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Deglacial to middle Holocene (16,600 to 6000 calendar years BP) climate change in the northeastern United States inferred from multi-proxy stable isotope data, Seneca Lake, New York

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Abstract

Climate change in the northeastern United States has been inferred for the last deglaciation to middle Holocene (~16,600 to 6000 calendar years ago) using multi-proxy data (total organic matter, total carbonate content, δ^{18} O calcite and δ^{13} C calcite) from a 5 m long sediment core from Seneca Lake, New York. Much of the regional postglacial warming occurred during the well-known Bolling and Allerod warm periods (~14.5 to 13.0 ka), but climate amelioration in the northeastern United States preceded that in Greenland by ~2000 years. An Oldest Dryas climate event (~15.1 to 14.7 ka) is recognized in Seneca Lake as is a brief Older Dryas (~14.1 ka) cold event. This latter cold event correlates with the regional expansion of glacial Lake Iroquois and global meltwater pulse IA. An increase in winter precipitation and a shorter growing season likely characterized the northeastern United States at this time. The Intra-Allerod Cold Period (~13.2 ka) is also evident supporting an "Amphi-Atlantic Oscillation" at this time. The well-known Younger Dryas cold interval occurred in the northeastern United States between 12.9 and 11.6 ka, consistent with ice core data from Greenland. In the Seneca Lake record, however, the Younger Dryas appears as an asymmetric event characterized by an abrupt, high-amplitude beginning followed by a more gradual recovery. Compared to European records, the Younger Dryas in the northeastern United States was a relatively low-amplitude event. The largest amplitude and longest duration anomaly in the Seneca Lake record occurs after the Younger Dryas, between ~11.6 and 10.3 ka. This "post-Younger Dryas climate interval" represents the last deglacial climate event prior to the start of the Holocene in the northeastern United States, but has not been recognized in Greenland or Europe. The early to middle Holocene in the northeastern United States was characterized by low-amplitude climate variability. A general warming trend during the Holocene Hypsithermal peaked at ~9 ka coincident with maximum summer insolation controlled by orbital parameters. Millennial- to century-scale variability is also evident in the Holocene Seneca Lake record, including the well-known 8.2 ka cold event (as well as events at ~7.1 and 6.6 ka). Hemispherical cooling during the Holocene Neoglacial in the northeastern United States began ~5.5 ka in response to decreasing summer insolation.

Introduction

As the threat of global warming increases, it has become important to develop multi-proxy records of deglacial to Holocene climate change in order to temporally extend short (<150 years) instrumental records of climate variability and to aid in the projection of future climates. This is particularly true for heavily populated, economically important, mid-latitude regions of the world such as the northeastern United States where future climate change may have major social and economic impacts.

The Intergovernmental Panel on Climate Change (IPCC 2001) has recently concluded that global mean surface temperatures increased by 0.6 ± 0.2 °C over the 20th century, which is the largest centennial temperature increase of the last millennium, culminating in the warmest decade (1990s) on record. Precipitation has also increased by 0.5–1.0% per decade during the 20th century over most mid-latitude continental areas of the Northern Hemisphere along with an ~2% increase in cloud cover (IPCC 2001). Although there are uncertainties, the IPCC has further concluded that most of the observed climate change is largely a result of anthropogenic increases in the concentration of atmospheric carbon dioxide. The IPCC (2001) projects that mean global surface temperature will likely rise by 1.4–5.8 °C by the end of the 21st century and that precipitation will continue to increase over northern mid-latitudes.

A major difficulty with these projections, however, is that climate change occurs as a result of both natural as well as anthropogenic forcing, on a global as well as regional basis, and on a variety of time scales. Thus, it is critical to be able to deconvolve natural *versus* anthropogenic climate signals on regional (as well as global) scales and to recognize climate change on a variety of time scales. Because of the short temporal nature of direct, instrumental climate data we must rely heavily on proxy records, especially those from the last ~16,600 calendar years.

Bottom sediment in lakes is a proven natural archive of mid-latitude climate and environmental change on the continents during and since the last deglaciation. This is especially true for hardwater lakes that seasonally precipitate calcium carbonate (calcite) which can be analyzed for stable oxygen and carbon isotopic composition and inferences made about past climates and environmental conditions (Kelts and Talbot 1990). Syracuse University has been investigating the stable isotope record of the Finger Lakes region of central New York State since the mid-1990s in an effort to develop composite multi-proxy records of deglacial and Holocene climate change for the northeastern United States. The first stable isotope record from the Finger Lakes was developed by Anderson et al. (1997) who used calcite-rich sediments from Seneca Lake to uncover a previously unrecognized cold paleoclimate following the well-known Younger Dryas climate reversal.

This discovery has prompted us to return to Seneca Lake and construct a more detailed, high-resolution, multi-proxy record of climate/environmental change for the last deglaciation to middle Holocene in the northeastern United States. Because the work of Anderson et al. (1997) was the initial record from the Finger Lakes it was, by design, completed at a relatively coarse sampling interval of 10 cm for sediment parameters and 5 cm (~200 years between samples) for stable isotopes. We have collected a new piston core from Seneca Lake (SL-102695; 142 m water) and sampled it, as well as Anderson et al.'s (1997) original core SL-17, at a 2 cm interval (~20–140 years between samples depending on sediment accumulation rate). The purpose of this paper is to present results of this new, high-resolution, multi-proxy sediment record from Seneca Lake. We discuss the implications of new results for climate change during the last deglaciation to middle Holocene in the northeastern United States and compare our record with the GISP2 ice core in Greenland (Figure 1).

Description of site studied

The Finger Lakes of central New York State consist of eleven, elongate, glacially scoured lake basins, which are typically divided into seven larger eastern lakes and four smaller western lakes (Mullins and Hinchey 1989; Mullins et al. 1996). The Finger Lakes were most recently eroded by a surge of the Laurentide ice sheet associated with Heinrich event H-1 ~14,500 ^{14}C years (~17,000 calendar years) ago (Mullins et al. 1996). Seneca Lake is the largest of the Finger Lakes having a maximum length of ~60 km and a maximum water depth of 186 m. The postglacial sediment fill beneath Seneca Lake is typically <10 m thick, although total sediment fill approaches 300 m (Mullins et al. 1996). A number of piston cores (<~6 m) have previously been collected from Seneca Lake. These cores recovered mostly pink, proglacial varves overlain by gray, postglacial,

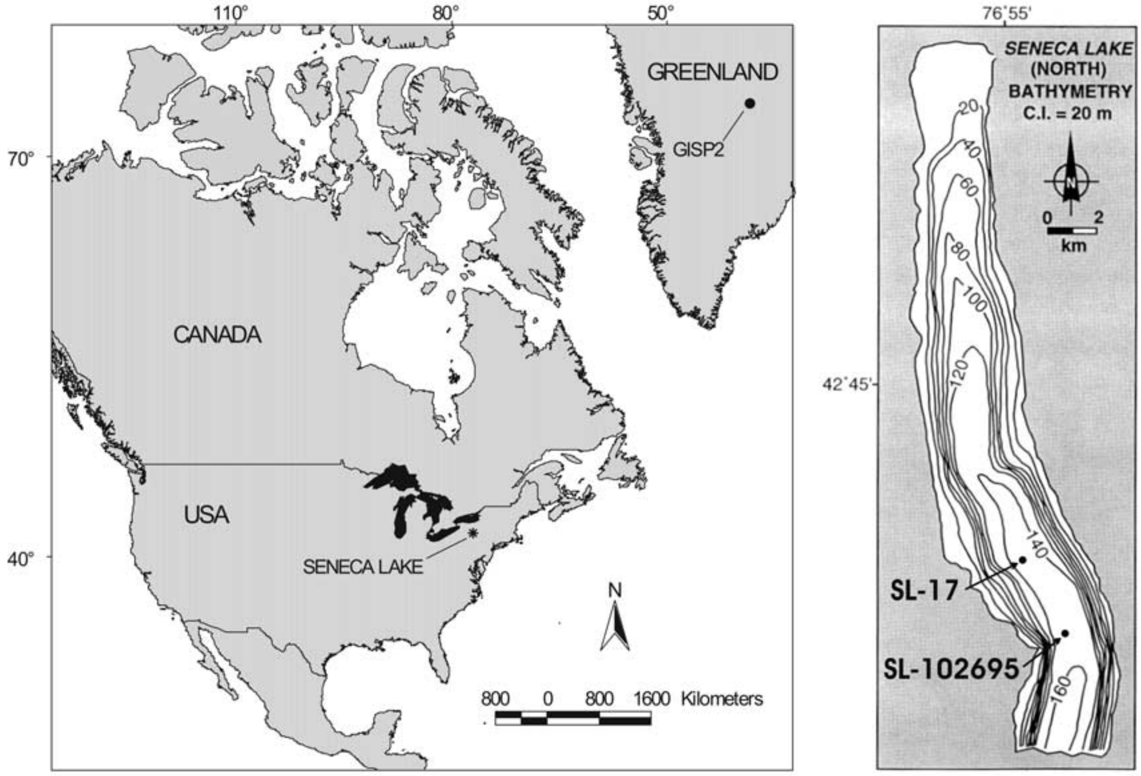

Figure 1. General index map illustrating the location of the Finger Lakes relative to the GISP2 Greenland ice core. Also shown is the bathymetry of Seneca Lake and the location of piston cores SL-17 and SL-102695 used in this study.

organic-rich mud from the profundal zone of the lake (Woodrow et al. 1969; Mullins and Hinchey 1989; Mullins et al. 1996; Anderson et al. 1997; Halfman and Herrick 1998; Meyers 2002). Radiocarbon dates on bulk organic matter near the contact between proglacial and postglacial sediment in Seneca Lake indicate an age of ~14,000 ^{14}C years before present (BP; ~16,600 calendar years BP) for this boundary (King et al. 1983; Anderson et al. 1997). Postglacial sediment in Seneca Lake is rich (up to 40 wt%) in fine-grained, authigenic calcium carbonate (calcite), with the exception of the late Holocene prior to ~1820 (Anderson et al. 1997; Halfman and Herrick 1998; Lajewski et al. 2003). Although modern, seasonal, open-water precipitation of calcite has yet to be directly documented for Seneca Lake, it has for other nearby eastern Finger Lakes, such as Cayuga, Owasco and Otisco (Effler and Johnson 1987; Effler et al. 1987, 2001).

In terms of its limnology, Seneca Lake is a hard-water, warm monomictic lake which stratifies thermally only during the summer (Bloomfield 1978; Callinan 2001). It is also presently a lake in transition from mesotrophic to oligotrophic conditions, due in part to the invasion of zebra mussels (Halfman et al. 2001). It is a hydrologically open lake receiving ~75% of its water inflow from spring snowmelt and it has a water residence time of ~12 years (Bloomfield 1978; Michel and Kraemer 1995; Callinan 2001). The lake is well-oxygenated throughout the water column all year. It does, however, contain elevated Cl^- and Na^+ concentrations in deep bottom waters as well as sediment pore waters (up to 30 parts per thousand) due to the flux of saline groundwater from underlying Silurian salt beds (Bloomfield 1978; Wing et al. 1995; Callinan 2001) that inhibits sediment bioturbation.

The modern climate of the Finger Lakes region is typical of its mid-latitude, continental interior setting with long, cold, snowy winters and short, hot, humid summers. Regional climate is greatly influenced by the position and shape of the polar front jet stream that controls air mass movements, storm

Table 1. Radiocarbon data.[1]

Lab no.	Core no.	Depth (cm)	Material	$\delta^{13}C$ (per mil)	Radiocarbon age	Calibrated age
15244	SL-17	87.5	Organics	−27.7	3510 ± 50	3700
15246	SL-17	188.5	Organics	−28.7	5620 ± 60	6340
15243	SL-17	292.5	Organics	−25.3	8280 ± 75	9250
15245	SL-17	387.5	Organics	−28.3	13,865 ± 100	16,630
26284	SL-102695	288.0	Orgaincs	−27.5	6065 ± 65	6953
26285	SL-102695	332.0	Organics	−27.7	7715 ± 65	8465
26287	SL-102695	432.0	Organics	−33.5	9065 ± 75	10,096

[1] All radiocarbon analyses performed at the University of Arizona (AA) AMS Laboratory, Tucson, AZ, after removal of all carbonate. Calibrated ages given as mean in calendar years prior to 1950 AD.

tracks as well as moisture supply/sources and isotopic composition of precipitation (Eichenlaub 1979; Kirby et al. 2001; Burnett and Mullins 2002). The Finger Lakes are also greatly influenced by lake-effect snow (highly depleted in ^{18}O) from the nearby Great Lakes. Gat et al. (1994) have estimated that ~5–15% of downwind summer and autumn atmospheric water vapor is derived from the Great Lakes which has lower $\delta^{18}O$ values than water vapor originating from the ocean. Significantly, more water vapor is likely derived from the Great Lakes in winter during lake-effect snowstorms.

Materials and methods

We collected a new piston core (SL-102695; ~5 m long) from Seneca Lake using Hobart and William Smith Colleges' research vessel EXPLORER, ~4 km to the south of Anderson et al.'s (1997) original core SL-17 (Figure 1). A high-resolution (2–24 kHz) Edge-Tech seismic reflection profile was also collected between the two core sites to ensure continuity of reflections and depositional sequences as defined by Mullins et al. (1996). The new core (SL-102695) was split, described and sub-sampled every 2 cm, as was Anderson et al.'s (1997) core (SL-17). Both cores were then analyzed for total weight percent organic matter and carbonate content by loss-on-ignition (LOI) at 550 and 1000 °C, respectively (Dean 1974). The LOI method slightly (3–4%) overestimates the total weight percent of carbonate present in clay-rich sediment because of the loss of water from the crystal lattice of clay minerals at 1000 °C (Dean 1974); thus, total carbonate values <5% are considered to have no carbonate. The two piston cores (SL-17 and SL-102695) were then correlated on the basis of their total carbonate content which allowed for the transfer of four previously obtained radiocarbon dates (Table 1) from Anderson et al.'s (1997) original core (SL-17) to new core SL-102695. In addition, three new AMS radiocarbon dates (Table 1) were obtained from bulk organic material in core SL-102695 (following the removal of carbonate) at the University of Arizona's AMS Radiocarbon Laboratory in Tucson. All radiocarbon dates ($N = 7$) were calibrated to calendar years using the program of Stuiver and Reimer (1993). These seven calibrated radiocarbon dates were then used to construct an age model for new core SL-102695 in calendar years prior to 1950. All ages referred to in this text are approximations; potential error can be obtained from data in Table 1.

Sub-samples from core SL-102695 were also analyzed every 2 cm by standard X-ray diffraction techniques in order to quantify the relative percentages (peak area method) of calcite *versus* dolomite. All sub-samples from core SL-102695 were then size separated by pipette techniques (Folk 1974) to isolate the <4 μm (clay-size) fraction, which contained only calcite, as confirmed by X-ray diffraction. These fine-grained calcite sub-samples were then sent to Mountain Mass Spectrometry in Evergreen, Colorado for standard stable oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) analysis.

Results

Similar to core SL-17 recovered by Anderson et al. (1997), the new core from Seneca Lake (SL-102695) bottomed in massive gray clay overlain by dark gray to black, laminated (mm-scale), organic-rich mud (Figure 2). The two cores can readily be correlated. Each core displays an abrupt

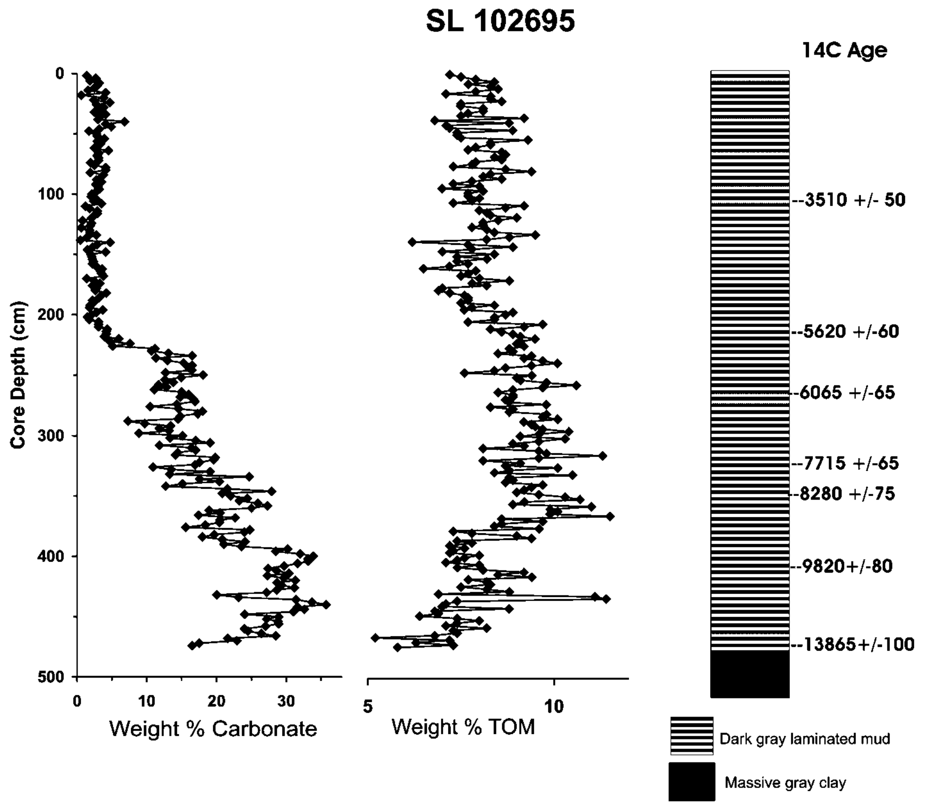

Figure 2. Generalized lithostratigraphy for core SL-102695 along with total organic matter (TOM) and total carbonate (TC) content for the entire core *versus* subsurface depth. Also shown are locations of radiocarbon dates along core.

increase in total carbonate near its base, a distinct decrease in carbonate content (negative anomaly) ~1 m above their base, and a drop to "zero" carbonate about 1.5 m above the top of the negative carbonate anomaly (Figure 3). Our age model for core SL-102695 (Figure 4) allowed for the transformation of depth in core SL-102695 to calendar years BP. For the remainder of this paper, we will focus on that portion of core SL-102695 that contains authigenic calcite available for stable isotope analysis (~16,600 to 6000 calendar years BP) which extends from the last deglaciation into the middle Holocene. For a discussion on the absence of late Holocene carbonate in the Finger Lakes and its return during historic time, the reader is referred to Mullins (1998a, b) and Lajewski et al. (2003).

Total organic matter

Total weight percent organic matter (TOM) during the last deglaciation to middle Holocene in Seneca Lake varies from a minimum of 5% to a maximum of ~12% displaying a general increase up-core, although anomalies of up to 4% are present (Figures 2 and 5). TOM values increase from the base of the core at 16.6 ka (thousands of years ago) followed by a negative anomaly that lasted about a millennium between 15.2 and 14.3 ka. TOM values reach a maximum value of 12% at 13.5 ka followed by a second negative anomaly centered at 13.2 ka (Figures 2 and 5). The largest negative anomaly in the TOM data lasts for about 1800 years between 11.9 and 10.1 ka followed by a rapid rise of 3% peaking at 9.7 ka. Another negative anomaly is centered at 8.3 ka with subsequent low-amplitude, high-frequency variability in TOM values that extend to the top of our record (Figures 2 and 5).

Total carbonate content

Total weight percent carbonate (TC) values display a distinct asymmetric distribution between 16.6

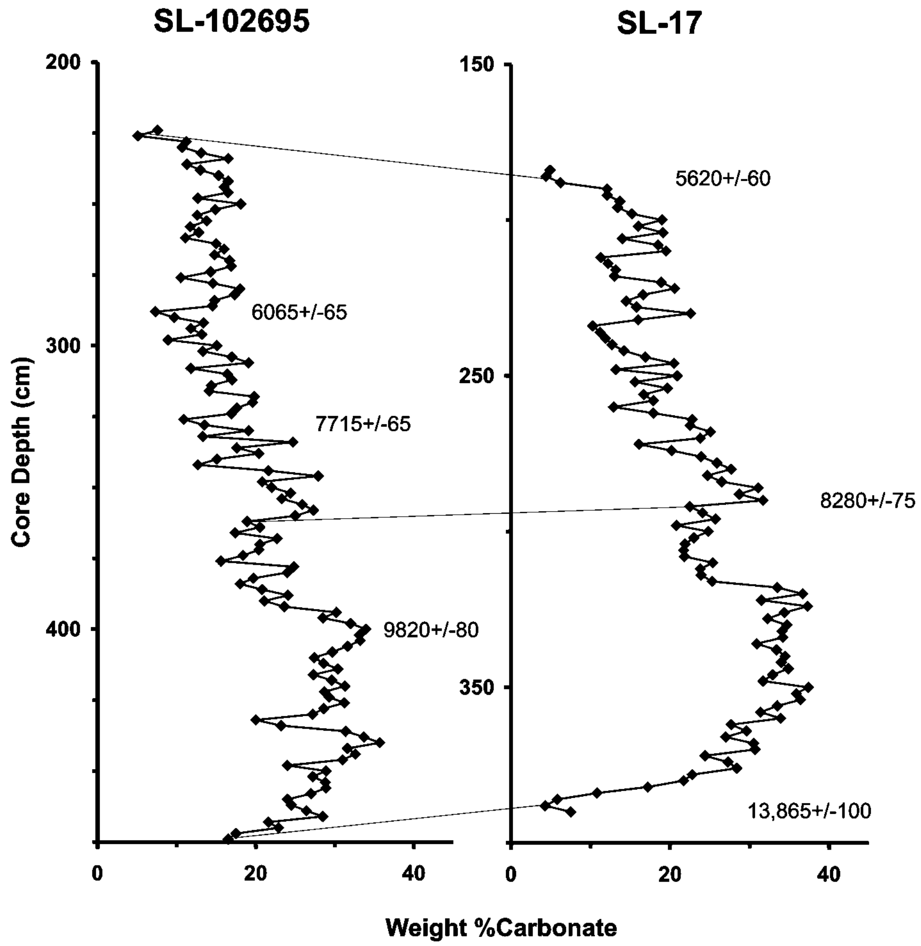

Figure 3. Correlation between cores SL-17 and SL-102695 based on TC content. Correlation allows transfer of three radiocarbon ages (Table 1) from core SL-17 (Anderson et al. 1997) to core SL-102695 as shown by lines. Additional radiocarbon ages for SL-102695 are also shown.

and 6.0 ka, characterized by an abrupt increase followed by a gradual decrease, although distinct anomalies are also present (Figures 3 and 5). TC values range from a maximum of 37% at 14.0 ka to a minimum value of 8% at 7.0 ka. TC values increase fairly steadily from 15% near the base of the core at 16.5 ka for ~2500 years when maximum values of 37% are reached (Figures 3 and 5). TC values are somewhat lower (8%) until 11.2 ka when a second peak (32%) occurs. A distinct drop (15%) in TC values is centered at 13.3 ka (Figures 3 and 5). A major negative TC anomaly (up to 20%) occurs between 11.3 and 10.1 ka, followed by a third peak in TC values (25%) at 9.2 ka (Figures 3 and 5). Subsequent TC values decline fairly steadily to 10% over the next 3000 years with negative anomalies (up to 10%) centered at 8.3, 7.1 and 6.6 ka (Figures 3 and 5).

Stable isotopes

$\delta^{18}O$ calcite values in core SL-102695 range from −6.5 to −8.5 per mil consistent with the range reported by Anderson et al. (1997). Similar to the TC data (Figures 3 and 5), the oxygen isotope data are characterized by an asymmetry with a relatively rapid rise in $\delta^{18}O$ values between 16.6 and 14.0 ka followed by a more gradual decline to 6.0 ka (Figure 6a, b). The record, however, is punctuated

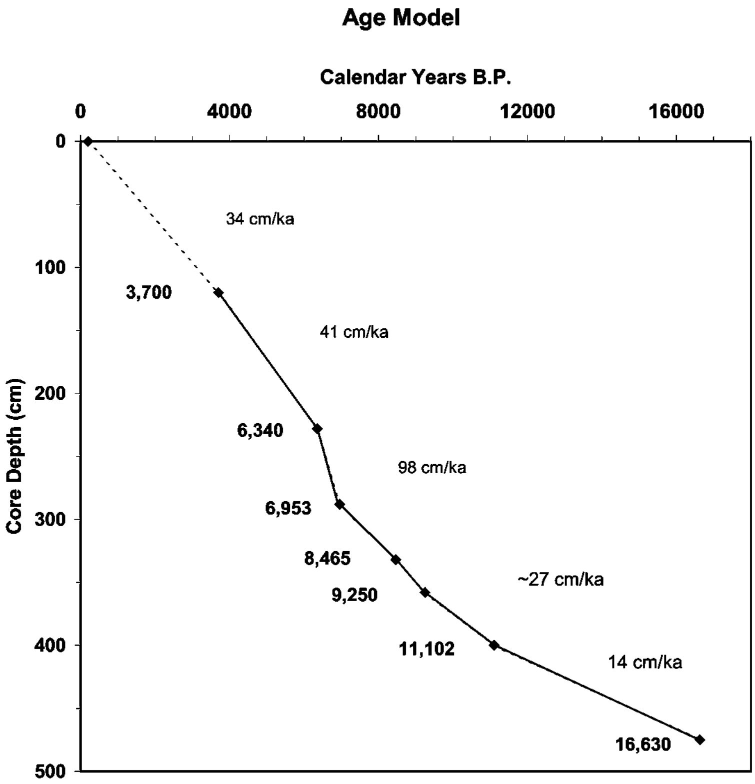

Figure 4. Age model (age *versus* depth) for core SL-102695 based on all available ($N = 7$) radiocarbon data. Four dates transferred, via TC correlation, from core SL-17 combined with three new dates from core SL-102695 (Table 1). Note variable sediment accumulation rates.

by a number of anomalies with amplitudes of up to 2.0 per mil. The relatively rapid rise of $\delta^{18}O$ values near the base of the core is interrupted by a negative anomaly centered at 14.0 ka (Figure 6a, b). $\delta^{18}O$ values drop by 1.3 per mil followed by an increase of nearly 2.0 per mil. A second, lower amplitude negative anomaly (0.5 per mil) occurs between 13.2 and 11.8 ka (Figure 6a, b). The longest duration (~1700 years) negative oxygen isotope anomaly occurs between 11.6 and 9.9 ka with the lowest $\delta^{18}O$ values of the entire record at 10.6 ka (Figure 6a, b). Here, $\delta^{18}O$ values drop rapidly by more than 1.0 per mil. Following this oxygen isotope anomaly is a series of lower amplitude (<0.5 per mil) negative anomalies at ~8.2, 7.2 and 6.8 ka (Figure 6a, b).

$\delta^{13}C$ calcite values in core SL-102695 range from ~0.0 to −3.5 per mil *versus* a range of only ~0.0 to −2.0 per mil reported by Anderson et al. (1997). The presence of more negative $\delta^{13}C$ values in core SL-102695 may simply be a function of its higher resolution. The overall trend of the carbon isotope data between the two cores is similar, though, in that both display a gradual up-core increase in $\delta^{13}C$ that is punctuated by a number of negative anomalies. $\delta^{13}C$ values increase gradually from the base of core SL-102695 at 16.6–12.0 ka where there is an abrupt decrease of $\delta^{13}C$ values of 1.0–2.0 per mil (Figure 6a, b). Following this relatively abrupt decline, $\delta^{13}C$ values again display a gradual overall increase to 6.0 ka. A negative anomaly occurs between 13.2 and 12.5 ka and is centered at 13.0 ka (Figure 6a, b). Here, $\delta^{13}C$ values decrease, then increase, by ~1.5 per mil. A second negative anomaly is present between 11.6 and 10.0 ka with a minimum $\delta^{13}C$ value occurring at 11.1 ka (Figure 6a, b). A third negative $\delta^{13}C$ anomaly occurs between 8.4 and 7.4 ka with a minimum value centered at 8.0 ka where $\delta^{13}C$ values drop, and then rebound, by 1.25 per mil. Two smaller scale $\delta^{13}C$ anomalies are centered at 7.1 and 6.6 ka (Figure 6a, b).

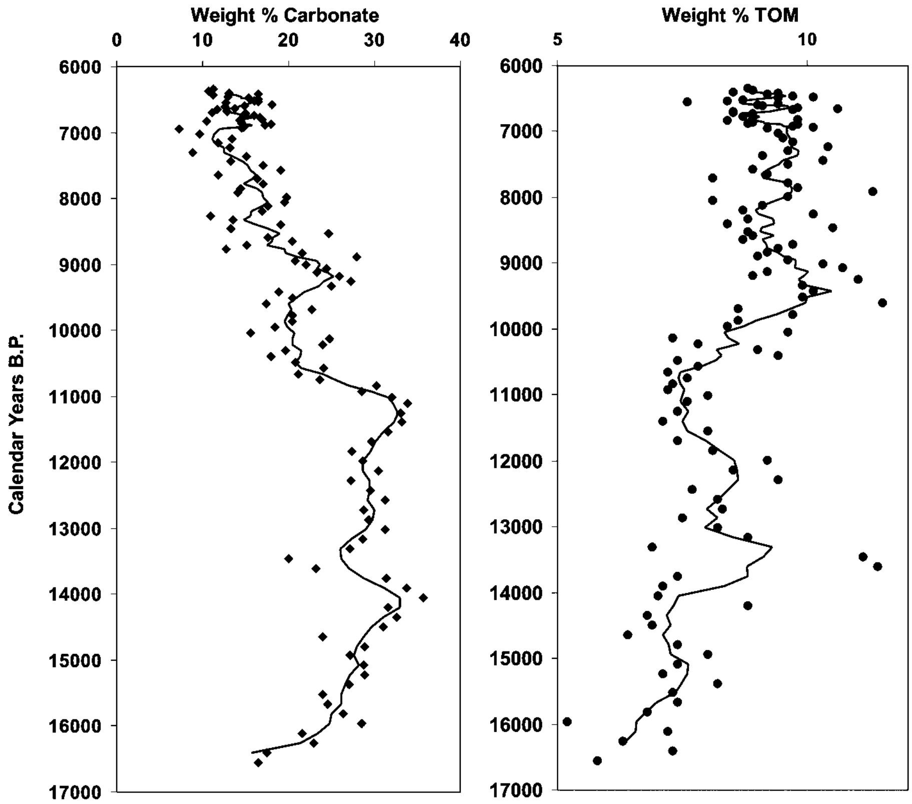

Figure 5. TOM and TC data for core SL-102695 for the period 16.6 to 6.0 ka which contains calcite for stable isotope analysis. Raw data shown as black diamonds or filled circles plus a five-point running average (solid curve).

Discussion

The total organic matter content of sediment in lakes is controlled by a number of variables. Dean and Gorham (1998) and Dean (1999) have found that most organic matter, in all but the most oligotrophic lakes, is authocthonous, generated by primary biological production within the lake basin; a general conclusion confirmed for Seneca Lake by Meyers (2002). Primary productivity, however, varies as a function of sunlight, temperature, nutrients and thermal stratification of the water column. Preservation of authocthonous organic matter in sediment at the bottom of lakes is also a function of oxygen concentrations in near bottom waters, as well as diagenesis within the sediment column. The amount of total sedimentary organic matter in a lake is further influenced by the flux of terrestrial vegetation from its drainage basin that is dependant upon the amount and timing of atmospheric precipitation (Meyers 2002).

Our TOM data (Figures 2 and 5) display an overall up-core increase between 16.6 and 6.0 ka. This could be a result of increased authocthonous primary production, increased flux of allochthonous organic matter and/or down-core diagenetic degradation of organic matter. Considering the number of TOM anomalies in our dataset, coupled with Dean and Gorham's (1998) conclusion that most lacustrine organic matter is authocthonous in addition to Meyers' (2002) data from Seneca Lake, we interpret our TOM data largely in terms of variations in primary production within the lake basin. We do this with the full knowledge that high-precipitation events can, over short time periods, result in the increased flux of terrestrially derived organic matter. If correct, this suggests an overall increase in primary production between 16.6 and 6.0 ka, probably in response to increasing nutrient supplies and temperature (thermal stratification) between the last deglaciation and the middle Holocene. During this time, summer insolation

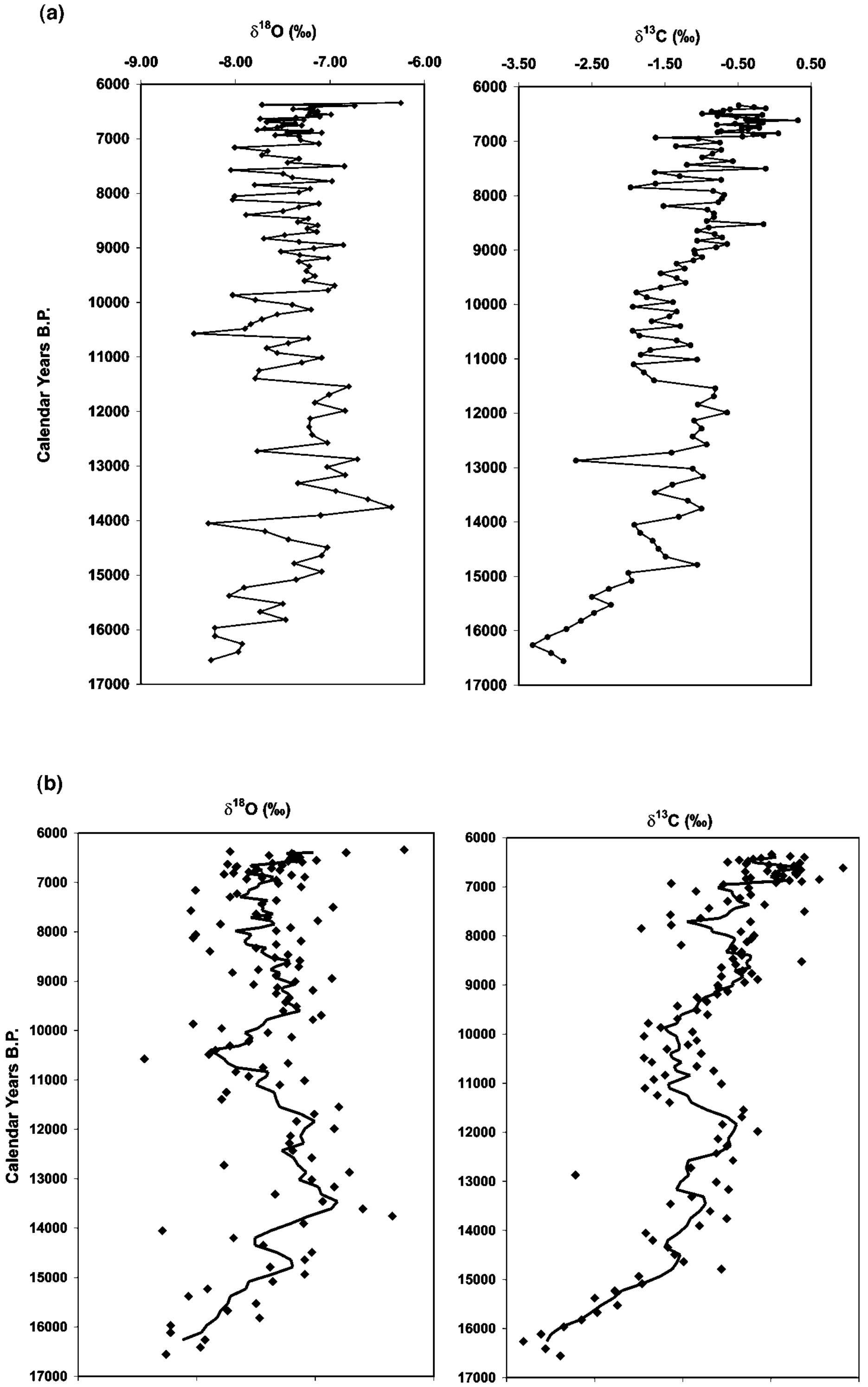

Figure 6. (a) $\delta^{18}O$ and $\delta^{13}C$ calcite raw data (black diamonds) from Seneca Lake core SL-102695 *versus* age. (b) Same data as in "a" with a five-point running average (solid curve).

increased (~8%) in the Northern Hemisphere in response to changing orbital parameters, such as precession of the equinoxes and obliquity (COHMAP 1988). Warmer summers would have increased chemical weathering rates in the watershed of Seneca Lake and thus the flux of nutrients to the lake, as well as allowed thermal stratification to become established sooner and last longer, both of which would promote an increase in authocthonous primary productivity over time. The prominent negative TOM anomalies observed in core SL-102695 (Figures 2 and 5) are most likely due to non-orbitally induced climate changes that varied sunlight, temperature, nutrient supply, atmospheric precipitation, terrestrial runoff and/or thermal stratification of the water column, all of which are linked to climate.

Calcite

The precipitation of calcite from hardwater lakes is also controlled by a complex set of factors (Kelts and Talbot 1990). The most important factor is the degree of saturation of surface waters with respect to calcite that is largely controlled by the concentration (activity) of calcium and carbonate ions as well as the solubility product of calcite (Drever 1997). Only saturated or supersaturated surface waters result in the widespread, open-water precipitation of calcite from lakes. Study of modern lakes has demonstrated that temperature is a major factor because it controls the solubility product of calcite as well as the thermal stratification of the water column (Hodell et al. 1998). Biological processes also play a critical role, particularly the rate of primary production (photosynthesis) and the abundance of picoplankton. Phytoplankton are known to mediate the precipitation of calcite by either acting as nucleation sites (picoplankton) or via photosynthetic removal of carbon dioxide and the increase of pH which can trigger the precipitation of calcite (Thompson et al. 1997; Hodell et al. 1998). Many of these factors, however, are linked to climate. Lajewski et al. (2003) recently discovered that historic age (<200 years) calcite in the Finger Lakes is largely a record of chemical weathering, as it controls the flux of calcium and carbonate/bicarbonate ions from watersheds and, thus, the saturation state of surface waters with respect to calcite. The rate of chemical weathering, however, is dependent upon both temperature and precipitation (Drever 1997), which are strongly linked to climate. Thus, despite the myriad of physical, chemical and biological controls on the precipitation of calcite from lakes, it can be used as a general proxy of climate change.

The TC record from Seneca Lake (Figures 3 and 5) is distinctly asymmetric, characterized by a relatively abrupt increase beginning 16.6 ka followed by a more gradual decline of values to 6.0 ka. Calcite concentration goes to zero in Seneca Lake ~5.5 ka near the transition from the relatively warm Holocene Hypsithermal to the cool Neoglacial (Anderson et al. 1997; Mullins 1998b; Meyers 2002). The relatively rapid increase in TC in Seneca Lake following the retreat of the Laurentide ice sheet probably reflects warming temperatures and the chemical weathering of calcareous glacial drift and limestone in its watershed. In contrast, the gradual decline in calcite content probably is a consequence of gradually cooling temperatures (reduced thermal stratification) and less intense chemical weathering associated with the onset of the Holocene Neoglacial. The specific TC anomalies observed in Seneca Lake (Figures 3 and 5) were likely influenced by shorter term climate variability which controlled the saturation state of surface waters with respect to calcite as well as other physical, chemical and biological processes that affect calcite precipitation.

Oxygen isotopes

A number of factors control the oxygen isotope composition of calcite precipitated from lakes. The temperature relationship is an inverse one with lower temperatures resulting in higher $\delta^{18}O$ values (Rozanski et al. 1993). Hilfinger et al. (2001), using historic age varves from nearby Fayetteville Green Lake and meteorological data, established that the isotopic composition of surface waters is the dominant control of $\delta^{18}O$ calcite values in lakes in the central New York region. The isotopic composition of surface waters in this area is largely a function of air masses and their isotopic composition and/or the amount of summer (high $\delta^{18}O$) *versus* winter (low $\delta^{18}O$) precipitation, including lake effect snow (very low $\delta^{18}O$). Kirby et al. (2001), also using historic age varves from Green Lake, found a statistically significant

($r = -0.79$) relationship between the latitudinal position of the winter polar front jet stream and the $\delta^{18}O$ value of calcite. Burnett and Mullins (2002) discovered (using modern precipitation and meteorological data) that when the upper troposphere trough over the northeastern United States is centered west of the Finger Lakes, it promotes the advection of air masses with water vapor that is enriched in ^{18}O (-5 to -10 per mil SMOW). When this atmospheric trough is centered over the Finger Lakes or slightly to the east, however, it results in precipitation that is depleted in ^{18}O (-20 to -25 per mil SMOW; Burnett and Mullins 2002). Thus, $\delta^{18}O$ values from the Finger Lakes can be used as a proxy for climate change and a general indicator of atmospheric circulation patterns over the northeastern United States (Hilfinger et al. 2001; Kirby et al. 2001, 2002a, b; Burnett and Mullins 2002).

The overall asymmetric nature (rapid rise followed by a more gradual decline) of the $\delta^{18}O$ calcite record from Seneca Lake (Figure 6a, b) suggests long term, orbital controls (precession and obliquity) on regional climate during the last deglaciation to middle Holocene. Distinct anomalies in this general trend (Figure 6a, b), however, argue for shorter term climate variability and its control on atmospheric circulation patterns over the northeastern United States as well as the isotopic composition of surface waters in Seneca Lake.

Carbon isotopes

Carbon isotope values of calcite in lake sediment have traditionally been interpreted in terms of changes in primary productivity (McKenzie 1985) because primary producers selectively remove ^{12}C during photosynthesis, rendering the dissolved inorganic carbon pool of surface waters relatively enriched in ^{13}C. Times of higher primary productivity should, thus, be reflected by relatively high $\delta^{13}C$ calcite values. McKenzie (1985) interpreted variable levels of primary production largely as a function of nutrient supply. This paradigm, however, has recently been challenged. The dissolved inorganic carbon pool of lakes can vary with the flux of terrestrial organic matter that may be enriched or depleted in ^{12}C as a function of moisture stress as well as the concentration of atmospheric carbon dioxide (Patterson and Mullins 2002). Hollander and Smith (2001) have also proposed an alternative model for hyper-eutrophic lakes that are dominated by chemoautotrophic or methanotrophic microbes which can result in very low $\delta^{13}C$ calcite values despite being highly productive. Carbon isotopes of calcite in lakes may also reflect the amount of atmospheric precipitation and cloud cover. Kirby et al. (2002b) discovered a statistically significant ($r = -0.74$) relationship between $\delta^{13}C$ calcite values and the amount of early summer (May–July) precipitation in central New York. They argued that increased cloud cover reduces solar radiation reaching the lake surface which results in lower levels of primary productivity and consequently lower $\delta^{13}C$ calcite values, independent of nutrient supply. Seneca Lake is not a hyper-eutrophic lake, however, and natural nutrient supply, atmospheric precipitation, humidity and cloud cover are variables that are strongly linked to climate. Thus, $\delta^{13}C$ calcite values can be used to infer climate variability over time.

The overall trend of $\delta^{13}C$ calcite values for Seneca Lake from 16.6 to 6.0 ka is one of a general increase with a significant step decrease at 12.0 ka (Figure 6a, b). Using the model of McKenzie (1985) these data would imply increasing nutrient supply, and thus primary productivity, in Seneca Lake over time, interrupted at 12.0 ka by a relatively abrupt decrease of nutrients. In contrast, using the model of Kirby et al. (2002b), these data would suggest decreasing levels of atmospheric precipitation and cloud cover over time with a relatively abrupt increase of precipitation/cloud cover at 12.0 ka. The Patterson and Mullins (2002) model for $\delta^{13}C$ calcite would also argue for an increase in precipitation/humidity at 12 ka in the Finger Lakes region.

Deglacial climate change

As illustrated by the above discussion, individual proxy datasets do not allow for unique interpretations of past climate or environmental change. A multi-proxy approach, which integrates different (TOM, TC, $\delta^{18}O$ calcite, $\delta^{13}C$ calcite) datasets provides an opportunity to limit and constrain paleoclimatic interpretations and inferences for the northeastern United States between 16.6 and 6.0 ka.

Climate variability in the Northern Hemisphere over the past 16,600 calendar years has been well

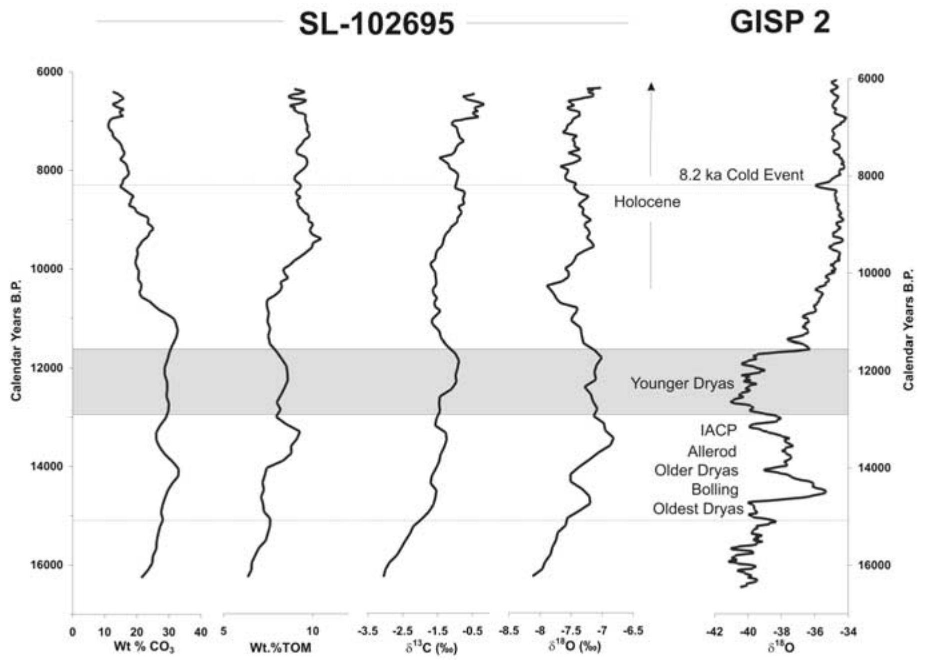

Figure 7. Multi-proxy data (five-point smooth) from Seneca Lake compared temporally with δ^{18}O ice data (five-point smooth) from the GISP2 ice core (Stuiver et al. 1995). Prominent climate events are highlighted.

established by a number of ice core datasets from Greenland, which have been summarized by Stuiver et al. (1995). These data define a number of cold and warm periods during the last deglaciation, such as the Bolling and Allerod warm periods as well as the Oldest, Older and Younger Dryas cold periods in addition to the brief Intra-Allerod Cold Period (IACP). Stuiver et al. (1995) argue in favor of a variety of potential forcing mechanisms including solar, oceanic and volcanic processes. By correlating our Seneca Lake multi-proxy record with the δ^{18}O ice record from Greenland (Figure 7), it is apparent that some of these well-known climate events are present in the Seneca Lake record whereas others are not, and new regional-scale climate events are evident.

Much of the early increase observed in all four proxy datasets from Seneca Lake (Figure 7) occurred during the deglacial warming trends of the Bolling (14.7–14.1 ka) and Allerod (14.0–13.2 ka) periods. All Seneca Lake proxies, however, begin to rise by at least 16.6 ka, shortly after regional retreat of the Laurentice ice sheet from its Heinrich event H-1 position (Mullins et al. 1996), suggesting that deglacial warming in the northeastern United States preceded that in Greenland by ~2000 years. Seltzer et al. (2002) have also documented an early warming of tropical South America that preceded the one in Greenland by at least 5000 years. This time transgressive nature of postglacial warming may be a function of latitudinal control of changing insolation, considering the latitudes of tropical South America (~13 °S), the Finger Lakes (~43 °N) and central Greenland (~73 °N).

Some of the climate proxy variability observed in Seneca Lake, though, does correlate with previously defined climate periods in Greenland ice core data (Figure 7). The Oldest Dryas cold period (15.1 to 14.7 ka) as defined in Greenland, is characterized in Seneca Lake by a distinct negative TOM anomaly and a subtle decrease in TC (Figures 2, 3 and 5), but not by any significant stable isotope anomaly (Figure 6a, b). This suggests a decrease in primary biological productivity, the preservation of TOM/TC and or the influx of terrestrial organic matter but no major change in atmospheric circulation patterns that affect δ^{18}O or δ^{13}C values.

The brief Older Dryas cold period (14.1 ka) in Greenland is reflected in Seneca Lake by a very abrupt, high-amplitude (up to 2.0 per mil) negative $\delta^{18}O$ anomaly as well as an abrupt 1.0 per mil negative $\delta^{13}C$ anomaly (Figures 6 and 7). If the $\delta^{18}O$ Older Dryas isotope anomaly in the Seneca Lake data was due entirely to temperature change, it would imply upwards of an 8 °C (~4 °C/1 per mil $\delta^{18}O$) *warming* in the Finger Lakes region. This appears to be unrealistic in terms of both magnitude and sign. Thus, we interpret the Older Dryas climate interval in the northeastern United States as a cool period characterized by relatively low $\delta^{18}O$ water values. Such an isotopic response may have been a consequence of a greater ratio of winter to summer atmospheric precipitation and/or greater amounts of lake effect snow (low $\delta^{18}O$ values) perhaps driven by an eastward shift of the persistent winter trough in the upper troposphere (jet stream). This scenario is likely following ice retreat north of Lake Ontario and the development of proglacial Lake Iroquois in the Lake Ontario drainage basin by 14.1 ka (Anderson and Lewis 1985; Muller and Calkin 1993; Pair and Rodriquez 1993). Glacial Lake Iroquois (low $\delta^{18}O$ meltwater) may also have extended directly into Seneca Lake at this time because of its relatively low elevation (Muller and Prest 1985). The Older Dryas period in the Finger Lakes also appears to have had a shorter growing season resulting in lower levels of primary productivity (due to the presence of a large, proximal, cold proglacial lake) which may explain the lower $\delta^{13}C$ calcite values observed at this time. The Older Dryas cold period further correlates with global meltwater pulse IA which was a time of rapid melting of ice sheets (Fairbanks et al. 1992), which explains the expansion of glacial Lake Iroquois out of the Lake Ontario basin. It may also have provided a climate change mechanism via influx of low density freshwater to the North Atlantic, reduction of thermohaline circulation and a decrease of heat transport to middle and high northern latitudes (Manabe and Stouffer 1999).

During the warming trend of the Allerod, Greenland ice core data have defined an abrupt, but short lived (<250 years), climate reversal 13.2 ka referred to as the IACP (Stuiver et al. (1995)). In the Seneca Lake record the IACP is manifested as an abrupt, high-amplitude drop in TC (up to 12%; Figures 3 and 5) while TOM drops by at least 4% at this time. Oxygen isotope values decline by ~1 per mil and $\delta^{13}C$ values drop by more than 1.5 per mil (Figure 6a, b). All these proxy indicators from Seneca Lake support the occurrence of the IACP in the northeastern United States, following drainage of glacial Lake Iroquois (Anderson and Lewis 1985). The IACP in Seneca Lake also correlates with a brief pre-Younger Dryas cold period originally defined in the Canadian Maritimes (Killarney Oscillation; Levesque et al. (1993a)). This climate reversal has subsequently been recognized around the North Atlantic Ocean and has been referred to as the Amphi-Atlantic Oscillation (Levesque et al. 1993b). In Europe it is known as the Gerzensee Oscillation (Bjorck et al. 1996). Although the origin of the IACP is not well understood, its similarities with the Younger Dryas climate reversal has led some to speculate a similar forcing mechanism of decreased thermohaline circulation, and thus heat transport, in the North Atlantic region (Levesque et al. 1993b).

The Younger Dryas climate reversal is probably the most studied and best known of all the deglacial climate events. It is particularly well defined in Europe, but less so in the northeastern United States (Peteet 1992; Peteet et al. 1993) outside of southern New England where oxygen isotope data suggest a 6–12 °C temperature drop (Shemesh and Peteet 1998). Anderson et al. (1997) previously recognized a Younger Dryas signal in Seneca Lake but only as a small (<0.5 per mil) decrease in $\delta^{18}O$ calcite values. In our new $\delta^{18}O$ calcite data from Seneca Lake, the Younger Dryas event extends from 12.9 to 11.6 ka which is consistent with its timing in the GISP 2 ice core (Stuiver et al. 1995). In the new Seneca Lake record (Figure 6a, b), the Younger Dryas begins with a very abrupt $\delta^{18}O$ calcite decrease of 1.0 per mil followed by about a millennium of less negative values, similar to that described by Anderson et al. (1997). The higher-resolution $\delta^{18}O$ data define a distinct asymmetry to the Younger Dryas in the northeastern United States that has not previously been recognized. $\delta^{13}C$ calcite values from Seneca Lake also display an abrupt, large amplitude decrease of 1.8 per mil at the start of the Younger Dryas followed by more positive values for the duration of this climate event (Figure 6a, b). These new data suggest that the Younger Dryas climate reversal occurred abruptly (<140 years) in the northeastern United States and was most severe in its early stages.

The Younger Dryas climate reversal has been attributed to the catastrophic drainage of glacial Lake Agassiz through the St. Lawrence River to the North Atlantic Ocean and a consequent reduction, or cessation, of thermohaline circulation (Broecker et al. 1989). This interpretation is widely accepted despite the fact that the Younger Dryas does not coincide with a major global meltwater pulse (Fairbanks et al. 1992). The catastrophic drainage of glacial Lake Agassiz to the North Atlantic at this time, however, can explain the abrupt onset of the Younger Dryas in the northeastern United States as well as the oxygen isotope depletion of atmospheric precipitation. Increased amounts of atmospheric precipitation, as evidenced by higher lake levels (Wellner and Dwyer 1996; Dwyer et al. 1996), may account for the relative subtle decrease of TC values by maintaining chemical weathering rates, as well as the increase in primary productivity via greater nutrient flux. A key finding of the new Seneca Lake data, though, is the asymmetry of the Younger Dryas event characterized by an abrupt, high-amplitude beginning followed by a more gradual recovery. These findings appear to be at odds with Greenland ice core data that indicate both an abrupt beginning and end to the Younger Dryas climate event (Taylor et al. 1993, 1997).

The largest anomaly in proxy data from Seneca Lake occurs *after* the Younger Dryas and defines the last deglacial climate event in the northeastern United States prior to the start of the Holocene. This "post-Younger Dryas climate interval" was originally identified by Anderson et al. (1997) and subsequently confirmed and dated (11.6 to 10.3 ka) by Kirby et al. (2002a) using stable isotope and radiocarbon data from Fayetteville Green Lake, New York. This millennial-scale event has not been recognized in Greenland ice cores (Figure 7) and represents a departure from traditional thought that the Younger Dryas climate reversal marked the end of the last glacial period and the beginning of the Holocene. As such, the "post-Younger Dryas climate interval" may be a regional-scale climate event.

In the new data from Seneca Lake, the post-Younger Dryas climate interval is characterized by a TC decrease of 18% between 11.3 and 10.1 ka which is the largest negative TC anomaly in the entire dataset (Figures 3 and 5). TOM values drop by 2% between 11.9 and 10.1 ka which is the longest duration TOM anomaly found in Seneca Lake (Figures 2 and 5). $\delta^{18}O$ calcite values decline by 1.7 per mil between 11.6 and 9.9 ka that is also the longest duration oxygen isotope anomaly in the Seneca Lake record. In the middle of this anomaly at 10.6 ka $\delta^{18}O$ values decrease by 1.2 per mil within ~140 years (Figure 6a, b). $\delta^{13}C$ calcite values also decrease during this event by more than 2.0 per mil between 11.6 and 10.0 ka which is the largest single carbon isotope anomaly in the entire dataset (Figure 6a, b). Most of this $\delta^{13}C$ decrease occurs during early stages of the event. All proxy data, however, display considerable variability throughout this climate interval suggesting that it was a period of relative climate instability in the northeastern United States (Figures 5 and 6).

The timing of this post-Younger Dryas climate interval in Seneca Lake, however, varies with different proxies from as early as 11.9 ka for TOM values to as late as 9.9 ka for $\delta^{18}O$ values. This is a somewhat greater range for this climate interval than that defined by Kirby et al. (2002a; 11.6 to 10.3 ka). Such a distinct, millennial-scale climate event following the Younger Dryas has not previously been identified around the North Atlantic. However, Nesje and Kvamme (1991) have identified a brief (<500 years) glacial re-advance in Norway, and Bjorck et al. (2001) have defined a short (<200 years) cooling event in the Northern Hemisphere, both at 10.3 ka, coincident with ice rafting event #7 in the North Atlantic (Bond et al. 2001).

Kirby et al. (2002a) have argued that the post-Younger Dryas climate interval in the northeastern United States was the consequence of a renewal of vigorous thermohaline circulation and heat transport following the Younger Dryas. They hypothesized that an abrupt increase of poleward heat flux in the North Atlantic created a strong thermal gradient between the North America continent and the North Atlantic Ocean that resulted in a large southward expansion (and possibly an eastward migration) of the winter polar front jet stream over the northeastern United States. Based on our new results, coupled with those of Kirby et al. (2002a), the end of the last deglaciation and the beginning of the Holocene in the northeastern United States appears to have occurred ~10.3 ka.

Holocene climate change

The Holocene has traditionally been viewed as being extremely stable climatically, especially in comparison to the last glacial period (Dansgaard et al. 1993). This view of the Holocene, however, is changing rapidly as data emerge which illustrate significant climate variability. Our stable isotope record from Seneca Lake extends from the early (10.3 ka) to middle (6.0 ka) Holocene, but when considered in context of other proxies, the data clearly document significant, albeit relatively low-amplitude, climate changes during this portion of the Holocene in the northeastern United States. Meyers (2002), based on study of carbon burial in Seneca Lake, has also argued for mid-Holocene climate instability.

After the end of the post-Younger Dryas climate interval (10.3 ka), all proxies from Seneca Lake display increasing values (Figure 7). All these increasing values imply a general warming trend and a more productive aquatic ecosystem for the first ~1500 years of the Holocene in the northeastern United States. Peak values at 9 ka are consistent with the timing of maximum Holocene summer insolation (~8% increase) in the Northern Hemisphere as controlled by precession of the equinoxes and obliquity (COHMAP 1988). Between 9 and 6 ka proxy values from Seneca Lake display a gradual decline (TC), remain relatively constant (TOM and $\delta^{18}O$), or gradually increase ($\delta^{13}C$; Figure 7). These changes occurred during the latter part of the warm Holocene Hypsithermal prior to the onset of the cool Neoglacial forced by decreasing summer insolation due to changes in orbital parameters (COHMAP 1988). At ~6 ka, TC values go to zero and our stable isotope record from Seneca Lake ends, consistent with the timing of ~5.5 ka defined by Anderson et al. (1997).

A number of significant anomalies occur, however, between 9 and 6 ka. Negative anomalies occur in all four proxy datasets at 8.2, 7.1 and 6.6 ka, with an additional anomaly in TOM and $\delta^{13}C$ values at 7.8 ka (Figures 5, 6 and 7). The 8.2 ka anomalies are particularly well defined and correlate with the "8.2 ka cold event" (8.4 to 8.0 ka) identified in Greenland ice cores (Alley et al. 1997) and European lake sediments (von Grafenstein et al. 1998). This short-lived cold event during the Holocene has been attributed to the catastrophic discharge of proglacial lakes into the North Atlantic and a reduction in thermohaline circulation (Barber et al. 1999), although other hypotheses, such as "stochastic resonance" (Alley et al. 2001) have also been proposed. Data from Seneca Lake suggest cooling and a lower level of aquatic primary productivity at this time. Lower $\delta^{18}O$ calcite values in Seneca Lake at this time imply an increase of ^{18}O depleted atmospheric precipitation. This could have been the result of a higher winter to summer ratio of precipitation, an increase of lake-effect snowfall and/or a moisture source depleted in ^{18}O. Overall, this 8.2 ka cold event appears similar to the Younger Dryas except lower in magnitude and duration. The remaining Holocene anomalies defined in Seneca Lake (7.8, 7.1 and 6.6 ka) may represent century-scale variability similar to the better known 8.2 ka event. Meyers (2002) has recently suggested that warmer, and cooler, summers in the northeastern United States (and thus variations in thermal stratification) during the mid-Holocene alternated every two-to-three centuries.

von Grafenstein et al. (1999) have compiled a stable oxygen isotope record from central Europe that covers essentially the same time period (15.5 to 5.0 ka) as the Seneca Lake record (16.6 to 6.0 ka). The major difference, though, is von Grafenstein et al. (1999) analyzed deep-water, benthic ostracods whereas we analyzed authigenic calcite precipitated from the epilimnion of Seneca Lake. von Grafenstein et al. (1999) also correlated their oxygen isotope lake record to the Greenland GRIP core whereas the Seneca Lake record has been correlated with the GISP2 ice core. von Grafenstein et al. (1999) report finding many of the well known, abrupt deglacial climate events (defined as negative $\delta^{18}O$ anomalies) which they attribute to changes in thermohaline circulation. In the European record, the most prominent anomaly is associated with the Younger Dryas climate reversal, in contrast to the Seneca Lake record in which the Younger Dryas is a relatively subtle event. In Seneca Lake, the most prominent anomaly is associated with the post-Younger Dryas climate interval, which is not observed in the data of von Grafenstein et al. (1999). This comparison indicates that the northeastern United States, central Greenland and central Europe experienced synchronous, at least hemisphere-wide climate changes during the last deglaciation, but that the post-Younger Dryas climate interval appears to be a regional event as described by Kirby et al. (2002a). The only significant Holocene climate event identified in the European record is the 8.2 ka cold event (von Grafenstein et al. 1998, 1999). In contrast, a multitude of Holocene climate events has now been identified in Seneca Lake.

Conclusions

A new, high-resolution, multi-proxy paleoclimate record from Seneca Lake has identified a number of climate changes during the last deglaciation to middle Holocene (16.6 to 6.0 ka) in the northeastern United States. These new results represent a significant improvement, in terms of resolution and definition of events, over that previously derived from Seneca Lake by Anderson et al. (1997) and Meyers (2002). Primary conclusions of this study are:

1. Gradual regional warming and increasing aquatic productivity occurred in the northeastern United States following deglaciation between 16.6 and 12.0 ka. Much of this warming trend occurred during the Bolling-Allerod warm periods identified in the GISP2 ice core. However, warming in the Finger Lakes region (~43 °N) started ~2000 years prior to the warming in central Greenland. This general warming trend was triggered by changes in orbital parameters (precession of the equinoxes and obliquity) as well as retreat of the Laurentide ice sheet. Increasing $\delta^{18}O$ calcite values suggest reorganization of atmospheric circulation and the influx of more ^{18}O-rich precipitation.
2. The Oldest Dryas (15.1 to 14.7 ka) cold event occurred in the northeastern United States characterized by a decrease in aquatic productivity (decreases in TOM and TC), but not accompanied by significant reorganization of atmospheric circulation (no $\delta^{18}O$ anomaly).
3. A brief Older Dryas (~14.1 ka) cold event is also recognized in the northeastern United States by an abrupt, high-amplitude decrease in both $\delta^{18}O$ and $\delta^{13}C$ calcite values. This cold event correlates with the expansion of glacial Lake Iroquois in the Finger Lakes region as well as global meltwater pulse IA. The region may have been characterized by increased winter season precipitation and/or lake-effect snow as well as a shorter growing season. Meltwater discharge to the North Atlantic may have reduced thermohaline circulation and the northward transport of heat adding to hemisphere-wide cooling.
4. A brief climate reversal correlative with the Intra-Allerod Cold Period is also recognized in Seneca Lake at ~13.2 ka characterized by a high-amplitude decrease in TC as well as decrease in TOM, $\delta^{18}O$ and $\delta^{13}C$ calcite values. This cold event is equivalent to the Killarney Oscillation in the Canadian Maritimes and the Gerzensee Oscillation in Europe. Collectively they represent the Amphi-Atlantic Oscillation of Levesque et al. (1993b) which is thought to be a response to decreased thermohaline circulation in the North Atlantic.
5. The well-known Younger Dryas cold period occurred in the northeastern United States between 12.9 and 11.6 ka consistent with observations from the GISP2 ice core. In the Seneca Lake record, the Younger Dryas appears as an asymmetrical climate anomaly defined by an abrupt decrease in both $\delta^{18}O$ and $\delta^{13}C$ calcite values at its beginning followed by a more gradual recovery. The region was characterized by reduced aquatic productivity and an influx of ^{18}O-depleted precipitation due to an increase of winter precipitation and/or lake-effect snow. Compared to European records, the Younger Dryas climate reversal appears to have been a relatively low-amplitude event in the northeastern United States.
6. The largest amplitude and longest duration multi-proxy anomaly in the Seneca Lake dataset correlates with the post-Younger Dryas climate interval as defined by Kirby et al. (2002a) between 11.6 and 10.3 ka. This climate reversal in the northeastern United States represents the last deglacial climate event before the start of the Holocene. The post-Younger Dryas climate interval has not previously been recognized in the GISP2 ice core. In Seneca Lake, it is defined by the largest anomaly in TC and $\delta^{18}O$ calcite values as well as the longest duration negative anomaly in TOM and $\delta^{13}C$ calcite values of the entire dataset. At ~10.6 ka, $\delta^{18}O$ calcite

values drop by 1.2 per mil within 140 years, and there is a 2.0 per mil decrease in $\delta^{13}C$ calcite that represents the single largest carbon isotope excursion between 16.5 and 6.0 ka.

7. The Holocene epoch in the northeastern United States started ~10.3 ka and was not climatically stable. All proxy data from Seneca Lake increase between 10.3 and 6.0 ka suggesting an overall warming trend and increasing levels of aquatic productivity. Peak proxy values are observed at ~9 ka coincident with a maximum in summer insolation controlled by orbital variability. Between 9 and 6 ka proxy values are variable during the latter half of the Holocene Hypsithermal. There is century-scale variability in the proxy data from Seneca Lake during this time including stable isotope decreases at ~8.2, 7.1 and 6.6 ka suggesting cooler conditions and reduced growing seasons. Only the 8.2 ka cold period has previously been identified in the GISP2 ice core which has been related to a proglacial lake discharge event and a reduction of thermohaline circulation in the North Atlantic. The 8.2 ka event has also been recognized in a lake record from central Europe indicating that it was at least a hemisphere-wide climate change. The Holocene Neoglacial in the northeastern United States began ~6.0 ka in response to an orbitally controlled decrease in summer insolation which has continued to the present.

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