Lakewater paleothermometry from Deep Lake, Minnesota during the deglacial–Holocene transition from combined δ¹⁸O analyses of authigenic carbonate and aquatic cellulose

William M. Buhay⁎, Brent B. Wolfe, Antje Schwalb

Department of Geography, University of Winnipeg, 515 Portage Avenue, Winnipeg, Manitoba R3B 2E9, Canada
Department of Geography and Environmental Studies, Wilfrid Laurier University, Waterloo, Ontario N2L 3C5, Canada
Institut für Umweltgeologie, Technische Universität Braunschweig, Langer Kamp 19c, D-38106 Braunschweig, Germany

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ABSTRACT

Carbonate, cellulose, and bulk organic isotope data from varved sediments of Deep Lake (Minnesota) provide a record of paleohydrologic and paleoclimatic change during the deglacial–Holocene transition from 12,000 to 7500 cal BP. Deep Lake became enriched in ¹⁸O in response to increased influence of maritime tropical moisture from the Gulf of Mexico between 12,000 and 9500 cal BP culminating in regional expansion of Pinus and Quercus, and then again as a result of increased aridity with the establishment of more zonal circulation and prairie vegetation by 8500 cal BP. Summer lake water temperatures simultaneously increased during the deglacial–Holocene transition, as suggested by decoupling of carbonate δ¹⁸O and cellulose-inferred lake water δ¹⁸O values between 11,000 and 9500 cal BP, and then declined briefly around 8600 cal BP, possibly in response to the cooling event associated with the final drainage of Glacial Lakes Agassiz and Ojibway into the Labrador Sea. Although the carbonate-cellulose paleothermometer generated unrealistically high values, these can readily be explained by imposing kinetic effects that occur during rapid carbonate precipitation and conservative estimates of a seasonal lag effect in the synthesis of cellulose with respect to carbonate. These new results suggest that climatic variations during the deglacial–Holocene transition in northwestern Minnesota were driven mainly by changes in large-scale atmospheric circulation and that Lake Agassiz played a comparatively minor role except during its final drainage.

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1. Introduction

Carbonate materials in lake sediments have been widely utilized as oxygen isotope (δ¹⁸O) archives of paleohydrologic and paleoclimatic information. Their oxygen isotope compositions are influenced primarily by both lake water oxygen isotope composition and lake water temperature. The latter is controlled by the isotope composition of source waters (precipitation, surface runoff and subsurface input), modified by secondary evaporative isotopic enrichment (von Grafenstein et al., 1999; Anderson and Abbott, 2001; Wolfe et al., 2003; Leng and Marshall, 2004). Thus, changes in climate, atmospheric circulation patterns, hydrological conditions, catchment characteristics, lake water temperature and other factors can lead to changes in lake sediment carbonate δ¹⁸O records and, consequently, these stratigraphic profiles may be challenging to interpret (Yu et al., 1997; Smith and Hollander, 1999; Hammarlund et al., 2002; Anderson et al., 2005).

In some previous studies, it has been necessary to assume that water temperature remained relatively constant, allowing the carbonate δ¹⁸O sediment profiles to be interpreted solely on the basis of shifting lake water oxygen isotope composition. Although valid in cases where benthic ostracodes are presumed to have calcified at relatively invariant or near constant bottom lake water temperatures (e.g., Schwalb et al., 1994; Xia et al., 1997; Hammarlund et al., 1999; von Grafenstein et al., 1996, 1999; von Grafenstein, 2002; Danis et al., 2003; Dettman et al., 2005), other studies that utilize authigenic carbonate formed in the epilimnion require assumptions regarding lake water temperature or isotopic composition that are not easily tested (Anderson et al., 1997; Yu et al., 1997; Leng et al., 2001; Hammarlund et al., 2002; Leng and Marshall, 2004; Liu et al., 2009).

In contrast, the oxygen isotope composition of aquatic cellulose is systematically enriched by about 27−28‰ compared to its ambient water independent of temperature (DeNiro and Epstein, 1981;
Edwards and McAndrews, 1989; Sternberg, 1989; Yakir, 1992; Sauer et al., 2001; Wolfe et al., 2001, 2007). This constant isotopic enrichment allows direct inference of lake water δ18O (δ18O_{lw}) from measured cellulose δ18O (δ18O_{cell}) of aquatic origin in lake sediments. Although δ18O_{lw} records inferred from cellulose oxygen isotope measurements are not immune to complexities that influence lake water oxygen isotope composition, this is a paleolimnological approach that has been applied in many settings to extract paleohydrologic and paleoclimatic information (Wolfe et al., 2001, 2007; Buhay et al., 2009; Jonsson et al., 2010; St. Amour et al., 2010). Additionally, as recently demonstrated by Rozanski et al. (2010), the coupling of authigenic carbonate δ18O and aquatic cellulose δ18O represents a powerful new method for quantitative reconstruction of both paleohydrology and palaeotemperature from lake sediments.

This paper combines sedimentology, new isotopic and elemental data from undifferentiated organic matter and isolated aquatic cellulose, and previously reported bulk carbonate isotope results (Hu et al., 1997, 1999) from the varved sediments of Deep Lake, Minnesota. This integration is used to refine the paleohydrology and to estimate the epilimnion paleotemperature of Deep Lake in the context of profound climate changes that occurred in central North America between 12,000 and 7500 cal BP. Previous work by Hu et al. (1997) showed a marked δ18O depletion in bulk carbonate between 10,500 and 9900 cal BP that interrupted an overall δ18O-enrichment trend from 12,000 to 9100 cal BP. The decrease in δ18O was attributed to decreased summer temperature and increased precipitation originating from the cold and δ18O-depleted glacial meltwaters of Lake Agassiz, which had expanded at about this time due to ice re-advancement (Marquette) over the lake's eastern outlets (Lowell and Teller, 1994; Hostetler et al., 2000; Leverington et al., 2000; Leverington and Teller, 2003; Teller and Leverington, 2004; Teller et al., 2005; Breckenridge, 2007; Breckenridge and Johnson, 2009). However, pollen studies at Deep Lake (Hu et al., 1997) and elsewhere in the region (Minnesota, Manitoba, northern Illinois) show that Pinus (Bartlein et al., 1984; Schwalb and Dean, 2002; Wright et al., 2004; Teller et al., 2008; Teed et al., 2009), Quercus (Strong and Hills, 2005; Yansa et al., 2007; Teller et al., 2008; Gonzales and Grimm, 2009) and Ulmus (Yansa et al., 2007; Teller et al., 2008; Gonzales and Grimm, 2009) continued to increase during this interval at the expense of Picea-dominated forest. The effects of glacial Lake Agassiz on regional climate in the northern Great Plains thus remain open for alternative interpretations (Bartlein and Whitlock, 1993; Hu et al., 1999; Yu and Wright, 2001; Dean et al., 2002; Schwalb and Dean, 2002; Yansa and Ashworth, 2005; Henne and Hu, 2010).

2. Regional setting

Deep Lake (47.6836° N, 95.4001° W, Fig. 1) is a hydrologically closed basin with a surface area of approximately 0.04 km² and a maximum depth of 21 m. Located in northwestern Minnesota, near the current prairie-forest border and the triple-junction of diverse competing airmasses (Arctic, Gulf of Mexico, Pacific), Deep Lake is ideally situated to record hydrologic and climatic changes associated with the deglacial–Holocene transition. Recovered Deep Lake sediments consist of easily identifiable varved couplets composed of light-coloured precipitated calcite alternating with dark-coloured clastic and organic debris (Hu et al., 1999).

3. Materials and methods

Sediment samples for bulk organic and cellulose elemental and isotope analyses were obtained from three overlapping cores from Deep Lake correlated by varves and from the same depth intervals as for carbonate carbon and oxygen isotope analyses where sufficient

Fig. 1. Deep Lake (47.6836° N, 95.4001° W) has a maximum depth of 21 m, surface area of about 0.04 km², and is a hydrologically-closed basin. Deep Lake is strategically located near the triple-junction of competing cold, dry air from the Arctic, warm, moist air from the Gulf of Mexico, and mild, dry air from the Pacific which contribute to strong seasonality and variation in the isotopic composition of precipitation (Bryson and Hare, 1974; Simpkins, 1995). The X symbol indicates the location of the sediment core (Hu et al., 1999). The four recovered sediment trap (ST-1, ST-2, ST-3, ST-5) locations are also indicated.
sediment was available (Hu et al., 1997, 1999). In May 2009, sediment traps were deployed at five sites (Fig. 1) to collect settling material at 5–6 m water depth. Four of the traps were later recovered in September 2009. These samples were also subjected to elemental analysis as well as carbonate and cellulose carbon and oxygen isotope analyses. Epilimnion temperatures were measured in Deep Lake weekly from May to August, 2009, using a YSI metre. Water samples were also collected in May 2009 at the four sediment trap sites (1 m depth).

All samples were treated with 10% HCl to remove carbonate material, rinsed repeatedly with distilled water, and oven-dried (>40 °C). Following the carbonate removal and drying, the sediment samples were sieved (<500 μm) to eliminate macrofossil plant debris of possible terrestrial origin. Organic carbon and nitrogen elemental content and carbon isotope composition were determined on the fine-grained fraction at the University of Winnipeg Isotope Laboratory (UWIL) using an elemental analyzer (EuroVector EA) attached to a continuous-flow isotope-ratio mass spectrometer (Elementar Americas IsoPrime). Additional sample treatment involved solvent extraction, bleaching and alkaline hydrolysis to remove non-cellulose organic constituents, oxhydroxide leaching to remove possible inorganic oxygen sources, and sodium polytungstate heavy liquid separation to isolate the sediment cellulose from remaining minerogenic material (Wolfe et al., 2001, 2007). The carbon and oxygen isotope composition of cellulose sediment was determined using the UWIL Elementar Americas IsoPrime. Subsamples of the material collected in the four recovered sediment traps were sent to the Saskatchewan Isotope Laboratory (SIL) for bulk carbonate carbon and oxygen isotope analyses. Carbonate carbon and oxygen isotope compositions were determined on the trap sediments using a Kiel Carbonate Device coupled with a Thermo Scientific MAT 253. The four water samples were also sent to SIL and analyzed using a Picarro L1102i Isotopic Liquid Water Analyzer.

Isotope results are expressed as “δ” values, which represent deviations in per mil (‰) from the VPDB standard for carbon and carbonate oxygen and the VSMOW standard for cellulose oxygen such that δsample = [(Rsample/Rstandard) − 1]×103 where R is the 13C/12C or 18O/16O ratio in the sample and standard. Results of δ13C analyses are normalized to −55.5 ‰ for Standard Light Antarctic Precipitation (SLAP; see Coplen, 1996). The δ13Ccellulose and δ18Ocellulose values have analytical uncertainties of ±0.1‰ and ±0.2‰, respectively (based upon a standard:sample ratio of 1:3; duplicate and triplicate sample repeats were run on every 5th and 10th samples, respectively). Sediment trap δ18Ocarb values have an analytical uncertainty of ±0.11‰. The water sample oxygen isotope values have an analytical uncertainty of ±0.1‰.

4. Results and discussion

4.1. Sedimentology

Deep Lake sediments deposited from 12,000 to 7500 cal BP consist of six discrete units (Fig. 2a). Siliclastic-dominated couplets deposited before about 11,000 cal BP are composed of light-coloured carbonate laminations with few diatoms, and dark-coloured organic laminations. Carbonate-dominated couplets deposited between 11,000 and 9500 cal BP and from 8900 to 8300 cal BP are characterized by light-coloured laminations containing micritic calcite, suggesting a mainly authigenic origin, and abundant diatoms. Dark-coloured laminations consist of diatoms and organic material. The
carbonate content between 11,000 and 9500 cal BP, as determined by loss-on-ignition, increases from 20 to 40 per cent (Hu et al., 1997) to over 80 per cent (Fig. 2b). Between 9500 and 8900 cal BP, carbonate couplets are distinguished by a higher organic content (15–25%) compared to the couplets deposited prior to this interval (5–15%) and carbonate content decreases to 40–60 per cent (Fig. 2b). Couplets deposited between 8300 and 7900 cal BP consist of silt, carbonate with diatoms, and organic sediment with diatoms. After 7900 cal BP, couplets contain mainly laminations of light-coloured micritic carbonate with abundant diatoms and dark-coloured organic sediment.

4.2. Paleohydrologic reconstruction

As indicated by the low and constant C/N weight ratios for the sediment core samples (mean C/N = 9.7 ± 1.2; Fig. 2c) and the four sediment trap samples (mean C/N = 11.7 ± 0.8), the fine-grained organic fraction is autochthonous in origin (Meyers and Lallierverges, 1999; Meyers, 2003; Das et al., 2008; Yamaguchi et al., 2010) supporting a direct calculation of lake water $^{18}O$ from cellulose $^{18}O$ ($^{18}O_{cell}$) (Fig. 2d; $^{18}O_{cell} =$ 0.973 $^{18}O_{calc} - 27.2$, Rozanski et al., 2010). Interpretation of $^{18}O_{calc}$ records requires differentiation of the isotopic composition of source water, reflecting the integrated signature of surface and subsurface inflow and precipitation, from hydrologic factors (i.e., mainly evaporative isotopic enrichment) that may subsequently modify the isotopic content of the lake water. Changing atmospheric circulation and moisture conditions during the deglaciation–Holocene transition in this region have resulted in shifting precipitation $^{18}O$ and evaporative $^{18}O$-enrichment, both of which are manifested in the cellulose-inferred $^{18}O_{cell}$ record. At nearby Pickerel Lake, South Dakota, ostracode $^{18}O$ values during the deglacial–Holocene transition are higher compared to mid- and late Holocene values and are attributed to increased summer insolation and stronger summer monsoons carrying $^{18}O$-enriched moisture from the Gulf of Mexico (Schwalb and Dean, 1998; Liu et al., 2003). Lake water $^{18}O$-enrichment between 10,500 and 9500 cal BP (Fig. 2d) at the more northerly located Deep Lake is consistent with this interpretation and likely reflects maximum influence of Gulf-derived moisture. Evidence for increasingly warm and moist conditions developing between 12,000 and 9500 cal BP in the Deep Lake region are also provided by 1) the general decline in Picea beginning at 11,500 cal BP and brief increase in Pinus and Quercus pollen between 10,000 and 9500 cal BP (see Hu et al., 1997; Strong and Hills, 2005) and 2) bulk organic, cellulose and carbonate $^{13}C$ trends to lower values likely indicating increasing influx of soil-derived $^{13}C$-depleted dissolved inorganic carbon (DIC) (Fig. 2e, g).

Pinus pollen percentages decline markedly between 9600 and 9200 cal BP at the expense of herbaceous taxa (Hu et al., 1997, 1999; Wright et al., 2004) due to increased aridity related to a shift to more zonal atmospheric circulation (Bradbury et al., 1993; Hu et al., 1999; Yu and Wright, 2001; Dean et al., 2002) and a shift in precipitation seasonality (Henderson et al., 2010). In central Iowa, weighted mean values of modern precipitation $^{18}O$ derived from a Gulf-Pacific source are 2–3‰ lower than moisture that originates exclusively over the Gulf of Mexico (Simpkins, 1995). Thus, reduced maritime influence from the Gulf of Mexico combined with greater moisture contribution from air masses derived from the Pacific following the Pinus maximum (10,000–9500 cal BP) may have led to more $^{18}O$-depleted precipitation in the Deep Lake region and lower $^{18}O_{calc}$ values between 9500 and 8600cal BP. Alternatively, at higher latitudes, the west may have caused moist Gulf air to condense at higher altitudes, which would also lead to isotopic depletion in precipitation (Hu et al., 1999; Smith and Holland, 1999). Therefore, lake water $^{18}O$-enrichment after 8500 cal BP is attributed mainly to a decline in regional effective moisture and an increase in regional temperature and lake water evaporation (Henderson et al., 2010). Drier conditions after 8500 cal BP are also consistent with $^{13}C$-enrichment in the bulk organic matter, cellulose and carbonate (Fig. 2e and g), likely reflecting reduced influx of soil-derived $^{13}C$-depleted DIC and productivity-driven $^{13}C$-enrichment in the lakewater DIC.

4.3. Paleotemperature reconstruction

Comparison of cellulose-inferred $^{18}O_{calc}$ (Fig. 2d) to $^{18}O_{calc}$ (Fig. 2f) shows generally similar trends prior to 11,000 and after 9000 cal BP suggesting that $^{18}O_{calc}$ may be largely controlled by changes in the oxygen isotope composition of the lake water, as initially proposed by Hu et al. (1997). However, a clear departure in these records occurs during the 11,000 to 9000 cal BP interval. In Fig. 2f, $^{18}O_{calc}$ decreases by nearly 3‰ from 11,000 to 10,000 and then increases by almost 5‰ from 10,000 to 9000 cal BP. In Fig. 2d, however, cellulose-inferred $^{18}O_{calc}$ increases by about 3‰ from 11,000 to 10,000 and then decreases by about 3‰ from 10,000 to 9000 cal BP. As noted above, Hu et al. (1997) interpreted the decreasing trend in the $^{18}O_{calc}$ record between 11,000 to 10,000 cal BP to be mainly a result of increased precipitation derived from isotopically-depleted Lake Agassiz and decreased summer temperature. The cellulose-inferred $^{18}O_{calc}$ reconstruction for Deep Lake is inconsistent with this interpretation as isotopic analyses on ostracodes from the sediments of Pickerel Lake, which also display relatively $^{18}O$-enriched values during this interval, and instead suggest that moisture was primarily derived from enhanced delivery of warm $^{18}O$-enriched air masses forming over the Gulf of Mexico (Schwalb and Dean, 1998). Further, a simulation of the influence of Lake Agassiz on atmospheric circulation suggests substantially reduced precipitation in the vicinity of Deep Lake at 11,000 cal BP (Hostetler et al., 2000). An alternative explanation for the decreasing $^{18}O_{calc}$ trend between 11,000 and 10,000 cal BP is an increase in summer lake water temperature (SLWT), which resulted in lower $^{13}C_{calc}$ values due to reduced equilibrium isotope fractionation but did not impart an isotope effect on cellulose $^{18}O$ because of the apparent insensitivity of cellulose-water oxygen isotope fractionation to temperature.

Quantitative reconstruction of SLWT from paired $^{18}O_{calc}$ and cellulose-inferred $^{18}O_{calc}$ samples using the calcite–water equilibrium equation (Kim and O’Neil, 1997) results in a wide range of values between 5 and 32°C ($\pm 5$°C) with an increase in SLWT during the deglacial–Holocene transition at roughly 11,000 cal BP (Fig. 2h). Reduced CO$_2$(aq) solubility due to warmer surface water temperatures in summer, perhaps enhanced by prolongation of the ice-free period, may partly account for the two-fold increase in carbonate content to over 80% between 11,000 and 9500 cal BP (Fig. 2b). An increase in carbonate content can also be observed in sediments from nearby Williams Lake (Schwalb et al., 1995) and Pickerel Lake (Schwalb and Dean, 1998) deposited around this time interval. An increase in SLWT during the deglacial–Holocene transition is also consistent with previously reported vegetation changes in the region (Bartlein et al., 1984; Hu et al., 1997; Strong and Hills, 2005) and coherent with simulated increases in regional temperatures during this time (Hostetler et al., 2000). Brief cooling occurred at 8700–8500 cal BP, which may be associated with the final drainage of glacial lakes Agassiz and Ojibway into the Labrador Sea (Hu et al., 1999; Teller et al., 2002). Given the uncertainties in the absolute sediment chronology, this short-lived cooling may relate to the widely reported 8200 cal BP cold event (Dean et al., 2002; Clarke et al., 2004, 2009; Hillaire-Marcel et al., 2007; Roy et al., 2011).
Table 1

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\delta^{18}O_{\text{carb}}$ (‰ VPDB)</th>
<th>$\delta^{18}O_{\text{cell}}$ (‰ VSMOW)</th>
<th>Cell-inferred $\delta^{18}O_{\text{w}}$ (‰ VSMOW)</th>
<th>Measured $\delta^{18}O_{\text{w}}$ (‰ VSMOW)</th>
<th>Epilimnion T measured (℃)</th>
<th>Epilimnion T calculated (℃)</th>
<th>Epilimnion T lag 1% (℃)</th>
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<td>ST-1</td>
<td>-4.5</td>
<td>23.7</td>
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<td>12.9</td>
<td>15.5</td>
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<td>11.4</td>
<td>17.8</td>
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<tr>
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<tr>
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<td>15.6</td>
<td>11.0</td>
</tr>
<tr>
<td>Ave</td>
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<td>23.2</td>
<td>-4.7</td>
<td>-8.1</td>
<td>11.9</td>
<td>15.7</td>
<td>11.1</td>
</tr>
</tbody>
</table>

While the trends in reconstructed SLWT during the deglaciation–Holocene transition are consistent with Deep Lake varve sedimentology, regional vegetation changes, other stratigraphic records and climate models, values higher than ~25 °C are likely unrealistic given the average measured epilimnion lake water temperature during summer 2009 was 11.9 °C. There are two possible explanations for the high SLWT values calculated using the carbonate-cellulose oxygen isotope paleothermometer. Rozanski et al. (2010) also encountered unrealistically high estimates of epilimnion temperatures for Lake Gosciaz, Poland, using the same approach. Results from modern process studies were used to suggest that kinetic-isotope depletion during rapid calcite precipitation led to average calculated epilimnion temperatures that were 4.2 °C higher than average measured epilimnion temperatures. Based on the sediment trap data, the average calculated epilimnion temperatures are 3.8 °C higher than the average measured epilimnion temperature (Table 1) — a result in close agreement with Rozanski et al. (2010).

The high SLWT values may also be due to a seasonal offset in the deposition of aquatic cellulose (autumn) compared to precipitation of authigenic carbonate (mid-late summer). While the sediment traps deployed in Deep Lake were not seasonally monitored, sediment trap studies at nearby Elk Lake indicate major algal production occurs during the spring and autumn when lake overturn results in nutrient replenishment (Nuhfer et al., 1993). The autumn and winter microalgae of the varved deposits of Elk Lake, which are largely composed of organic matter, however tend to be more prominent than the spring overturn deposit which may even be missing in some years due to abrupt warming and stratification (Nuhfer et al., 1993). During the deglaciation–Holocene transition, increased summer insolation may have further inhibited the formation of a spring overturn deposit, which may partly explain why the oldest varves at Elk Lake spanning 10,300 to 8300 cal BP are characterized by almost pure summer–winter microalgae. A similar sequence of sedimentation at Deep Lake would lead to calculation of elevated SLWT because cellulose-inferred $\delta^{18}O_{\text{w}}$ values would reflect additional $^18O$-enrichment due to both isotopically-enriched rainfall and lake water evaporation captured in autumn aquatic production following mid-late summer carbonate precipitation. This seasonal offset may have been especially pronounced between 10,500 and 9500 cal BP due to maximum summer monsoonal activity, and after 8500 cal BP as a result of increased aridity. For example, lower and more reasonable SLWT values can readily be generated by employing a cellulose-carbonate lag enrichment of only 1‰ prior to 10,500 and between 9500 and 8500 cal BP, and 2‰ between 10,500 and 9500 and after 8500 cal BP, in accordance with the proposed greater seasonal isotopic offset in lake water composition during these latter two intervals (Fig. 2b).

Results from contemporary lake water $^18O$ measurements of Deep Lake, and sediment trap cellulose and carbonate $^18O$ analyses, provide additional support for a seasonal lag effect in the formation of cellulose compared to carbonate. Cellulose-inferred lake water $^18O$ values from the sediment traps are, on average, ~3.4‰ higher than the May 2009 lake water $^18O$ measurements (Table 1). This indicates that cellulose production occurs later in the season, following an increase in lake water oxygen isotope composition due to evaporative isotopic enrichment and/or input of isotopically-enriched rainfall. Notably, imposing a lag $^18O$-enrichment of only 1‰ on the Deep Lake sediment trap cellulose $^18O$ data (i.e., assume sediment trap cellulose formed in lake water 1‰ higher than that of the sediment trap carbonate) generates close agreement between the average calculated epilimnion temperature (11.1 °C) and the average measured epilimnion temperature (11.9 °C; Table 1). Thus, the lake water oxygen isotope composition that was contemporaneous with the precipitation of carbonate likely falls between the measured May 2009 lake water $^18O$ values and the values inferred from the sediment trap cellulose $^18O$ analyses. Further assessment of possible mechanisms to explain the SLWT results would require more intensive sampling to obtain seasonal carbonate, cellulose and lake water $^18O$ data.

5. Conclusions

The paleohydrologic and paleotemperature record derived from multiple isotopic archives extracted from the varved sediments of Deep Lake, Minnesota, can be reconciled within the pre-existing framework of large-scale atmospheric circulation changes and resulting vegetation development during the deglaciation–Holocene transition. The reconstructions suggest that glacial Lake Agassiz played a less important role in regional climate than previously thought, although the lake appears to possibly have had some impact during its final drainage (Bradbury et al., 1993; Hu et al., 1997, 1999; Dean et al., 2002). Overall, these isotopic records are consistent with an increase in maritime tropical moisture from the Gulf of Mexico and warming between 12,000 and 9500 cal BP. This was followed by a brief period of cooling, tentatively linked to the drainage of glacial lakes Agassiz and Ojibway, and a subsequent increase in temperature and aridity with the establishment of more zonal circulation by 8500 cal BP. The findings, like those of Rozanski et al. (2010), also highlight the strong potential for generating quantitative paleotemperature reconstructions from coupled $^18O$ measurements of authigenic carbonate and aquatic cellulose in lake sediment records.

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