Late glacial–Holocene atmospheric circulation and precipitation in the northeast United States inferred from modern calibrated stable oxygen and carbon isotopes

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ABSTRACT

As global climate changes because of anthropogenic influences, it has become critical to better understand past climate and its various forcing mechanisms as a baseline for future comparison. To this end, we present a continental isotopic record from an 11.2-m-long wetland piston core sampled at 10–50 yr resolution; the core was taken in the heavily populated, economically vibrant northeastern United States (adjacent to Fayetteville Green Lake) and spans 14,600–3200 cal. yr B.P.

We use a historically based correlation between $\delta^{18}O_{calcite}$ obtained from individual varves in a box core from Fayetteville Green Lake and winter atmospheric circulation over the northeast United States to examine the way in which changes in winter circulation have influenced $\delta^{18}O$ in precipitation from 14,600 to 3200 cal. yr B.P. Our correlation analysis suggests that in periods during which the circumpolar westerlies are expanded, storms track more frequently from the Gulf of Mexico region, delivering precipitation with relatively high $\delta^{18}O$ values to the study site. By contrast, contracted westerlies result in more frequent low-$\delta^{18}O_{precipitation}$ cross-continental storms. By using this relationship we model winter-vortex latitudes over the northeast United States for the prehistoric oxygen isotope record, focusing on millennial-scale change, abrupt transitions, and multidecadal- to centennial-scale variability. The $\delta^{18}O_{calcite}$ and winter-vortex latitude records are characterized by a long-term asymmetric change interrupted by two notable, abrupt transitions at ca. 11,600 cal. yr B.P. and ca. 5200 cal. yr B.P. Several forcing mechanisms are considered including precession of the equinoxes (millennial-scale), ice-sheet-margin retreat (millennial-scale), thermohaline circulation (abrupt transitions), and ocean-atmosphere linkages (decadal to centennial scale).

Analysis of historical $\delta^{13}C_{calcite}$ values from a box core of varved Fayetteville Green Lake sediment and correlation of these values to early summer precipitation amounts reveal a relationship in which high $\delta^{13}C_{calcite}$ values (usually attributed to greater primary productivity) correspond with low annual precipitation amounts. From this relationship, we propose a climate-control hypothesis in which less early summer precipitation enhances productivity by increasing sunlight availability through reduced total cloud cover. We use this relationship to interpret early summer precipitation and cloud cover for the period from 14,600 to 3200 cal. yr B.P. The $\delta^{13}C_{calcite}$, precipitation and cloud-cover data are characterized by fluctuations about a mean value with multiple abrupt transitions occurring throughout the length of the record; there is no obvious trend in the $\delta^{13}C_{calcite}$ data. Spectral analysis indicates that both the $\delta^{13}C_{calcite}$ and $\delta^{18}O_{calcite}$ data are characterized by a variety of time scales with the most significant periods in the multidecadal to centennial time frame, corroborating other research that has determined a strong multidecadal to centennial periodicity in late glacial–Holocene climate proxy records.

Keywords: Quaternary, Holocene, isotopes, atmosphere, precipitation, lakes.

INTRODUCTION

The late glacial to Holocene transition was characterized by abrupt climate changes in response to large-scale atmospheric and oceanic reorganizations that responded to both insolation controls and retreat of Northern Hemisphere ice sheets (Broecker and Denton, 1989; Stuiver et al., 1995). As the climate system ''equilibrated,'' however, with the gradual deterioration of the Northern Hemisphere continental ice sheet, a more stable Holocene climate mode emerged (Dansgaard et al., 1993). The perception that Holocene climate is truly stable, however, has been challenged (Denton and Karlén, 1973; Wendland and Bryson, 1974; O'Brien et al., 1995). In fact, Holocene climate is now considered to have been relatively unstable, characterized by multiple climates denoted by abrupt episodes of climate transition, albeit with smaller amplitudes than during glacial times (Wendland and Bryson, 1974; O'Brien et al., 1995). As we enter a period of climate change where anthropogenic influences present unknown consequences, it is imperative that climate records from the recent past (i.e., Holocene) be obtained to establish a baseline for comparison (IPCC Working Group, 2001). Perhaps most impor-

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GSA Bulletin; October 2002; v. 114; no. 10; p. 1326–1340; 13 figures; 2 tables.

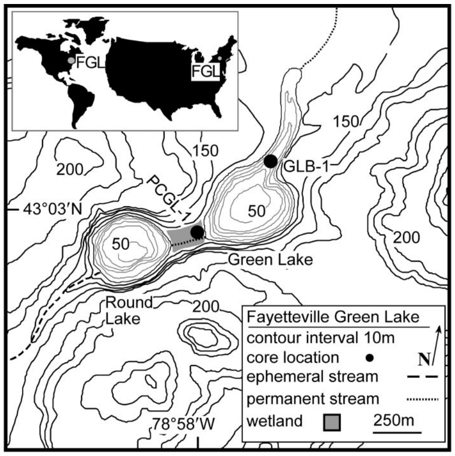

Figure 1. Hemispheric and regional perspective of Fayetteville Green Lake with topography and core locations shown. Bathymetry in meters below lake level. FGL—Fayetteville Green Lake.

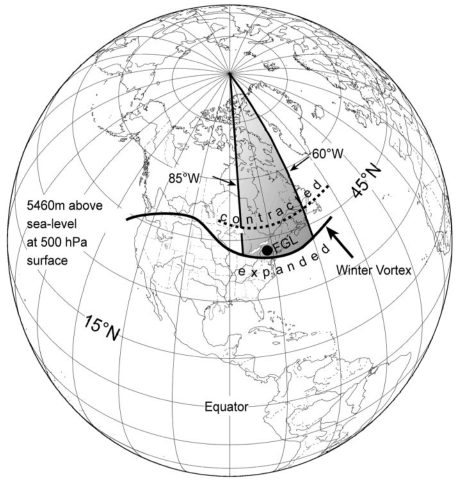

Figure 2. Schematic diagram showing contracted and expanded winter-vortex positions at 500 hPa geopotential height (5460 m above sea level) over North America (Yarnal and Leathers, 1988; Burnett, 1993). Shaded region represents longitudinal width of winter vortex used for this study. FGL—Fayetteville Green Lake.

tant, we must document rapid climate transitions and their potential forcings to better understand how our future climate, modulated by humans, will change.

Unlike ice cores and deep-sea sediment cores, which are distally located from populated regions, we present data from a continental site (Fayetteville Green Lake) located in a socially and economically important region (the northeast United States) (Fig. 1). Moreover, Fayetteville Green Lake is located under the approximate mean position of the core of the circumpolar westerlies, or the circumpolar vortex (Yarnal and Leathers, 1988). Strictly speaking, the *circumpolar vortex* refers to a continuous band of fast-moving air that circumambulates the midlatitudes. In this paper, we focus specifically on a narrow band of the circumpolar westerlies between 60°W and 85°W longitude that best describes the position of the westerlies over the northeast United States (Fig. 2). The westerlies involve a region of the midlatitude atmosphere defined by the strongest thermal and pressure gradients (Harman, 1991). At the core of the westerlies is the polar-front jet stream, within which midlatitude storms form and track (Namias, 1978; Whittaker and Horn, 1984; Harman, 1991; Knappenberger and Michaels, 1993). As the distribution of Earth's heat budget changes over time, the mean position and strength of the polar-front jet stream, and associated storms, also changes. Consequently, the position of the westerlies over the northeast United States causes the region to be highly sensitive to climate change directly related to atmospheric circulation processes (Balling and Lawson, 1982; Yarnal and Leathers, 1988) Fayetteville Green Lake is located in this region.

Here, we present a stable oxygen and carbon isotope record sampled at 10–50 yr resolution from a well-dated sediment core obtained from a wetland adjacent to Fayetteville Green Lake, New York. By using relationships derived from modern calibrations between isotope data obtained from individual varves from a box core of sediment (also from Fayetteville Green Lake) and meteorological indices (Kirby et al., 2001), we characterize present-day northeastern United States winter atmospheric circulation and storm tracks (via $\delta^{18}O_{calcite}$ data) and local, early summer precipitation and cloud cover (via $\delta^{13}C_{calcite}$ data) from 14,600 to 3200 calendar yr B.P. From these data, we discuss various components of the natural climate system and their potential forcings at multidecadal through millennial scales with a specific focus on abrupt climate transitions. These results provide a natural baseline for comparison to today's anthropogenically influenced climate system for the northeast United States.

STUDY SITE

For this study, we focus on Fayetteville Green Lake, a small meromictic lake located 15 km east of Syracuse, New York (Fig. 1). First described in 1839 as Lake Sodom, Fayetteville Green Lake lies within an isolated, topographic depression (Vanuxem, 1839). The lake's formation remains equivocal; however, massive floodwater discharge, perhaps in the form of a plunge-pool during glacial retreat, likely played a critical role (see review by Hilfinger and Mullins, 1997).

The name Fayetteville Green Lake is derived from the green color of the water during the late-spring and summer months when abundantly precipitated calcite causes the preferential reflection of green light wavelengths (Wetzel, 1983). Fayetteville Green Lake is surrounded by dolostone outcrops of the Syracuse Formation except to the north where the lake drains (Vanuxem, 1839). The only permanent surface influent derives from Round Lake (located ~200 m northwest of Fayetteville Green Lake), and chemical studies indicate that the two lakes are limnologically similar (Takahashi et al., 1968). Several large ravines along the lake's adjacent declivities record past significant erosion. The steep-sided lake basin is bordered by Silurian shales and evaporites of the Syracuse Formation above 18 m water depth and gypsiferous Vernon Shales below 18 m water depth (Muller, 1967; Thompson et al., 1990). Together, the Syracuse dolostones and Vernon Shales play important roles in the lake's limnology. The leaching of calcium (Ca^{2+}) and sulfate (SO_4^{2-}) from the Vernon Shale by groundwater at ~18–20 m water depth has created a permanent chemocline (density gradient) within the lake, preventing seasonal whole-lake mixing (Takahashi et al., 1968; Thompson et al., 1990). Consequently, Fayetteville Green Lake is meromictic, such that surface waters (mixolimnion: upper 18–20 m) and bottom waters (monimolimnion) do not mix. Fayetteville Green Lake is also a hard-water lake because of the abundance of bicarbonate (HCO_3^-), calcium (Ca^{2+}), and carbonate (CO_3^{2-}) dissolved from surrounding carbonate rocks (Turano and Rand, 1967). Furthermore, the lake is oligotrophic (i.e., low annual primary productivity) because the small size of its drainage basin (4.3 km^2) limits the influx of nutrients (Thompson et al., 1990). Climatologically, the Fayetteville Green Lake region is characterized by warm (20 °C), humid (9.4 cm average total precipitation from June through August) summers and cold (−3.9 °C), wet (70.5 cm average total snowfall from December through February) winters with pronounced seasonal contrasts (U.S. National Weather Service Cooperative Station Network; station at Syracuse, New York). Seasonal precipitation is characterized also by distinct $\delta^{18}O_{precipitation}$ values (relative to VSMOW [Vienna standard mean ocean water]): summer average values = −6.9‰ ± 3.7‰, $n = 43$; winter average values = −14.2‰ ± 5‰, $n = 24$. (Syracuse, New York data from Syracuse University Isotope Laboratory, Kirby et al., 2002).

For several reasons, Fayetteville Green Lake is an excellent site for developing paleoclimate records. Foremost, Fayetteville Green Lake is topographically isolated with a small drainage basin (Fig. 1), thereby reducing complexities associated with vast, complex hydrologic pathways, such as those associated with the nearby Great Lakes. Furthermore, a wetland environment lies adjacent to Fayetteville Green Lake within which >11 m of Holocene sediment fill is preserved, thus enabling the acquisition of relatively thick, continuous Holocene sediment records (Hilfinger and Mullins, 1997) (Fig. 1). Fayetteville Green Lake's meromixis produces permanent bottom-water anoxia, yielding conditions favorable for preservation of varves (i.e., annually deposited layers) (Ludlam, 1969). In addition, Fayetteville Green Lake is subject to the seasonal, biologically mediated precipitation of calcite by the cyanobacterium *Synechococcus* sp., which is the dominant autotrophic organism in Fayetteville Green Lake (Thompson et al., 1997). This calcite precipitation occurs within the mixolimnion, predominantly at water depths of 8–12 m (Thompson et al., 1997). Calcite precipitation is greatest from May into early August, accounting for >80% of the summer part of varves (Thompson et al., 1997). Thompson et al. (1997) also demonstrated that within the littoral zone of the lake, the same process of calcite precipitation occurs by a benthic variety of *Synechococcus* sp., which locally produces bioherms. Because the mixolimnion, where calcite precipitates, is characterized by a short water-residence time (1–2 yr; Takahashi et al., 1968), the oxygen isotope values from calcite will provide high-resolution (<2 yr) records of $\delta^{18}O_{lake\ water}$ variability. Previous work by Hilfinger et al. (2001) has shown that $\delta^{18}O_{calcite}$ values are influenced more by Fayetteville Green Lake $\delta^{18}O_{lake\ water}$ values, and thus by moisture source, than by water temperature. Michel and Kraemer (1995) showed that ~75% of the annual water budget to lakes in the Fayetteville Green Lake region is contributed by winter precipitation (snow or rain) and the subsequent spring runoff. Consequently, the $\delta^{18}O_{calcite}$ data are interpreted as primarily recording winter-moisture variability (Hilfinger et al., 2001; Kirby et al., 2001, 2002).

METHODS

Box Core from Fayetteville Green Lake

Discussed in detail by Kirby et al. (2001, 2002), box core GLB-1 was collected in 22 m of water from the ''neck'' of Fayetteville Green Lake. Calcite $\delta^{18}O$ and $\delta^{13}C$ values were determined for the historical period (A.D. 1906–1980) on the summer layer of individual varves ($n = 74$). All isotope analyses were performed by following the same procedure as that for the wetland core (see next section).

Wetland Piston Core

An 11.2-m-long hand-driven, square-rod piston core (PCGL-1) was collected from the wetland between Fayetteville Green Lake and Round Lake, New York (W75°58′, N43°02′) (Fig. 1). The core was split, visually described, and subsampled at the Syracuse University core laboratory. Age control for core PCGL-1 is based on six radiocarbon dates on bulk peat material or isolated wood fragments. All radiocarbon dates were converted to calendar (cal.) years B.P. (Stuiver and Reimer, 1993). In addition, we used a spliced date from the Younger Dryas termination (11,640 ± 240 cal. yr B.P.) derived from correlation with the GISP2 ice core record (Alley et al., 1993). (Splicing independent age models to the GISP2 ice-core age model is a commonly employed technique for late glacial–Holocene climate records because of the accuracy and precision of the GISP2 ice-core late glacial–Holocene age model.) Our spliced-date age model was used to guide us to collect subsamples ($n = 117$) at ~100 yr increments between 14,600 and 3200 cal. yr B.P. for lithologic analysis. Subsamples were analyzed for total organic matter and carbonate content by loss-on-ignition at 550 °C and 1000 °C, respectively (Dean, 1974). Weight percentages of total organic matter and carbonate were added together and subtracted from 100 wt%; the residual was interpreted as ''total inorganic content'' (i.e., nonorganic, noncarbonate material).

For isotope analyses, samples ($n = 1310$) were obtained at ~10 yr and ~50 yr time-averaged intervals for the periods 14,610–5030 cal. yr B.P. and 5030–3200 cal. yr B.P., respectively. The switch to a 50-yr time-averaged sampling interval at 5030 cal. yr B.P. was caused by a significant reduction in sediment-accumulation rate, and the lack of calcium carbonate younger than 3200 cal. yr B.P. prevented us from obtaining isotope values above this point in the piston-core samples. Time-averaged samples were used to eliminate spurious or anomalous data points that reflect annual, meteorological phenomena and not true climatological change. We use the term ''time-averaged sampling'' here to denote whole-width sediment sampling (never >2.8 cm total length, as determined by our age model) between two successive points. Because of the limitations of high-resolution studies from nonvarved, possibly bioturbated, records, we concluded that a 10 yr time-averaged sample spacing was the smallest sampling interval we could use to confidently define climatological (rather than meteorological) change and, at the same time, take into account the natural process of sediment homogenization associated with bioturbation. All isotope analyses were performed on the <63 μm size fraction that consists predominantly of biologically mediated calcite precipitate derived from *Synechococcus* sp. (Thompson et al., 1997). Comparison of calcite $\delta^{18}O$ and $\delta^{13}C$ values between the <63 μm size fraction (Kirby et al., 2001) and <4 μm size fraction (Hilfinger et al., 2001) revealed no significant differences, thus saving considerable sediment-preparation time. Furthermore, several samples ($n = 25$) from zones of abundant microfauna were examined at <400× magnification to determine whether *Synechococcus* sp.–derived calcite was contaminated by microfauna fragments; there was no evidence of contamination. Several samples ($n = 25$) were analyzed also by X-ray diffraction to determine whether the <63 μm size fraction was contaminated by detrital dolomite; the dolomite contribution consisted of <5%. Aragonite, associated with microfaunal contamination, was absent as well. Consequently, we are confident that the <63 μm size fraction truly represents *Synechococcus* sp.–derived biologically mediated calcite precipitate.

Isotope analyses were performed by using a Finnigan MAT 252 gas-ratio mass spectrometer directly coupled to a Kiel III carbonate-preparation device. Samples were reacted with 103% phosphoric acid and, prior to analysis, roasted in vacuo at 200 °C to remove volatile organic components and water. All samples were also corrected for acid/water fractionation effects, ^{17}O contribution, and temperature fractionation. Samples were held at 50 °C and reacted for 15 s to eliminate potential interference by small percentages (<5%) of detrital dolomite. Samples are reported in standard delta notation relative to VPDB (Vienna Peedee belemnite) by using standards NBS-18 and NBS-19 as well as an in-house standard

TABLE 1. RADIOCARBON DATA FOR CORE PCGL-1

Depth (cm)	Material	Lab I.D.	^{14}C age (yr)	Calibrated age (yr B.P.)	$\delta^{13}C_{(organic)}$ (‰)
21–29	Peat	TX-9133	2157 ± 50	2140	−28.8
137–142	Peat	TX-9134	4433 ± 58	5030	−31.3
498	Wood	AA-32433	5470 ± 55	6300	−27.9
723–728	Peat	TX-9136	7567 ± 74	8340	−27.6
895	Wood	AA-28864	8560 ± 65	9490	−30.5
1074	Wood	AA-32434	11,480 ± 130	13,530	−28.5

for calibration. Precision is better than ±0.1‰ for both carbon and oxygen isotope values.

Open-Water Versus Littoral-Zone $\delta^{18}O_{calcite}$

We addressed two important questions concerning the $\delta^{18}O$ values of calcite from Fayetteville Green Lake. The first question examined the nature of isotopic fractionation between the lake water and precipitated calcite. In other words, does the calcite precipitate in equilibrium with the lake water? Second, we sought to determine the similarity of $\delta^{18}O_{calcite}$ values between open-water (i.e., mixolimnion water, whose oxygen isotopes were sampled via the carbonate in the lake core) calcite and littoral-zone calcite (i.e., from the wetland core, considered to be the analogue of the littoral zone). This question is fundamental to our research because we use modern calibrations on open-water calcite for interpretation of littoral-zone (i.e., wetland) calcite. If we are to confidently transfer our modern calibrations from one environment to another, the $\delta^{18}O_{calcite}$ must precipitate under similar conditions.

To address the first question—does the calcite precipitate in equilibrium with the lake water?—we tested for equilibrium fractionation between the $\delta^{18}O_{calcite}$ and $\delta^{18}O_{lake\ water}$ by examining a variety of data collected from the littoral zone including lake-water temperature, $\delta^{18}O_{calcite}$ from *Chara* sp. plants on which the benthic variety of *Synechococcus* sp. precipitates, and $\delta^{18}O_{lake\ water}$ (Takahashi et al., 1968; N. Bounso, 2000, upublished commun.; J.B. Thompson, unpublished data). To predict water temperature, $\delta^{18}O_{lake\ water}$, and $\delta^{18}O_{calcite}$ for comparison with our measured values, we use the equation for equilibrium oxygen isotope fractionation by Kim and O'Neil (1997),

$$1000 \ln \alpha_{calcite\text{-}H_2O} = (18.03 \times 10^3\ T^{-1}) - 32.42, \qquad (1)$$

where α is the fractionation factor between calcite and water and T is the temperature of the water in degrees kelvin.

To address question two—are open-water $\delta^{18}O_{calcite}$ and littoral-zone $\delta^{18}O_{calcite}$ values derived under similar conditions (i.e., can the calcite precipitated by the planktic and benthic varieties of *Synechococcus* sp. be used interchangeably)?—we performed a series of comparative isotope analyses. They compared littoral-zone calcite removed from living *Chara* sp. plants during the early fall of 1999 (i.e., used as a modern wetland environment analogue) to open-water calcite extracted from individual summer varves in box core GLB-1 (A.D. 1906–1980) from Fayetteville Green Lake.

Isotope Calibrations Methods

Oxygen Isotopes in Calcite

The relationship between the historical varved $\delta^{18}O_{calcite}$ values from Fayetteville Green Lake box core GLB-1 and winter atmospheric circulation has been previously shown in Kirby et al. (2001, 2002).

Carbon Isotopes in Calcite

We also examined the relationship between $\delta^{13}C_{calcite}$ values from individual summer varves from box core GLB-1 and several meteorological and/or climatological indices including temperature, precipitation, snowfall, vortex latitude, and solar data. The strongest relationship was found between $\delta^{13}C_{calcite}$ and early summer (May–July) precipitation amount for Syracuse, New York, for the period A.D. 1906–1980, during which both data sets overlap. We examined several seasonal precipitation groupings; however, the months May through July were selected because they best represent the period of maximum calcite precipitation in Fayetteville Green Lake (Thompson et al., 1997). Seasonal precipitation data were obtained from the U.S. National Weather Service Cooperative Station Network for Syracuse, New York. Both data sets were smoothed through the use of 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 co-vary.

Spectral Analysis

Spectral analysis is a common statistical procedure for evaluating periodicity in paleoclimate time series. For this study, we used two spectral analysis techniques to examine the isotope time series: the Blackman-Tukey method and maximum entropy method. The Blackman-Tukey (B-T) method is widely used in paleoclimatology for its ability to present spectral features with calculated confidence levels (Paillard et al., 1996, Muller and MacDonald, 2000). The B-T method also allows the user considerable freedom (e.g., bandwidth, lags, etc.) in selecting procedures, thus maximizing confidence in the results obtained. The maximum entropy method (MEM) is also commonly used in paleoclimate research because of its high resolution when computing spectral powers. However, unlike the B-T method, the MEM does not allow for the calculation of confidence intervals; thus, it is not recommended for use as the sole method of spectral analysis (Paillard et al., 1996). Using the two methods together, however, enhances our interpretation of the data by assessing two separate analyses.

RESULTS

Wetland Piston Core

An age model was constructed for core PCGL-1 by assuming a linear sediment-accumulation rate between each date including the GISP2 splice (Table 1; Fig. 3) (Kirby et al., 2002).

Wetland core PCGL-1 consists of five types of components (Fig. 4A): (1) gravel (>25% total inorganic content with rock fragments present), (2) marl (>90% calcium carbonate), (3) mossy marl defined by ≤20% mossy material within marl, (4) moss mat defined by ≥20% aquatic moss with marl, and (5) peat (>90% total organic matter). Seven peat and/or moss mat layers have been identified in core PCGL-1, including the uppermost peat that extends to the surface. The dominant moss identified is *Drepanocladus aduncus*, which thrives in very shallow (<1 m), nearshore environments adjacent to calcareous (hard water) lakes (J.A. Janssens, 1996, personal commun., Lambda-Max Ecological Research Company).

Total organic matter and carbonate contents are inversely correlated ($r = -0.98$) throughout the core (Fig. 4, B and C). A significant shift in the relative dominance of total organic matter to calcium carbonate occurs at ca. 3200 cal. yr B.P. (Fig. 4, B and C). Total inorganic

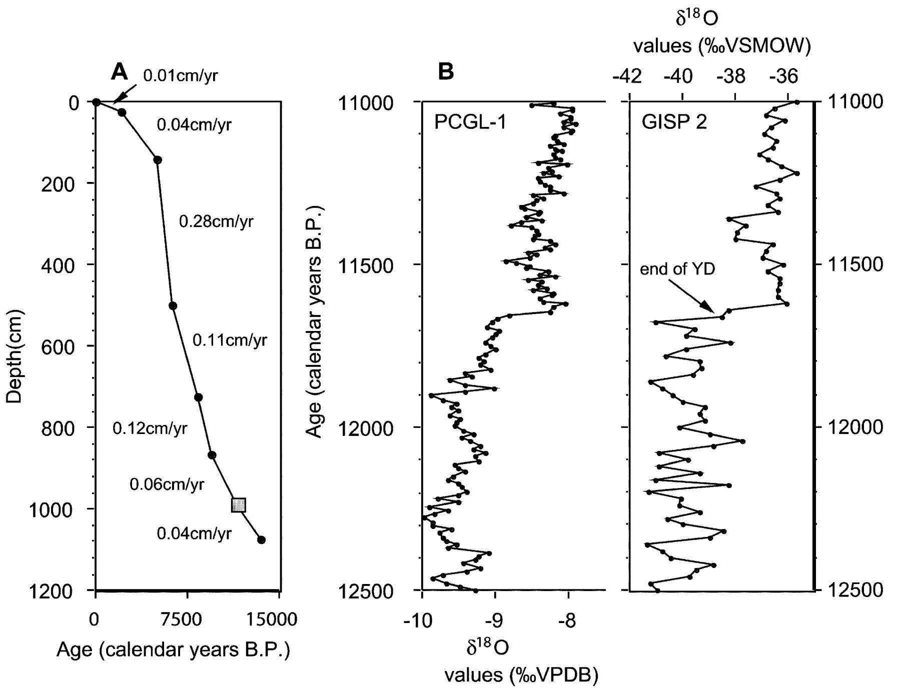

Figure 3. Age-model development. (A) Age model used for wetland core PCGL-1 based on conversion of calibrated ^{14}C dates to calendar years B.P. (black circles) (Stuiver and Reimer, 1993). Spliced GISP2 date (gray box; 11,640 ± 250 calendar yr B.P.) is included at 992.5 cm. Linear sedimentation rates are labeled on graph between respective dates. Error bars are smaller than circles on graph. (B) Comparison of core PCGL-1 (5-point moving average) and GISP2 ice core data (Alley et al., 1993). Both records show a clear step-function increase toward higher $\delta^{18}O$ values at the termination of the Younger Dryas (YD) cold event; we have interpreted this step-function change at both study sites as synchronous.

TABLE 2. OXYGEN ISOTOPE CALCITE-WATER EQUILIBRIUM DATA

	Water temp. (°C)	$\delta^{18}O$ calcite (VPDB)	$\delta^{18}O$ lake water (VSMOW)
Measured	15.0	−9.9	−9.5
Predicted	15.6	−9.7	−9.6

content decreases from ca. 14,600 to ca. 10,800 cal yr B.P., after which a relatively constant level is maintained. A notable exception, correlative to a thin moss-mat unit, is a brief interval at ca. 8900 cal. yr B.P. where inorganic contents reach 13% (Fig. 4, A and D).

Stable oxygen isotope results for wetland core PCGL-1 are shown in Figure 5A. $\delta^{18}O_{(calcite)}$ values range from −11.2‰ to −7.5‰ with average value of −9.1‰ between 14,600 and 3200 cal. yr B.P. The oxygen isotope data are characterized by small-amplitude, high-frequency variation throughout the entire record superimposed on a longer-term, asymmetric trend (Fig. 5A). This asymmetric trend is illustrated in Figure 5A by the dashed line adjacent to the isotope data. The dashed line shows a gradual decrease in $\delta^{18}O_{calcite}$ values from 14,600 to 11,600 cal. yr B.P. that is terminated by an abrupt shift to higher isotope values from 11,600 to 10,300 cal. yr B.P. Following the 1300 yr interval of high $\delta^{18}O_{calcite}$ values is a long-term decrease in oxygen isotope values that is terminated by an abrupt shift to lower oxygen isotope values at 5200 cal. yr B.P.

Stable carbon isotope results are shown in Figure 5B. $\delta^{13}C_{calcite}$ values range from −4.2‰ to −0.4‰ with an average value of −2.3‰ between 14,600 and 3200 cal. yr B.P. There is no obvious trend in the carbon data over the length of the record. The carbon isotope data are, however, characterized by frequent and abrupt, large-amplitude (multidecadal through millennial time scales) change from ca. 14,600 to ca. 10,300 cal. yr B.P. For example, a 3.8‰ shift to lower $\delta^{13}C_{calcite}$ values occurs from 10,900 to 10,400 cal. yr B.P. (Fig. 5B). From ca. 10,300 (beginning of the Holocene) to ca. 3200 cal. yr B.P., the carbon isotope data are also characterized by large-amplitude variability (shifts by <2.5‰ at multidecadal time scales) (Fig. 5B). There are also several millennial-scale intervals of relatively uniform $\delta^{13}C_{calcite}$ values from 10,300 to 3200 cal. yr B.P. (Fig. 5B). $\delta^{18}O_{(calcite)}$ and $\delta^{13}C_{(calcite)}$ are not significantly correlated for the period 14,600–3200 cal. yr B.P. (r = 0.1). It is interesting that there are no consistent relationships between the wetland core's lithology and either isotope data set.

Open-Water Versus Littoral-Zone $\delta^{18}O_{calcite}$

Table 2 shows the results of the equilibrium fractionation test. If conditions of equilibrium fractionation occur between the lake water and calcite during calcite precipitation, we would expect that our measured data should be very similar to the data predicted by Kim and O'Neil's (1997) equation. Table 2 clearly shows the similarity between the measured data and the predicted data. From this, we conclude that the processes controlling the precipitation of calcite and its subsequent isotopic value are occurring under conditions of equilibrium fractionation between the lake water and the calcite. These results help to eliminate potential complications associated with nonequilibrium fractionation processes (Arthur et al., 1983).

Figure 6 shows results of the test for similarity between open-water $\delta^{18}O_{calcite}$ and littoral-zone $\delta^{18}O_{calcite}$. These results illustrate that oxygen and carbon isotope values are similar for both the open-water and littoral-zone settings (Fig. 6). $\delta^{18}O_{calcite}$ values are essentially the same, whereas a small <0.5‰ offset exists between the open-water $\delta^{13}C_{calcite}$ and littoral-zone $\delta^{13}C_{calcite}$. The small carbon offset likely reflects the contribution of ^{12}C from the recycling of low-$\delta^{13}C$ *Synechococcus* sp. by zooplankton in the lower mixolimnion (Fig. 6) (Thompson et al., 1990). From these results, we conclude that there are no significant differences in the factors (i.e., water temperature and $\delta^{18}O_{lake\ water}$) controlling the isotopic composition of the calcite that is precipitating in the two settings. Thus, we feel confident that both the wetland calcite and open-water calcite are formed under similar conditions and that we can use our open-water–based calibration for the wetland environment.

Isotope Calibrations

Oxygen Isotopes in Calcite

As shown by Kirby et al. (2001), there is a strong historical relationship between $\delta^{18}O_{calcite}$ from the Fayetteville Green Lake box core and the winter-vortex latitude. Periods of vortex

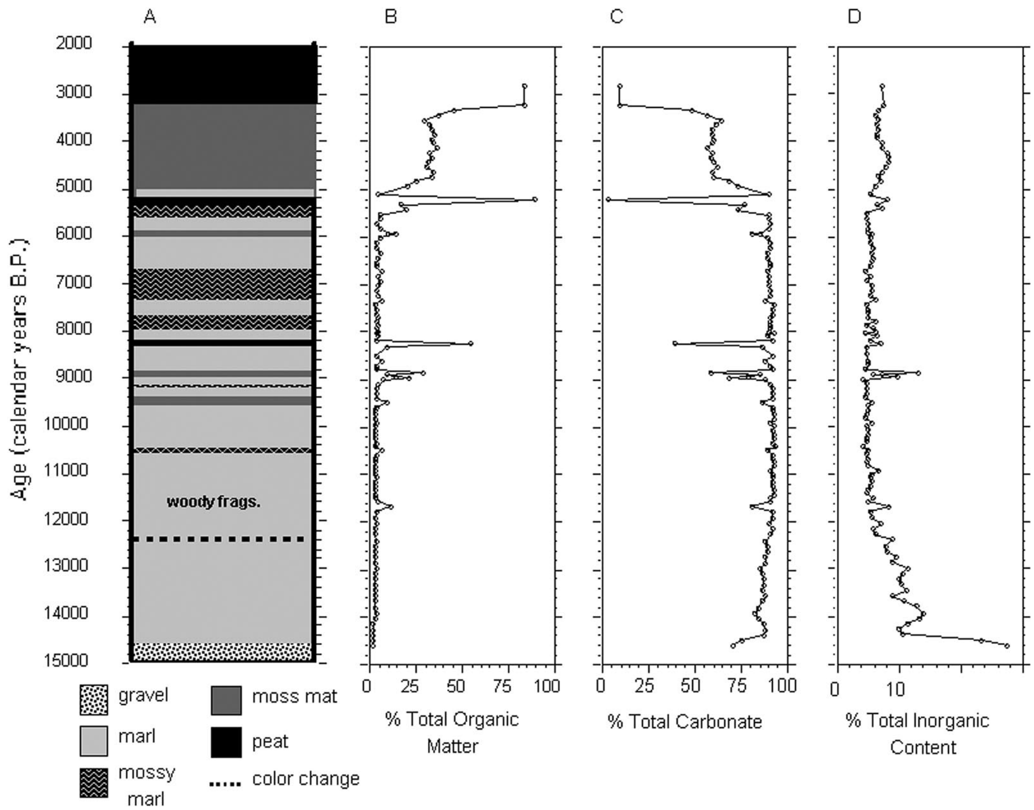

Figure 4. Wetland-core sedimentology from core PCGL-1 with age model. (A) Components of core by type. (B) Percent total organic matter. (C) Percent total carbonate. (D) Percent total inorganic content.

expansion (to lower latitudes) are characterized by relatively high $\delta^{18}O_{calcite}$ values, whereas periods of a contracted vortex (to higher latitudes) are associated with relatively low $\delta^{18}O_{calcite}$ values. This relationship reflects preferential storm-track migration with vortex latitude (Kirby et al., 2001). We applied a transfer function [equation 2 from Kirby et al., 2002: vortex latitude = (–3.12) · ($\delta^{18}O_{calcite}$ values versus age that are plotted in Fig. 5A) + 10.60] to calculate vortex latitudes during the late glacial-Holocene. The data reveal the same asymmetric shape as is seen in the isotope data, which is not surprising considering that the modeled vortex latitudes were derived from the measured $\delta^{18}O_{calcite}$ data. Figure 7 includes the historical range of vortex variability for the period A.D. 1948–1998. Comparison of historical vortex range and modeled vortex range demonstrates that approximately half of the past 14,600 cal. yr lie within the historically measured range of values (Fig. 7). From this observation, we conclude that our model calculations (results shown in Fig. 7) are not without historical precedent.

Carbon Isotopes in Calcite

The relationship between the historical record of total early summer precipitation amount at Syracuse, New York, and the Fayetteville Green Lake box-core $\delta^{13}C_{calcite}$ values, as evaluated through linear regression analysis, is shown in Figure 8. The correlation coefficient (r) is -0.74 and indicates a strong, statistically significant ($p < 0.001$; $n = 74$) inverse relationship between early summer precipitation totals and carbon isotope values. This suggests that 55% of Fayetteville Green Lake $\delta^{13}C_{calcite}$ variability can be explained by changes in the amount of early summer precipitation. Periods of high early summer precipitation are characterized by relatively low $\delta^{13}C_{calcite}$ values, whereas periods of low early summer precipitation are associated with relatively high $\delta^{13}C_{calcite}$ values.

Spectral Analysis

Spectral analysis was performed only between ca. 14,600 and ca. 5030 cal. yr B.P. to avoid complications associated with the change in sampling interval. Both the Blackman-Tukey method (B-T) and maximum entropy method (MEM) (Paillard et al., 1996) demonstrate that multidecadal- to centennial-scale periodicities characterize the $\delta^{13}C_{calcite}$ time series (Fig. 9). By using the 95% confidence level as a cutoff for significant periodicities in the B-T results, combined with periods cross-correlated to the MEM analysis, we assign significance to the following periods in the $\delta^{13}C_{(calcite)}$ data: ~400, ~200, ~180, ~115, ~100, ~90, ~80, and ~65 yr (Fig. 9). The $\delta^{18}O_{(calcite)}$ data also exhibit multidecadal- to centennial-scale periodicities (Fig. 10). By using the same tests for significance as with the $\delta^{13}C_{calcite}$ data, only one period is assigned significance at the 95% confidence level in the $\delta^{18}O_{calcite}$ time series: ~63 yr. However, the presence of similar spectral peaks in both the B-T and MEM analyses at ~263, ~106, and ~87 yr for the $\delta^{18}O_{calcite}$ time series suggests that these latter periods may also be important. If so, similar periods exist for both oxygen and carbon isotopes at ~100, ~90, and ~60 yr (Figs. 9 and 10).

DISCUSSION

Relationship Between Winter-Vortex Latitude, Storm Tracks, and $\delta^{18}O_{calcite}$

Climatologically, storm tracks and precipitation are strongly related to winter-vortex size and shape (Namias, 1978; Whittaker and

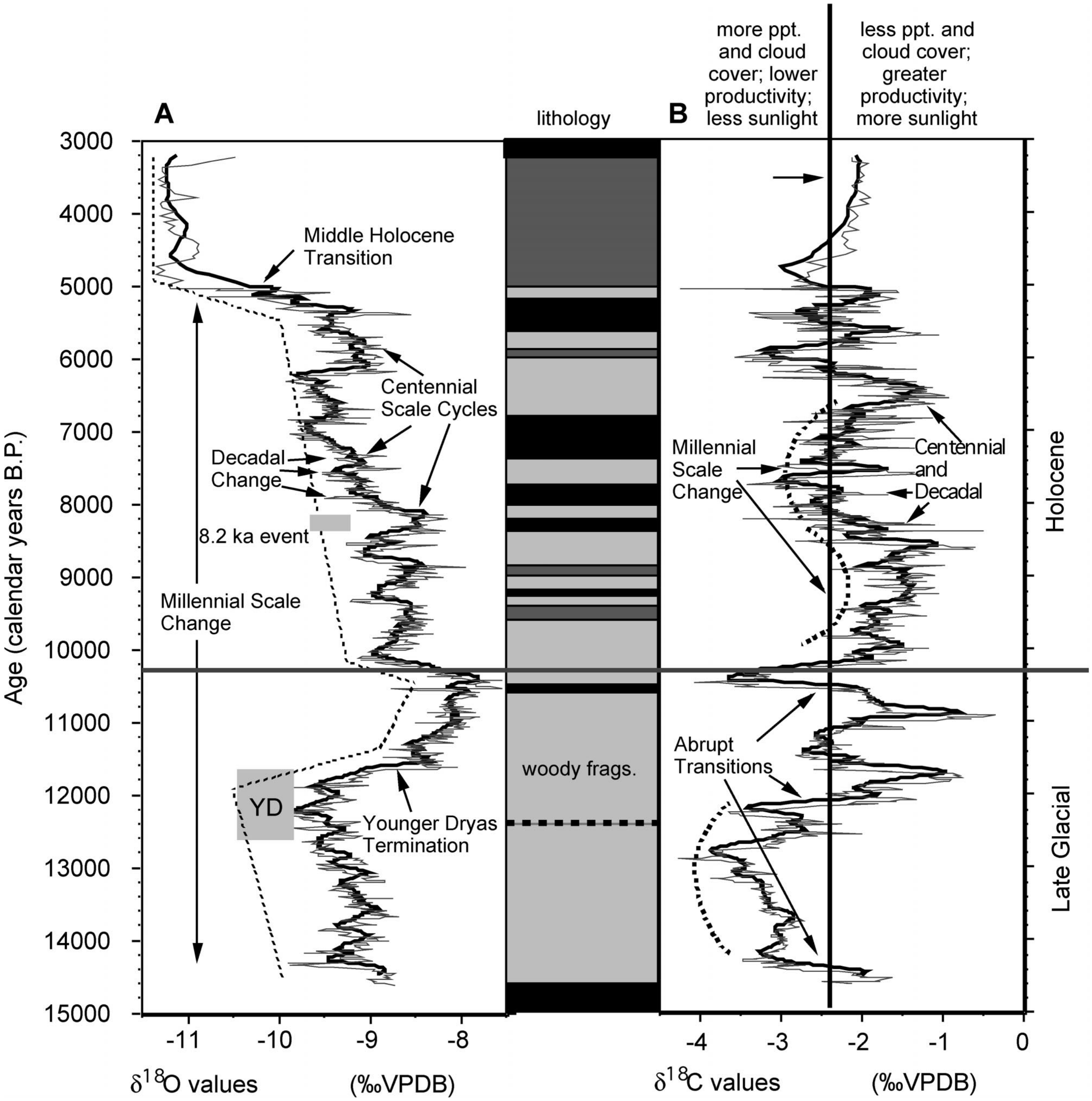

Figure 5. Isotope data with lithology for wetland core PCGL-1. (A) Stable oxygen isotope data. Dashed line draws attention to the first-order, asymmetric shape of the isotope curve. Isotope data discussed in text are labeled and shown by arrows (see text for complete listing). Notable climate events are also labeled: 8200 cal. yr B.P. cold event (Alley et al., 1997; Barber et al., 1999; von Grafenstein et al., 1999); Younger Dryas (YD) cold event (Broecker et al., 1989). (B) Stable carbon isotope data. Average value for length of record is shown as black line at −2.4‰. Amount of precipitation (ppt) and cloud cover is shown by positioning of isotope curves to left or right of the mean value (vertical bold line) for the period 14,600–3200 cal. yr B.P. (see labeling at top of graph B). For description of lithologies, see Figure 4. Thin black line—raw data; thick black line—10-point moving average.

Horn, 1984; Knappenberger and Michaels, 1993; Rodionov, 1994). Storms tracking from the southwest and southeast into the northeast United States are associated with expanded vortex geometries, higher humidity, and greater total precipitation because they derive their moisture from the Gulf of Mexico and/or subtropical Atlantic (Whittaker and Horn, 1984; Knappenberger and Michaels, 1993; Rodionov, 1994) (Fig. 11). Correlation analysis between historical winter-vortex latitudes and $\delta^{18}O_{calcite}$ (sampled from the lake box core) indicate that an expanded vortex (i.e., shifted to lower latitudes) is associated with the precipitation of calcite with relatively high $\delta^{18}O$ values, reflecting moisture sources with higher $\delta^{18}O_{source\ water}$ (Fig. 11). Conversely, storms tracking from the continental interior (cross-

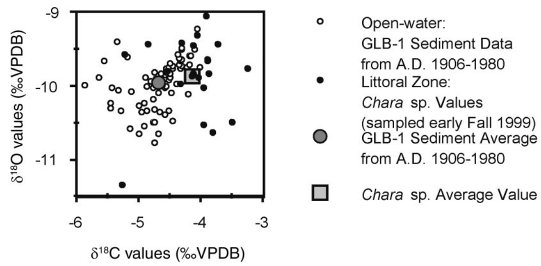

Figure 6. Comparison of littoral-zone calcite and open-water calcite isotope values.

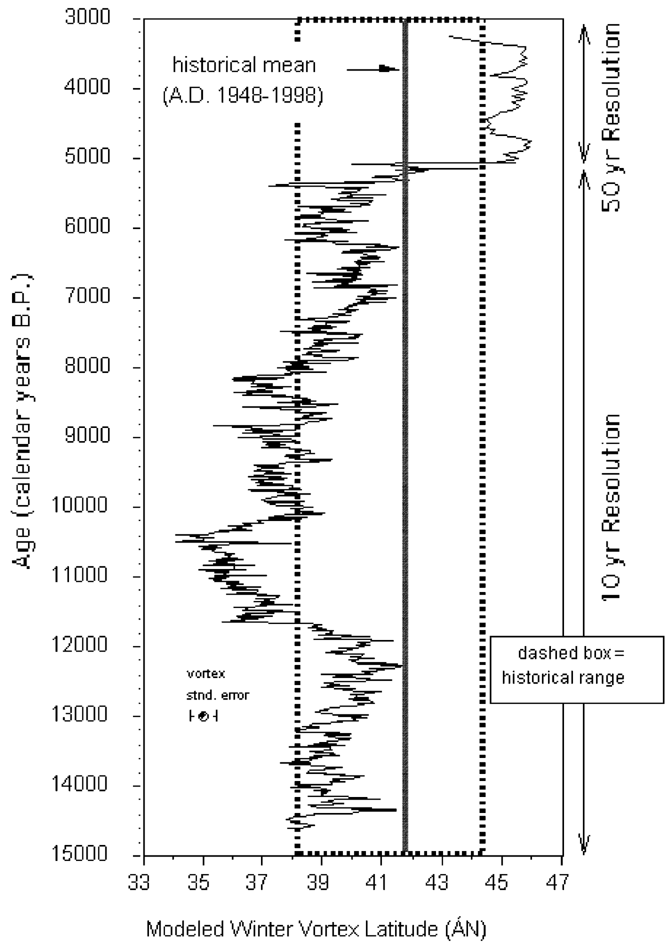

Figure 7. Modeled winter-vortex latitudes. Historical (A.D. 1948–1998) latitude range (dashed box) of the winter vortex is shown to illustrate the large latitudinal range of the winter vortex in comparison to modeled winter-vortex latitudes. Mean latitude position from A.D. 1948 to 1998 is shown by thick, solid line. Values to the left of the thick, solid line represent a vortex position that is expanded to the south; values to the right of the thick, solid line represent a contracted vortex position (i.e., shifted to the north), both relative to the twentieth-century mean value of lat 41.8°N.

continental storms) are associated with a contracted vortex (i.e., shifted to higher latitudes), lower humidity, and less total precipitation (Whittaker and Horn, 1984; Knappenberger and Michaels, 1993; Rodionov, 1994) (Fig. 11). Historical correlation analyses between winter-vortex latitudes and $\delta^{18}O_{calcite}$ indicate that a contracted vortex is associated with the precipitation of calcite with relatively low $\delta^{18}O$ values, reflecting moisture sources with relatively low $\delta^{18}O_{source\ water}$, such as from lake-effect snow that is common winter precipitation in the study region (Fig. 11) (Norton and Bolsenga, 1993). It is also likely that cross-continental storms are characterized by low $\delta^{18}O_{precipitation}$ because of the progressive distillation (i.e., removal) of ^{18}O from atmospheric moisture with increasing distance from the storms' predominantly Pacific Ocean source (Dansgaard, 1964; Rozanski et al., 1993).

Oxygen Isotope Record

Late Glacial–Holocene

Over millennia, the distribution of incoming solar radiation (insolation) at the Earth's surface is strongly related to variations in Earth-Sun orbital parameters (Imbrie and Imbrie, 1979). Together, complex gravitational interactions produce three orbital characteristics that change over well-defined periods: (1) eccentricity—the shape of the Earth's orbit relative to the Sun (ca. 100 ka), (2) obliquity—the degree of Earth's axial tilt (ca. 41 ka), and (3) precession of the equinoxes—the timing of Earth's solstice and equinox relative to the Sun during the Earth's orbital path (ca. 21 ka) (Berger, 1978; Imbrie and Imbrie, 1979). When the net radiative effects of these three orbital characteristics are combined, an insolation curve can be calculated (Berger, 1978). For example, the amount of winter insolation at northern midlatitudes (45°N) has progressively increased over the past 10,000 yr predominantly because of combined changes in the precession of the equinoxes and obliquity (Fig. 12A) (Berger, 1978; Kutzbach and Street-Perrott, 1985). In other words, Northern Hemisphere winters have become warmer over the course of the Holocene (if a linear relationship between long-term insolation change and Earth's climate is assumed).

Of the three orbital characteristics just listed, precession of the equinoxes has the largest radiative forcing potential (~40 W/m^2) by controlling the Earth-Sun distance as a function of season, particularly between 0° and 60° north and south latitude (Crowley and North, 1991). Over the past 12,000 cal. yr B.P., precession of the winter solstice has changed significantly from winter aphelion (the winter solstice occurring at the greatest Earth-Sun distance) at ca. 11,500 cal. yr B.P. to winter perihelion (the winter solstice occurring at the least Earth-Sun distance) at ca. 1500 cal. yr B.P. (Fig. 12B) (Crowley and North, 1991). This long-term change over the late glacial–Holocene has greatly altered seasonality (i.e., strength of seasonal thermal gradient) from cold winters and warm summers (i.e., increased seasonality) at 11,500 cal. yr B.P. to relatively warm winters and relatively cool

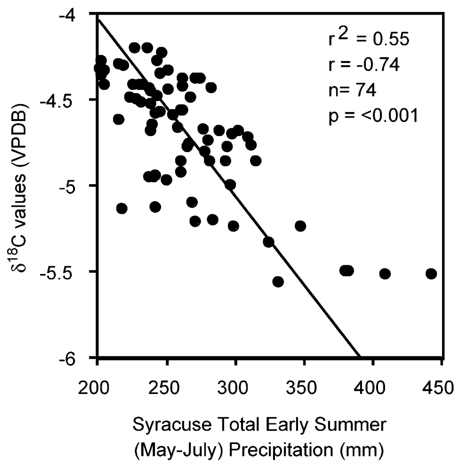

Figure 8. Correlation diagram between carbon isotope values from varves extracted from the Fayetteville Green Lake box core and the total early summer (May–July) precipitation amount at Syracuse, New York (A.D. 1906–1980).

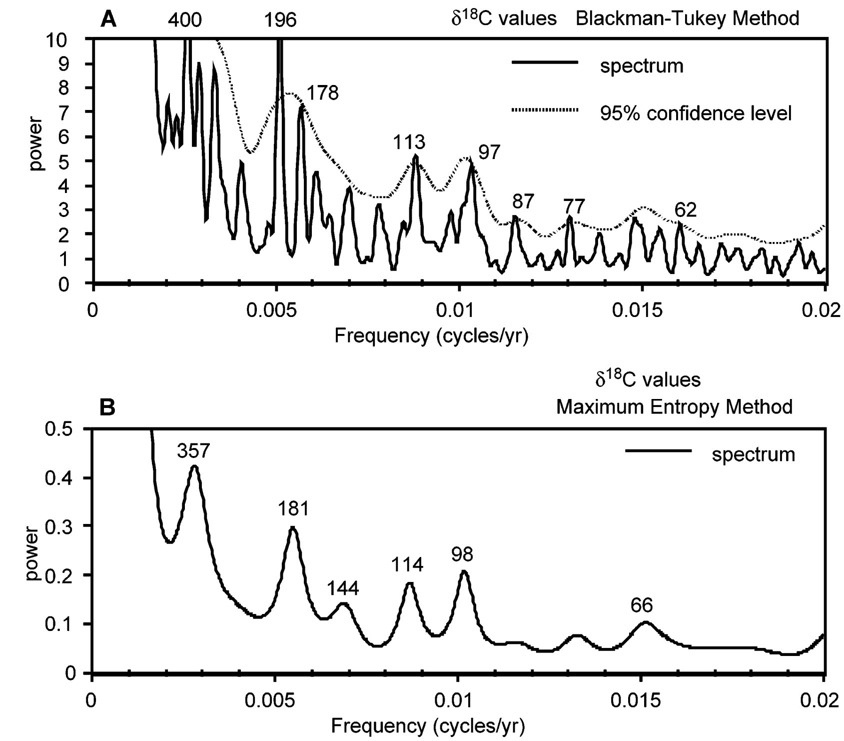

Figure 9. Carbon isotope spectral analysis for wetland core PCGL-1. (A) Blackman-Tukey method with 95% confidence level shown. Data prewhitened by 0.5 to reduce low-frequency spectral domination. Bandwidth for raw B-T analysis is 0.0015. (B) Maximum entropy method with a filter length consisting of 4.3% of series. By using data from both techniques, we assign significance to the following periods: ~400, ~200, ~180, ~115, ~100, and ~65 yr. Both analyses performed with AnalySeries 1.2 after Paillard et al. (1996).

summers (i.e., decreased seasonality) at 1500 cal. yr B.P. (Bradley, 1985). Despite the asymmetry of the oxygen isotope record (Fig. 5A), we hypothesize that millennia-scale change in insolation as controlled by precession of the equinoxes has played an important first-order role in midlatitude winter climate, particularly since 11,600 cal. yr B.P., as recorded by the $\delta^{18}O_{calcite}$ data at Fayetteville Green Lake (Fig. 12). Prior to 11,600 cal. yr B.P., the relative proximity of the Laurentide ice sheet likely played the dominant first-order role in midlatitude winter climate, thus diminishing the effect of insolation at this time. We attribute the late glacial to Holocene shift in dominant first-order climate-forcing mechanisms as the reason for the asymmetry in the $\delta^{18}O_{calcite}$ record (Fig. 5A).

The $\delta^{18}O_{calcite}$ data before 11,600 cal. yr B.P. are characterized by a gradual decrease from −9.0‰ to −9.7‰ (Fig. 5A). By applying the historically derived (A.D. 1948–1998) relationship between $\delta^{18}O_{calcite}$ and the winter-vortex latitude to the $\delta^{18}O_{calcite}$ data from the wetland core, we show a gradual northward contraction (by ~3° latitude or ~330 km) of the winter vortex over the northeast United States from 14,600 to 11,600 cal. yr B.P. (Fig. 7). We suggest that the gradual contraction of the vortex was forced by the progressive northward retreat of the Laurentide ice sheet's southern margin. As the ice sheet receded, the average winter position of the vortex would have approximately mirrored the ice-margin retreat, moving progressively northward. As a result, the relative contribution of low-$\delta^{18}O_{precipitation}$ cross-continental storms would have increased as the vortex position migrated north (Fig. 13A).

From 11,600 to 3200 cal. yr B.P., $\delta^{18}O_{calcite}$ data are characterized, on a first-order basis, by a gradual decrease in values from −8‰ to −11‰ (Fig. 5A). If we assume that the historically defined relationship between $\delta^{18}O_{calcite}$ and winter-vortex latitude extends through the Holocene, then our data show that the overall decrease in $\delta^{18}O_{calcite}$ values reflects a gradual northward contraction of the winter vortex over the northeast United States (Fig. 7).

This contraction of the winter vortex over the northeast United States was likely in direct response to the long-term winter-season warming caused by an increase in winter-season insolation (Fig. 12A). As previously mentioned, winter-season Earth-Sun distance decreased during the Holocene, consequently increasing the radiative potential of winter-season insolation. As winters warmed, the total area of cold, polar air within the boundaries of the circumpolar vortex would have decreased, pulling the average latitudinal position of the vortex northward (Fig. 13A). If we assume that the modern relationship between $\delta^{18}O_{calcite}$ and the winter-vortex position applied, the long-term trend in winter-vortex contraction would have increased the frequency of cross-continental storms characterized by both less total winter precipitation and relatively low $\delta^{18}O_{precipitation}$ values (Fig. 13A).

Abrupt Transitions

Younger Dryas Termination (ca. 11,600 cal. yr B.P.). Occurring in less than six decades (Alley et al., 1993), the Younger Dryas termination is characterized by an abrupt ~1.0‰ increase in $\delta^{18}O_{calcite}$ values (Fig. 5A). If we assume that the historically derived relationship between winter-vortex latitude and $\delta^{18}O_{calcite}$ applied, the change in $\delta^{18}O_{calcite}$ values at the Younger Dryas termination suggests a significant change in vortex size (~4° latitude or ~440 km), storm tracks, and $\delta^{18}O_{precipitation}$. As discussed at length by Kirby et al. (2002), the Younger Dryas termination, as recorded in the wetland core $\delta^{18}O_{calcite}$ at

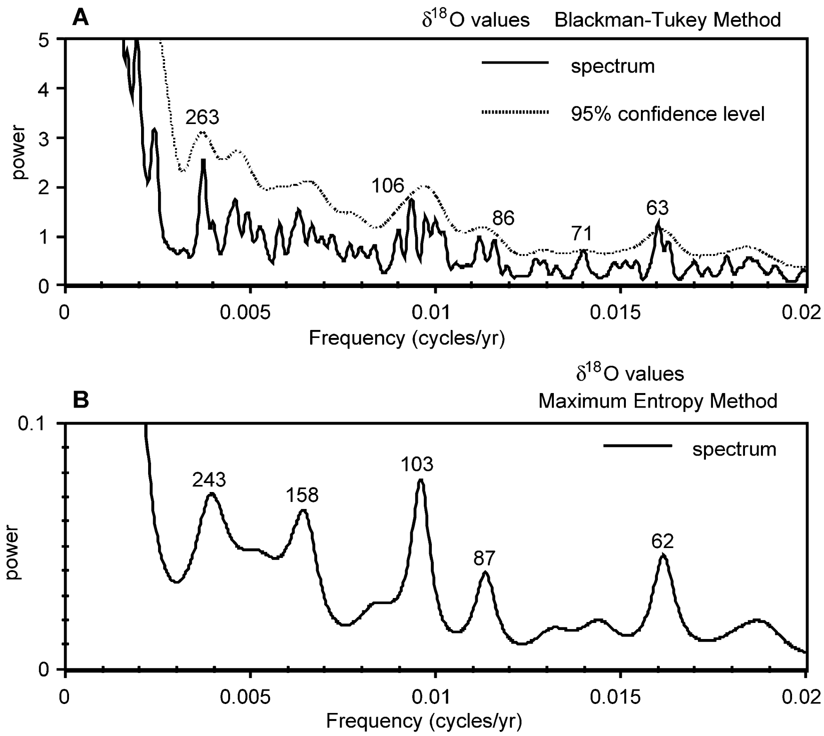

Figure 10. Oxygen isotope spectral analysis for wetland core PCGL-1. (A) Blackman-Tukey method with 95% confidence level shown. Data prewhitened by 0.5 to reduce low-frequency spectral domination. Bandwidth for raw B-T analysis is 0.0015. (B) Maximum entropy method with a filter length consisting of 4.3% of series. By using data from both techniques, we assign significance to the following periods: ~263(?), ~106, ~87(?), and ~63 yr. Both analyses performed with AnalySeries 1.2 after Paillard et al. (1996).

Fayetteville Green Lakes, likely represents a direct response to a sudden, intense period of poleward heat transport in the ocean following the end of the Younger Dryas cold event, forced by the renewal of vigorous thermohaline circulation (Boyle and Keigwin, 1987; Manabe and Stouffer, 1999). According to our $\delta^{18}O_{calcite}$ versus vortex relationship, the expanded vortex greatly increased the frequency of moisture-rich storms moving up the east coast of North America from southern sources with relatively high $\delta^{18}O_{precipitation}$ (Figs. 7 and 13B).

Middle Holocene Transition (ca. 5200 cal. yr B.P.). The second transition, referred to as the middle Holocene transition, occurred at ca. 5200 cal. yr B.P. The middle Holocene transition (Fig. 5A) is characterized by a modal shift in mean isotopic values from ~–9.5‰ to ~–11.0‰. There are several authors who have produced climate-proxy data and/or climate models indicating a similar large-scale climate transition at ca. 5200 cal. yr B.P. (Dwyer et al., 1996; Yu et al., 1997; Mullins, 1998; Thompson et al., 1998; Rodbell et al., 1999; Sandweiss et al., 1999; Steig, 1999; Mullins and Halfman, 2001), and some authors have proposed atmospheric circulation change as a potential cause of this transition (Yu et al., 1997; Ganopolski et al., 1998; Thompson et al., 1998; Claussen et al., 1999; Rodbell et al., 1999; Sandweiss et al., 1999; Steig, 1999; Mullins and Halfman, 2001).

By using the historical relationship we have defined between winter-vortex latitude and $\delta^{18}O_{calcite}$, we, too, suggest that significant changes in atmospheric circulation occurred at ca. 5200 cal. yr B.P. Such a change in atmospheric circulation may have caused a dramatic contraction of the winter vortex (to higher latitudes) and an increase in the frequency of cross-continental, moisture-poor, low-$\delta^{18}O_{precipitation}$ storms (Figs. 7 and 13C). Warmer winters forced by changes in precession of the equinoxes would have favored vortex contraction (Fig. 12). Furthermore, without the presence of the Laurentide ice sheet at this time, the vortex would have contracted to higher average latitudes than during the late glacial, such as during the Younger Dryas, when the Laurentide ice-sheet margin placed a constraint on how far north the vortex could move.

A decrease in winter-season total moisture through a contracted winter vortex is likely to have caused regional lake levels to decline. Associated with this transition in the wetland piston core PCGL-1 from Fayetteville Green Lake is a permanent lithologic change from deeper (marls) to shallower water (moss mats and peat) (Fig. 4). Similar lake-level declines are observed regionally at Owasco, Cayuga, and Canadaigua as in Wellner and Dwyer, 1996, Late Pleistocene–Holocene lake level fluctuations and paleoclimates at Canadaigua Lake. Lakes beginning at ca. 5200 cal. yr B.P. (Dwyer et al., 1996; Wellner and Dwyer, 1996; Mullins, 1998).

In addition to regional lake-level data, there are sundry other global and regional climate-proxy data supporting a large-scale climate transition at ca. 5200 cal. yr B.P. (i.e., middle Holocene). Yu et al. (1997) presented authigenic-marl isotope data from a small lake near Toronto, Canada, that show a dramatic lake-level decline and $\delta^{18}O_{calcite}$ decrease at ca. 5200 cal. yr B.P. These authors proposed that a change in atmospheric circulation and storm tracks forced the observed change in $\delta^{18}O_{calcite}$ (Yu et al., 1997). Mullins and Halfman (2001) present high-resolution seismic data from Owasco Lake, New York, that show evidence of erosion at water depths up to 26 m. Because a 26 m lake-level decrease at this time is unlikely, and not supported by regional data, these authors attributed this erosional surface to a fundamental change in atmospheric circulation that strengthened surface winds and water circulation (Mullins and Halfman, 2001). From the Midwestern United States (Iowa), Baker et al. (1998) presented pollen and $\delta^{13}C_{calcite}$ (from stalagmites) data that show a dramatic shift in dominant pollen assemblages (deciduous to prairie species) as well as a change to higher $\delta^{13}C$ values beginning at ca. 5500 cal. yr B.P. South American sedimentologic data from Ecuador over the past 15,000 cal. yr B.P. suggest a dramatic increase in clastic deposition attributed to the establishment of modern El Niño–Southern Oscillation (ENSO) conditions by the middle Holocene (Rodbell et al., 1999). It is possible that the large-scale climate shift related to atmospheric circulation at ca. 5200 cal. yr B.P. played a role in the initiation of modern ENSO conditions at this time (Rodbell et al., 1999; Sandweiss et al., 2001). Both Steig (1999) and Sandweiss et al. (1999) published short, summary papers documenting the global distribution of data supporting a middle Holocene climate transition as shown in a variety of climate-proxy data (e.g., isotopic, palynologic, sedimentologic, and cultural). Clearly, there is a consensus in the literature that a sig-

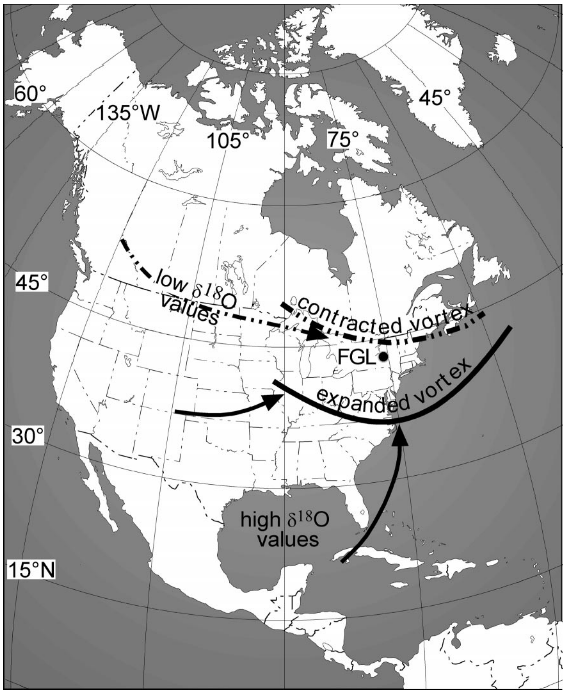

Figure 11. Map showing winter vortex with storm tracks and associated $\delta^{18}O_{precipitation}$ values. Map derived from relationship between historical oxygen isotope (i.e., $\delta^{18}O$) values in precipitation and winter vortex. Storm tracks for expanded and contracted vortexes are after Whittaker and Horn (1984).

nificant middle Holocene climate transition occurred involving large-scale changes in atmospheric circulation.

We suggest that changes in precession of the equinoxes constituted the dominant forcing mechanism that caused atmospheric circulation to change in the middle Holocene. A series of recent GCM (general circulation model) efforts investigating middle Holocene climate change have shown that subtle variations in insolation related to precession (i.e., strength of seasonal cycle) can produce significant climatological responses on a global scale (Ganopolski et al., 1998; Claussen et al., 1999; Kerwin et al., 1999). These climatological responses involve feedbacks among the biosphere, hydrosphere, and atmosphere (Ganopolski et al., 1998; Claussen et al., 1999; Kerwin et al., 1999). As shown by the historically derived relationship between winter-vortex latitude and $\delta^{18}O_{calcite}$, the winter vortex contracted significantly at 5200 cal. yr B.P., likely in response to this proposed precessional forcing (Fig. 7). The gradual transition to warmer winters would have reduced the southward penetration of cold polar air masses, thus placing the average position of the winter circumpolar vortex over the northeast United States at higher latitudes (Figs. 7 and 13C).

Multidecadal- to Centennial-Scale Variability

Spectral analysis of the oxygen isotope time series reveals periods at ~63, ~87, ~106, and ~263 yr (i.e., multidecadal to centennial) (Fig. 10). The spectral data previously discussed indicate that the multidecadal- to centennial-scale variability is periodic and thus is likely forced by a periodic climate-forcing mechanism. As a result, we can rule out known climate forcings that do not occur over multidecadal to centennial periodicities, such as volcanism, trace-gas variability, or random behavior (Crowley and Kim, 1993). We are, therefore, left with two possible multidecadal- to centennial-scale climate forcings—solar forcing and ocean-atmosphere linkages (Crowley and Kim, 1993). An analysis of the historical oxygen isotope record compared to known solar indices indicates that solar forcing is an unlikely candidate (Kirby et al., 2001). By using both GCMs and observational data, it has been shown that ocean-atmosphere linkages occur on a variety of decadal- to multidecadal-scale periods (i.e., ~21, ~27, ~35, ~50, ~65–70, ~88 yr) (Mysak et al., 1990; Delworth et al., 1993; Schlesinger and Ramankutty, 1994; Mann et al., 1995; Wohlleben and Weaver, 1995; Timmerman et al., 1998). At least two of the latter periods (~65–70 and ~88) are observed in the Fayetteville Green Lake oxygen isotope data. Although speculative, we propose that the observed multidecadal to centennial variability in the oxygen data likely reflect a periodic ocean-atmosphere forcing mechanism, perhaps involving a meltwater-feedback system related to thermohaline circulation (Mysak et al., 1990; Delworth et al., 1993; Wohlleben and Weaver, 1995; Timmerman et al., 1998).

Carbon Isotope Record

Lake Productivity—Precipitation and Cloud Cover

Aquatic primary productivity is influenced by a variety of factors including temperature, light, turbidity, length of thermal stratification, CO_2 concentration, pH, cloud cover, and nutrient supply (Wetzel, 1983). Because of the multiple variables influencing primary productivity, interpretation of $\delta^{13}C_{calcite}$ data from lacustrine environments can be quite complex. Thompson et al. (1997) examined $\delta^{13}C_{calcite}$ values in the Fayetteville Green Lake basin by using a combination of laboratory-cultured calcite and calcite collected from the lake-water column. $\delta^{13}C_{calcite}$ results of culture experiments indicate that *Synechococcus* sp. organisms, Fayetteville Green Lake's primary producers, preferentially incorporate ^{12}C during photosynthesis; the effect is a permanent fractionation of ~3‰–4‰ between the calcite precipitated around the bacteria's cell membrane and the carbon fixed in their body by photosynthesis *Synechococcus* sp. (Thompson et al., 1997). Thompson et al. (1997) also determined that the initial seasonal bloom of *Synechococcus* sp., on which the calcite precipitates, was strongly controlled by water temperature and light intensity.

To date, two basic models exist for interpreting $\delta^{13}C_{calcite}$ from lacustrine settings: (1) the McKenzie (1985) model, and (2) the Hollander and Smith (2001) model. The McKenzie (1985) model, developed for open-water lake conditions, states that increased primary productivity preferentially removes ^{12}C during photosynthesis, increasing dissolved inorganic $\delta^{13}C$ values and ultimately resulting in calcite with higher $\delta^{13}C$ values. The effect of this preferential removal of ^{12}C by photoautotrophs (i.e., primary producers) is enhanced during periods of high primary productivity (McKenzie, 1985). The Hollander and Smith (2001) model states that under conditions of extreme eutrophication, the contribution of ^{12}C to the carbon pool may increase through microbial processes (e.g., chemoau-

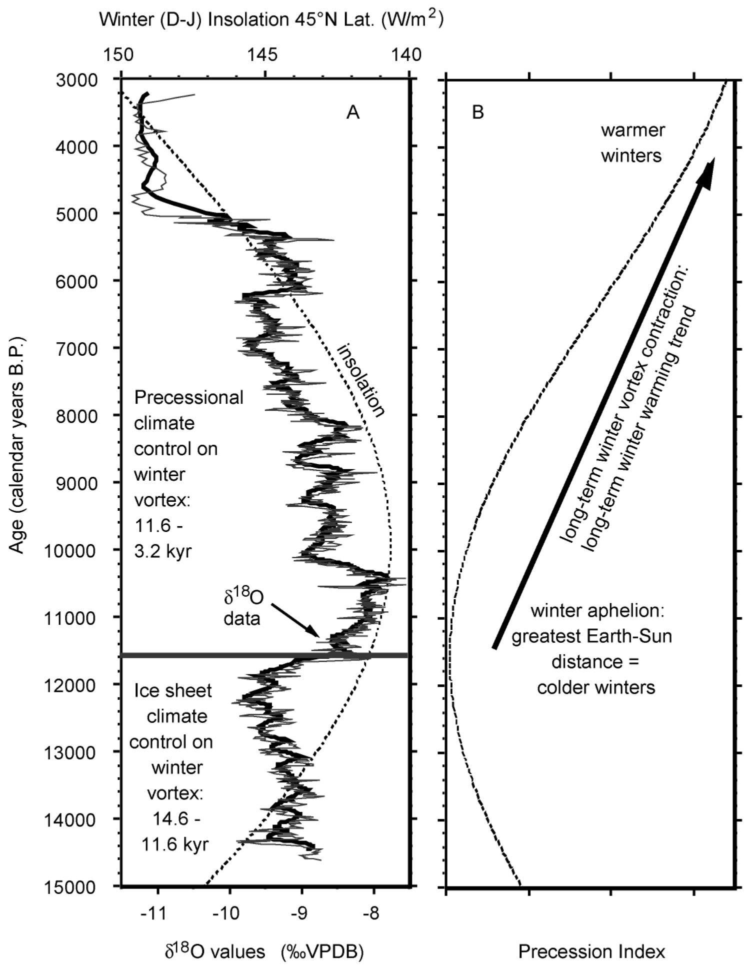

Figure 12. Oxygen isotopes, winter (December–January) insolation, and precession index from 15,000 to 3000 cal. yr B.P. (A) Comparison of oxygen isotope data and winter insolation at 45°N latitude (insolation data after Berger, 1978). Two first-order climate forcings discussed in text are labeled with respective intervals of dominance. Change from ice-sheet to precessional control occurs at ca. 11,600 cal. yr B.P. Thin gray line is raw oxygen isotope data; thick black line is oxygen isotope data smoothed by a 10-point moving average. (B) Precession of the equinoxes index showing the long-term change in Earth-Sun position during the late glacial–Holocene (Berger, 1978). Note the change from colder to warmer winters over the late-glacial to late Holocene during which the winter vortex contracts (Fig. 10).

totrophs and methanotrophs), resulting in calcite with low $\delta^{13}C$ values. The Hollander and Smith (2001) hypothesis is best suited for basins susceptible to severe seasonal eutrophication via intense nutrient loading.

Our piston core site, located in a wetland, represents neither the open-water conditions of the McKenzie (1985) model nor the eutrophic lake system of Hollander and Smith (2001). To best explain our carbon isotope record, we offer an alternative hypothesis based on a modern relationship observed between $\delta^{13}C_{calcite}$ and early summer (May–July) precipitation amount (Fig. 8). We observe an inverse relationship where greater amounts of early summer precipitation are associated with lower $\delta^{13}C_{calcite}$ values. Contrary to the traditional interpretation that links greater precipitation to higher primary productivity via enhanced drainage basin runoff and increased nutrient flux (Wetzel, 1983), we observe the opposite scenario; greater annual precipitation causes an apparent decrease in primary productivity (i.e., lower $\delta^{13}C_{calcite}$ values). This relationship appears to weaken at precipitation amounts of >300 mm where $\delta^{13}C_{calcite}$ values no longer change linearly; the reason for this plateau effect is unclear (Fig. 8). Fayetteville Green Lake, however, has a very small drainage basin (4.3 km^2) that significantly limits nutrient flux to the lake. As a result, Fayetteville Green Lake is oligotrophic. In other words, primary productivity in Fayetteville Green Lake is not reflecting nutrient flux into the lake, thus explaining the apparent contradiction with traditional precipitation-productivity models. In addition, *Synechococcus* sp. requires very low nutrient levels (Molot and Brown, 1986), thus supporting our contention that primary production in Fayetteville Green Lake is not controlled by nutrient flux. The modern relationship between $\delta^{13}C_{calcite}$ and early summer total precipitation supports this contention by indicating that increased precipitation does not cause a subsequent increase in primary productivity.

To explain the precipitation and $\delta^{13}C_{calcite}$ relationship, we invoke a precipitation-cloud feedback hypothesis. Precipitation of rain is the product of complex evaporation–dew point–condensation processes (Barry and Chorley, 1998). A significant part of this process is the formation of clouds from which the precipitation is derived. Because clouds have a very high albedo (reflective potential), more cloud cover means less sunlight penetration to the Earth's surface. Sunlight is essential to photoautotrophs such as *Synechococcus* sp., the major primary producer in Fayetteville Green Lake (Thompson et al., 1997). If sunlight availability is reduced, it follows that primary productivity will also be reduced. As a first-order forcing, we propose that primary productivity decreases during intervals of greater total precipitation because of increased cloud cover and reduced sunlight (Fig. 5B). Other side effects related to precipitation and cloud cover could reinforce the proposed reduction in primary productivity. For example, less sunlight will reduce the net radiative forcing of incoming solar radiation. In turn, a decrease in radiative forcing will cool lake-water temperatures, perhaps during the productivity season. As a result, lower temperatures will help to reduce primary productivity by lowering the metabolic rates of the primary producers (Wetzel, 1983). We do not observe, however, any significant relationship between $\delta^{13}C_{calcite}$ and surface-air temperature, a proxy for surface-water temperature. Lastly, greater early summer precipitation may enhance erosion and runoff from the surrounding drainage basin, causing a decrease in the depth of the photic zone via increased water turbidity, again inhibiting primary productivity. At present, we have no data to support or refute the influence of water turbidity on $\delta^{13}C_{calcite}$.

The carbon record is characterized by high-

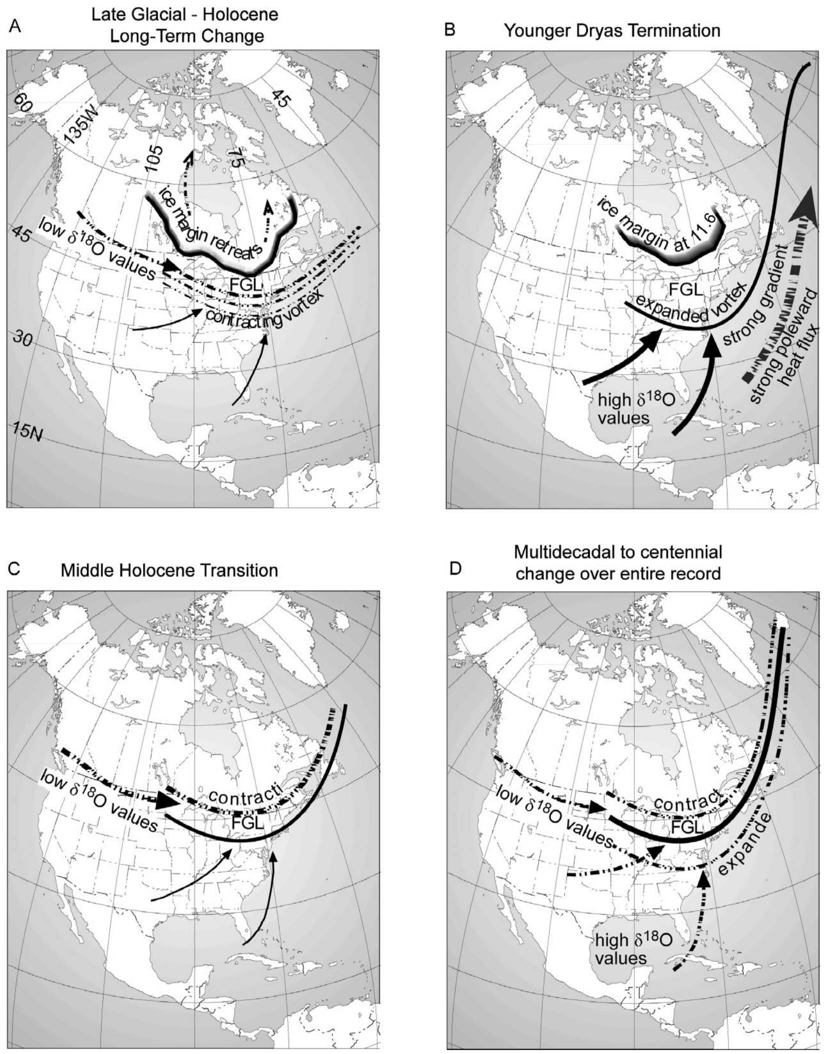

Figure 13. Winter circumpolar vortex and storm-track maps for oxygen isotope discussion. (A) Late Glacial–Holocene long-term change (ca. 12,000 to ca. 3000 cal. yr B.P.). Progressively thicker dashed lines represent the progressive northward migration of the winter vortex in response to retreat and eventual reduction of Laurentide ice sheet influence by 11,600 cal. yr B.P. (see text). Approximate ice-margin position at ca. 13,000 cal. yr B.P. is shown according to Lewis and Anderson (1989). Progressive winter-vortex contraction increases the contribution of low-$\delta^{18}O_{precipitation}$ cross-continental storms. (B) Younger Dryas termination (ca. 11,600 cal. yr B.P.). Period of intense poleward heat transport in the ocean following the renewal of vigorous thermohaline circulation favored an expanded vortex and the advection of moisture-rich, high-$\delta^{18}O_{precipitation}$ southern storms from 11,600 to 10,300 cal. yr B.P. (C) Middle Holocene transition (ca. 5200 cal. yr B.P.). Large-scale change in dominant climate mode caused a dramatic shift in storms' tracks to favor low-$\delta^{18}O_{precipitation}$ cross-continental patterns. (D) Multidecadal- to centennial-scale change. Dashed lines represent the range of winter-vortex variability associated with multidecadal- to centennial-scale ocean-atmosphere linkages as discussed in text. Solid black line represents the mean historical position of the winter vortex about which the winter vortex fluctuates (Yarnal and Leathers, 1988). Note: Approximate thickness of winter-vortex line denotes relative importance of storm track (e.g., thicker = greater influence). Only map A shows latitude/longitude information. FGL—Fayetteville Green Lake.

ly variable $\delta^{13}C_{calcite}$ values that fluctuate around a mean value of −2.4‰ that we have plotted as a vertical line in Figure 5B. By using the historically derived relationship that we have shown between $\delta^{13}C_{calcite}$ and early summer precipitation (i.e., cloud cover), we can divide the carbon isotope record into (1) periods of high productivity and lower early summer precipitation amount, and (2) periods of low productivity and higher early summer precipitation amount, as a first-order interpretation (Fig. 5B).

As shown by Figure 5B, some of the $\delta^{13}C_{calcite}$ changes are quite abrupt (<20–50 yr). Abrupt changes in $\delta^{13}C_{calcite}$ suggest that the wetland environment of Fayetteville Green Lake responded quickly to the climate forcing with minimal lag time between the forcing and the effect. Figure 5B also shows that several millennial-scale intervals of gradual, cyclical change in $\delta^{13}C_{calcite}$ occurred. For example, the millennial-scale interval between 10,300 and 8200 cal. yr B.P. may have been characterized by relative decreases in precipitation and cloud cover and an associated increase in primary productivity (Fig. 5B). It is interesting that this interval corresponds to the early part of the regionally identified Holocene Hypsithermal, a period when summer average temperatures were 2–3 °C higher than today (e.g., Pielou, 1991; Mullins, 1998). It is possible that this interval of low cloud cover and high productivity reflects ''optimum'' climate conditions of the Holocene Hypsithermal during which productivity increased.

Spectral analysis of the carbon record indicates periods at ~65, ~100, ~115, ~180, ~200, and ~400 yr (Fig. 9). On the basis of historical analysis, solar forcing of carbon isotopes at Fayetteville Green Lake is not apparent (Kirby et al., 2001), despite the fact that our spectral data show several peaks within the solar-forcing spectral domain (Stuiver et al., 1995). As discussed in the oxygen isotope section on multi-decadal to centennial scale variability, it is more likely that the multidecadal-scale variability in the $\delta^{13}C_{calcite}$ record is related to ocean-atmosphere linkages of the climate system that cause regional climate change, particularly climate change manifested through the atmosphere and its affect on precipitation.

CONCLUSIONS

Our study uses historically calibrated isotope (oxygen and carbon) records to define and interpret a continental, late glacial–Holocene (14,600–3200 cal. yr B.P.) isotope data set. From our analysis, we derive eight significant conclusions:

1. Gradual retreat of the Laurentide ice sheet's southern margin forced the winter vortex to contract northward from 14,600 and 11,600 cal. yr B.P., during which an increase in low-$\delta^{18}O_{precipitation}$ cross-continental storms occurred.

2. Millennial-scale change in insolation (i.e., due to precession of the equinoxes) from 11,600 to 3200 cal. yr B.P. caused a gradual winter warming and northward vortex contraction over the course of the late glacial–Holocene, as recorded by $\delta^{18}O_{calcite}$ values.

3. The Younger Dryas termination ($<$60 yr in duration) at ca. 11,600 cal. yr B.P. was forced by the sudden renewal of thermohaline circulation; this change caused an expansion southward of the winter vortex that lasted for ~1300 yr (i.e., post–Younger Dryas climate interval; Kirby et al., 2002).

4. The middle Holocene transition ($<$260 yr) at 5200 cal. yr B.P. was forced by insolation change related to the strength of seasonal contrast (i.e., precession of the equinoxes) and caused a rapid contraction of the northeast United States winter vortex as atmospheric circulation reorganized.

5. Multidecadal- to centennial-scale climate variability as recorded in $\delta^{18}O_{calcite}$ was forced by ocean-atmosphere linkages related to modulation of thermohaline circulation that caused contraction-expansion-contraction cycles of the winter-vortex position over a variety of time scales.

6. A historical relationship between $\delta^{13}C_{calcite}$ and early summer precipitation amount is used to develop a precipitation and cloud-cover proxy wherein an increase in early summer precipitation amount (i.e., increased cloud cover and reduced sunlight availability) reduces primary productivity, and vice versa.

7. Spectral analysis shows that multidecadal- to centennial-scale variability characterizes both $\delta^{18}O_{calcite}$ and $\delta^{13}C_{calcite}$ records for the length of the studied records.

ACKNOWLEDGMENTS

The funding to pursue this research was provided by Syracuse University Graduate School, Sigma Xi, and the Geological Society of America. We especially thank C. Callinan and B. Garabedian of the New York State Department of Environmental Conservation for box-core collection at Fayetteville Green Lake; Jesse Coburn and Martin Hilfinger for wetland piston-core collection; Green Lakes State Park Staff, especially John Livingston, for allowing access to field sites; and, M. Tomljanovich (Colgate University) for help with time-series analysis. Thorough and thoughtful reviews by Lynn Soreghan, Michael Engel, and Michael Soreghan greatly improved this manuscript's clarity.

REFERENCES CITED

Alley, R.B., Meese, D.A., Shuman, C.A., Gow, A.J., Taylor, K.C., Grootes, P.M., White, J.W.C., Ram, M., Waddington, E.D., Mayewski, P.A., Zielinski, G.A., 1993, Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event: Nature, v. 362, p. 527–529.

Alley, R.B., Mayewski, P.A., Sowers, T., Stuiver, M., Taylor, K.C., and Clark, P.U., 1997, Holocene climatic instability: A prominent, widespread event 8200 yr ago: Geology, v. 25, p. 483–486.

Arthur, M.A., Anderson, T.F., Kaplan, I.R., Veizer, J., and Land, L.S., 1983, Stable isotopes in sedimentary geology: Society of Economic Paleontologists and Mineralogists Short Course 10, 139 p.

Baker, R.G., Gonzalez, L.A., Raymo, M., Bettis, E.A., III, Reagan, M.K., and Dorale, J.A., 1998, Comparison of multiple proxy records of Holocene environments in the Midwestern United States: Geology, v. 26, p. 1131–1134.

Balling, R.C., and Lawson, M.P., 1982, Twentieth century changes in winter climatic regions: Climatic Change, v. 4, p. 57–69.

Barber, D.C., Dyke, A., Hillaire-Marcel, C., Jennings, A.E., Andrews, J.T., Kerwin, M.W., Bilodeau, G., McNeely, R., Southon, J., Morehead, M.D., Gagnon, J.M., 1999, Forcing of the cold event of 8200 yr ago by catastrophic drainage of Laurentide lakes: Nature, v. 400, p. 344–348.

Barry, R.G., and Chorley, R.J., 1998, Atmosphere, weather, and climate: New York, Routledge, 409 p.

Berger, A., 1978, Long-term variations of daily insolation and Quaternary climatic change: Journal of the Atmospheric Sciences, v. 35, p. 2362–2367.

Boyle, E.A., and Keigwin, L., 1987, North Atlantic thermohaline circulation during the past 20,000 yr linked to high-latitude surface temperature: Nature, v. 330, p. 35–40.

Bradley, R.S., 1985, Paleoclimatology: Reconstructing climates of the Quaternary: San Diego, California, International Geophysics Series, Academic Press, v. 64, 613 p.

Broecker, W.S., and Denton, G.H., 1989, The role of ocean-atmosphere reorganizations in glacial cycles: Geochimica et Cosmochimica Acta, v. 53, p. 2465–2501.

Broecker, W.S., Kennett, J.P., Flower, B.P., Teller, J.T., Trumbore, S., Bonani, G., and Wolfli, W., 1989, Routing of meltwater from the Laurentide ice sheet during the Younger Dryas cold episode: Nature, v. 341, p. 318–321.

Burnett, A.W., 1993, Size variations and long-wave circulation within the January Northern Hemisphere circumpolar vortex: Journal of Climate, v. 6, p. 1914–1920.

Claussen, M., Kubatzki, C., Brovkin, V., and Ganopolski, A., 1999, Simulation of an abrupt change in Saharan vegetation in the mid-Holocene: Geophysical Research Letters, v. 26, p. 2037–2040.

Crowley, T.J., and Kim, K-Y., 1993, Toward development of a strategy for determining the origin of decadal-centennial scale climate variability: Quaternary Science Reviews, v. 12, p. 375–385.

Crowley, T.J., and North, G.R., 1991, Paleoclimatology: New York, Oxford University Press, p. 339.

Dansgaard, W., 1964, Stable isotopes in precipitation: Tellus, v. 16, p. 436–468.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahljensen, D., Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjornsdottir, A.E., Jouzel, J., Bond, G., 1993, Evidence for general instability of past climate from a 250-kyr ice-core record: Nature, v. 364, p. 218–220.

Dean, W.E., 1974, Determination of carbonate and organic matter in calcareous sedimentary rocks by loss on ignition: Comparison with other methods: Journal of Sedimentary Petrology, v. 44, p. 242–248.

Delworth, T., Manabe, S., and Stouffer, R.J., 1993, Interdecadal variations of the thermohaline circulation in a coupled ocean-atmosphere model: Journal of Climate, v. 6, p. 1993–2011.

Denton, G.H., and Karlén, W., 1973, Holocene climate variations—Their pattern and possible causes: Quaternary Research, v. 3, p. 155–205.

Dwyer, T.R., Mullins, H.T., and Good, S.C., 1996, Paleoclimatic implications of Holocene lake-level fluctuations, Owasco Lake, New York: Geology, v. 24, p. 519–522.

Ganopolski, A., Kubatzki, C., Claussen, M., Brovkin, V., and Petoukhov, V., 1998, The influence of vegetation-atmosphere-ocean interaction on climate during the mid-Holocene: Science, v. 280, p. 1916–1919.

Harman, J.R., 1991, Synoptic climatology of the westerlies: Process and patterns: Washington, D.C., Association of American Geographers, 75 p.

Hilfinger, M.F., IV, and Mullins, H.T., 1997, Geology, limnology, and paleoclimatology of Green Lakes State Park, New York, *in* Raynes, T.W., et al., eds., 69th Annual New York State Geological Association Field Trip Guide: Clinton, New York, Hamilton College, p. 127–159.

Hilfinger, M.F., IV, Mullins, H.T., Burnett, A., and Kirby, M.E., 2001, A 2500 year sediment record from Fayetteville Green Lake, New York: Evidence for anthropogenic impacts and historic isotope shift: Journal of Paleolimnology, v. 26, p. 293–305.

Hollander, D.J., and Smith, M.A., 2001, Microbially mediated carbon cycling as a control on the $\delta^{13}C$ of sedimentary carbon in eutrophic Lake Mendota (USA): New models for interpreting isotopic excursions in the sedimentary record: Geochimica et Cosmochimica Acta, v. 65, p. 4321–4337.

Imbrie, J., and Imbrie, K.P., 1979, Ice ages, solving the mystery: Cambridge, Harvard University Press, 224 p.

IPCC Working Group, 2001, Intergovernmental Panel on Climate Change, summary for policy makers: Geneva, Switzerland, World Meteorological Organisation and United Nations Environmental Programme, http://www.ipcc.ch, last accessed on 18 June 2002.

Kerwin, M.W., Overpeck, J.T., Webb, R.S., DeVernal, A., Rind, D.H., and Healy, R.J., 1999, The role of oceanic forcing in mid-Holocene Northern Hemispheric climatic change: Paleoceanography, v. 14, p. 200–210.

Kim, S-T., and O'Neil, J.R., 1997, Equilibrium and nonequilibrium oxygen isotope effects in synthetic carbonates: Geochimica et Cosmochimica Acta, v. 61, p. 3461–3475.

Kirby, M.E., Mullins, H.T., Patterson, W.P., and Burnett, A.W., 2001, Lacustrine isotopic evidence for multidecadal natural climate variability related to the circumpolar vortex over the northeast USA during the past millennium: Geology, v. 9, p. 807–810.

Kirby, M.E., Patterson, W.P., Mullins, H.T., and Burnett, A.W., 2002, Post-Younger Dryas climate interval linked to circumpolar vortex variability: Evidence from Fayetteville Green Lake, New York: Climate Dynamics (in press), DOI 10.107/s00382-002-0227-y, published online 29 March 2002.

Knappenberger, P.C., and Michaels, P.J., 1993, Cyclone tracks and wintertime climate in the mid-Atlantic region of the USA: International Journal of Climatology, v. 13, p. 509–531.

Kutzbach, J.E., and Street-Perrott, F.A., 1985, Milankovitch forcing of fluctuation in the level of tropical lakes from 18 to 0 kyr BP: Nature, v. 317, p. 130–134.

Lewis, C.F.M., and Anderson, T.W., 1989, Oscillations of levels and cool phases of the Laurentian Great Lakes caused by inflows from Glacial Lakes Agassiz and Barlow-Ojibway: Journal of Paleolimnology, v. 2, p. 99–146.

Ludlam, S., 1969, Fayetteville Green Lake, New York: III. The laminated sediments: Limnology and Oceanography, v. 14, p. 848–857.

Manabe, S., and Stouffer, R.J., 1999, The role of thermohaline circulation in climate: Tellus, v. 51, A-B, p. 91–109.

Mann, M.E., Park, J., and Bradley, R.S., 1995, Global interdecadal and century-scale climate oscillations during the past five centuries: Nature, v. 378, p. 266–270.

McKenzie, J.A., 1985, Carbon isotopes and productivity in the lacustrine and marine environment, *in* Stumm, W., ed., Chemical processes in lakes: New York, John Wiley and Sons, p. 99–118.

Michel, R.L., and Kraemer, T.F., 1995, Use of isotopic data to estimate water residence times of the Finger Lakes, New York: Journal of Hydrology, v. 164, p. 1–18.

Molot, L.A., and Brown, E.J., 1986, Method for determining the temporal response of microbial phosphate transport affinity: Applied and Environmental Microbiology, v. 51, p. 524–531.

Muller, E.H., 1967, Geologic setting of Green and Round Lakes near Fayetteville, New York, *in* Jackson, D.F., ed., Some aspects of meromixis: Syracuse, New York, Syracuse University, Department Civil Engineering, p. 96–121.

Muller, R.A., and MacDonald, G.J., 2000, Ice ages and astronomical causes: Data, spectral analysis, and mechanisms: Chichester, UK, Praxis Publishing, p. 47–105.

Mullins, H.T., 1998, Holocene lake level and climate change inferred from marl stratigraphy of the Cayuga Lake Basin, New York: Journal of Sedimentary Research, v. 68, p. 569–578.

Mullins, H.T., and Halfman, J.D., 2001, High-resolution seismic reflection evidence for middle Holocene environmental change, Owasco Lake, New York: Quaternary Research, v. 55, p. 322–33.

Mysak, L.A., Manak, D.K., and Marsden, R.F., 1990, Sea-ice anomalies observed in the Greenland and Labrador Seas during 1901–1984 and their relation to an interdecadal Arctic climate cycle: Climate Dynamics, v. 5, p. 111–133.

Namias, J., 1978, Multiple causes of the North American abnormal winter 1976–77: Monthly Weather Review, v. 106, p. 279–295.

Norton, D.C., and Bolsenga, S.J., 1993, Spatiotemporal trends in lake effect and continental snowfall in the Laurentian Great Lake, 1951–1980: Journal of Climate, v. 6, p. 1943–1956.

O'Brien, S.R., Mayweski, P.A., Meeker, L.D., Meese, D.A., Twickler, M.S., and Whitlow, S.I., 1995, Complexity of Holocene climate as reconstructed from a Greenland ice core: Science, v. 270, p. 1962–1964.

Paillard, D.L., Labeyrie, L., and Yiou, P., 1996, Macintosh program performs time-series analysis: Eos (Transactions, American Geophysical Union), v. 77, p. 379.

Pielou, E.C., 1991, After the ice ages: Chicago, University of Chicago Press, p. 366.

Rodbell, D.T., Seltzer, G.O., Anderson, D.M., Abbott, M.B., Enfield, D.B., and Newman, J.H., 1999, An ~15,000-year record of El Nino–driven alluviation in southwestern Ecuador: Science, v. 283, p. 516–520.

Rodionov, S.N., 1994, Association between winter precipitation and water level fluctuations in the Great Lakes and atmospheric circulation patterns: Journal of Climate, v. 7, p. 1693–1706.

Rozanski, K., Araguas-Araguas, L., and Gonfiantini, R., 1993, Isotopic patterns in modern global precipitation: American Geophysical Union Monograph, Climate change in continental isotopic records, v. 78, p. 1–36.

Sandweiss, D.H., Maasch, K.A., and Anderson, D.G., 1999, Transitions in the mid-Holocene: Science, v. 283, p. 499–500.

Sandweiss, D.H., Maasch, K.A., Burger, R.L., Richardson J.B., III, Rollins, H.B., and Clement, A., 2001, Variation in Holocene El Niño frequencies: Climate records and cultural consequences in ancient Peru: Geology, v. 7, p. 603–606.

Schlesinger, M.E., and Ramankutty, N., 1994, An oscillation in the global climate system of period 65–70 yr: Nature, v. 367, p. 723–726.

Steig, E., 1999, Mid-Holocene climate change: Science, v. 286, p. 1485–1487.

Stuiver, M., and Reimer, P.J., 1993, Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program: Radiocarbon, v. 35, p. 215–230.

Stuiver, M., Grootes, P.M., and Braziunas, T.F., 1995, The GISP2 $\delta^{18}O$ climate record of the past 16,500 yr and the role of the Sun, ocean, and volcanoes: Quaternary Research, v. 44, p. 341–354.

Takahashi, T., Broecker, W., Li, Y.H., and Thurber, D., 1968, Chemical and isotopic balances for a meromictic lake: Limnology and Oceanography, v. 13, p. 272–292.

Thompson, J.T., Ferris, F.G., and Smith, D.A., 1990, Geomicrobiology and sedimentology of the mixolimnion and chemocline in Fayetteville Green Lake, New York: Palaois, v. 5, p. 52–75.

Thompson, J.B., Schultze-Lam, S., Beveridge, T.J., and Des Marais, D.J., 1997, Whiting events: Biogenic origin because of the photosynthetic activity of cyanobacterial picoplankton: Limnology and Oceanography, v. 42, p. 133–141.

Thompson, L.G., Davis, M.E., Mosley-Thompson, E., Sowers, T.A., Henderson, K.A., Zagorodnov, V.S., Lin, P.N., Mikhalenko, V.N., Campen, R.K., Bolzan, J.F., Cole-Dai, J., Francou, B., 1998, A 25,000-year tropical climate history from Bolivian ice cores: Science, v. 282, p. 1858–1864.

Timmerman, A., Latif, M., Voss, R., and Grotzner, A., 1998, Northern hemispheric interdecadal variability: A coupled air-sea mode: Journal of Climate, v. 11, p. 1906–1931.

Turano, V.S., and Rand, M.C., 1967, Some chemical observations on Fayetteville Green Lake, New York, *in* Jackson, D.F., ed., Some aspects of meromixis: Syracuse, New York, Syracuse University, Department of Civil Engineering, p. 152–187.

Vanuxem, L., 1839, Third annual report of the geological survey of the third district: Documents of the Assembly of the State of New York, 62nd Session, v. 5, p. 241–285.

von Grafenstein, U., Erlenkeuser, H., Brauer, A., Jouzel, J., and Johnsen, S.J., 1999, A mid-European decadal isotope-climate record from 15,500 to 5000 yr B.P.: Science, v. 284, p. 1654–1657.

Wellner, R.W., and Dwyer, T.R., 1996, Late Pleistocene–Holocene lake level fluctuations and paleoclimates at Canadaigua Lake, New York, *in* Mullins, H.T., and Eyles, N., eds., Subsurface geologic investigations of New York Finger Lakes: Implications for late Quaternary deglaciation and environmental change: Geological Society of America, Special Paper 311, p. 65–75.

Wendland, W.M., and Bryson, R.A., 1974, Dating climatic episodes of the Holocene: Quaternary Research, v. 4, p. 9–24.

Wetzel, R.G., 1983, Limnology: New York, Saunders College Publishing, 767 p.

Whittaker, L.M., and Horn, L.H., 1984, Northern Hemisphere extratropical cyclone activity for four midseason months: Journal of Climatology, v. 4, p. 297–310.

Wohlleben, T.M.H., and Weaver, A.J., 1995, Interdecadal climate variability in the subpolar North Atlantic: Climate Dynamics, v. 11, p. 459–467.

Yarnal, B., and Leathers, D.J., 1988, Relationships between interdecadal and interannual climatic variations and their effect on Pennsylvania climate: Annals of the Association of American Geographers, v. 78, p. 624–641.

Yu, Z., McAndrews, J.H., and Eicher, U., 1997, Middle-Holocene dry climate caused by changes in atmospheric circulation patterns: Evidence from lake levels and stable isotopes: Geology, v. 25, p. 251–254.

Manuscript Received by the Society 16 July 2001
Revised Manuscript Received 19 February 2002
Manuscript Accepted 9 April 2002

Printed in the USA