results. Other tests, such as fast Fourier transform and maximum entropy method, were also performed (Paillard et al., 1996); all tests provided similar results.

The relationship between the historic varved $\delta^{18}O_{calcite}$ values and winter circulation was examined using an index of vortex size measured at the 500 mbar atmospheric pressure level. The size of the vortex was determined by calculating the average latitude of the vortex over the region between long 60°W and 85°W long (Fig. 1B). Vortex latitudes were derived from the National Center for Environmental Prediction (NCEP) Reanalysis Data Set for each winter (December–February) during the period 1948–1998 (Kalnay et al., 1996); however, we focused on a 32 yr period (1948–1980) during which varved $\delta^{18}O_{calcite}$ and 500 mbar data coexist. The average latitude of the vortex was determined following the technique described by Burnett (1993) and required the identification of a 500 mbar geopotential height that best represents the core of the westerlies. Both data sets were smoothed using a five-point moving average to remove interannual noise. A Pearson correlation was used to determine the degree to which the isotope and vortex data covary.

RESULTS

The core (Fig. 2A) consists of laminated (i.e., varved) marls separated by a mossy, unlaminated marl unit. The $\delta^{18}O_{calcite}$ values range between -9.1‰ and -11.0‰; over the past 1000 yr, $\delta^{18}O_{calcite}$ values average -10.1‰ (clearly labeled in Fig. 3B).

Oxygen isotope values are characterized by a strong ~22 yr periodicity for the historic record (Fig. 3, B and C), whereas $\delta^{18}O_{calcite}$ values for the prehistoric record are characterized by significant periodicities at ~26 and ~34 yr (Fig. 3, B and D).

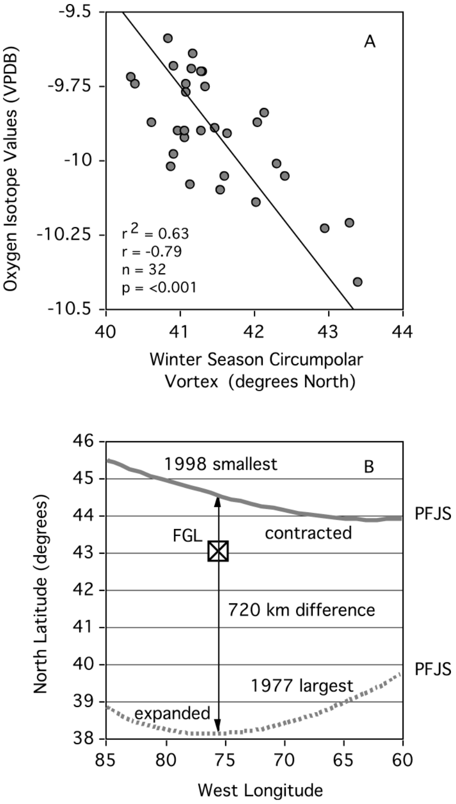

Figure 4. A: Correlation analysis between oxygen isotope values and winter vortex latitude. B: Winter vortex comparison. PFJS is polar front jet stream; FGL is Fayetteville Green Lake; VDPB is Vienna Peedee belemnite.

The correlation between $\delta^{18}O_{calcite}$ values and winter vortex latitude is -0.79, which is statistically significant ($p = <0.001$; Fig. 4A). Using the Durbin-Watson statistic, a moderate degree of autocorrelation was determined. As a result, we re-ran the regression using Newey-West standard errors that corrected for the autocorrelation; the resultant regression remained statistically significant. This inverse relationship suggests that when the winter vortex is at lower latitudes (expanded), $\delta^{18}O_{calcite}$ values are high. The coefficient of determination (r^2) is 0.63, indicating that 63% of the isotopic variance is explained by changes in vortex latitude. We note that this correlation is indirect; i.e., the isotope values are derived from summer varves, which are interpreted to record $\delta^{18}O_{lake\ water}$, which is interpreted to record predominantly winter precipitation.

In the latitudinal range of the winter vortex over eastern North America for the entire record (1948–1998), the mean positions of the smallest vortex size (1998) and the largest vortex size (1977) are nearly 720 km apart (Fig. 4B). Both vortices feature trough formation over eastern North America. These results demonstrate the large latitudinal range of the winter vortex during the historic period.

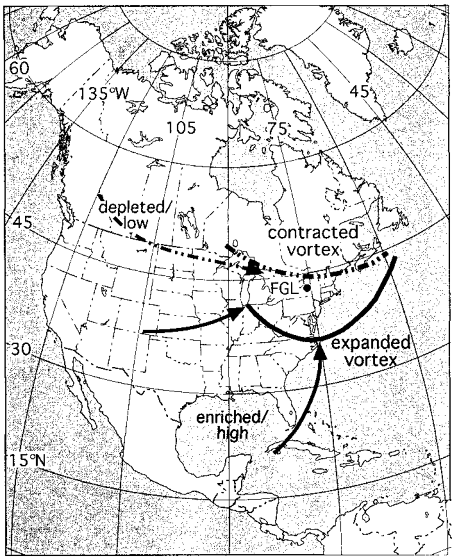

Figure 5. Map showing winter vortex with storm tracks and associated $\delta^{18}O$ precipitation values derived from relationship between isotope and winter vortex (Fig. 4A). Storm tracks for expanded and contracted vortices are after Whittaker and Horn (1984). FGL is Fayetteville Green Lake.

DISCUSSION

An important component of the mid-latitude westerlies is the presence of wave features operating over different spatial scales (Harman, 1991). Long-wavelength features, such as the trough observed in the mean flow over eastern North America, serve as conduits through which smaller, faster moving waves flow. These short waves are associated with divergent air aloft and create surface low-pressure systems (Harman, 1991). Consequently, variations in the position of the winter vortex will produce changes in the development and movement of winter surface storms.

The January storm climatology of Whittaker and Horn (1984) shows three primary storm tracks for eastern North America that are linked ultimately to the position of the vortex. Areas of high winter-storm frequency include an east coast track from Florida into New England, a central track extending from Colorado through Michigan, and a cross-continental track through the north-central United States (Fig. 5). The east coast track is associated with a deep trough and expanded vortex, and can produce significant precipitation via its access to Atlantic water vapor (high $\delta^{18}O_{precipitation}$; Fig. 5). A slightly less expanded vortex, in which storms move northeastward through the midwestern United States, would also yield relatively high $\delta^{18}O_{precipitation}$ via moisture from the Gulf of Mexico (Fig. 5). The cross-continental storms, associated with a contracted vortex, do not have access to Atlantic moisture and are characterized by low $\delta^{18}O_{precipitation}$ values. Furthermore, a contracted vortex is associated with increased overall storm frequency across the northeast United States, serving to augment total winter precipitation (Angel and Isard, 1998). An increase in winter precipitation relative to inputs during other seasons would produce a net isotopic depletion in $\delta^{18}O_{calcite}$.

Calcite $\delta^{18}O$ values from Fayetteville Green Lake show a pervasive 20–30 yr periodicity (i.e., multidecadal) over the past 1000 yr. This observation of a multidecadal periodicity favors a climate system with a periodic forcing. Consequently, we can eliminate climate-forcing mechanisms that do not occur regularly or over multidecadal time scales, such as atmospheric trace-gas variability or volcanism. Using Rind and Overpeck's (1993) list of potential decadal- to century-scale forcings, there remain two viable climate forcings that may explain our results: solar forcing and ocean-atmosphere linkages.

Our first hypothesis contends that the observed multidecadal periodicity is forced by solar activity. This hypothesis involves a series of feedbacks between solar activity, solar wind flux, cloud cover (Tinsley and Heelis, 1993), planetary albedo, and variations in vortex latitude. As an initial test of this hypothesis, we explored the correlations between the winter vortex data and three well-defined solar proxies: solar irradiance ($r = -0.15$; $n = 50$) (Lean and Rind, 1998), the AA geomagnetic index ($r = -0.30$; $n = 50$) (Cliver et al., 1996), and sunspot data ($r = -0.03$; $n = 50$) (Lean and Rind, 1998). Our correlation analysis shows no significant results.

Our second hypothesis is that the vortex responds to ocean-atmosphere links. Several researchers have shown that the ocean-atmosphere system has a multidecadal component (e.g., Mysak et al., 1990; Timmerman et al., 1998). We postulate that ocean-atmosphere links reflect multidecadal change in poleward ocean-heat transport, ultimately controlling the rate of thermohaline circulation (Broecker et al., 1990; Timmerman et al., 1998). For example, a decrease in poleward ocean-heat transport (conveyor weakened) will cause the winter vortex to expand. Expanded geometries enhance cyclones with coastal and midwestern origins (high $\delta^{18}O_{precipitation}$). Furthermore, an expanded vortex would decrease winter cyclone frequency (Angel and Isard, 1998), relatively enriching lake waters with high $\delta^{18}O$ values through an increase in summer precipitation and/or evaporation. As a result, years of an expanded vortex yield lacustrine calcite with higher $\delta^{18}O$ values. In contrast, an increase in poleward heat transport (conveyor strengthened) will cause the winter vortex to contract, increasing Pacific-derived moisture (low $\delta^{18}O_{precipitation}$) as well as storm frequency.

CONCLUSIONS

Our results indicate that natural winter climate variability for the northeastern United States over the past 1000 yr is characterized by a multidecadal periodicity, as reflected in $\delta^{18}O_{calcite}$ values from Fayetteville Green Lake. We favor an ocean-atmosphere linkage hypothesis involving poleward ocean-heat transport, thermohaline circulation, vortex latitude, and primary storm tracks as the best explanation for the observed multidecadal winter climate variability. If solar variability plays a role, its relationship remains unclear.

Perhaps most intriguing, however, our results show strong evidence that the multidecadal periodicity of natural winter climate variability has progressed relatively unfettered over the past 1000 yr. This periodicity has prevailed despite significant climate excursions such as the Medieval Warm Period, the Little Ice Age, and, most recently, global warming.

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