Quaternary Research 86 (2016) 67–78

Contents lists available at ScienceDirect

Quaternary Research

journal homepage: http://www.journals.elsevier.com/quaternary-research

Estimating the regional climate signal in a late Pleistocene and early Holocene lake-sediment $\delta^{18}O$ record from Vermont, USA.

Maximilian Benedict Mandl [a, b, *], Bryan Nolan Shuman [a], Jeremiah Marsicek [a], Laurie Grigg [c]

[a] Department of Geology and Geophysics, University of Wyoming, Dept. 3006, 1000 E. University Ave., Laramie, WY 82071, USA
[b] ETH Zuerich, Institut fuer Geochemie und Petrologie, Clausiusstrasse 25, 8092 Zurich, Switzerland
[c] Earth and Environmental Science, Norwich University, 158 Harmon Drive, Northfield, VT 05663, USA

ARTICLE INFO

Article history:
Received 14 January 2015
Available online 3 May 2016

Keywords:
Holocene
Oxygen isotope
Carbonate
Vermont
Lake
Younger Dryas
Bchron
Principal component analysis

ABSTRACT

We present a new oxygen isotope ($\delta^{18}O$) record from carbonate-rich lake sediments from central Vermont. The record from Twin Ponds spans from 13.5 cal ka BP (1950 AD) to present, but contains a 6 ka long hiatus starting shortly after 7.5 cal ka BP. We compare the record for ca. 13.5–7.5 cal ka BP with published $\delta^{18}O$ data from the region after using a Bayesian approach to produce many possible chronologies for each site. Principal component analysis then identified chronologically-robust, multi-site oxygen isotope signals, including negative values during the Younger Dryas, but no significant deviations from the early Holocene mean of the regional records. However, differences among sites indicate significant trends that likely relate to interacting changes in the regional gradients of seasonal temperatures and precipitation as well as moisture sources, moisture pathways, and aridity that were controlled by large-scale climatic controls such as insolation, the progressive decline of the Laurentide Ice Sheet, and changes in oceanic circulation. Centennial shifts punctuate these trends at ca. 9.3 and 8.2 cal ka BP, and reveal that the local character of these short-lived features requires a detailed understanding of lake hydrology and regional isotopic gradients to yield reliable information for regional climate reconstructions.

Introduction

Stable isotope records of late-Quaternary environmental change from lake sediments in the northeastern United States show high variability among sites on millennial to decadal time scales (e.g., Kirby et al., 2002b; Hou et al., 2007, 2012; Zhao et al., 2010). The variability even across small distances (e.g., <350 km) contradicts the notion that stable isotopes from lake sediments may record coherent regional changes, and makes it difficult to decompose the records into a regional signal and local noise. Albeit with a higher selectivity for specific climate processes, in principle the same difficulties remain even with newly emerging proxies, such as compound specific isotope analysis (e.g., Huang et al., 2002, 2004; Hou et al., 2007). Stable isotope datasets used for paleoclimate reconstruction from the northeastern United States contain noteworthy deviations from the canonical oxygen isotope ($\delta^{18}O$) record of the late Pleistocene and early Holocene found in Greenland ice cores (e.g., compare Stuiver et al., 1995; Kirby et al., 2002b; Vinther et al., 2006). These differences may provide important insights into the synoptic climate patterns of the past, but the uniqueness of the individual lake records creates challenges for interpretation.

Records from single sites have been interpreted to primarily depend on various factors, such as air temperature (Zhao et al., 2010) or past variability of the circumpolar vortex over the northeast United States (Kirby et al., 2002a). However, at least seven different factors can influence $\delta^{18}O$ in $CaCO_3$ in lake sediments and create isotopic variations, assuming that the sedimentary carbonate is minimally influenced by detrital carbonate sources. Several of these factors are climatically controlled: the temperature of meteoric condensation; $\delta^{18}O$ of the source moisture and distance-dependent depletion of heavy isotopes (circulation patterns); moisture balance (aridity); and seasonality of precipitation at the site (Dansgaard, 1964; Jouzel et al., 2000; Bowen and Wilkinson,

* Corresponding author. ETH Zuerich, Institut fuer Geochemie und Petrologie, Clausiusstrasse 25, 8092 Zurich, Switzerland.
E-mail address: maximilian.mandl@erdw.ethz.ch (M.B. Mandl).

http://dx.doi.org/10.1016/j.yqres.2016.02.009
0033-5894/

2002). Shifts in the spatial gradients in the isotopic composition of precipitation and surface water created by these factors may also produce important and counter-intuitive differences between records. In addition to the climatic influences on $\delta^{18}O$ of $CaCO_3$ in lake sediments, the local hydrology can further change the ultimate $\delta^{18}O$ signal recorded in the lake carbonates by changing the water isotopic composition, lake residence time, and temperatures in the area of $CaCO_3$ crystallization, which can change independently of climate as sediment accumulation causes changes in water depth and morphology (Dansgaard, 1964; Gat, 1995; Kim and O'Neil, 1997; Gibson et al., 2002; Henderson and Shuman, 2009; Henderson et al., 2010; Jones and Imbers, 2010; Steinman et al., 2010, 2013; Steinman and Abbott, 2013). Consequently, unique combinations of climate, hydrology, lake morphology, and sedimentation processes at each lake can create complex signals that can be hard to compare across sites.

During the late Pleistocene and early Holocene in the northeastern United States, changes in atmospheric temperature, moisture source and pathway, moisture balance, and seasonality of precipitation were driven by multiple forcings (Renssen et al., 2009), which acted on a variety of time- and geographic-scales (Bartlein, 1997). These external forcings include insolation (Berger and Loutre, 1991) and atmospheric greenhouse gases (Monnin et al., 2001, 2004). Related changes in the extent of the Laurentide ice sheet (Dyke, 2004) and in the strength of oceanic circulation (e.g., Atlantic Meridional Overturning, the Gulf Stream, and the Labrador Current (Ruddiman and McIntyre, 1981; Sachs, 2007) exert a strong influence on the northeastern United States. Pollen, chironomid, lake-level, and other lake sediment datasets provide evidence of these effects including cold regional conditions (7–17°C below Holocene temperatures) during the Younger Dryas Chronozone (YD; Levesque et al., 1997; Hou et al., 2007; Shuman et al., 2007, 2009) and a warm, but exceptionally dry early Holocene (>400 mm/yr drier than today; Shuman et al., 2007, 2009; Marsicek et al., 2013; Newby et al., 2014). After the century-scale climate event at ca. 8.2 cal ka BP (thousands of calibrated radiocarbon years before 1950 AD), which briefly cooled the region (Alley et al., 1997; Shuman et al., 2002; Alley and Ágústsdóttir, 2005), regional fossil pollen and lake-level data indicate a rapid increase in effective moisture (Shuman et al., 2002; Marsicek et al., 2013) and a potential shift in the seasonality of precipitation from the summer to the winter months (Shuman and Donnelly, 2006; Shuman et al., 2006). In addition to the temperature and evaporation effects on regional $\delta^{18}O$, isotope-enable climate models indicate that changes in atmospheric circulation and ocean isotopic composition could have produced regional $\delta^{18}O$ changes of >1‰ during events such as at 8.2 cal ka BP; the changes could have produced substantial temporal and spatial heterogeneity in isotopic records especially by shifting spatial gradients in the isotopic composition of precipitation (e.g., LeGrande and Schmidt, 2008).

To detect how such regional, climate-related effects interacted with local-scale controls, we compare changes in measured $\delta^{18}O$ values in a new lake core from Twin Ponds, Vermont, with two comparable $\delta^{18}O$ records from freshwater lakes located elsewhere in the northeastern United States. We hypothesize that despite the complexities associated with oxygen isotope data from bulk sediments due to site-specific processes, an underlying signal may still be shared across sites. In context with this overarching hypothesis, we address several related questions: (1) Which signals does the new $\delta^{18}O$ record from Twin Ponds share with the two comparison sites in New York and New Jersey? (2) Which significant differences exist among the records? (3) What do the similarities and differences among the three $\delta^{18}O$ records reveal about the patterns and processes of climate change in the northeastern United States and about hemispheric-to-global climate dynamics? Investigating similarities and differences in $\delta^{18}O$ values in $CaCO_3$ at different sites across the region allows us to detect robust, replicated components of the isotopic record, and ultimately, we seek to provide new insight into the regional climate changes inferred from the other available climate archives from the region.

To address our questions, we first present a new $\delta^{18}O$ record from 13.5 cal ka BP to present from Twin Ponds, VT, and then compare our new data with the previously published datasets from Green Lake, NY (Kirby et al., 2002b), and Lake Grinnell, NJ (Zhao et al., 2010; Fig. 1). Together, the three records from Vermont, upstate New York, and New Jersey span a large section of the northeastern United States, extending over a latitudinal distance of ca. 350 km, and a longitudinal distance of ca. 270 km. Following Parnell et al. (2008), we propagate age uncertainty at each site to create an error-sensitive reanalysis of isotope records and discuss the significance of including age-uncertainty in paleoisotopic climate reconstructions. Subsequently, we apply a principal component analysis (PCA) to the suite of records to isolate regionally-coherent changes in oxygen isotope composition that represent significant deviations from the background range of variability (i.e., stochastic or local variability that is not reproducible across sites). Finally, we consider the regional oxygen isotope signals in the context of existing studies of paleoclimate dynamics in the northeastern United States during the late Pleistocene and early Holocene.

Methods

Study site

Twin Ponds (44° 01′ 41.6″ N, 72° 34′ 45.6″ W, 372 m elevation) in Brookfield, VT, consists of two connected kettle ponds located within the carbonaceous phyllite and limestone member of the Devonian-aged Waits River formation (Fig. 1A; Ratcliffe et al., 2011). The formation of the current lake followed the northward retreat of the Laurentide Ice Sheet in this region between 14.7 and 14 cal ka BP (Ridge, 2003), and was not later than 13.5 cal ka BP (this study). Twin Ponds has one outlet and two inlets. We extracted our sediment core on a *Chara*-rich carbonate bench in shallow water (48 cm water depth) on the southeastern margin of the western pond (Fig. 1A). This location was chosen to maximize the distance from allocthonous sediment sources at the inlets. Subsurface influx of calcium-rich groundwater results in inorganic precipitation and deposition of carbonates, mostly calcite. Seasonal temperature changes and biomediation potentially drive the autochthonous carbonate deposition in the vicinity of the core site (Dean and Fouch, 1983).

Today, the lake has a maximum depth of 8 m in the western basin, which has a surface area of 3.0 ha. The residence time of water in the lake has not been determined, but the isotopic composition of the lake water ($\delta^{18}O$: −8.3‰ VSMOW; δD: −58.4‰ VSMOW; sample collected November 1, 2012) indicates much less evaporative loss from the lake than others in the region (Fig. 1C).

Core preparation and isotope analysis

In November 2012, we collected three 70-mm diameter hand-driven piston cores from Twin Ponds, VT. Three 1 m long, sequential segments of core VT12-TP12-48A were extracted less than 1 m from the closest shoreline, which was composed of a >10 m wide sedge peat fringe (Fig. 1A). When aligned, the segments of core 48A span a sediment depth of 275 cm below the sediment-water contact.

https://doi.org/10.1016/j.yqres.2016.02.009 Published online by Cambridge University Press

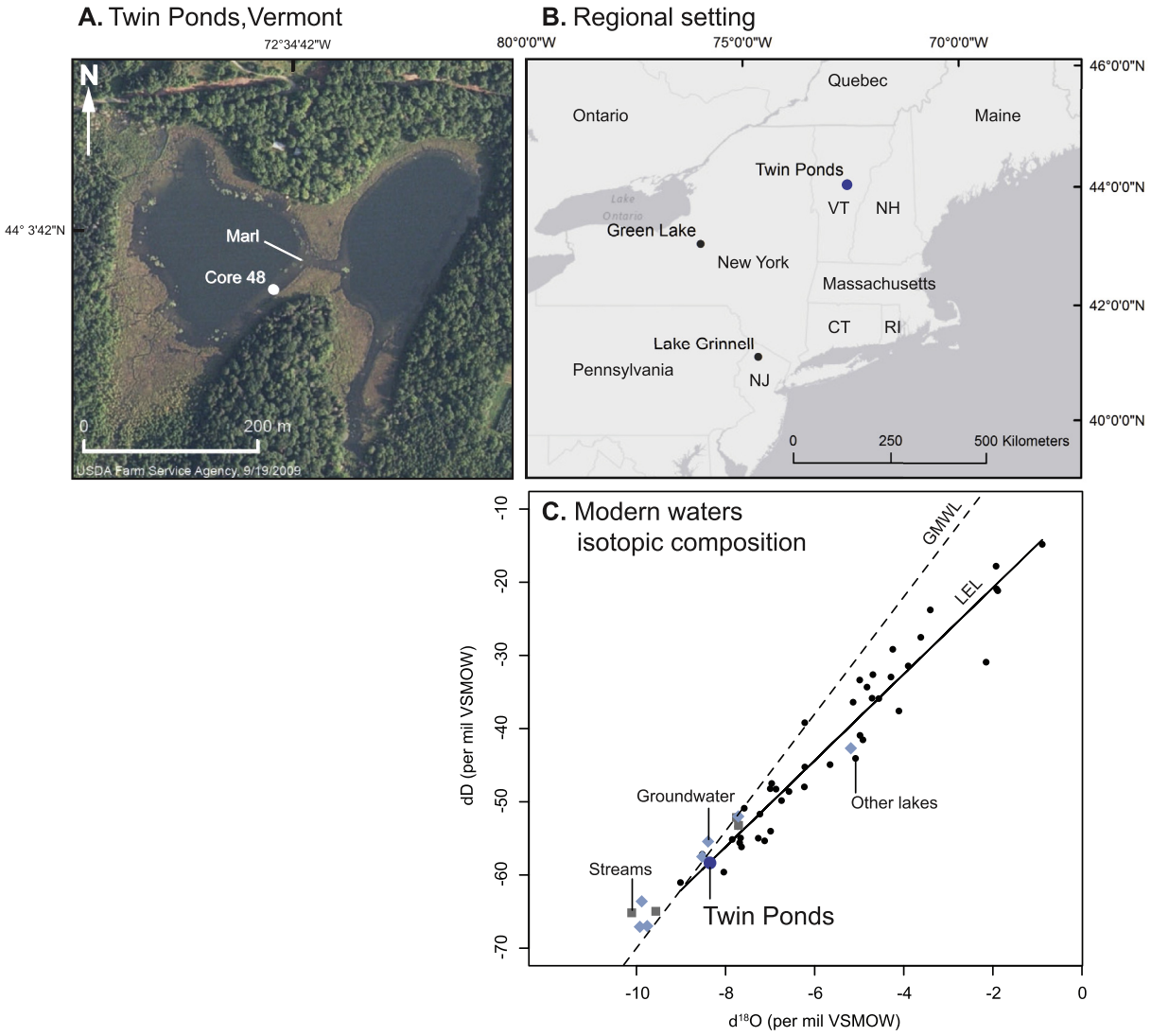

Figure 1. (A) Aerial view of Twin Ponds showing the location of the coring site and marl deposition. (B) Map of the northeastern United States, showing the location of Twin Ponds (VT, this study), Lake Grinnell (NJ), and Green Lake (NY). (C) Modern waters isotopic composition of Twin Ponds (solid blue circle), other lakes in the region (solid black circles), groundwater (blue diamonds), and streams (gray squares). The position of Twin Ponds relative to the GMWL and the LEL highlights that Twin Ponds is not significantly isotopically enriched by evaporation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

We logged the cores using a GEOTEK Multi-Sensor Core Logger at the University of Wyoming and then split the cores along their long axis. The split cores were sampled at contiguous 1 cm increments, and the outer 1–2 mm of sediment was removed to minimize contamination related to coring. Following the procedure described by Dean (1974), we analyzed the organic matter and inorganic carbonate content of each sample by loss on ignition at 550°C and 1100°C, respectively. The loss of mass (CO_2) at 1100°C was corrected to yield $CaCO_3$ content according to the stoichiometric equation $CaCO_3 <-> CaO + CO_2$ (Dean, 1974).

Manually extracted macroscopic charcoal (>125 μm) from 9 sample intervals yielded ^{14}C dates by Accelerator Mass Spectrometry (AMS; Table 1) at the Keck Carbon Cycle AMS Laboratory at the University of California, Irvine. The Bchron software package (Parnell, 2014) was used to calibrate all of the ^{14}C ages to calendar years based on the IntCal09 calibration dataset (Reimer, 2009), to estimate mean ages, and to propagate age uncertainties based on the uncertainty of the ^{14}C age constraints to each individual core interval between ^{14}C age constraints (Fig. 2; Haslett and Parnell, 2008).

Samples from 1 to 5 cm intervals throughout the core were analyzed for oxygen and carbon isotope composition. The samples were closely spaced in the older sections of the core to obtain detail from the late Pleistocene and early Holocene, and set apart further in the younger, organic-rich sections, which were not the primary focus of this study. The carbonate fraction of the core samples were disaggregated in a supersonic bath, sieved, rinsed with 18 MΩ cm deionized water, decanted, and dried at < 90°C for up to 72 h. The stable isotope analysis on the homogenized <63 μm carbonate fraction was performed at the UW Stable Isotope Facility (UWSIF) using a Thermo Finnigan Delta Plus XP mass spectrometer in conjunction with a TC LC PAL Autosampler and a Thermo Finnigan GasBench II (2σ standard uncertainty as reported by the facility: 0.2‰). To assure the consistency of our methods, we created several grams of an internal secondary carbonate standard from 4 cm^3 of carbonate-rich core material applying the same techniques as for our regular samples. Small amounts of the secondary standard

https://doi.org/10.1016/j.yqres.2016.02.009 Published online by Cambridge University Press

Table 1
Results from the ^{14}C analyses of charcoal and/or wood fragments extracted from selected samples from Twin Ponds core 48A.

UCIAMS #	Core section	Depth in section	Depth in core	Fraction Modern	± (1σ)	D^{14}C (‰)	± (1σ)	^{14}C age (BP)	± (1σ)
119950	1B	75–76	49.5	0.9202	0.0027	−79.8	2.7	670	25
121903	1B	83–84	57.5	0.4204	0.0012	−579.6	1.2	6960	25
119951	1B	96–97	70.5	0.8222	0.0021	−177.8	2.1	1575	25
121902	2B	10–11	80.5	0.4491	0.0019	−550.9	1.9	6430	35
119953	2B	14–15	84.5	0.3683	0.0016	−631.7	1.6	8025	35
121901	2B	25–26	95.5	0.3755	0.0013	−624.5	1.3	7870	30
119952	2B	54–55	124.5	0.3394	0.0011	−660.6	1.1	8680	30
121904	3B	59–61	232.5	0.2892	0.0018	−710.8	1.8	9970	60
121905	3B	80–82	255.5	0.2521	0.0011	−747.9	1.1	11,070	40

were then reprocessed as an independent sample, submitted for isotope analysis with each batch of core samples, and compared across batches to ensure the consistency and comparability of all isotope measurements.

A linear correction using UWSIF carbonate standards, with known values, was applied to the $\delta^{18}O$ data. In addition, the data was adjusted for sample-size and instrument dependent effects by applying a second linear correction, which was done by pre-measuring different amounts of the same UWSIF standard.

Statistical analysis and site comparison

To emphasize regional similarities and variability across independent cores, we compared the $\delta^{18}O$ data (expressed as ‰ VPDB) exclusively by their age constraints. We assigned multiple age estimates to each location in the stratigraphy of our core as well as to the comparative records from NY and NJ by using the Bchron package in R (R Core Team, 2013; Parnell, 2014). Bchron propagates the error associated with ^{14}C dating, calibrates ^{14}C dates into calendar years based on the IntCal09 calibration curve (Reimer, 2009), and estimates 10,000 possible ages for each sample-interval for the entire core. Bchron computes the ages by applying a Markov Chain Monte Carlo method, which is constrained by the individual ^{14}C measurements, the associated error of these measurements and their calibration, and the principle of superposition, meaning that younger sediments are always deposited on top of older sediments.

To facilitate cross-site analyses, we linearly interpolated isotopic values from each core using the function *approx* in R (R Core Team, 2013) and generated isotopic values for every 50 yr time interval based on each of the 10,000 possible chronologies for each site. The $\delta^{18}O$ samples have unknown ages and varied spacing in time, but because common 50 yr intervals are required for cross-site comparison, we rely on the interpolation to determine the range of possible $\delta^{18}O$ values at each site for each 50-yr interval. Generally, any interpolation can flatten out peaks in the dataset, but we determined experimentally that the 50 yr spacing was small enough to minimize that effect given the sampling intervals of the three cores. Due to the mechanics of this method, time intervals at the beginning and towards the end of the record have fewer than 10,000 possible isotopic values because not all of the 10,000

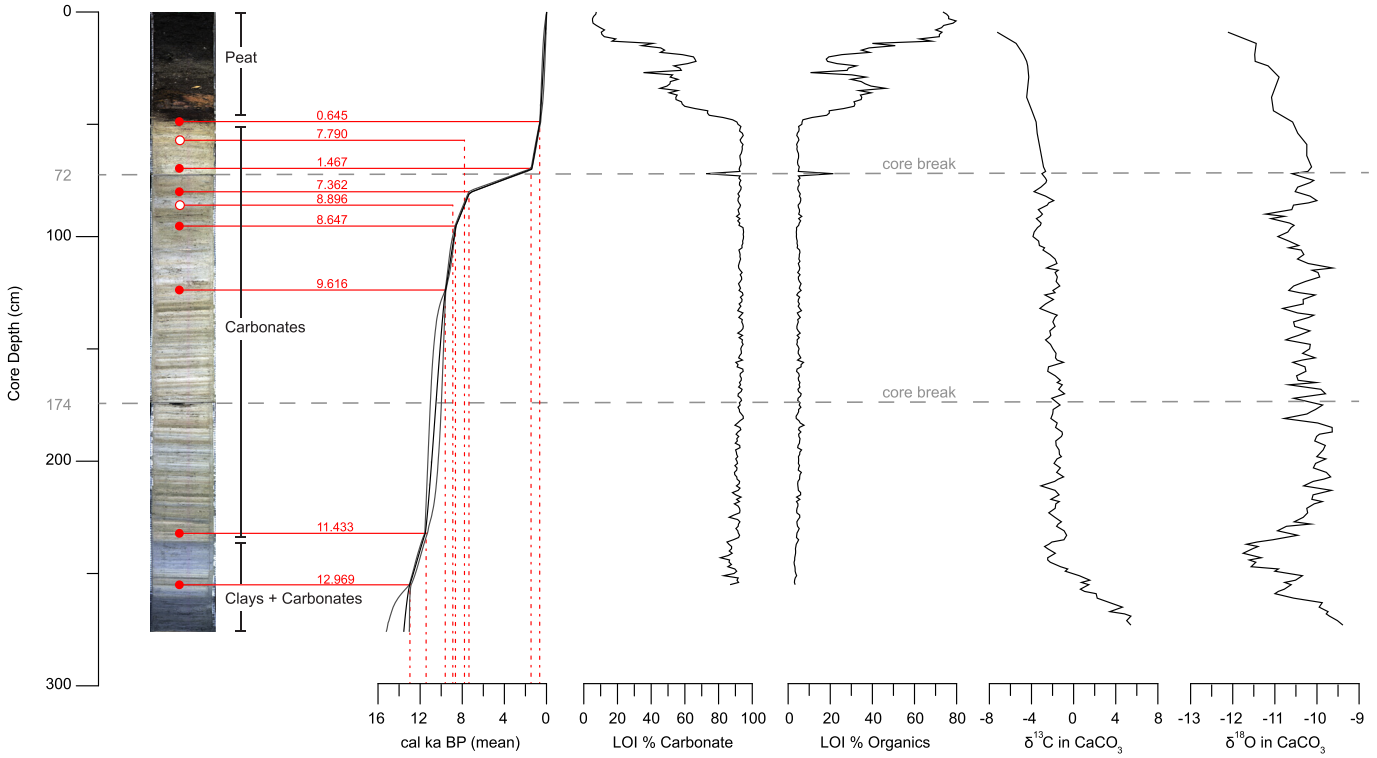

Figure 2. A compilation of the ^{14}C-derrived mean age model (5% and 95% values represented by dashed lines), $CaCO_3$ content, organic content, $\delta^{13}C$, and $\delta^{18}O$ from the core 48A from Twin Ponds, VT, plotted against core depth. Calibrated ages (cal ka BP, highlighted in red) were calculated using Bchron. Two outliers (UCIAMS121903 & UCIAMS119953, represented by open circles) were omitted in this analysis due to an age inversion. The hiatus starting shortly after 7.5 cal ka BP is clearly visible. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

https://doi.org/10.1016/j.yqres.2016.02.009 Published online by Cambridge University Press

possible age models extend to the extremes of the time domain. To prevent artificially extending the temporal range of records based on a few extreme age-depth models, we did not apply our analysis to 50-yr intervals that were bracketed by fewer than 2500 possible sample ages. We focus on samples with mean ages of 13.5 cal ka BP–7.5 cal ka BP, and thus the time period from the beginning of the Twin Ponds record to the onset of a multi-millennial hiatus in the record.

Paleoclimate data has been routinely generated in the northeastern United States, but only the records from Green Lake and Lake Grinnell satisfied four important requirements for comparison with the Twin Ponds record: (1) published $\delta^{18}O$ data from bulk carbonate sediments, (2) overlapping time scale, (3) an average temporal resolution of not less than one sample per 100 yr, and (4) sufficient age control (radiocarbon date density) to provide meaningful comparisons. One limitation of using data from Lake Grinnell in our analysis was that the record started later than the record from Green Lake and Twin Ponds. The length of the Lake Grinnell record and the onset of the hiatus at Twin Ponds limited our multi-core comparison to 12.6–7.5 cal ka BP.

Bchron age models enabled us to make 10,000 possible comparisons of the three sites based on independently derived and resampled age–depth relationships at each site. Every one of the iterations contained one set of possible isotopic values for every 50-yr interval for each site. By applying the *princomp* function in R to each of the 10,000 manifestations of the data at the sites, we obtained 10,000 possible PCA scores, which allowed us to incorporate the age uncertainty into the PCA. To compute our PCA scores, we calculated the eigenvectors and eigenvalues of the correlation matrix instead of the covariance matrix to standardize the differing amplitude of isotopic variation at the three sites and to prevent the record with the highest variance from skewing the principal components. We applied the function, *quantile*, to the 10,000 possible scores of the principal components, to calculate the median (50%), 5%, and 95% values from the distribution of PCA scores. We similarly used *quantile* to quantify the range of $\delta^{18}O$ uncertainty for each 50 yr time interval at each site. Because the arbitrary assignment of signs to the scores minimized the mean signal in the ensemble of PCA results, we multiplied arrays of scores by (−1) if their largest offset from zero was a positive number; doing so ensured that the largest magnitude scores always appeared as negative deviations from the mean. Our method closely resembles similar approaches introduced by Anchukaitis and Tierney (2013), Marcott et al. (2013), and Steinman et al. (2014).

Using the ensemble of different age models, we also calculated the differences in the $\delta^{18}O$ values between Twin Ponds and each of the other sites by subtracting the unsorted populations of possible isotope values at one site from the corresponding population at the same time interval at the comparative site. For both the PCA scores and the differences, we focus on periods of time when the 95% range of values did not include zero as the significant features of the record.

Results

^{14}C dating

We obtained radiocarbon ages for 9 charcoal samples (Table 1). The median ages of the youngest and oldest samples dates to 0.67 ^{14}C ka BP (0.65 cal ka BP) and 11.07 ^{14}C ka BP (12.97 cal ka BP) respectively. Two of the ages are not in stratigraphic order (UCIAMS121903 & UCIAMS119953), which we attribute to reworking of old sediments in the near-shore core environment. Thus, we omitted these two dates from our final age model (Fig. 2). Throughout the older portion of our record (13.5–7.7 cal ka BP), sediments accumulated at rates between 0.2 and 0.8 mm per yr. After ca. 7.5 cal ka BP, the net accumulation of sediment slowed to ≤0.02 mm/yr, giving rise to a hiatus that lasted until <1.4 cal ka BP, although the specific timing and location of the hiatus is subject to the choice of acceptable radiocarbon ages. Importantly, this uncertainty does not affect our analysis of the late Pleistocene and early Holocene portion of the record.

Loss-on-ignition

The LOI record from Twin Ponds, VT, illustrates that carbonate sediments dominate much of the record (Fig. 2). Organic matter increases significantly above the sedimentary hiatus, reaches a maximum associated with a layer of dense, woody peat at 0–35 cm depth, and is low during an interval of sandy sediments at 45–73 cm depth. These features, as well as the potential sedimentary hiatus, appear consistent with a period of shallow water. Before the recent increase in organic matter, the YD stands out as the most lithologically-distinct time interval, with less organic matter and carbonate in the sediment than during other periods (Fig. 2). Organic matter and $CaCO_3$ content prior to the hiatus exhibit no correlation ($R = 0.10$). From 13.5 to 7.5 cal ka BP, the organic content ranges from 2.5% to 7.3% and the $CaCO_3$ content ranges from 81.4% to 95.2%. Because the sediment cores were collected away from lake's current stream inputs (Fig. 1A), have carbonate concentrations that are persistently >80%, and consist of predominantly calcite (based on XRD analyses; Serravezza, M., personal communication, 2013), we assume that the isotopic record is not substantially influenced by detrital components.

Late Pleistocene and early Holocene isotopic data

The $\delta^{18}O$ record from Twin Ponds extends from a mean age of 13.52 cal ka BP to present, with the multi-millennial hiatus beginning shortly after ca. 7.5 cal ka BP (Fig. 2). The analyses of our internal secondary standard confirm that the samples were prepared and analyzed consistently throughout the record ($\delta^{18}O_{STD} = -10.9 \pm 0.1$‰, Std. Dev., $n = 5$).

The dataset starts with the highest values of the record ($\delta^{18}O = -9.3$‰) and then drops off sharply at the beginning of a >1 ka long, negative excursion reaching values as low as −11.8‰ at 12.11 cal ka BP (Fig. 3, lowermost, blue (in the web version) line). The $\delta^{18}O$ values then increase steadily, with a short negative excursion of 0.5‰ centered at 11.51 cal ka BP. Between ca. 11.2 and 10.6 cal ka BP, the record reaches a local plateau, which contains two of the highest $\delta^{18}O$ values of the Holocene-portion of the record and a negative excursion centered at 10.63 cal ka BP. A millennial trend downward follows until 9.30 cal ka BP, when a local maximum marks the second highest value in the record ($\delta^{18}O = -9.6$‰). A subsequent trend towards lower $\delta^{18}O$ values persists until two local minima at 8.34 and 8.17 cal ka BP ($\delta^{18}O = -11.1$‰ and $\delta^{18}O = -11.2$‰, respectively), which mark the two lowest isotopic values after 11.74 cal ka BP. After 8.17 cal ka BP, the resolution of the record decreases due to lower sediment accumulation, ultimately leading to the apparent hiatus.

When age uncertainty is taken into account (Fig. 4), the relative sequence of the details of the $\delta^{18}O$ record from Twin Ponds and the comparison sites is not obvious anymore. Despite the uncertainty, the negative millennium-scale excursion centered at 12.1 cal ka BP, during the YD, remains a notable feature, which can be compared across sites. Similarly, negative excursions at Twin Ponds at ca. 11.5 cal ka BP, 10.6 cal ka BP, and 8.3 to 8.2 cal ka BP remain robust features for cross-site comparison as are peak $\delta^{18}O$ values at 10.8 and 9.3 cal ka BP (Fig. 4).

https://doi.org/10.1016/j.yqres.2016.02.009 Published online by Cambridge University Press

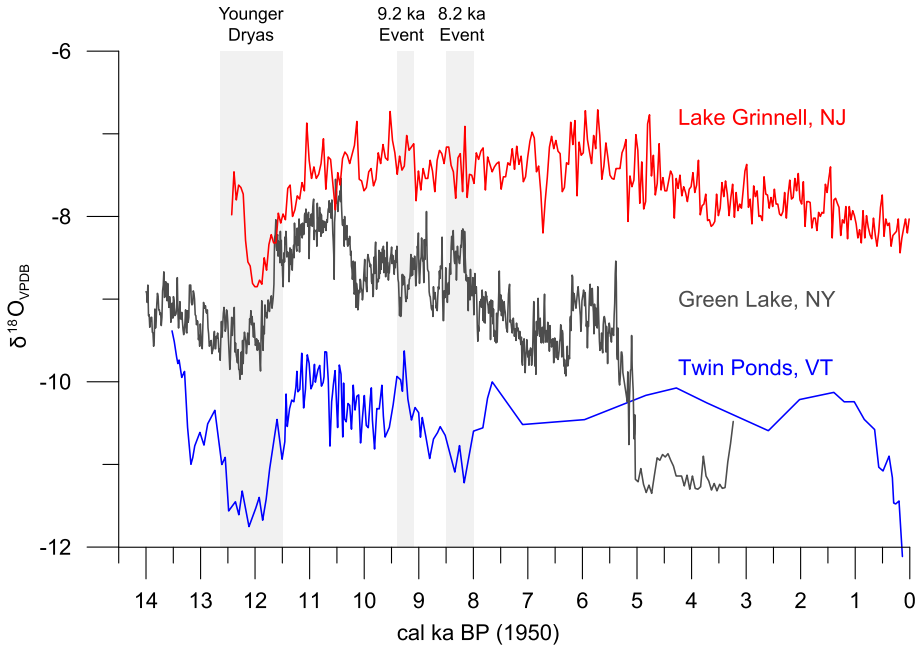

Figure 3. $\delta^{18}O$ values from Lake Grinnell (Zhao et al., 2010) and Green Lake (Kirby et al., 2002b), plotted using the original age model next to a plot of $\delta^{18}O$ vs. mean calibrated age (Parnell et al., 2008) from Twin Ponds (this study). Vertical, gray bars outline the approximate time interval of climate anomalies described by other studies (e.g., Broecker et al., 1989; Grafenstein et al., 1998, 1999; Barber et al., 1999; Bauer et al., 2004; Fleitmann et al., 2008; Yu et al., 2010).

Comparison across sites

The mean $\delta^{18}O$ value at Twin Ponds prior to the hiatus (13.5–7.5 cal ka BP) equals −10.4‰. For comparison, mean $\delta^{18}O$ at Green Lake, the most inland site, is −8.8‰, and therefore 1.6‰ higher than at Twin Ponds. Likewise, the mean $\delta^{18}O$ at Lake Grinnell is 2.8‰ higher than $\delta^{18}O$ at Twin Ponds from 12.4 to 7.5 cal ka BP, the time period the two records share prior to the hiatus at Twin Ponds.

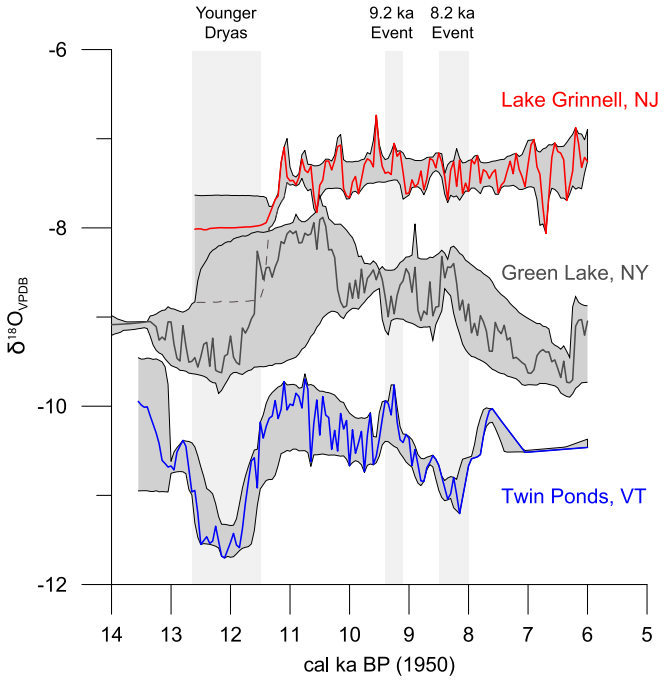

Figure 4. Reanalysis of the published data from Lake Grinnell and Green Lake as well as the data from this study (Twin Ponds) using the Bchron age model (Parnell et al., 2008; Parnell, 2014). Uncertainties, represented by the gray area (90% confidence interval) and bracketed by the 5% and 95% values, surround the median value for each individual core. Depending on the number and relative spacing between distance of ^{14}C dates, the records underwent a variable degree of smoothing due to the fluctuating magnitude of the uncertainties.

Even accounting for the age uncertainties, the large increase in $\delta^{18}O$ at the end of the YD is readily identified in all three records (Fig. 4), but the YD-age isotopic excursion at Twin Ponds is more distinct than at Green Lake and potentially longer than at Lake Grinnell. After the end of the YD, Twin Ponds and Green Lake both reached Holocene maxima. These high, early Holocene $\delta^{18}O$ values distinguish the more northerly lakes from Lake Grinnell in New Jersey. The northern sites also both trended towards a heavier isotopic composition for 2.5–4 ka after ca. 10.5 ka, but no equivalent decline in isotopic values appear on a comparable time scale in New Jersey.

In addition to these similarities over long time scales, some short-lived events may be common across records. For example, based on the originally published ages for Green Lake and Lake Grinnell, and the mean ages for Twin Ponds, we cannot rule out the possibility that all three records capture a negative isotopic shift in phase with each other from 10.6 to 10.5 cal ka BP (Fig. 3). At Twin Ponds, the minimum centered at 10.63 cal ka BP is the lowest $\delta^{18}O$ value (−10.8‰) during the early Holocene maximum from 11.5 to 9.9 cal ka BP. A similar isotopic anomaly occurs in the other two records with median ages of 10.55 and 10.53 cal ka BP, and thus falls within the age uncertainty of each other and the event in Vermont. The age uncertainty allows for the alignment of anomalies at ca. 10.6–10.5 ka to be spurious, especially at Green Lake, but the median $\delta^{18}O$ values at both Lake Grinnell and Twin Ponds retain a synchronous event (Fig. 4).

Between 9.4 and 9.1 cal ka BP, the $\delta^{18}O$ record from Twin Ponds exhibits a positive isotopic anomaly, which differs from the pattern at the other two sites (Figs. 3 and 4). No distinctive anomaly appears at this time at Lake Grinnell, while Green Lake records a negative isotopic excursion (Figs. 3 and 4). The reverse pattern occurs at 8.4 to 8.0 cal ka BP with a positive anomaly at Green Lake and a negative anomaly at Twin Ponds (Figs. 3 and 4). The apparent E–W oriented anti-phase relationship between Green Lake and

https://doi.org/10.1016/j.yqres.2016.02.009 Published online by Cambridge University Press

Twin Ponds during isotopic excursions at ca. 9.3 and ca. 8.2 cal ka BP is weakened, but remains evident in the data when dating uncertainties are considered (Fig. 4). Accounting for the uncertainties, the east-west difference between Twin Ponds and Green Lake (Fig. 5) only differs significantly from zero during these two episodes. Likewise, the north-south difference between Twin Ponds and Lake Grinnell only differs significantly from zero from 9 to 8 ka (Fig. 5).

PCA analysis

The principal component analysis (PCA) reveals that 53.4 ± 11.3% of the variance in the three datasets is captured by the first principal component (PC1; Fig. 6). All three datasets load roughly equally onto PC1 (Table 2). PC1 primarily represents the differences between the YD and the Holocene in all three records; the PC1 scores only differ significantly from zero during the YD (Fig. 6). Unlike PC1, the second two components (PC2 and PC3) have median scores that are not significantly different from zero based on the large envelopes of age-related uncertainty. The second principal component (PC2; Fig. 6) is dominated by Lake Grinnell, but explains a total of 28.5 ± 6.6% of the shared variance. The third principal component (PC3; Fig. 6) accounts for 18.1 ± 5.8% of the variance in the datasets. These uncertainty margins reflect the low ratio of climate signal to local noise once PC1 is extracted from the record.

Following the significant YD-age excursion, PC1 registers the highest scores of the record during the early Holocene. Afterward, PC1 scores decrease continuously from ca. 10.6 to 10.0 cal ka BP and center around zero from ca. 9.0 to 7.5 cal ka BP. The scores that represent these Holocene trends do not deviate significantly from zero. Neither do negative excursions at ca. 10.5, 10.0, 8.7, and 8.3 cal ka BP and positive excursions at ca. 10.9 and 9.3 cal ka BP. The variations in PC2 and PC3 are even less prominent and, including a negative peak centered at 11.4 cal ka BP in the PC2 scores, fail to record any major changes that exceed the range of uncertainty associated with potential differences in sample ages. The isotopic records from each site are sufficiently different that even accounting for age uncertainties, only the YD represents a period with a significant common departure of all three records from the background range of variability. The lack of additional significant signals arises, in part, from the absence of an early Holocene maximum at Lake Grinnell (Fig. 4) and from the opposite direction of the anomalies at ca. 9.3 and ca. 8.2 cal ka BP at Twin Ponds and Green Lake (Figs. 4 and 5).

Comparison with other records

During the YD, PC1 is consistent with records from the North Atlantic region, such as the NGRIP ice core oxygen isotope record from northern Greenland (Fig. 7); the timing and magnitude of the change at Twin Ponds is not meaningfully different than at NGRIP (Fig. 7). The termination of the YD-age excursion in all three lake records also seems to be at the same time as in the NGRIP record within the age uncertainties.

After the YD, PC1 changes may not be significantly different from the long-term mean, but also indicate that oxygen isotopic values at lakes in the northeast U.S. increased more gradually (until 11.2–10.5 cal ka BP) than at NGRIP. A trend toward decreasing $\delta^{18}O$ values after 10.6 cal ka BP at the two northern sites is also not evident in the Greenland data (Fig. 7). Thus, after the termination of the YD, the millennial trends in PC1 and NGRIP are anti-phased relative to each other. Around the time of the 9.2 ka-event (Fleitmann et al., 2008), a negative isotopic excursion in the NGRIP record coincides with a small, positive excursion in PC1, which is driven primarily by the positive excursion at Twin Ponds. However, both the NGRIP record and PC1 undergo negative excursions in the period from 8.5 to 8.0 cal ka BP (primarily driven by the Twin Ponds

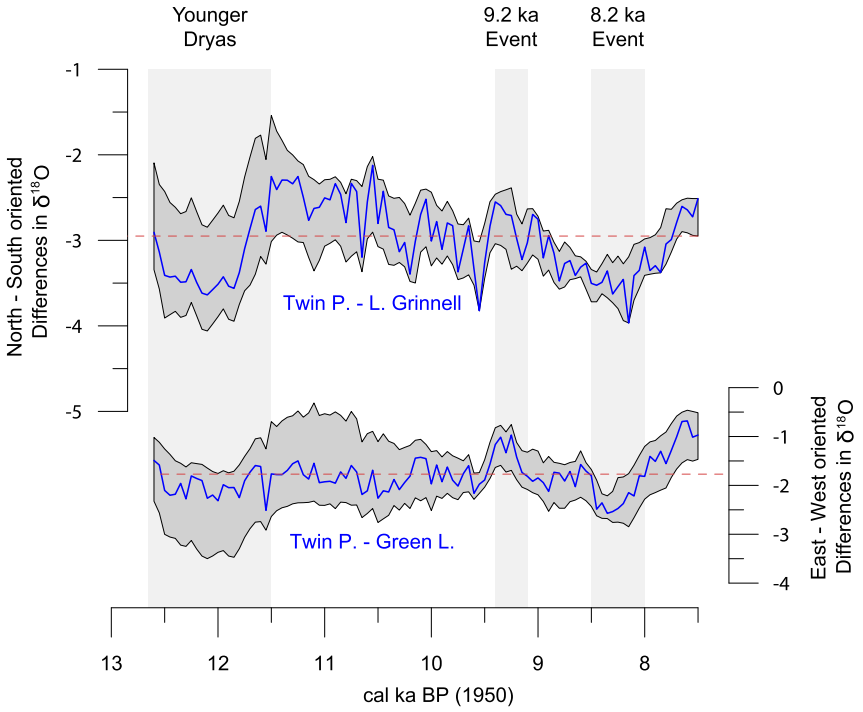

Figure 5. North-South (Lake Grinnell – Twin Ponds) and East-West (Twin Ponds – Green Lake) oriented isotopic differences in the northeastern United States. The gray areas depict the 90% confidence intervals and surround the median values. The dashed red lines represent the mean isotopic difference over the time interval depicted on the graph. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

https://doi.org/10.1016/j.yqres.2016.02.009 Published online by Cambridge University Press

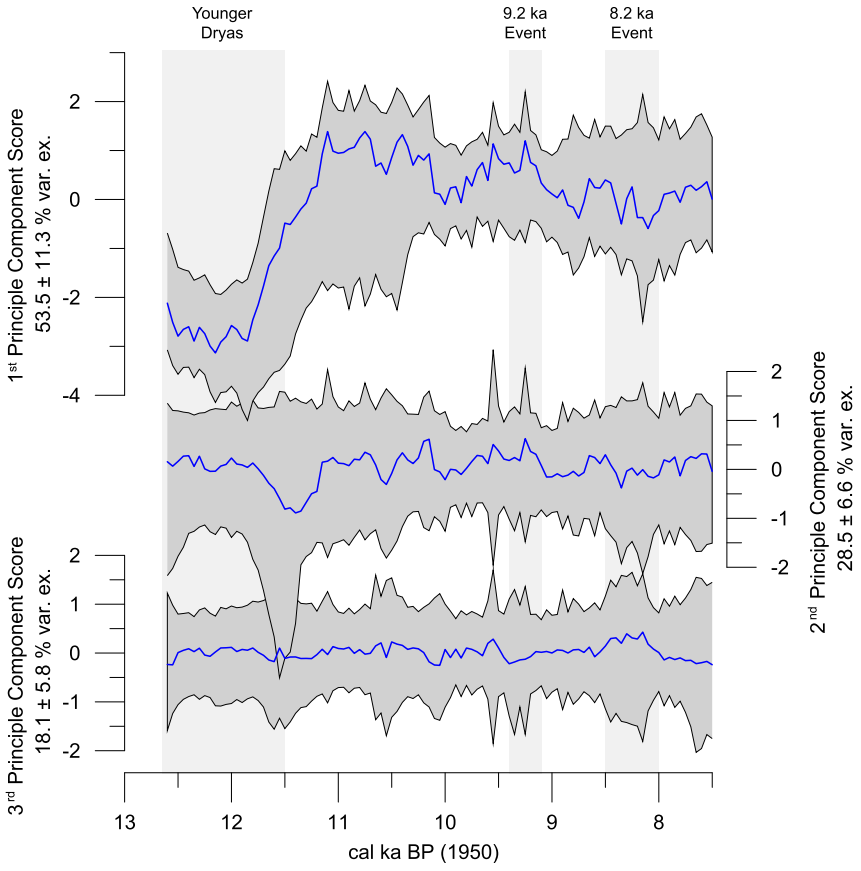

Figure 6. The first, second, and third principal component (PC1, PC2, PC3) of the three isotopic records from the northeastern United States. The uncertainty envelope depicted by the gray area (90% confidence interval) and bracketed by the 5% and 95% values surrounds the median (blue lines) of PC1, PC2, and PC3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

record), although the timing and duration of the anomalies differ between NGRIP and the northeastern U.S. Thus, the existing oxygen isotope records from the northeast U.S. differ spatially, but also indicate that any regional isotopic changes during the early Holocene differed from the sequence of $\delta^{18}O$ observed in Greenland (Fig. 7).

Discussion

Coherent regional changes

PC1 represents the only significant common signal among the three records: Low scores from 12.6 to 11.5 cal ka BP followed by a rapid rise to Holocene levels. Other aspects of PC1 do not significantly deviate from zero, but are notable for indicating a pattern replicated at both Twin Ponds and Green Lake: high scores from ca. 11.0 to 10.6 cal ka BP followed by a decline to around zero from ca. 9.0 to 7.5 cal ka BP.

The low scores from 12.6 to 11.5 cal ka BP occur during the YD and correspond to low isotopic values in ice cores from Greenland (Broecker et al., 1989; Rasmussen et al., 2006; Vinther et al., 2006). Reduced AMOC (Atlantic meridional overturning circulation), low sea-surface temperatures, and extensive sea ice in the North Atlantic during the YD (Clark et al., 2001) had a strong influence on the climate of the northeast U.S. as well as Greenland (Rind et al., 1986; Cwynar and Levesque, 1995; Levesque et al., 1997) and the negative isotopic values may represent the regional temperature depression. The regional coherency of the $\delta^{18}O$ signal represented by PC1 may stem from the large magnitude of the YD temperature change relative to Holocene changes (e.g., Huang et al., 2002; Shuman et al., 2007). Potentially, only a change of this magnitude can sufficiently overprint local factors to produce a regionally coherent signal. Thus, the presence of a clear YD signal in a record is not a sufficient indicator that the remaining variability is climatically significant or interpretable beyond the locality of the sampling site.

Table 2
Parameters obtained from the Principal Component Analysis (PCA).

	PC1	± (Std. Dev.)	PC2	± (Std. Dev.)	PC3	± (Std. Dev.)
Standard Deviation	1.26	0.13	0.92	0.11	0.73	0.12
Variance Explained	53.5%	11.3	28.5%	6.6	18.1%	5.8
Twin Ponds	0.60	0.13	0.46	0.29	0.65	0.18
Lake Grinnell	0.54	0.18	0.67	0.31	0.51	0.22
Green Lake	0.59	0.14	0.58	0.30	0.56	0.20

https://doi.org/10.1016/j.yqres.2016.02.009 Published online by Cambridge University Press

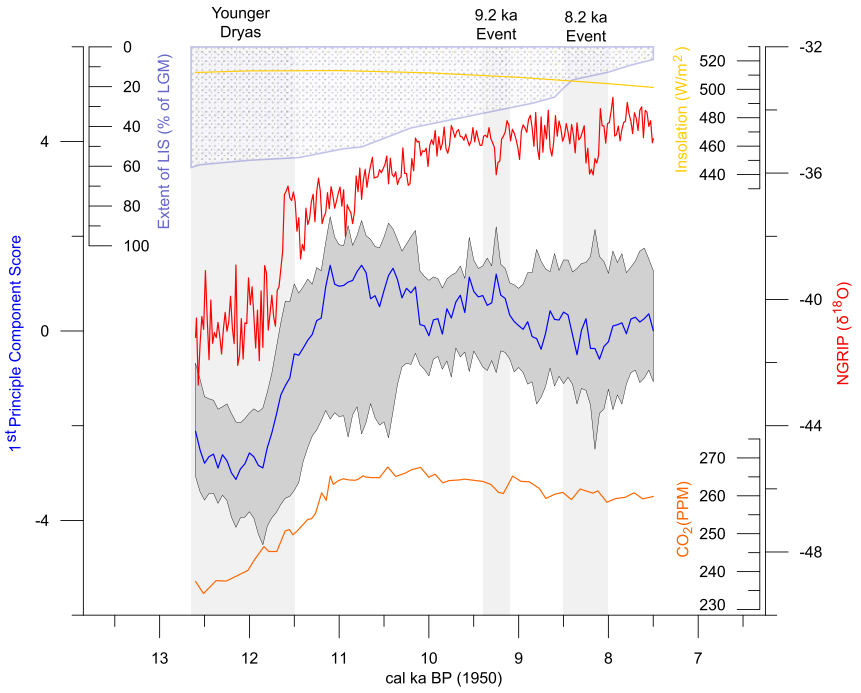

Figure 7. The first principal component (blue) and the NGRIP (red) both include the YD. These trends can be compared with CO_2 in the atmosphere (Monnin et al., 2004; orange). Notably, the shrinking Laurentide Ice Sheet (purple area), insolation (Berger and Loutre, 1991), and PC1 have similar trends during the early Holocene. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Additionally, the large, albeit not significant, $\delta^{18}O$ difference between Lake Grinnell and Twin Ponds during the YD (Fig. 5) also coincides with an exceptionally steep latitudinal gradient in lake-surface temperature during the YD (Levesque et al., 1997). Thus, atmospheric circulation may have shifted in a manner that enhanced the isotopic change at Twin Ponds during the YD. If so, the $\delta^{18}O$ record would provide an overestimate of the YD temperature change there.

Other factors may have also amplified the strong YD signal. For example, climate models predict, and lake-level changes indicate, that aridity in the northeastern U.S. likely increased rather than decreased during the YD; a southward shift of the jet stream and a strengthening of the anticyclone over the Laurentide Ice Sheet could have contributed to the aridity (Bartlein et al., 1998; Kutzbach et al., 1998; Webb et al., 1998; Newby et al., 2009, 2011). If so, enhanced evaporative losses from the lake likely would have generated positive isotopic changes and dampened the apparent temperature signal. However, low relative humidity and low dew point temperatures (the temperature during condensation and associated fractionation) or a shift in the balance of summer and winter precipitation that favored a large contribution from cold-season, isotopically-light precipitation could have amplified the negative signal during the YD. Consequently, more factors were likely to amplify the isotopic change than dampen it and, regardless of the specific cause and factors involved, to dominate and overprint any local, hydrological, or lake-dependent variables influencing the oxygen isotopic composition of the lake sediments (Steinman and Abbott, 2013; Steinman et al., 2013). The same may not be true of the Holocene portion of the record.

Following the YD, PC1 scores decreased from initially high values prior to ca. 10.6 cal ka BP, while the north-south (but not east-west) isotopic gradient strengthened (Figs. 5–7). The trend towards lower PC1 scores generally indicates decreasing coherency of $\delta^{18}O$ signals relative to the YD. Given the complexities of $\delta^{18}O$ records from bulk sediments (Steinman and Abbott, 2013; Steinman et al., 2013), the increasing heterogeneity of the records is not surprising in the absence of a dominant, overprinting climate event. Based on other paleoclimate proxies, a regionally-coherent component of the $\delta^{18}O$ signal at the three sites during the early Holocene could have been driven by a reduction in regional aridity (Webb et al., 1993; Newby et al., 2000; Shuman et al., 2001, 2002; Marsicek et al., 2013), but a significant common signal was not shared by all three sites. As noted above, the effects of enhanced lake evaporation and low dew point temperatures could have produced interference among effects and dampen any coherent regional changes.

Differences among sites

Shifts in isotopic gradients are a common feature of climate change, and occur on the scales of seasons (Bowen and Revenaugh, 2003) to centuries (e.g., as simulated by LeGrande et al., 2006). For this reason, we anticipated to be able to detect changes in the gradients between the three oxygen isotope records. The differences that we detected (Fig. 5) may stem from either local, lake-scale factors (e.g., changes in evaporative losses) or large-scale gradients in the isotopic composition of lake source-waters (e.g., precipitation; Henderson and Shuman, 2009). Consistent with the expected latitudinal and continental trends, the southernmost site (Lake Grinnell) is most positive and the northernmost site (Twin Ponds) is most negative (Figs. 2 and 3). Green Lake may be expected to have similar $\delta^{18}O_{precipitation}$ values as Twin Ponds (Bowen and Revenaugh, 2003), but its high $\delta^{18}O$ values relative to Twin Ponds may indicate greater local evaporation at Green Lake.

Evidence for the strengthening of the north-south isotopic gradients after 10.6 ka (Figs. 2 and 5) could suggest reduced evaporative enrichment of ^{18}O in the northern lakes after the early Holocene. Given that Twin Ponds does not show significant evidence of evaporative enrichment today (Fig. 1C), the high $\delta^{18}O$ values at both Green Lake and Twin Ponds in the early Holocene

https://doi.org/10.1016/j.yqres.2016.02.009 Published online by Cambridge University Press

could also confirm that atmospheric circulation, including a southerly position of the polar front, reduced north-south isotopic differences when the Laurentide ice sheet remained an important regional climate control (Kirby et al., 2002a; Shuman et al., 2002, 2006).

In either case, the northward retreat and subsequent decline of the Laurentide Ice Sheet likely contributed to reductions in regional aridity and in the $^{18}O/^{16}O$ ratios in the water of the two northern lakes (Shuman et al., 2002). As long as the Laurentide Ice Sheet existed, the climate in the northeastern United States was heavily influenced by a permanent high-pressure system and the associated anticyclone due to increased albedo and the geometry of the Laurentide Ice Sheet (Bromwich et al., 2004), causing a predominantly northerly wind direction and permanently dry conditions in the northeastern United States (Bartlein et al., 1998; Webb et al., 1998). The changes in aridity may have also coincided with changes in atmospheric circulation that favored an increasingly long moisture pathway or an insolation-driven decline in summer temperatures (Webb et al., 1993). Two anticipated alternative effects on early Holocene isotopic values related to the demise of the ice sheet – a shift towards summer precipitation (Shuman and Donnelly, 2006) and an increase in annual temperatures (Liu et al., 2012) – would have resulted in a positive direction of $\delta^{18}O$ change and are therefore inconsistent with the trend in the records.

Other isotopic anomalies visible in the raw isotope data, particularly the isotopic shifts around 9.2 and 8.2 cal ka BP, are sufficiently well constrained in time that they could not have had the same sign at all three sites and thus fail to register in the PCA (Fig. 6). Instead, they register as significant east-west differences between Twin Ponds and Green Lake (Fig. 5). Possibly, these events represent independent, isotopic changes arising from site-specific variations, such as changes in hydrology and sediment geochemical variations (e.g., a persistent state of disequilibrium; Steinman et al., 2013). Many of the details of the three records likely have such an explanation and, therefore, do not produce either significant anomalies in the PCA scores or the site-to-site differences. The events at ca. 9.2 and 8.2 cal ka BP, however, appear as the latter: significant site-to-site differences even after accounting for age uncertainties, which are discernible once the individual $\delta^{18}O$-records from Lake Grinnell, Green Lake, and Twin Ponds were subtracted from each other (Fig. 5).

Several specific analyses of regional gradients are relevant here. Moisture and temperature gradients between coastal and inland sites in Massachusetts and Connecticut changed during the Holocene (Marsicek et al., 2013; Newby et al., 2014), which suggests that E–W temperature, precipitation, and isotopic gradients could have also been susceptible to significant change during century-scale events in the early Holocene. Likewise, Levesque et al. (1997) detected a change in the north-south gradient in lake surface temperature in association with the YD. LeGrande and Schmidt (2008) simulated non-uniform changes in $\delta^{18}O$ in precipitation due to a meltwater pulse into the North Atlantic. Multiple studies (e.g., Teller et al., 2002; Bauer et al., 2004; Morrill and Jacobsen, 2005; Fleitmann et al., 2008; LeGrande and Schmidt, 2008; Hou et al., 2012; Morrill et al., 2013) indicate the occurrence of a YD-style depression in the AMOC at 9.2 and 8.2 cal ka BP, and thus a temporary decrease in $\delta^{18}O$ in lake sediments. However, the attendant circulation changes could also yield isotopic or moisture-balance gradient changes, which would mask (Lake Grinnell) or counter-act (Green Lake) temperature driven isotopic excursions.

Assuming concurrency of the isotope anomalies, we observed that, at 9.3 and 8.2 cal ka BP, the eastern lake (Twin Ponds) and the western lake (Green Lake) experience opposite sign change, which could indicate 1) a reduction in the east-west isotopic gradient at 9.3 cal ka BP, as occurs seasonally today (e.g., Bowen and Revenaugh, 2003) and with temperature gradients during the YD (Levesque et al., 1997), and 2) an amplification of the gradient at 8.2 cal ka BP. The different directions of change may reflect the background climate state at the time (higher insolation and a larger ice sheet at 9.3 than at 8.2 cal ka BP). Alternatively, the gradient change could indicate local differences in evaporation during these events; evaporative effects may have been important at both Green Lake and Twin Ponds, but not at Lake Grinnell, which may have always had little influence of evaporation and lake-water isotopic values consistent with the meteoric inputs (Zhao et al., 2010). In either case, the prominent anomalies that we detect are of similar age as the isotopic anomalies in Greenland even if the sign of the changes differ, which leaves the option open that these events did influence the northeastern United States, but did so in different ways in different areas (Fig. 7).

On a broader spatial scale, the NGRIP record and PC1 are negatively correlated with each other after the end of the YD and indicate a potential shift in the isotopic gradient between the northeast U.S. and Greenland (Fig. 7). This gradient change over millennial scales may represent circulation changes driven by the loss of the Laurentide Ice Sheet or shifting insolation that produced patterns like those associated with the North Atlantic Oscillation today, which cause eastern North America and Greenland to show contrasting temperature trends (e.g., Hurrell and Van Loon, 1997).

Conclusions

Our isotopic record from Twin Ponds, VT, adds to the picture of a dynamic and non-uniformly changing climate in the northeastern United States during the late Pleistocene and early Holocene. The new isotope record includes a feature synchronous with the YD in Greenland, an early Holocene maximum in $\delta^{18}O$ values, and additional, rapid isotopic change around 9.3 and 8.2 cal ka BP. The comparison of $\delta^{18}O$ records between Green Lake, Lake Grinnell, and Twin Ponds highlights regional similarities and differences during the late Pleistocene and early Holocene in the northeastern United States; when we obtained 10,000 plausible age relationships for each of the isotopic datasets, our Monte Carlo-type propagation of age-uncertainty emphasizes that only the isotopic signal of the YD is definitively shared by all three records.

The low scores in PC1 during the YD support cooling and a potential shift from summer to winter precipitation, as indicated by other datasets. Thus, the change in climatic conditions during the YD was regionally coherent and prominent, overprinting all other influences on $\delta^{18}O$ in lake sediments. Less coherency is apparent in the records after the YD, but a gradual decrease in oxygen isotopic values is captured by both Twin Ponds and Green Lake after 10.6 cal ka BP. Consequently, an early Holocene change in the north-south isotopic gradient may be consistent with regional aridity and attendant circulation changes attributable to the changing effects of insolation and the Laurentide Ice Sheet. The decreasing trend in PC1 after 10.6 cal ka BP is also negatively correlated with an increase in $\delta^{18}O$ in the NGRIP record, which could relate to circulation changes analogous to shifting North Atlantic pressure gradients today. Additional, short-lived circulation and gradient changes may be represented by the anti-phased responses of Green Lake and Twin Ponds around ca. 9.3 and 8.2 cal ka BP. If so, the different directions of change at these times indicate that different dynamics were involved in the two events.

The prominence of the low PC1-scores during the YD underlines the notion that isotopic changes during periods with a large-magnitude climatic change, and with positive interference among isotopic effects, may produce more uniform oxygen isotope signals in multiple lakes than during other periods. PC1 scores are significantly different from zero during the YD, a period for which our

https://doi.org/10.1016/j.yqres.2016.02.009 Published online by Cambridge University Press

original hypothesis seems justified. The uniform record of isotopic change during the YD contrasts starkly with more variable records thereafter. As the Laurentide Ice Sheet became less dominant and stopped to produce regional climate effects, the three lake sediment records indicate more isotopic, and likely climatic, divergence. The lack of significant post-YD anomalies in PC1 highlights the number of variables potentially impacting isotopic records and the pitfalls of assuming that conclusions obtained from bulk oxygen records span entire regions. Therefore, in the absence of a dominant climate forcing, the hypothesis that a shared climate signal underlies even the complex mélange of influences on bulk $\delta^{18}O$ in lake carbonates, does not hold up after the termination of the YD. The lack of strong Holocene signals arose, in part, from the difficulties in constraining short-lived isotopic anomalies in time, but site-specific anomalies may not represent regional signals. The dominance of local controls may require climate changes of the magnitude experienced during the YD to overprint them in a consistent fashion across many lakes, even in the same region.

Acknowledgments

We would like to thank K. Risley for assistance in the field and the laboratory. This manuscript greatly benefited from comments by J. Shinker and C. Eggleston. This research was funded by NSF Ecosystems (DEB-1146297). We also thank Z. Yu for sharing the published data from Lake Grinnell.

References

Alley, R.B., Ágústsdóttir, A.M., 2005. The 8k event: cause and consequences of a major Holocene abrupt climate change. Quaternary Science Reviews 24, 1123–1149.
Alley, R.B., Mayewski, P.A., Sowers, T., Stuiver, M., Taylor, K.C., Clark, P.U., 1997. Holocene climatic instability: a prominent, widespread event 8200 yr ago. Geology 25, 483–486.
Anchukaitis, K.J., Tierney, J.E., 2013. Identifying coherent spatiotemporal modes in time-uncertain proxy paleoclimate records. Climate Dynamics 41, 1291–1306.
Barber, D.C., Dyke, A., Hillaire-Marcel, C., Jennings, A.E., Andrews, J.T., Kerwin, M.W., Bilodeau, G., McNeely, R., Southon, J., Morehead, M.D., Gagnon, J.-M., 1999. Forcing of the cold event of 8200 years ago by catastrophic drainage of Laurentide lakes. Nature 400, 344–348.
Bartlein, P., Anderson, K., Anderson, P., Edwards, M., Mock, C., Thompson, R., Webb, R., Webb III, T., Whitlock, C., 1998. Paleoclimate simulations for North America over the past 21,000 years: features of the simulated climate and comparisons with paleoenvironmental data. Quaternary Science Reviews 17, 549–585.
Bartlein, Patrick J., 1997. Past environmental changes: characteristic features of quaternary climate variations. In: Huntley, Brian, Cramer, Wolfgang, Morgan, Alan V., Prentice, Honor C., Allen, Judy R.M. (Eds.), Past and Future Rapid Environmental Changes: the Spatial and Evolutionary Responses of Terrestrial Biota, NATO ASI Series 147. Springer Berlin Heidelberg, pp. 11–29.
Bauer, E., Ganopolski, A., Montoya, M., 2004. Simulation of the cold climate event 8200 years ago by meltwater outburst from Lake Agassiz. Paleoceanography 19.
Berger, A., Loutre, M.-F., 1991. Insolation values for the climate of the last 10 million years. Quaternary Science Reviews 10, 297–317.
Bowen, Gabriel J., Revenaugh, Justin, 2003. Interpolating the isotopic composition of modern meteoric precipitation. Water Resources Research 39.
Bowen, G.J., Wilkinson, B., 2002. Spatial distribution of $\delta^{18}O$ in meteoric precipitation. Geology 30, 315–318.
Broecker, Wallace S., Kennett, James P., Flower, Benjamin P., Teller, James T., Trumbore, Sue, Bonani, Georges, Wolfli, Willy, 1989. Routing of meltwater from the Laurentide ice sheet during the Younger Dryas cold episode. Nature 341, 318–321.
Bromwich, D.H., Toracinta, E.R., Wei, H., Oglesby, R.J., Fastook, J.L., Hughes, T.J., 2004. Polar MM5 simulations of the winter climate of the Laurentide ice sheet at the LGM*. Journal of Climate 17, 3415–3433.
Clark, P.U., Marshall, S.J., Clarke, G.K.C., Hostetler, S.W., Licciardi, J.M., Teller, J.T., 2001. Freshwater forcing of abrupt climate change during the last Glaciation. Science 293, 283–287.
Cwynar, L.C., Levesque, A.J., 1995. Chironomid evidence for late-glacial Climatic Reversals in Maine. Quaternary Research 43, 405–413.
Dansgaard, W., 1964. Stable isotopes in precipitation. Tellus 16, 436–468.
Dean, W.E., 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition; comparison with other methods. Journal of Sedimentary Research 44, 242–248.
Dean, W.E., Fouch, T.D., 1983. Lacustrine Environment: Chapter 2: PART 1.
Dyke, A.S., 2004. An outline of North American deglaciation with emphasis on central and northern Canada. Developments in Quaternary Sciences 2, 373–424.
Fleitmann, D., Mudelsee, M., Burns, S.J., Bradley, R.S., Kramers, J., Matter, A., 2008. Evidence for a widespread climatic anomaly at around 9.2 ka before present. Paleoceanography 23.
Gat, J.R., 1995. Stable isotopes of fresh and saline lakes. In: Lerman, A., Imboden, D., Gat, J.R. (Eds.), Physics and Chemistry of Lakes. Springer-Verlag, Berlin, pp. 139–165.
Gibson, J.J., Prepas, E.E., McEachern, P., 2002. Quantitative comparison of lake throughflow, residency, and catchment runoff using stable isotopes: modeling and results from a regional survey of Boreal lakes. Journal of Hydrology 262, 128–144.
Grafenstein, U.von, Erlenkeuser, H., Brauer, A., Jouzel, J., Johnsen, S.J., 1999. A Mid-European decadal isotope-climate record from 15,500 to 5000 years B.P. Science 284, 1654–1657.
Grafenstein, U. von, Erlenkeuser, H., Müller, J., Jouzel, J., Johnsen, S., 1998. The cold event 8200 years ago documented in oxygen isotope records of precipitation in Europe and Greenland. Climate Dynamics 14, 73–81.
Haslett, J., Parnell, A., 2008. A simple monotone process with application to radiocarbon-dated depth chronologies. Journal of the Royal Statistical Society: Series C Applied Statistics 57, 399–418.
Henderson, A.K., Nelson, D.M., Hu, F.S., Huang, Y., Shuman, B.N., Williams, J.W., 2010. Holocene precipitation seasonality captured by a dual hydrogen and oxygen isotope approach at Steel Lake, Minnesota. Earth and Planetary Science Letters 300, 205–214.
Henderson, A.K., Shuman, B.N., 2009. Hydrogen and oxygen isotopic compositions of lake water in the western United States. Geological Society of America Bulletin 121, 1179–1189.
Hou, J., Huang, Y., Oswald, W.W., Foster, D.R., Shuman, B., 2007. Centennial-scale compound-specific hydrogen isotope record of Pleistocene–Holocene climate transition from southern New England. Geophysical Research Letters 34.
Hou, J., Huang, Y., Shuman, B.N., Oswald, W.W., Foster, D.R., 2012. Abrupt cooling repeatedly punctuated early-Holocene climate in eastern North America. The Holocene 22, 525–529.
Huang, Y., Shuman, B., Wang, Y., Webb, T., 2002. Hydrogen isotope ratios of palmitic acid in Lacustrine sediments record late Quaternary climate variations. Geology 30, 1103–1106.
Huang, Y., Shuman, B., Wang, Y., Webb, T., 2004. Hydrogen isotope ratios of individual lipids in lake sediments as novel tracers of climatic and environmental change: a surface sediment test. Journal of Paleolimnology 31, 363–375.
Hurrell, J.W., Van Loon, H., 1997. Decadal variations in climate associated with the North Atlantic Oscillation. In: Climatic Change at High Elevation Sites. Springer, pp. 69–94.
Jones, M.D., Imbers, J., 2010. Modeling Mediterranean lake isotope variability. Global Planetary Change 71, 193–200.
Jouzel, J., Hoffmann, G., Koster, R.D., Masson, V., 2000. Water isotopes in precipitation:: data/model comparison for present-day and past climates. Quaternary Science Reviews 19, 363–379.
Kim, S.-T., O'Neil, J.R., 1997. Equilibrium and nonequilibrium oxygen isotope effects in synthetic carbonates. Geochimica et Cosmochimica Acta 61, 3461–3475.
Kirby, M., Patterson, W., Mullins, H., Burnett, A., 2002a. Post-Younger Dryas climate interval linked to circumpolar vortex variability: isotopic evidence from Fayetteville Green Lake, New York. Climate Dynamics 19, 321–330.
Kirby, M.E., Mullins, H.T., Patterson, W.P., Burnett, A.W., 2002b. Late glacial–Holocene atmospheric circulation and precipitation in the northeast United States inferred from modern calibrated stable oxygen and carbon isotopes. Geological Society of America Bulletin 114, 1326–1340.
Kutzbach, J., Gallimore, R., Harrison, S., Behling, P., Selin, R., Laarif, F., 1998. Climate and biome simulations for the past 21,000 years. Quaternary Science Reviews 17, 473–506.
LeGrande, A.N., Schmidt, G.A., 2008. Ensemble, water isotope–enabled, coupled general circulation modeling insights into the 8.2 ka event. Paleoceanography 23.
LeGrande, A.N., Schmidt, G.A., Shindell, D.T., Field, C.V., Miller, R.L., Koch, D.M., Faluvegi, G., Hoffmann, G., 2006. Consistent simulations of multiple proxy responses to an abrupt climate change event. Proceedings of the National Academy of Sciences of the United States of America 103, 837–842.
Levesque, A.J., Cwynar, Les C., Walker, Ian R., 1997. Exceptionally steep north–south gradients in lake temperatures during the last Deglaciation. Nature 385, 423–426.
Liu, Y., Brewer, S., Booth, R.K., Minckley, T.A., Jackson, S.T., 2012. Temporal density of pollen sampling affects age determination of the mid-Holocene hemlock (Tsuga) decline. Quaternary Science Reviews 45, 54–59.
Marcott, S.A., Shakun, J.D., Clark, P.U., Mix, A.C., 2013. A reconstruction of regional and global temperature for the past 11,300 years. Science 339, 1198–1201.
Marsicek, J.P., Shuman, B., Brewer, S., Foster, D.R., Oswald, W.W., 2013. Moisture and temperature changes associated with the mid-Holocene Tsuga decline in the northeastern United States. Quaternary Science Reviews 80, 129–142.
Monnin, E., Indermühle, A., Dällenbach, A., Flückiger, J., Stauffer, B., Stocker, T.F., Raynaud, D., Barnola, J.-M., 2001. Atmospheric CO_2 concentrations over the last glacial termination. Science 291, 112–114.
Monnin, E., Steig, E.J., Siegenthaler, U., Kawamura, K., Schwander, J., Stauffer, B., Stocker, T.F., Morse, D.L., Barnola, J.-M., Bellier, B., Raynaud, D., Fischer, H., 2004. Evidence for substantial accumulation rate variability in Antarctica during the

Holocene, through synchronization of CO_2 in the Taylor Dome, Dome C and DML ice cores. Earth and Planetary Science Letters 224, 45–54.
Morrill, C., Jacobsen, R.M., 2005. How widespread were climate anomalies 8200 years ago? Geophysical Research Letters 32.
Morrill, C., LeGrande, A.N., Renssen, H., Bakker, P., Otto-Bliesner, B.L., 2013. Model sensitivity to North Atlantic freshwater forcing at 8.2 ka. Climate of the Past 9, 955–968.
Newby, P.E., Donnelly, J.P., Shuman, B.N., MacDonald, D., 2009. Evidence of centennial-scale drought from southeastern Massachusetts during the Pleistocene/Holocene transition. Quaternary Science Reviews 28, 1675–1692.
Newby, P.E., Killoran, P., Waldorf, M.R., Shuman, B.N., Webb, R.S., Webb III, T., 2000. 14,000 years of sediment, vegetation, and water-level changes at the Makepeace Cedar Swamp, Southeastern Massachusetts. Quaternary Research 53, 352–368.
Newby, P.E., Shuman, B.N., Donnelly, J.P., Karnauskas, K.B., Marsicek, J., 2014. Centennial-to-millennial hydrologic trends and variability along the North Atlantic Coast, USA, during the Holocene. Geophysical Research Letters 41, 4300–4307.
Newby, P.E., Shuman, B.N., Donnelly, J.P., MacDonald, D., 2011. Repeated century-scale droughts over the past 13,000 yr near the Hudson River watershed, USA. Quaternary Research 75, 523–530.
Parnell, A., 2014. Bchron: Radiocarbon Dating, Age-depth Modelling, Relative Sea Level Rate Estimation, and Non-parametric Phase Modelling. R package version 3.1. http://CRAN.R-project.org/package=Bchron/.
Parnell, A.C., Haslett, J., Allen, J.R.M., Buck, C.E., Huntley, B., 2008. A flexible approach to assessing synchroneity of past events using Bayesian reconstructions of sedimentation history. Quaternary Science Reviews 27, 1872–1885.
R Core Team, 2013. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. http://www.R-project.org/.
Ratcliffe, N.M., Stanley, R.S., Gale, M.H., Thompson, P.J., Walsh, G.J., 2011. Bedrock Geologic Map of Vermont. U.S. Geological Survey Scientific Investigations Map, 3184, 3 sheets, Scale 1:100,000.
Rasmussen, S.O., Andersen, K.K., Svensson, A.M., Steffensen, J.P., Vinther, B.M., Clausen, H.B., Siggaard-Andersen, M.-L., Johnsen, S.J., Larsen, L.B., Dahl-Jensen, D., Bigler, M., Röthlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M.E., Ruth, U., 2006. A new Greenland ice core chronology for the last glacial termination. Journal of Geophysical Research 111.
Reimer, P., 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. Radiocarbon 51, 1111–1150.
Renssen, H., Seppä, H., Heiri, O., Roche, D.M., Goosse, H., Fichefet, T., 2009. The spatial and temporal complexity of the Holocene thermal maximum. Nat. Geosci 2, 411–414.
Ridge, J.C., 2003. Chapter 3: the last Deglaciation of the northeastern United States: a combined varve, paleomagnetic, and calibrated ^{14}C chronology. New York State Museum Bulletin 497, 15–45.
Rind, D., Peteet, D., Broecker, W., McIntyre, A., Ruddiman, W., 1986. The impact of cold North Atlantic sea surface temperatures on climate: implications for the Younger Dryas cooling (11–10 k). Climate Dynamics 1, 3–33.
Ruddiman, W.F., McIntyre, A., 1981. The North Atlantic Ocean during the last deglaciation. Palaeogeography Palaeoclimatology Palaeoecology 35, 145–214.
Sachs, J.P., 2007. Cooling of Northwest Atlantic slope waters during the Holocene. Geophysical Research Letters 34.
Schmidt, G.A., LeGrande, A.N., Hoffmann, G., 2007. Water isotope expressions of intrinsic and forced variability in a coupled ocean-atmosphere model. Journal of Geophysical Research Atmospheres 112, 2156–2202.
Shuman, B., Bartlein, P., Logar, N., Newby, P., Webb III, T., 2002. Parallel climate and vegetation responses to the early Holocene collapse of the Laurentide Ice Sheet. Quaternary Science Reviews 21, 1793–1805.
Shuman, B., Bartlein, P.J., Webb, T., 2007. Response to "Comments on: 'the magnitude of millennial- and orbital-scale climatic change in eastern North America during the Late-Quaternary' by Shuman et al." Quaternary Science Reviews 26, 268–273.
Shuman, B., Bravo, J., Kaye, J., Lynch, J.A., Newby, P., Webb III, T., 2001. Late quaternary water-level variations and vegetation history at crooked pond, Southeastern Massachusetts. Quaternary Research 56, 401–410.
Shuman, B., Donnelly, J.P., 2006. The influence of seasonal precipitation and temperature regimes on lake levels in the northeastern United States during the Holocene. Quaternary Research 65, 44–56.
Shuman, B., Huang, Y., Newby, P., Wang, Y., 2006. Compound-specific isotopic analyses track changes in seasonal precipitation regimes in the Northeastern United States at ca 8200 cal yr BP. Quaternary Science Reviews 25, 2992–3002.
Shuman, Bryan N., Newby, Paige, Donnelly, Jeffrey P., 2009. Abrupt climate change as an important agent of ecological change in the Northeast U.S. throughout the past 15,000 Years. Quaternary Science Reviews 28, 1693–1709.
Steinman, B.A., Abbott, M.B., 2013. Isotopic and hydrologic responses of small, closed lakes to climate variability: hydroclimate reconstructions from lake sediment oxygen isotope records and mass balance models. Geochimica et Cosmochimica Acta 105, 342–359. http://dx.doi.org/10.1016/j.gca.2012.11.027.
Steinman, B.A., Abbott, M.B., Nelson, D.B., Stansell, N.D., Finney, B.P., Bain, D.J., Rosenmeier, M.F., 2013. Isotopic and hydrologic responses of small, closed lakes to climate variability: comparison of measured and modeled lake level and sediment core oxygen isotope records. Geochimica et Cosmochimica Acta 105, 455–471. http://dx.doi.org/10.1016/j.gca.2012.11.026.
Steinman, B.A., Abbott, M.B., Mann, M.E., Ortiz, J.D., Pompeani, D.P., Stansell, N.D., Anderson, L., Finney, B.P., Bird, B.W., 2014. Ocean-atmosphere forcing of centennial hydroclimate variability in the Pacific Northwest. Geophysical Research Letters 41, 2553–2560.
Steinman, B.A., Rosenmeier, M.F., Abbott, M.B., Bain, D.J., 2010. The isotopic and hydrologic response of small, closed basin lakes to climate forcing from predictive models: application to paleoclimate studies in the upper Columbia River basin. Limnological Oceanography 55, 2231–2245.
Stuiver, M., Grootes, P.M., Braziunas, T.F., 1995. The GISP2 $\delta^{18}O$ climate record of the past 16,500 years and the role of the sun, ocean, and volcanoes. Quaternary Research 44, 341–354.
Teller, J.T., Leverington, D.W., Mann, J.D., 2002. Freshwater outbursts to the oceans from glacial Lake Agassiz and their role in climate change during the last Deglaciation. Quaternary Science Reviews 21, 879–887.
Vinther, B.M., Clausen, H.B., Johnsen, S.J., Rasmussen, S.O., Andersen, K.K., Buchardt, S.L., Dahl-Jensen, D., Seierstad, I.K., Siggaard-Andersen, M.-L., Steffensen, J.P., Svensson, A., Olsen, J., Heinemeier, J., 2006. A synchronized dating of three Greenland ice cores throughout the Holocene. Journal of Geophysical Research: Atmospheres 111.
Webb III, T., Anderson, K.H., Bartlein, P.J., Webb, R.S., 1998. Late quaternary climate change in eastern North America: a comparison of pollen-derived estimates with climate model results. Quaternary Science Reviews 17, 587–606.
Webb, R.S., Anderson, K.H., Webb III, T., 1993. Pollen response-surface estimates of late-quaternary changes in the moisture balance of the Northeastern United States. Quaternary Research 40, 213–227.
Yu, S.-Y., Colman, S.M., Lowell, T.V., Milne, G.A., Fisher, T.G., Breckenridge, A., Boyd, M., Teller, J.T., 2010. Freshwater outburst from lake superior as a trigger for the cold event 9300 years ago. Science 328, 1262–1266.
Zhao, C., Yu, Z., Ito, E., Zhao, Y., 2010. Holocene climate trend, variability, and shift documented by Lacustrine stable-isotope record in the northeastern United States. Quaternary Science Reviews 29, 1831–1843.

https://doi.org/10.1016/j.yqres.2016.02.009 Published online by Cambridge University Press