Climate Dynamics (2002) 19: 321–330
DOI 10.1007/s00382-002-0227-y

M.E. Kirby · W.P. Patterson · H.T. Mullins
A.W. Burnett

Post-Younger Dryas climate interval linked to circumpolar vortex variability: isotopic evidence from Fayetteville Green Lake, New York

Received: 19 February 2001 / Accepted: 4 January 2002 / Published online: 29 March 2002

Abstract The late-Glacial/Holocene transition in the North Atlantic-European sectors has long been known to be a period of rapid climate change. There is, however, a continued need for acquiring and developing paleoclimate archives spanning this interval from continental settings. Here we report on a lacustrine (Fayetteville Green Lake) isotope record sampled at a 10-year resolution from the NE USA over the late-Glacial/Holocene interval (14,600–8000 cal year BP). Based on prior isotopic and hydrologic research from Green Lake, the $\delta^{18}O_{(calcite)}$ values predominantly reflect winter moisture source and thus winter atmospheric patterns. Furthermore, we use historic (AD 1948–1980) winter circulation data and $\delta^{18}O_{(calcite)}$ values from varved sediments to examine the relationship between the circumpolar vortex latitude and isotopes which results in a strong ($r = -0.79$; $r^2 = 0.63$) negative relationship. Using the linear regression from the isotope-vortex relationship, we model the winter vortex latitude for the late-Glacial/Holocene transition over the NE USA. In addition, we identify an interval from 11,600 to 10,300 cal year BP (the post-Younger Dryas climate interval) wherein the mean winter vortex over the NE USA was expanded by ~6° latitude (~36.1°N; i.e., ~630 km) from its mean historic position between AD 1948–1998 (~41.8°N). Renewal of more vigorous thermohaline circulation following the Younger Dryas cold event may have forced the post-Younger Dryas climate interval. Increased poleward heat transport due to an active oceanic conveyor would have strengthened the thermal contrast between the NE USA and the North Atlantic thereby enhancing atmospheric pressure gradients and firmly establishing the semi-permanent winter trough over the NE USA. Consequently, storms tracked more frequently up the east coast of the United States from the Gulf of Mexico and Atlantic regions delivering precipitation with relatively high $\delta^{18}O$ values to the NE USA. Alternatively, the relative dominance of seasonal precipitation may have changed resulting in less total winter precipitation (low $\delta^{18}O$) causing lake waters to become relatively enriched in high $\delta^{18}O$ summer precipitation. Both hypotheses are good candidates for testing by global circulation modeling (GCM). The termination of the post-YD interval at 10,300 cal year BP and the beginning of the Holocene was likely forced by a gradual decrease in thermohaline circulation and poleward heat transport as freshwater input from melting of high-latitude ice sheets increased.

1 Introduction

The transition from full glacial to interglacial conditions was a period of climatic instability (Denton and Karlén 1977; O'Brien et al. 1995; Stuiver et al. 1995; Bond et al. 1997; Yu et al. 1997; Mullins 1998; Campbell et al. 1998). Although improving, there is a relative dearth of decadal to centennial-scale, continental, late-Glacial/Holocene paleoclimate archives. Here we present a lacustrine sediment record of oxygen isotope variability sampled at 10-year resolution from ~14,600 to ~8000 calendar years BP (hereafter cal yrs BP, all radiocarbon dates converted to calendar years before present using Calib 3.0; Stuiver and Reimer 1993). These data document the first NE USA record of the late-Glacial/Holocene climate transition at decadal resolution. Variable

---

M.E. Kirby (✉) · W.P. Patterson · H.T. Mullins
Department of Earth Sciences,
Heroy Geology Laboratory,
Syracuse University, Syracuse, New York 13244, USA
E-mail: kirby@earth.usc.edu

A.W. Burnett
Department of Geography,
Colgate University, Hamilton,
New York 13346, USA

M.E. Kirby
Now at: University of Southern California,
Department of Earth Sciences,
Los Angeles, CA 90089-0740, USA

climate modes characterize the entire isotope record highlighted by an abrupt (< 60 years), long-lived (> 1300 years) climate interval between ~11,600–10,300 cal yrs BP, hereafter, termed the post-Younger Dryas (post-YD) climate interval. Because the isotope data record atmospheric circulation processes, which are not easily related to specific temperatures, we define the post-Younger Dryas climate interval as a period characterized by its anomalous $\delta^{18}O_{(calcite)}$ values and atmospheric circulation patterns.

Several abrupt climate change events have been identified throughout the late-Glacial (defined here beginning at 14,600 cal yr BP; Stuiver et al. 1995) and Holocene periods. The most notable events are the Bolling-Allerod warm period (Stuiver et al. 1995), the Younger Dryas cold interval (Mangerud et al. 1974; Broecker et al. 1989; Stuiver et al. 1995; Yu and Eicher 1998), the 8200 cal yr BP cold, dry event (Alley et al. 1997; Barber et al. 1999; von Grafenstein et al. 1999), and more recently, the mid-Holocene transition (Steig 1999; Sandweiss et al. 1999; Mullins and Halfman 2001). Several authors have previously identified a post-Younger Dryas climate interval in the NE USA, but low-resolution records have generally limited their atmospheric interpretation (Fritz et al. 1975; Lewis and Anderson 1992; Anderson et al. 1997; Hu et al. 1997). Another critical limitation is that only a few paleoclimate records have calibrated their atmospheric hypotheses with historic data (Smith and Hollander 1999; Black et al. 1999).

Our research presents a statistical method for reconstructing regional-scale atmospheric circulation over the NE USA for the period 14,600–8000 cal yr BP. This model was constructed using a linear transfer function developed from the relationship between lacustrine $\delta^{18}O_{(calcite)}$ and circulation during historic times (i.e., AD 1948–1980). This function is then applied to the prehistoric $\delta^{18}O_{(calcite)}$ record, thus yielding a model of atmospheric circulation during the late-Glacial/Holocene transition.

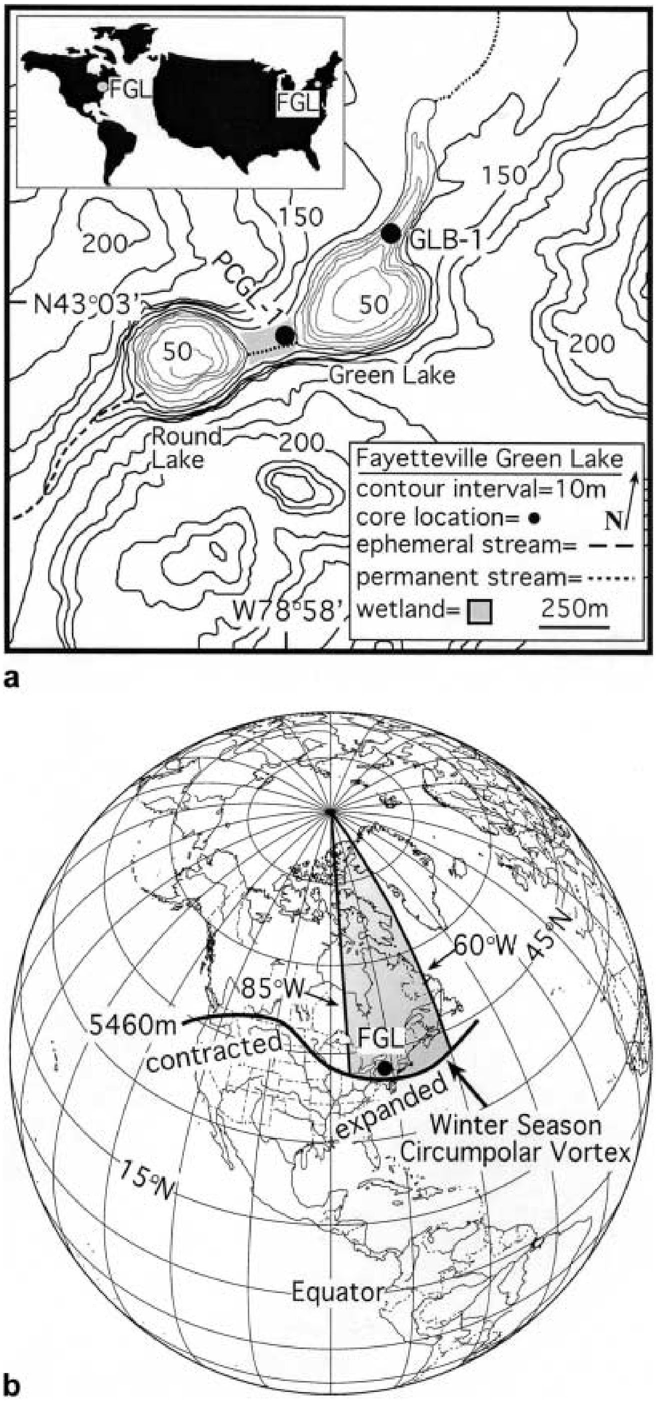


Fig. 1. **a** Study site map with core location. *FGL*, Fayetteville Green Lake; *PCGL-1*, wetland piston core; *GLB-1*, lake box core. *Insets* illustrate global and regional locations, respectively. **b** Approximate mean winter circumpolar vortex position at the 5460 m 500 hPa geopotential height field (Yarnal and Leathers 1988; Burnett 1993a)

2 Study site and background

Fayetteville Green Lake is an excellent study site for developing paleoclimate proxy records (Fig. 1a). Foremost, Fayetteville Green Lake is topographically isolated with a small drainage basin (4.33 km^2) thereby reducing complexities associated with vast, complex hydrologic pathways. Furthermore, Green Lake is meromictic (i.e., permanently stratified) produced by the inflow of saline-rich (dense) groundwater at ~18 m water depth (see review by Hilfinger and Mullins 1997). The inflow of this saline-rich groundwater maintains a permanent chemocline at ~18 m water depth separating the mixolimnion (upper 18 m of water that mix seasonally) from the monimolimnion (18–52 m where waters are permanently removed from direct atmospheric contact; Takahashi et al. 1968). Thus, bottom waters are permanently anoxic yielding conditions favorable for preservation of varves (i.e., annually deposited layers; 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 portion of the varves (Thompson et al. 1997). The short water residence time (1–2 year; Takahashi et al. 1968) of the mixolimnion in Green Lake, where the calcite precipitates, assures that oxygen isotope values from calcite will record high-resolution (< 2 year) climate variability. Previous work by Hilfinger et al. (2001) has shown that the $\delta^{18}O_{(calcite)}$ values are influenced more by Green Lake $\delta^{18}O_{(water)}$ values than by temperature. Furthermore, approximately 75% of annual, regional water budgets for lakes in the

Green Lake area are contributed by winter precipitation (snow or rain) and subsequent spring runoff (Michel and Kraemer 1995). Consequently, we interpret the $\delta^{18}O_{(calcite)}$ data from Green Lake as primarily recording winter moisture source variability (Kirby et al. 2001).

The winter climate of the Fayetteville Green Lake region is strongly influenced by the westerlies and the polar front jet stream (Klein 1957; Zishka and Smith 1980; Burnett 1993a). Because of the circumpolar nature of the westerlies, it is often referred to in its entirety as the circumpolar vortex (Angell 1992). The strength of the vortex, as measured by wind speed and vortex size, varies seasonally with strongest conditions during the winter months when the temperature gradient between the cold polar latitudes and the warmer low latitudes is greatest (Harman 1991). This variation reflects seasonally changing global energy transfer (Barry et al. 1975; Balling and Lawson 1982; Harman 1991).

Embedded within the circumpolar westerlies are wave features that operate over a wide range of spatial and temporal scales. The largest of these features are the semi-stationary upper troposphere Rossby waves (i.e., long waves, Harman 1991). These waves, which have strong geographic preferences, possess continental size wavelengths, and serve a fundamental role in middle latitude climate. Some of these long waves, such as the trough over the NE USA, are largely controlled by relatively stable boundary conditions, certainly over the interval of time discussed here (Harman 1991). In the case of the NE USA trough, the position of the Rocky mountains and the strong thermal contrast between the North Atlantic ocean and the adjacent North American continent "anchor" the NE USA trough as a semi-stationary long wave (Douglas et al. 1982; Manabe and Broccoli 1990; Harman 1991). Together, the orographic and the land-sea thermal contrast act as geologic-scale (i.e., millennia) climate boundary forcings on preferential atmospheric circulation patterns (Manabe and Broccoli 1990; Harman 1991). In fact, the combined influences of these latter forcings are so dominant that models and observational studies of atmospheric circulation addressing the early-Holocene transition/glacial period indicate that a trough pattern existed over the NE USA at all times (Delcourt and Delcourt 1984; COHMAP 1988; Kageyama et al. 1999; Kageyama and Valdes 2000). Furthermore, the NE USA trough pattern prevailed regardless of the influence of the Laurentide ice sheet, although its size and shape would have been subject to obvious modification (COHMAP 1988; Kageyama and Valdes 2000).

As this discussion shows, the winter season vortex over northeastern North America is dominated by troughing (Fig. 1b). This trough serves as a conduit through which fast moving, shorter wavelength features flow. Short waves are important sources of divergent air flow within the westerlies, and thus play a major role in the development and movement of surface low pressure systems (Harman 1991). During periods when the trough is expanded over eastern North America, surface storms will develop at more southerly latitudes. Several studies of circulation variability have shown that the size and wave structure of the circumpolar vortex change over a wide range of time scales ranging from interannual to millennial (Namias 1978; Barry 1981; Douglas et al. 1982; COHMAP 1988; Burnett 1993b).

3 Methods

3.1 Core collection and age control

An 11.2 m-long, hand-driven, square-rod piston core (PCGL-1) composed of marl and peat layers was collected from the wetland between Fayetteville Green Lake and Round Lake, New York (W75°58′, N43°02′; Fig. 1a). Also collected was a 0.65 m-long box core (GLB-1) from 22 m water depth in the neck region of Green Lake (Fig. 1a).

Age control for core PCGL-1 is based on six radiocarbon dates of peat layers and/or wood fragments (Table 1, Fig. 2a) plus a spliced date from the Younger Dryas termination (11,640 ± 250 cal yr BP), taken from the GISP 2 ice core record (Alley et al. 1993; Fig. 2b). An age model was constructed assuming a linear sediment accumulation rate between the respective ^{14}C dates and the GISP 2 splice. We note that the termination of the Younger Dryas cold event is a well-documented, well-dated boundary in the Northern Hemisphere, thus making the spliced age of 11,640 cal yr BP used in our age model a reliable age marker (O'Brien et al. 1995; Yu and Eicher 1998; von Grafenstein et al. 1999; Wang et al. 1999; Willemse and Tornqvist 1999). The historic portion (AD 1906–1980) of core GLB-1 was dated using varve count chronology ($n=74$; standard error = ±3 years using 4 total varve counts), index varves (Ludlam 1969), and a distinctive flood unit deposited in AD 1922 (Kirby et al. 2001).

3.2 Isotopes

Using our age model, isotope samples were obtained at ~10-year intervals of core sediment (< 1.5 cm) for the period 14,600 to 8000 cal yr BP. Time-averaged samples were used to eliminate the impact of high frequency atmospheric variability (i.e., anomalous $\delta^{18}O$ spikes). All isotopic analyses were conducted on the < 63 µ-size fraction which consists predominantly of biologically mediated calcite precipitate (Thompson et al. 1997). $\delta^{18}O_{(calcite)}$ values for the historic period were determined on the summer portion of individual varves (AD 1906–1980; $n=74$) from box core GLB-1. Prehistoric samples were collected from the wetland piston core PCGL-1. 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 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 analyzed at 50 °C and reacted for 15 s to eliminate potential interference caused by small percentages (< 5%) of detrital dolomite. This procedure proved highly effective in eliminating dolomite interference. Samples are reported in standard delta notation relative to VPDB using standards NBS-18 and NBS-19 as well as an in-house standard for calibration. Precision is better than ±0.1‰ for both carbon and oxygen isotope values.

Table 1. Radiocarbon data

Core reference	Depth (cm)	Material	Laboratory reference	^{14}C age	Calibrated age	$\delta^{13}C_{(organic)}$
PCGL-1	21–29	Peat	TX-9133	2157 ± 50	2140	–28.8
PCGL-1	137–142	Peat	TX-9134	4433 ± 58	5030	–31.3
PCGL-1	498	Wood	AA-32433	5470 ± 55	6300	–27.9
PCGL-1	723–728	Peat	TX-9136	7567 ± 74	8340	–27.6
PCGL-1	895	Wood	AA-28864	8560 ± 65	9490	–30.5
PCGL-1	1074	Wood	AA-32434	11,480 ± 130	13530	–28.5

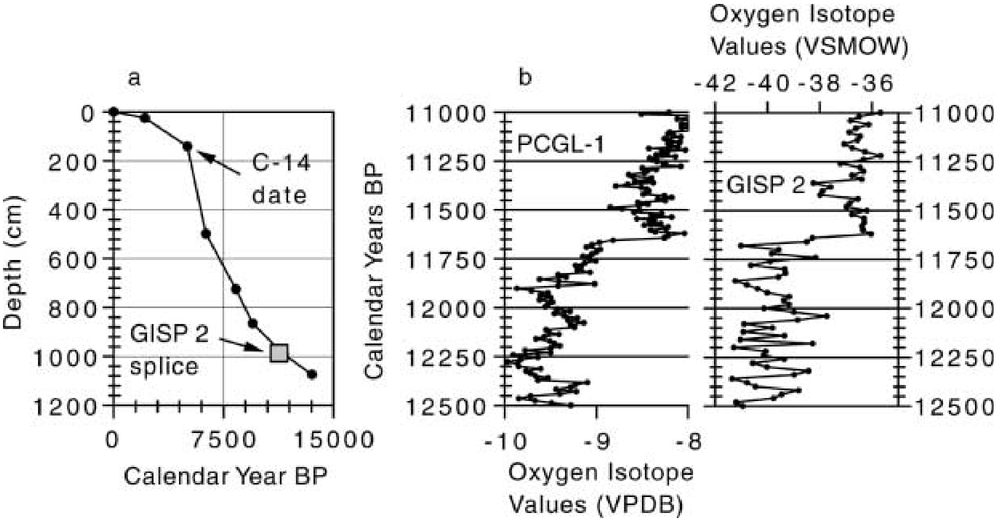


Fig. 2. **a** Age model used for core PCGL-1 based on calibrated ^{14}C dates (Table 1). Spliced GISP 2 date of 11,640 ± 250 calendar years BP is included at 992.5 cm (Alley et al. 1993). **b** Comparison of core PCGL-1 (5 point moving average) and GISP 2 ice core data (Alley et al. 1993). Both records show a clear step-function increase toward higher $\delta^{18}O$ values at the termination of the Younger Dryas cold event; we have interpreted this step-function change as coeval between the both core sites

3.3 Atmospheric circulation and oxygen isotopes

The statistical relationship between winter circulation over the Green Lakes region and $\delta^{18}O_{(calcite)}$ was determined through a comparison of historical circulation data and $\delta^{18}O_{(calcite)}$ data. For this study, the average latitude of the westerly vortex over the region between 60°W and 85°W was used to characterize circulation over the study region (Fig. 1b). The vortex latitude calculation followed the technique described by Burnett (1993a) and involved the use of 500 hPa geopotential height data over northeastern North America. These data were obtained from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis data set for winter during the period AD 1948–1998 (Kalnay et al. 1996). We focused on a 32-year interval between AD 1948–1980 because it represents the interval over which varved $\delta^{18}O_{(calcite)}$ and 500 hPa data co-exist. The vortex measurement technique required the identification of a 500 hPa geopotential height that best represents the core of the westerlies. The 5460 m height was chosen for this analysis after reviewing several winter 500 hPa maps for North America. A linear regression was used to determine the degree to which the isotope data are influenced by vortex position. Prior to analysis, both data sets were smoothed using a 5-point moving average to remove interannual noise. An inherent assumption for this research is that the historic record of annual vortex variability can be transferred to decadal-scale variability over the record of study (i.e., late-Glacial/Holocene). Using historical climate data, Douglas and others (1982) showed that transference of seasonal-to-annual climate changes to decadal-scale change is not unreasonable due to the teleconnected nature of the atmospheric system. To further evaluate the magnitude of contraction or expansion of the winter vortex over time, we examined the smallest (most contracted) circumpolar vortex winter year (1998) versus the largest (most expanded) circumpolar vortex winter year (AD 1977) between AD 1948–1998.

4 Results

4.1 Isotopes

Figure 3 shows the isotope data for the period 14,600 to 8000 cal yr BP. From these data, we divide the record into three parts: (1) the late-Glacial from 14,600 to 11,600 cal yr BP including the Younger Dryas cold event (12,600 to 11,600 cal yr BP); (2) the post-Younger Dryas climate interval between 11,600 ± 250 (error based on Alley et al. 1993 from GISP 2 ice core record) and 10,300 ± 160 cal yr (average error calculated from post-YD termination date and date at 895 cm; see Table 1); and (3) the Holocene beginning at 10,300 cal yr BP.

The Younger Dryas cold event is not a high amplitude event in our isotope data as it is in much of the NE USA (Fig. 3) (Fritz et al. 1975; Lewis and Anderson 1992; Anderson et al. 1997; Hu et al. 1997). The transition from the end of the late-Glacial (termination of the Younger Dryas cold event), a period of relatively low $\delta^{18}O_{(calcite)}$ values, to the post-Younger Dryas climate interval occurs in less than 60 years (according to our age model) and is characterized by an isotopic shift of ~1‰ (Fig. 3). The post-YD climate interval is characterized by a ~1,300-year period of anomalously high $\delta^{18}O_{(calcite)}$ values (Fig. 3). Two notable isotopic excursions occur within the post-YD interval: the first between ~11,500 and ~11,300 cal yr BP, perhaps coeval to global meltwater pulse IB at 11,300 cal yr BP (Fairbanks 1989; Bard et al. 1996), and the second at ~10,500 cal yr BP (origin unknown) (Fig. 3). The transition out of the post-YD climate interval, which begins at ~10,300 cal yr BP, is less rapid, occurring over approximately 250 years with an isotopic shift of ~1.5‰ (Fig. 3).

4.2 The prehistoric vortex record

The relationship between the historical winter season vortex and $\delta^{18}O_{(calcite)}$, as captured through linear regression analysis, is shown graphically in Fig. 4a and is described mathematically by Eq. (1).

$$\delta^{18}O_{(calcite)} = (-0.20)(\text{vortex latitude}) - 1.57 \qquad (1)$$

Figure 4b shows the raw $\delta^{18}O_{(calcite)}$ values and vortex data plotted on a double-Y axis graph. The Pearson's correlation coefficient that is derived from Eq. (1) is –0.79 and indicates a strong, statistically significant inverse relationship between vortex variability and oxygen isotopes. Overall, this equation suggests that 63% of the Green Lake $\delta^{18}O_{(calcite)}$ variability can be explained by changes in the size of the winter vortex over the study region. Periods of vortex expansion are characterized by relatively high $\delta^{18}O_{(calcite)}$ values, whereas a contracted vortex is associated with relatively low $\delta^{18}O_{(calcite)}$ values. We use this strong relationship to reconstruct winter vortex size throughout the extent of the prehistoric $\delta^{18}O_{(calcite)}$ record under the standing assumption that the historic annual vortex record captures a fair representation of vortex natural variability. Equation (2) is the transfer function used to model vortex latitudes from prehistoric isotope data over the Green Lakes region (Fig. 5).

$$\text{Vortex latitude} = (-3.12)(\delta^{18}O_{(calcite)}) + 10.60 \qquad (2)$$

The standard error of the predicted vortex latitude using this transfer function (2) is $\pm 0.54°$.

Over the extent of the pre-historic isotope record, we use the historic relationship to model the circumpolar vortex (Fig. 5). The location of the circumpolar vortex between 11,600–10,300 cal yr BP averaged 36.1°N latitude whereas the circumpolar vortex from the preceding interval (14,600–11,600 cal yr BP) averaged 39.3°N latitude. The circumpolar vortex average latitude from the succeeding interval (8000–10,300 cal yr BP) was 37.4°N. For comparison, the mean vortex latitude during historic time (AD 1948 to 1998) has been ~41.8°N. The difference between the mean vortex latitude from 11,600–10,300 cal yr BP and AD 1948 to 1998 is approximately 630 km, or the modern distance between Norfolk, Virginia and Binghamton, New York (both at 76°W longitude; Fig. 6a).

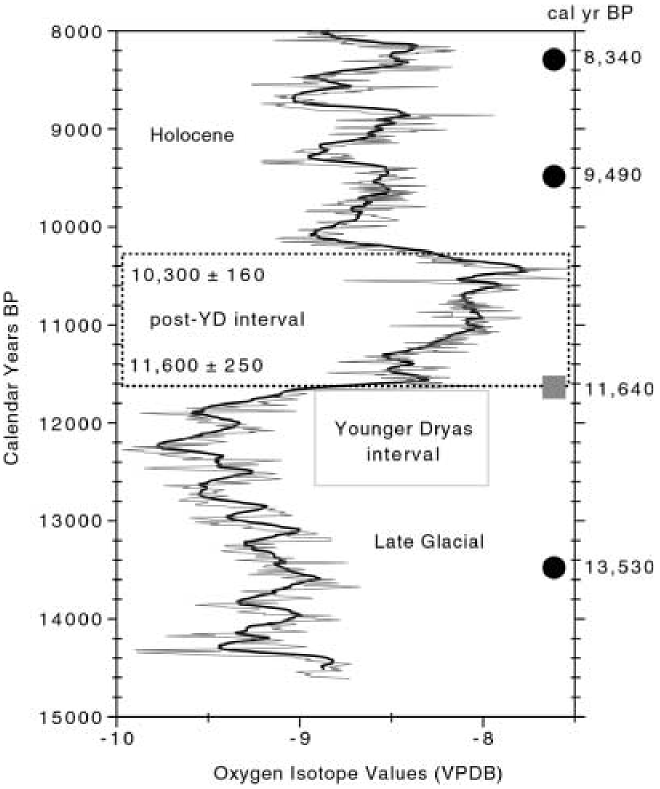


Fig. 3. Raw $\delta^{18}O_{(calcite)}$ isotope data for the entire core record. Section discussed (post-Younger Dryas Climate Interval) in text is *highlighted* by *dashed line-box* including ages and errors. Also note that the Younger Dryas cold event is shown at its approximate location as per our age model by the *solid line-box*. *Black circles*, calibrated ^{14}C dates (Stuiver and Reimer 1993); *gray square* GISP 2 splice date

Examining both the most contracted and the most expanded winter circumpolar vortices during historic time (AD 1948–1998) indicates that a trough overlies the study region in the winter during both extremes (Kalnay et al. 1996). The difference, however, in the mean winter position of the circumpolar vortex over Green Lake between the two extremes (1977 = most expanded; 1998 = most contracted) during the historic period is nearly 720 km (Fig. 4b). These results clearly demonstrate that the winter circumpolar vortex has a very large range of variability from contracted to expanded geometries on an annual as well as multi-decadal basis. Furthermore, the historic data indicate that our model estimate of 630 km difference during the post-YD climate interval is not without short-term historic precedent.

5 Discussion

5.1 Late-Glacial/Holocene atmospheric circulation, isotopes, and the post-YD climate interval

As shown by Hilfinger and others (2001), $\delta^{18}O_{(calcite)}$ values from Green Lake predominantly record moisture source variability, in particular, winter season moisture (Kirby et al. 2001). Our analysis of $\delta^{18}O_{(calcite)}$ values from across the late-Glacial/Holocene transition indicates significant isotopic variability and thus a high degree of moisture source change.

Knappenberger and Michaels (1993) have shown that variations in winter storm tracks over the northeastern United States can have significant impacts on winter precipitation. Areas of high winter storm frequency include an east coast track from Florida into New England, a central track extending from Colorado through Michigan (Ohio Valley), and a cross-continental track across the north-central United States (Fig. 6a). Cyclones along this latter track are often referred to as "Alberta Clipper" storms (Eichenlaub 1979). The east coast storm track, which is associated with a deep trough and an expanded vortex over the NE USA, can produce large quantities of precipitation through its access to Atlantic water vapor (Fig. 6a) (Namias 1978; Knappenberger and Michaels 1993). Given this water vapor source, such storms would advect precipitation with relatively high $\delta^{18}O$ values throughout the NE USA. The "latitude effect" is largely responsible for the gradational depletion in $\delta^{18}O_{(water\ vapor)}$ with increasing latitude, thus low-latitude sources are relatively enriched

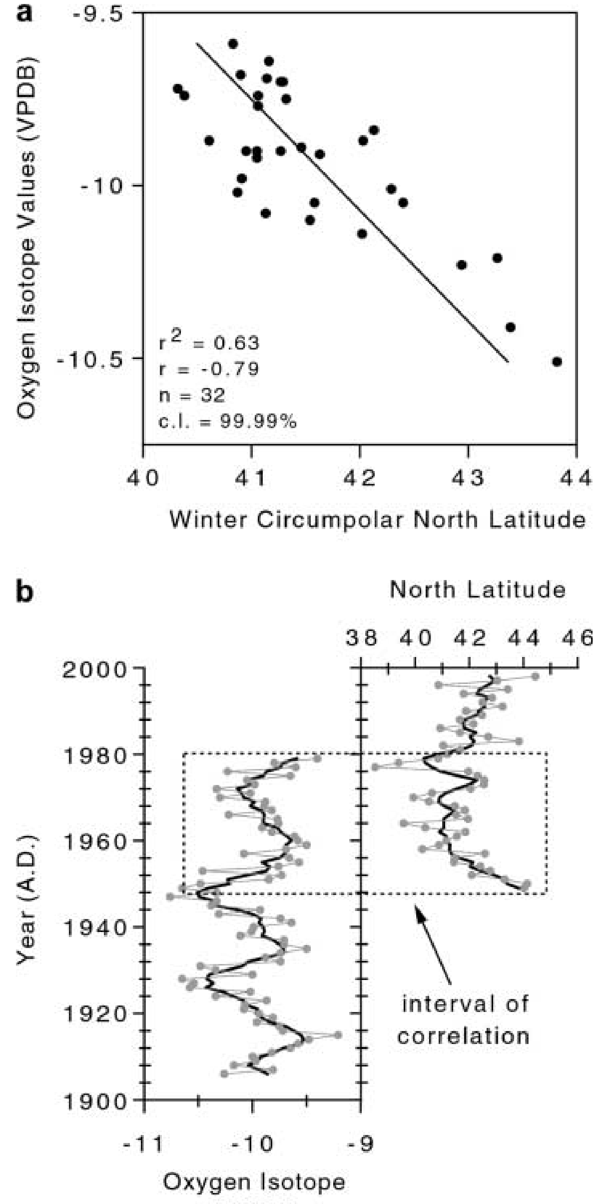


Fig. 4. **a** Regression analysis between oxygen isotope values and winter circumpolar vortex. Both the Pearson correlation coefficient (r) and the coefficient of determination (r^2) are shown. This correlation is statistically significant to the 99.99% confidence level (c.l.). **b** *Left graph* shows raw and smoothed (5-point moving average) $\delta^{18}O_{(calcite)}$ data for core GLB-1. *Right graph* shows raw and smoothed (5-point moving average) vortex latitude data between 60° and 85°W longitude

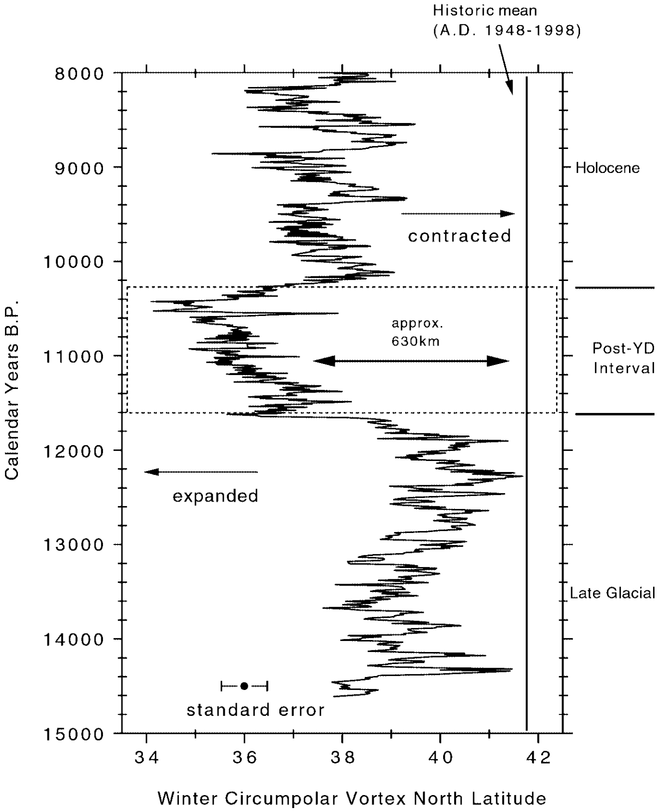
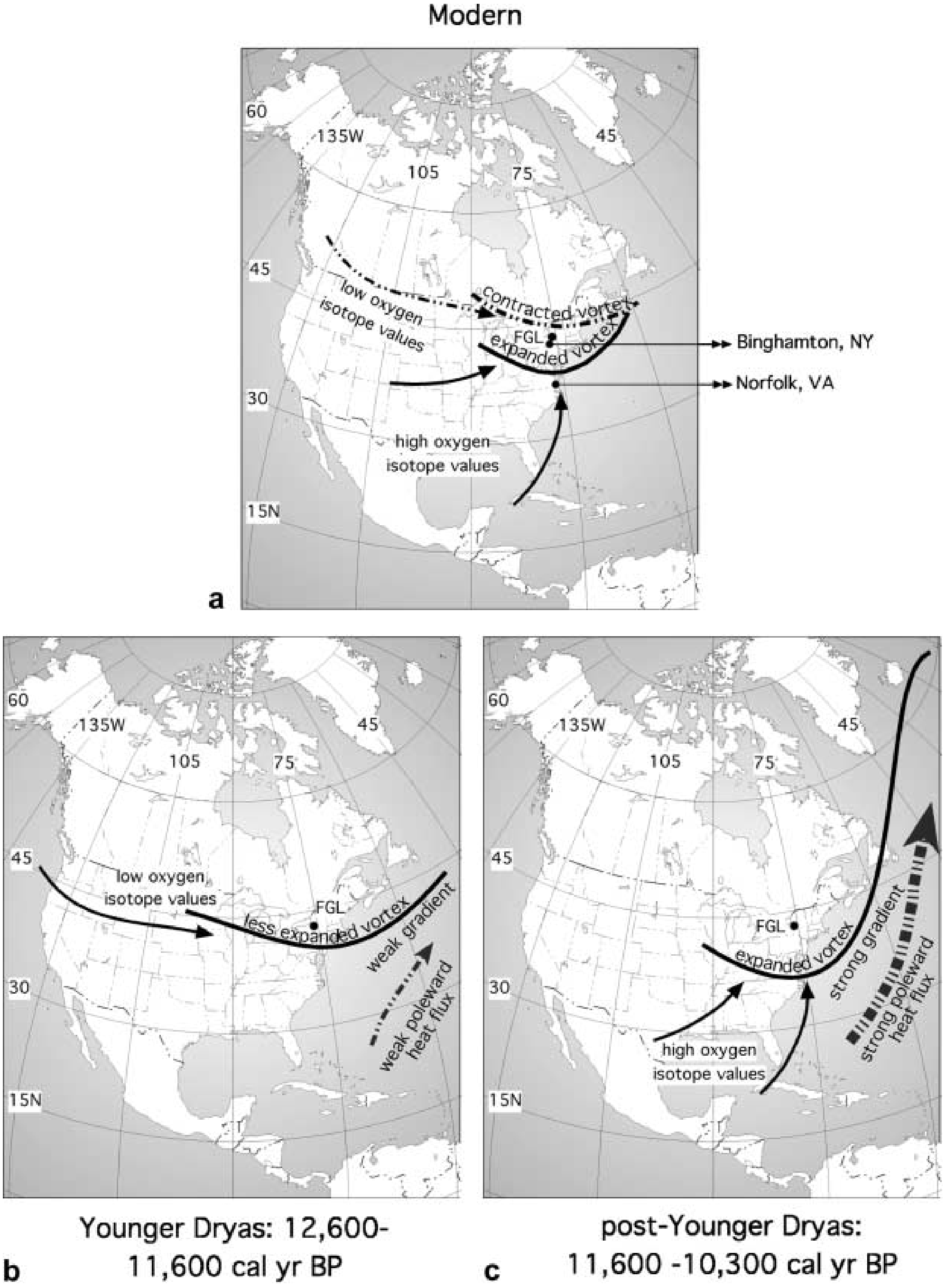


Fig. 5. Modeled winter circumpolar vortex as determined by a transfer function (see text). For comparison, the mean winter circumpolar vortex position (*gray line* at 41.8°N latitude) for period of recorded data (AD 1948–1998) is shown; largest difference between the historic winter circumpolar vortex and the post-YD climate interval is approximately 630 km. Standard error for modeled circumpolar vortex is ±0.54° latitude

in ^{18}O compared to high-latitude moisture sources (Dansgaard 1964; Rozanski et al. 1993). A slightly less expanded vortex, with storms moving northeastward through the midwest, would also yield relatively high $\delta^{18}O_{(precipitation)}$ values, for the same reasons above, through their ability to tap into the relatively high $\delta^{18}O$ moisture sources from the Gulf of Mexico (Fig. 6a). Conversely, Alberta Clipper type storms, which are associated with a contracted circumpolar vortex, do not have access to Atlantic moisture and are characterized by precipitation with relatively low $\delta^{18}O$ values due to progressive Rayleigh distillation ("rain-out" of ^{18}O) across the continental interior and the orographic affect on eastward migrating storm systems (Fig. 6a) (Dansgaard 1964; Manabe and Broccoli 1990; Rozanski et al. 1993).

According to our transfer function, the average winter vortex latitude over the NE USA during the post-Younger Dryas climate interval was, at maximum, ~630 km further south than its mean historic position (AD 1948–1998). On average, $\delta^{18}O_{(calcite)}$ values were 0.5‰ to 1.0‰ higher during the post-YD climate interval than during the periods before and after (Fig. 3). One explanation for the relatively high $\delta^{18}O_{(calcite)}$ values during the post-YD climate interval is an increase in the contribution of winter precipitation from moisture sources with relatively high $\delta^{18}O$ values such as the low-latitude Atlantic Ocean and the Gulf of Mexico (Fig. 6a). Alternatively, a change in the relative ratio of winter to summer precipitation may have occurred during the post-YD interval. A greater contribution of summer precipitation characterized by relatively higher $\delta^{18}O$ values as



b Younger Dryas: 12,600-11,600 cal yr BP

c post-Younger Dryas: 11,600 -10,300 cal yr BP

Fig. 6. **a** Map showing modern winter circumpolar vortex with associated $\delta^{18}O_{(precipitation)}$ values. Derived from relationship between isotope and winter circumpolar vortex (Fig. 4a). Contracted vortex position based on AD 1998 data (44.4°N); expanded vortex position based on AD 1977 data (38.5°N). Storm tracks after Zishka and Smith (1980) and Knappenberger and Michaels (1993). Locations of *Binghamton*, *New York* and *Norfolk*, *Virginia* are also shown to schematically represent approximate difference between post-YD climate interval average latitude and historic average latitude (630 km). Norfolk, Virginia represents approximate modeled latitude position during the post-YD climate interval. **b** Map illustrating the proposed Younger Dryas winter vortex shape and position (40.5°N) with dominant storm tracks. **c** Map illustrating the proposed post-Younger Dryas interval winter vortex shape and position (36.1°N) with dominant storm tracks

compared to "high" winter $\delta^{18}O_{(precipitation)}$ may have out-weighed the winter precipitation isotope signal thereby imprinting a relatively high $\delta^{18}O_{(calcite)}$ signature during the post-YD climate interval during the months of calcite formation. Modern oxygen isotope measurements of seasonal precipitation from the Green Lake region clearly show that summer precipitation is characterized by higher $\delta^{18}O$ values than winter precipitation (Syracuse, New York data from Syracuse University Isotope Laboratory: winter average = –14.2‰ ± 5 VSMOW, n = 24; summer average = –6.9‰ ± 3.7 VSMOW, n = 43).

5.2 Possible driving mechanism

5.2.1 Thermohaline circulation

What caused the post-Younger Dryas climate interval in the NE USA? We hypothesize that the post-YD climate interval may have been caused by the abrupt renewal of thermohaline circulation in the North Atlantic following the Younger Dryas (Fig. 6b, c, Boyle and Keigwin 1987; Broecker et al. 1989; Alley et al. 1993; Fawcett et al. 1997). The relatively cold, NE USA continental interior (just south of the still-extant Laurentide ice sheet) juxtaposed with newly warmed North Atlantic waters via renewed thermohaline circulation and increased poleward heat transport, may have acted as the impetus for strengthening the semi-permanent winter trough (vortex expansion) over the NE USA (Fig. 6c). The strong land-sea thermal contrast in the northwest Atlantic region would have increased longitudinal atmospheric pressure gradients over the NE USA producing relatively strong atmospheric circulation coincident with an expanded vortex. As a result, large cyclones would have traveled up the east coast and/or through the Ohio Valley depositing relatively high $\delta^{18}O_{(precipitation)}$ across the NE USA (Fig. 6c). It has been shown, both empirically (Namias 1978; Barry 1981; Balling and Lawson 1982) and theoretically (Barry et al. 1975; Hartmann and Short 1979; Crowley 1984; Timmerman et al. 1998; Kageyama and Valdes 2000), that poleward heat transport, particularly within the mid-latitudes, significantly effects atmospheric circulation and, thus, the underlying region's climate.

To test the hypothesis that an increase in poleward heat transport and subsequent changes in atmospheric circulation occurred during the post-YD interval, high-resolution paleoclimate data which record atmospheric processes (preferably winter season) should be examined both regionally and hemispherically. If, in fact, a large trough existed over the NE USA during the post-YD interval, it should be expected that a similarly large ridge existed "down-wind" (to the east) of the NE USA as a result of increased poleward heat transport (e.g., northeast Atlantic Ocean and northwestern Europe). Research by von Grafenstein and others (1999) on oxygen isotope ratios of calculated paleo-precipitation shows an interval essentially coeval (~11,400 to ~10,400 cal yr BP) to our post-YD climate interval wherein European temperatures were relatively high and "out-of-phase" with Greenland temperatures (von Grafenstein et al. 1999). In other words, an expanded trough over the NE USA extending into Greenland was balanced downwind by a large ridge which advected warm, moisture-rich precipitation over northwestern Europe, thus creating the out-of-phase relationship between Greenland and Europe during the post-YD interval as observed by von Grafenstein and others (1999). This finding provides support that the post-YD climate interval in NE USA may have had a down-wind signal and thus a hemispheric climatic impact. We note that palynological research by Delcourt and Delcourt (1984) similarly propose extensive vortex meridionality (expansion) over the NE USA during this time.

We find additional support for thermohaline forcing of the post-YD interval in a modeling paper by Fawcett and others (1997). Their research demostrates that a strong shift in winter season storm tracks occurred at the end of the Younger Dryas. This shift in winter season storm tracks resulted in the preferential advection of cyclones along the east coast of North America and into Greenland. These results suggest a mechanism to explain both the dramatic shift in isotope values observed at Green Lake and the rapid increase in snow accumulation rates in Greenland at the YD termination (Alley et al. 1993). In light of Fawcett and others' (1997) model results, and those by Manabe and Stouffer (1999), both of which demonstrate the profound climate effect linked to changes in thermohaline circulation, we suspect that future modeling efforts using isotope tracers in precipitation will provide additional support for our proposed thermohaline-forced, post-YD interval.

Our alternative explanation is that a relative increase in the contribution of summer to winter precipitation may have occurred in response to this change in poleward heat transport. There exist, however, no records of seasonality of precipitation during this interval in the NE USA, thus, this hypothesis is, as yet, difficult to test. We note that several modeling efforts aimed at understanding isotopic development over time using GCMs have been quite intriguing (Cole et al. 1993; Charles et al. 1994, 2001). Although outside the realm of our research, GCM testing would provide valuable insight into our seasonality of precipitation hypothesis.

Finally, we propose that the post-YD interval terminated as increasing freshwater flux into the North Atlantic via polar warming slowed thermohaline circulation to "Holocene" levels. A general plateau in Cd/Ca ratios, a proxy for rate of thermohaline circulation, after 10,400 cal yr BP, corroborate our hypothesis that thermohaline circulation reached a point of equilibration as the post-YD climate interval concluded (Boyle and Keigwin 1987; Keigwin et al. 1991). Continued development of high-resolution paleoclimate data that record atmospheric processes from the both the NE USA and northwestern Europe will help to further characterize this interval.

6 Conclusion

Analysis of a well-dated, high-resolution $\delta^{18}O_{(calcite)}$ record from the NE USA reveals significant isotopic variability during the late-Glacial/Holocene transition as well as an interval of anomalously high $\delta^{18}O_{(calcite)}$ values between 11,600 and 10,300 cal yr BP. Because $\delta^{18}O_{(calcite)}$ is predominantly a winter moisture source signal, we analyzed the historic record of winter vortex latitude and lacustrine stable oxygen isotope data to examine the potential relationship between winter atmospheric circulation and oxygen isotope values. From the derived relationship, we modeled the winter vortex latitude for the late-Glacial/Holocene transition. Our results reveal a high degree of vortex variability during this period reflecting a highly dynamic atmosphere and associated changes in moisture sources. Moreover, a period of 1300 years between 11,600 and 10,300 cal yr BP was revealed wherein oxygen isotope values were anomalously high compared to the values before and after the interval. We refer to this period as the post-Younger Dryas climate interval, defined by a greatly expanded trough system over the NE USA and the resultant advection of precipitation with relatively high $\delta^{18}O$ values from the Atlantic and Gulf of Mexico. We hypothesize that the proposed post-Younger Dryas climate interval was forced by the abrupt renewal of relatively vigorous thermohaline circulation following the Younger Dryas cooling event that increased poleward heat transport and created an enhanced land-sea (longitudinal) thermal contrast. Greater land-ocean thermal contrasts forced changes in atmospheric circulation patterns by increasing atmospheric pressure gradients and thus expanding the semi-permanent winter trough system over the NE USA. The position of the expanded trough over the NE USA increased the frequency of storms advected across the NE USA from the Atlantic and Gulf regions delivering winter precipitation with relatively high $\delta^{18}O$ values during the post-YD climate interval. Alternatively, a change (increase) in the relative contribution of summer to winter precipitation may have also occurred, accounting for at least part of this observation. Both of these hypotheses would benefit from testing with global circulation models. Termination of this interval may be related to a reduction in thermohaline circulation associated with an increase in the flux of freshwater into the North Atlantic from the preceding interval of enhanced poleward heat transport.

Acknowledgements Thanks are extended to Syracuse University Graduate School, Sigma Xi, and Geological Society of America whom provided the funding to pursue this research. Special thanks to Cliff Callinan and Bruce Garabedian of the New York State Department of Environmental Conservation for box core collection, Jesse Coburn and Martin Hilfinger for piston core collection; and, to the Green Lakes State Park Staff, especially John Livingston for allowing access to field sites. We thank three anonymous reviewers whom greatly helped to improve this manuscript's clarity.

References

Alley RB, plus 10 others (1993) Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event. Nature 362: 527–529

Alley RB, Mayewski PA, Sowers T, Stuiver M, Taylor KC, Clark PU (1997) Holocene climatic instability: a prominent, widespread event 8200 years ago. Geology 25: 483–486

Anderson WT, Mullins HT, Ito E (1997) Stable isotope record from Seneca Lake, New York: evidence for a cold paleoclimate following the Younger Dryas. Geology 25: 135–138

Angell JK (1992) Relation between 300-mb north polar vortex and equatorial SST, QBO, and sunspot number and the record contraction of the vortex in 1988–89. J Clim 5: 22–29

Balling RC, Lawson MP (1982) Twentieth century changes in winter climatic regions. Clim Change 4: 57–69

Barber DC, plus 10 others (1999) Forcing of the cold event of 8200 years ago by catastrophic drainage of Laurentide lakes. Nature 400: 344–348

Bard E, plus 6 others (1996) Deglacial sea-level record from Tahiti corals and the timing of global meltwater discharge. Nature 382: 241–244

Barry RG (1981) The nature and origin of climatic fluctuations in northeastern North America. Geogr phys Quat 35: 41–47

Barry RG, Andrews JT, Mahaffy MA (1975) Continental ice sheets: conditions for growth. Science 190: 979–981

Black DE, plus 5 others (1999) Eight centuries of North Atlantic ocean atmosphere variability. Science 286: 1709–1713

Bond G, plus 9 others (1997) A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. Nature 278: 1257–1266

Boyle EA, Keigwin L (1987) North Atlantic thermohaline circulation during the past 20,000 years linked to high-latitude surface temperature. Nature 330: 35–40

Broecker WS, plus 6 others (1989) Routing of meltwater from the Laurentide ice sheet during the Younger Dryas cold episode. Nature 341: 318–321

Burnett AW (1993a) Size variations and long-wave circulation within the January northern hemisphere circumpolar vortex. J Clim 6: 1914–1920

Burnett AW (1993b) Regional synchronies and amplitude changes in the January 500-mb middle latitude geopotential height record. Phys Geog 14: 99–113

Campbell ID, Campbell C, Apps MJ, Rutter NW, Bush ABG (1998) Late-Holocene ~1500 yr climate periodicities and their implications. Geology 26: 471–473

Charles CD, Rind D, Jouzel J, Koster RD, Fairbanks RG (1994) Glacial-Interglacial changes in moisture sources for Greenland: influences on the ice core record of climate. Science 263: 508–507

Charles CD, Rind D, Healy R, Webb R (2001) Tropical cooling and the isotopic composition of precipitation in general circulation model simulations of the ice age climate. Clim Dyn 17: 489–502

COHMAP (1988) Climatic changes of the last 18,000 years: observations and model simulations. Science 241: 1043–1052

Cole JE, Rind D, Fairbanks RG (1993) Isotopic responses to interannual climate variability simulated by an atmospheric general circulation model. Quat Sci Rev 12: 387–406

Crowley TJ (1984) Atmospheric circulation patterns during glacial inception: a possible candidate. Quat Res 21: 105–110

Dansgaard W (1964) Stable isotopes in precipitation. Tellus 16: 436–468

Delcourt PA, Delcourt HR (1984) Late Quaternary paleoclimates and biotic responses in eastern North America and the western North Atlantic ocean. Palaeogeogr Palaeoclim Palaeoecol 48: 263–284

Denton GH, Karlén W (1973) Holocene climate variations – their pattern and possible causes. Quat Res 3: 155–205

Douglas AV, Cayan DR, Namias J (1982) Large-scale changes in North Pacific and North American weather patterns in recent decades. Mon Weather Rev 110: 1851–1862

Eichenlaub V (1979) Weather and climate of the Great Lakes Region. University of Notre Dame Press, South Bend, Indiana, USA

Fairbanks RG (1989) A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep ocean circulation. Nature 342: 637–642

Fawcett PJ, Agustsdottir AM, Alley RB, Shuman CA (1997). The Younger Dryas termination and North Atlantic deep water formation: insights from climate model simulations and Greenland ice cores. Paleoceanography 12: 23–28

Fritz P, Anderson TW, Lewis CFM (1975) Late-Quaternary climatic trends and history of Lake Erie from stable isotope studies. Science 190: 267–269

Harman JR (1991) Synoptic climatology of the westerlies: process and patterns. Association of American Geographers, Washington, DC, USA

Hartmann DL, Short DA (1979) On the role of zonal asymmetries in climate change. J Atmos Sci 36: 519–528

Hilfinger MF IV, Mullins HT (1997) Geology, limnology, and paleoclimatology of Green Lakes State Park, New York. In: Raynes TW, Bailey DG, Tewsksbury BJ (eds) 69th Annual New York State Geological Association Field Trip Guide Hamilton College, Clinton, New York, USA, pp 127–159

Hilfinger MF IV, Mullins HT, Burnett A, Kirby ME (2001) A 2500 year sediment record from Fayetteville Green Lake, New York:

evidence for anthropogenic impacts and historic isotope shift. J Paleolimn 26: 293–305

Hu FS, Wright HE Jr, Ito E, Lease K (1997) Climatic effects of glacial Lake Agassiz in the midwestern United States during the last deglaciation. Geology 25: 207–210

Kageyama M, Valdes PJ (2000) Impact of the North American ice-sheet orography on Last Glacial maximum eddies and snowfall. Geophys Res Lett 27: 1515–1518

Kageyama M, Valdes PJ, Ramstein G, Hewitt C, Wyputta U (1999) Northern hemisphere storm tracks in present day and last glacial maximum climate simulations: a comparison of the European PMIP models. J Clim 12: 742–760

Kalnay E, plus 21 others (1996) The NCEP/NCAR 40-year Reanalysis Project. Bull Am Meteorol Soc 77: 437–471

Keigwin LD, Jones GA, Lehman SJ, Boyle EA (1991) Deglacial meltwater discharge, North Atlantic deep circulation, and abrupt climate change. J Geophys Res 96: 16,811–16,826

Klein WH (1957) Principal tracks and mean frequencies of cyclones and anticyclones in the Northern Hemisphere. US Weather Bur Res Pa 40: 1–60

Kirby ME, Mullins HT, Patterson WP, Burnett AW (2001) Lacustrine isotopic evidence for multidecadal natural climate variability related to the circumpolar vortex over the NE USA during the past millennium. Geology 29: 807–810

Knappenberger PC, Michaels PJ (1993) Cyclone tracks and wintertime climate in the mid-Atlantic region of the USA. Int J Climatol 13: 509-531

Lewis CFM, Anderson TW (1992) Stable isotope (O and C) and pollen trends in eastern Lake Erie, evidence for a locally-induced climate reversal of Younger Dryas age in the Great Lakes basin. Clim Dyn 6: 241–250

Ludlam S (1969) Fayetteville Green Lake, New York. III. The laminated sediments. Limn Oceanogr 14: 848–857

Manabe S, Broccoli AJ (1990) Mountains and arid climates of middle latitudes. Science 247: 192–195

Manabe S, Stouffer RJ (1999) The role of thermohaline circulation in climate. Tellus 51A-B: 91–109

Mangerud J, Anderson ST, Birklund BE, Donner JJ (1974) Quaternary stratigraphy of Norden, a proposal for terminology and classification. Boreas 3: 109–128

Michel RL, Kraemer TF (1995) Use of isotopic data to estimate water residence times of the Finger Lakes, New York. J Hydrol 164: 1–18

Mullins HT (1998) Holocene lake level and climate change inferred from marl stratigraphy of the Cayuga Lake Basin, New York. J Sediment Res 68: 569–578

Mullins HT, Halfman J (2001) High-resolution seismic reflection evidence for middle Holocene environmental change, Owasco Lake, New York. Quat Res 55: 322–331

Namias J (1978) Multiple causes of the North American abnormal winter 1976–77. Mon Weather Rev 106: 279–295

O'Brien SR, plus 5 others (1995) Complexity of Holocene climate as reconstructed from a Greenland ice core. Science 270: 1962–1964

Rozanski K, Araguas-Araguas L, Gonfiantini R (1993) Isotopic patterns in modern global precipitation. Am Geophys Union Monogr 78: 1–36

Sandweiss DH, Maasch KA, Anderson DG (1999) Transitions in the mid-Holocene. Science 283: 499–500

Smith MA, Hollander DJ (1999) Historical linkage between atmospheric circulation patterns and oxygen isotopic record of sedimentary carbonates from Lake Mendota, Wisconsin, USA. Geology 27: 589–592

Steig EJ (1999) Mid-Holocene climate change. Science 286: 1485–1487

Stuiver M, Reimer PJ (1993) Extended ^{14}C base and revised CALIB 3.0 ^{14}C age calibration program. Radiocarbon 35: 215–230

Stuiver M, Grootes PM, Braziunas TF (1995) The GISP2 δ^{18}O climate record of the past 16,500 years and the role of the Sun, ocean, and volcanoes. Quat Res 44: 341–354

Takahashi T, Broecker W, Li YH, Thurber D (1968) Chemical and isotopic balances for a meromictic lake. Limno Oceanogr 13: 272–292

Thompson JB, Schultze-Lam S, Beveridge TJ, Des Marais DJ (1997) Whiting events: biogenic origin due to the photosynthetic activity of cyanobacterial picoplankton. Limn Oceanog 42: 133–141

Timmerman A, Latif M, Voss R, Grotzner A (1998) Northern hemispheric interdecadal variability: a coupled air-sea mode. J Clim 11: 1906–1931

von Grafenstein U, Erlenkeuser H, Brauer A, Jouzel J, Johnsen SJ (1999) A mid-European decadal isotope-climate record from 15,500 to 5000 years BP. Science 4: 1654–1657

Wang L, plus 6 others (1999) Holocene variations in Asian Monsoon moisture: a bidecadal sediment record from the South China Sea. Geophys Res Lett 26: 2889–2892

Willemse NW, Tornqvist TE (1999) Holocene century-scale temperature variability from West Greenland lake records. Geology 27: 580–584

Yarnal B, Leathers DJ (1988) Relationships between interdecadal and interannual climatic variations and their effect on Pennsylvania climate. Ann Assoc Am Geogr 78: 624–641

Yu Z, Eicher U (1998) Abrupt climate oscillations during the last deglaciation in central North America. Science 282: 2235–2238

Yu Z, McAndrews JH, Eicher U (1997) Middle-Holocene dry climate caused by changes in atmospheric circulation patterns: evidence from lake levels and stable isotopes. Geology 25: 251–254

Zishka KM, Smith PJ (1980) The climatology of cyclones and anticyclones over North America and surrounding ocean environs for January and July, 1950–77. Mon Weather Rev 108: 387–401