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Late Holocene climate change in central Sweden inferred from lacustrine stable isotope data

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ABSTRACT: Stable isotopes (δ18O and δ13C) of lacustrine carbonates (Chara spp. algae and Pisidium spp. molluscs) from a lake sedimentary sequence in central Sweden were analysed to infer changes in lake hydrology and climate during the late Holocene. Results from analysis of lake water isotopes (δ18O and δ2H) show that Lake Blektjärnen water isotope composition is responsive to the balance between evaporation and input water (E/I ratio). A high E/I ratio results from a dry and probably warmer climate, decreasing the relative importance of precipitation input. Under such conditions evaporation and atmospheric equilibration probably enrich lake water in 18O and 13C, respectively, which is reflected in the isotopic composition of the carbonates in the lake. From the relatively positive δ18O values we infer that conditions were dry and warm between 4400 and 4000 cal. a BP, whereas more negative values indicate that conditions were wetter and probably cooler between 4000 and 3000 cal. a BP. A drier climate is inferred from more positive values between 2500 and 1000 cal. a BP. However, a successive depletion after ca. 1750 cal. a BP, also detected in several other δ18O records (carbonate and diatom), suggest increasingly wetter conditions in Scandinavia after that time, which is probably related to increased strength of the zonal flow. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS: stable isotopes; lake hydrology; humidity; late Holocene; central Sweden.

Introduction

During the Holocene (the present interglacial that commenced ca. 11 650 cal. a BP; Walker et al., 2009) periods of marked climate change have been detected in palaeoclimatic archives in northern Europe. Climate has changed on millennial (e.g. Marchal et al., 2002; Mayewski et al., 2004; Moberg et al., 2005) as well as on centennial to annual scales (e.g. Grudd et al., 2002; Hammarlund et al., 2002; Rosqvist et al., 2007; Grudd, 2008). Results show that the climate was maritime, i.e. warmer and wetter, in Fennoscandia between ca. 10 000 and 8000 cal. a BP (Hammarlund et al., 2003; Seppä et al., 2005), and that between ca. 8000 and 5000 cal. a BP mean annual temperatures were at least 1°C higher than today (Heikkilä and Seppä, 2003; Seppä et al., 2005; Antonsson and Seppä, 2007). A change in climate mode between ca. 5000 and 4000 cal. a BP that led to a more unstable colder and humid climate has been detected in lake and glacier records (Nesje et al., 2001, 2008; Seppä and Birks, 2001; Hammarlund et al., 2003; Bjune et al., 2005; Jessen et al., 2005; Seppä et al., 2005; Antonsson et al., 2008; de Jong et al., 2009; Ojala et al., 2008). Climate variability in Fennoscandia is related to changes in the North Atlantic ocean and atmospheric circulation, although the forcing is still not understood (Wanner et al., 2008).

This study aims to reconstruct lake water δ18O variation as a means of inferring changes in moisture supply in an area where such information is scarce. Other studies in northern Sweden have shown that variations in stable isotopes in lacustrine sediments reflect changes in precipitation and temperature that can be related to shifts in atmospheric circulation patterns (Hammarlund et al., 2002; Rosqvist et al., 2004, 2007). Here we focus on the late Holocene between 4400 cal. a BP and the present. We use oxygen (δ18O) and carbon (δ13C) isotopes of Chara encrustations and shells of Pisidium molluscs obtained from Lake Blektjärnen, a hard-water lake located east of the Scandes Mountains in central Sweden, to reconstruct past changes in evaporation/inflow ratio (E/I). Charophytes are photosynthesising green algae that precipitate calcite mainly between June and August (cf. Mörner and Wallin, 1977), whereas Pisidium are bottom-dwelling filter-feeding bivalves mainly active during the ice-free season (late May to early November) (Kilgour and Mackie, 1991) with life spans of approximately 1–4 years (Holopainen and Hanski, 1986; Killeen et al., 2004). Isotope analyses of both Chara and Pisidium thus provide us with the opportunity to identify whether changes in the E/I ratio occurred mainly during summer (Chara) or during a longer season (Pisidium).
Site description

Lake Blektjärnen (62°′ 14′′ N, 14°′ 39′′ E; 330 m above sea level (a.s.l.)) is a small hard-water lake located in central Sweden. It is situated ~200 m north-northeast of the northern shore of Lake Näkten (Fig. 1(A–D)), to which it was connected during the last deglaciation and early Holocene (Lundqvist, 1969). Lake Blektjärnen has a surface area of approximately 0.05 km² and a catchment area of ~0.45 km² (Fig. 1(E)) and is 10 m deep (mean water depth ~4 m). The lake has an estimated water volume of 156 000 m³. Lake water residence time has been calculated to >1 year based on the modern lake volume and the amount of mean annual effective precipitation (precipitation–evaporation) falling in the catchment. At present the only outflow is via a pipe placed ~50 cm below the lowest shoreline (Fig. 1(E)); maximum measured flow rates from this pipe were 1.5–2 L s⁻¹.

The vegetation in the catchment is woodland dominated by birch, willow and pine. The beach of Lake Blektjärnen is composed of calcareous gyttja, which indicates that lake level has been higher in the past. The bedrock around Lake Blektjärnen is composed of Cambro-Silurian sedimentary rocks, mostly alum shale and limestone (Norling, 2002), which extend to the north and northwest, while igneous rocks predominate in the south (Fig. 1(C)). The catchment is covered in a layer of Quaternary sediments (sandy till and clayey till) ~0.5 m thick (Lundqvist, 1969) (Fig. 1(B)). The region was ice free by ca. 10 000 cal. a BP (Lundqvist, 2002) and is characterised by several calcareous lakes. During the deglaciation ice-dammed lakes formed, which were subsequently drained. Lake Näkten and Lake Blektjärnen were part of such an ice-dammed lake which had a paleoshoreline up to 365 m a.s.l. (Lundqvist, 1969), 35 m above the present level. The base of the Lake Blektjärnen sediment sequence is composed of clayey sand, which is over lain by clayey silt and clay, and calcareous gyttja. A date of 7850 ± 60 ¹⁴C a BP obtained on macrofossils (Betula twig) at ~620–625 cm depth (8729 ± 249 cal. a BP) (S. Andersson, unpublished) provides a minimum age for the end of the ice lake stage and the start of lake infilling.

Mean annual precipitation (1961–1990) measured at the nearest meteorological station, Östersund, is 564 mm a⁻¹, with maximum monthly precipitation in July (86 mm), while the lowest occurs in February (29 mm). Mean annual temperature is +3.0 °C and average temperatures for January and July are ~9.0 °C and +14.0 °C, respectively (1961–1990) (Alexandersson and Eggertsson Karlström, 2001), and evaporation amounts to ~400 mm a⁻¹ (Bringfelt and Forsman, 2004). The climate in the

Figure 1 (A) Map of Scandinavia with the location of Lake Blektjärnen. (B) Quaternary deposits in the area modified after Lundqvist (1969) and (C) bedrock map modified after Gorbatschev et al. (1997), Karis and Strömberg (1998) and Sturkell et al. (1998). Field area is indicated by a box (dotted line). (D) Lake Blektjärnen and other surface waters where water was sampled. (E) Lake Blektjärnen and its catchment (dotted line). The coring site is marked by a black dot and Q₄ax denotes the location of the modern pipe.
study area is more continental, i.e. drier and cooler, compared to the climate at the lake sites located in the Scandes Mountains, where other palaeoclimatic reconstructions have been conducted (Rosqvist et al., 2004; St Amour, 2009). Lake Blektjärnen was chosen as it has a small catchment and is effectively a closed lake despite the small modern outflow. Therefore, water loss is predominantly controlled by evaporation and the lake water isotope composition is probably responsive to the balance between evaporation and input water. Because of this, changes in humidity can potentially produce significant changes in water $\delta^{18}O$ and $\delta^{13}C$ values (Leng and Marshall, 2004). We assume that lower humidity, or more arid climatic conditions, leads to higher (less negative) $\delta^{18}O$ and $\delta^{13}C$ values that reflect $^{18}O$ and $^{13}C$ enrichment due to increased evaporation and atmospheric equilibration. In contrast, increased humidity or wetter climatic conditions result in lower (more negative) $\delta^{18}O$ and $\delta^{13}C$ values that reflect less $^{18}O$ and $^{13}C$ enrichment because of reduced evaporation and atmospheric equilibration (Li and Ku, 1997). Changes in humidity often lead to covariance between $\delta^{18}O$ and $\delta^{13}C$ isotopes in lacustrine carbonate (Talbot, 1990), which can also be evident on a seasonal basis. For example, during the summer months $\delta^{18}O$ and $\delta^{13}C$ in lake water becomes enriched due to increased evaporation and productivity (Turner et al., 1982) but this relationship can be lost during the winter months due to lake water recharge by precipitation. However, non-evaporating lakes can also have higher $\delta^{18}O$ due to addition of enriched $^{18}O$ from summer precipitation (Tyler et al., 2007), but the amount of $\delta^{18}O$ change will be significantly less.

Materials and methods

Fieldwork

Fieldwork was conducted in 2005, 2006 and 2008. Long sediment cores were extracted from the lake bed from the frozen lake surface at a water depth of 400 cm using a Russian corer (Jowsey, 1965) (100 cm length, diameter 5 cm), with overlaps of 50 cm in April 2006 (Fig. 1(D)). The cores were placed in PVC tubes and wrapped in plastic, before being transferred to cold-room storage until required for analysis. This study focused on the uppermost 100 cm of the 266 cm long sediment sequence. To obtain enough material for all planned analyses six parallel cores were obtained between 400 and 500 cm below the water surface.

Surface water samples were collected from lakes and a stream in the proximity of Lake Blektjärnen (Fig. 1(D)). Properties for each lake were calculated based on estimated catchment and lake area and mean water depth (Table 1). Modern water samples were taken in May and September in 2008 in order to detect seasonal $\delta^{18}O$ and $\delta^2H$ variation of water due to precipitation and evaporation effects (Fig. 1(D) and Table 2). At Lake Blektjärnen water samples were taken from the lake and its modern outlet in April, May, July, September and October (2005, 2006, 2008) (Fig. 1(D) and Table 2).

Laboratory work

The lithostratigraphy of the parallel sediment cores was described and cores were correlated with each other based on specific marker horizons (i.e. organic-rich layers). One core was continguously sampled (in 1 cm segments) for terrestrial plant macrofossils, Chara spp. and Pilidium spp. shells (sample set I), another for tephra analysis (sample set II) and a third for measurements of total organic carbon and total carbon content (%TOC and %TC, respectively) (sample set III).

The isotope analysis of the water samples was undertaken at the Department of Geology and Geochemistry Stockholm University, and at the NERC Isotope Geosciences Laboratory (NIGL), British Geological Survey. At Stockholm the water samples were analysed for $^{18}O$/$^{16}O$ ratios using the CO$_2$–H$_2$O technique with a Gasbench II coupled to a Finnigan Delta plus mass spectrometer, whereas the $^2H/^1H$ ratios were measured using the Cr oxidation method with an H-device coupled to a Finnigan MAT 252 mass spectrometer. At NIGL, the waters were equilibrated with CO$_2$ using an ISOPREP 18

<table>
<thead>
<tr>
<th>Name of lake</th>
<th>Estimated catchment area (km$^2$)</th>
<th>Estimated lake volume (m$^3$)</th>
<th>Inflow and outflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blektjärnen</td>
<td>0.56</td>
<td>160 000</td>
<td>Modern outflow</td>
</tr>
<tr>
<td>Bjurtjärnen</td>
<td>0.94</td>
<td>44 000</td>
<td>Yes</td>
</tr>
<tr>
<td>Karsätjärnen</td>
<td>0.7</td>
<td>63 000</td>
<td>Yes</td>
</tr>
<tr>
<td>Kullstatjärnen</td>
<td>1</td>
<td>360 000</td>
<td>Yes</td>
</tr>
<tr>
<td>Skutetjärnen</td>
<td>0.3</td>
<td>80 000</td>
<td>Yes</td>
</tr>
<tr>
<td>Vitsjön</td>
<td>0.63</td>
<td>440 000</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 2 $\delta^{18}O$ and $\delta^2H$ analytical results of water samples collected in Lake Blektjärnen and surrounding lakes and streams. Samples were analysed at the Department of Geology and Geochemistry Stockholm University, and at NIGL, Nottingham, UK (marked in bold). See Fig. 1(D) for location of sites.

<table>
<thead>
<tr>
<th>Location of water samples</th>
<th>Date of sampling (day/month/year)</th>
<th>$\delta^{18}O$ (%)</th>
<th>$\delta^2H$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blektjärnen (lake)</td>
<td>27/7/2005</td>
<td>~9.95</td>
<td>~80.78</td>
</tr>
<tr>
<td></td>
<td>25/10/2005</td>
<td>~9.82</td>
<td>~79.97</td>
</tr>
<tr>
<td></td>
<td>4/4/2006</td>
<td>~10.23</td>
<td>~82.89</td>
</tr>
<tr>
<td></td>
<td>7/9/2006</td>
<td>~9.7</td>
<td>~80.52</td>
</tr>
<tr>
<td></td>
<td>23/5/2008</td>
<td>~11.07</td>
<td>~86.3</td>
</tr>
<tr>
<td></td>
<td>15/7/2008</td>
<td>~10.41</td>
<td>~82.1</td>
</tr>
<tr>
<td></td>
<td>16/9/2008</td>
<td>~10.31</td>
<td>~83.6</td>
</tr>
<tr>
<td>Blektjärnen (outlet)</td>
<td>27/7/2005</td>
<td>~9.97</td>
<td>~80.59</td>
</tr>
<tr>
<td></td>
<td>25/10/2005</td>
<td>~9.97</td>
<td>~81.29</td>
</tr>
<tr>
<td></td>
<td>7/9/2006</td>
<td>~9.7</td>
<td>~81.24</td>
</tr>
<tr>
<td></td>
<td>23/5/2008</td>
<td>~11.13</td>
<td>~86.4</td>
</tr>
<tr>
<td></td>
<td>16/9/2008</td>
<td>~10.38</td>
<td>~83.3</td>
</tr>
<tr>
<td>Snow (in the catchment of Blektjärnen)</td>
<td>4/4/2006</td>
<td>~17.05</td>
<td>~130.04</td>
</tr>
</tbody>
</table>
device for analysis of $^{18}$O/$^{16}$O ratios with mass spectrometry performed on a VG SIRA. For hydrogen isotope analysis, an online Cr reduction method was used with a EuroPyroOH-3110 system coupled to a Micromass Isoprimemass spectrometer. Isotopic ratios ($^{18}$O/$^{16}$O and $^{2}$H/$^{1}$H) are expressed as delta units, $^8$18O and $^8$2H ($\%$ parts per mil), and defined in relation to the international standard, VSMOW (Vienna Standard Mean Ocean Water). The precision of measurements is $\pm 0.1\%$ for $^8$18O and $\pm 1\%$ for $^8$2H for samples analysed at both Stockholm University and NIGL.

Sample set I

The first set of samples was gently wet-sieved through a 125 $\mu$m sieve under running water. Terrestrial plant macrofossils, Chara spp. encrustations and Pisidium spp. shells were extracted by hand and examined under a binocular microscope. Betula seeds, catkin bracts and Pinus needles were selected for $^14$C measurements, cleaned by extra rinsing with distilled water, dried, weighed and sent for analysis at the accelerator mass spectrometry (AMS) unit at the Tandem Laboratory, Uppsala.

Chara encrustations (5–10 tubular encrustations, $\sim$1–2 mm in size) were cleaned in distilled water, dried in plastic beakers and ground to a fine powder, whereas the Pisidium shells (two single shells per sample) were gently crushed and H$_2$O$_2$ was added for 30 min to remove organic material. Methanol was added and samples were placed in an ultrasonic bath for 30 s, filtered and dried at 50 °C overnight. The crushed Chara spp. and Pisidium spp. were weighed ($\sim$100 $\mu$g) and placed in glass vials, and stable isotope measurements ($^{18}$O/$^{16}$O and $^{13}$C/$^{12}$C ratios) were conducted on a Kiel device coupled to a Finnegan MAT 252 mass spectrometer, at the Department of Geology and Geochemistry, Stockholm University. The isotope ratios (18O/16O and 2H/1H) are expressed as delta notation (in deviations per mil), and defined in relation to the V-PMDB standards.

The samples were ground and combusted in pure oxygen, with the evolved CO$_2$ content analysed by infrared radiation in an Erika CS 500 carbon analyser, with an accuracy of $\pm 1\%$. The machine measures the carbon content in percentage dry weight; TOC at 550 °C and TC at 950 °C. The TOC content was calculated as a percentage using the molar weight of carbon of 12 and an estimated organic matter composition of CH$_2$O, with a molar weight of 30. The difference between %TOC and %TC was used to calculate the CaCO$_3$ content (CaCO$_3$), with a molar weight of 100, as a percentage in the sediments. The residue (i.e. non-organic compounds) was calculated as residue = 100 – (OC × 30/12) + (CaCO$_3$ × 100/12) (Fig. 3).

**Results**

Isotope composition of lake and stream waters in the study area

Samples of water collected from the stream Gravbäcken had $^8$18O values close to $-13.5\%$ and $^8$2H values of $-98\%$ for both May and September in 2008 and fall on the Global Meteoric Water Line (GMWL) (Fig. 2 and Table 2). Water sampled in lakes Bjurtråget, Karsåttråget, Kullstattråget and Skutettråget in May 2008 had $^8$18O values between $-12.5\%$ and $-13.5\%$ and $^8$2H values between $-94\%$ and $-97\%$, which are close to the GMWL (Fig. 2). However, the $^8$18O and $^8$2H values of water collected in these lakes in September 2008 were slightly enriched, with $^8$18O values between $-11.5\%$ and $-12\%$ and $^8$2H values between $-88.5\%$ and $-90.5\%$ (Fig. 2 and Table 2).

The isotopic composition of the water samples from lake Blektjarnten collected in April, July, September and October 2005, 2006 and 2008 have $^8$18O values between $-9.7\%$ and $-10.2\%$, and $^8$2H values between $-80\%$ and $-83.6\%$ (Fig. 2 and Table 2). However, water samples from May 2008, which were taken in the lake and from its outlet, were relatively depleted, with $^8$18O values of $-11\%$ and $^8$2H values of $-86\%$. Together, the water samples from Lake

**Figure 2** $^8$18O and $^8$2H of sampled lakes and their outlets. Samples taken in May are marked by open squares and samples taken in September by filled squares. Lakes Bjurtråget, Karsåttråget, Kullstattråget and Skutettråget and their outlets Vikbäcken, Karsån and Kullstabäcken (open squares), and the stream Gravbäcken (diamonds) plot on or close to the global meteoric water line (GMWL). Water samples from lakes Blektjarnten (triangles) and Vitsjön (filled circles) display enriched values and plot on a local evaporation line (LEI) (dotted line). The GMWL is shown as a black line: $^8$2H = 8 $^8$18O + 10 (Craig, 1965)

Blektjärnen and its outlet plot on a Local Evaporation Line (LEL) which intersects the GMWL at a $\delta^{18}$O value of $-13.5\%$ and a $\delta^2$H value of $-98\%$ (Fig. 2), and these values are assumed to be the mean weighed $\delta^{18}$O and $\delta^2$H of precipitation for the region.

Measured $\delta^{18}$O and $\delta^2$H in water sampled from Lake Vitsjön in May 2008 has similar values to those from Lake Blektjärnen. However, the April 2006 and September 2008 samples were more enriched, indicating that evaporation was more predominant compared to Lake Blektjärnen, probably because of the great surface area and no direct outflow of Lake Vitsjön (Fig. 2).

Lithostratigraphy

The sediments of Lake Blektjärnen between 500 and 404 cm depth from the lake surface, representing 4400 cal. a BP to the present, are described here. The sediments comprise partly laminated calcareous gyttja, which varies in colour (Munsell Soil Color Chart, 2000) from yellowish white (2.5Y 7/2) to dark brown (2.5Y 3/2) (Fig. 3). The laminae are more pronounced between ~470 and 430 cm depth, whereas no laminae are found between ~415 and 404 cm depth. A distinct dark-brown organic layer, composed of ~80% organic carbon, is seen between ~463 and 462 cm depth. Small air voids found throughout the sediment sequence (~1 mm in size) could be signs of bioturbation by bottom-dwelling and borrowing molluscs (Håkanson and Jansson, 1983).

The CaCO$_3$ decreases from ~75% to ~60% between 500 and 470 cm depth, followed by a sharp decrease to ~4% in the organic-rich layer at 463 and 462 cm depth (Fig. 3). Between 460 and 404 cm depth the values fluctuates around ~80%. The TOC increases from ~20% at the bottom of the section to a maximum of ~90% at 463–462 cm depth. A sharp decrease follows and the values are relatively stable around 10% to the top of the core. The residue is <10% for most of the record except between 466 and 454 cm depth, where it increases to ~20% (Fig. 3).

Isotope analyses

The *Pisidium* shells and *Chara* encrustations recovered from the sediments indicate generally good preservation conditions. However, in the interval between 475 and 460 cm, *Chara* encrustations are not present and there are fewer *Pisidium* shells. *Chara* $\delta^{18}$O values generally vary between ~10% and ~12% (Fig. 3), the lowest values occurring between ~490 and 480 cm depth, whereas values around ~10% to ~11% occur between 480 cm and 422 cm depth. Low $\delta^{18}$O values of ~11% and ~12% follow, before a trend towards relatively higher values from 409 cm depth to the surface. *Chara* $\delta^{13}$C vary between ~1.5% and ~4% and follow a similar trend to that seen in the $\delta^{18}$O record. The lowest $\delta^{13}$C values (~4%) occur between ~490 and 480 cm depth, above which values are slightly higher (between 458 and 436 cm depth). Above 436 cm depth values become gradually lower until the uppermost part (above 410 cm depth) which is characterised by a trend towards higher values (Fig. 3).

The record of *Pisidium* $\delta^{18}$O and $\delta^{13}$C is less complete compared to that for *Chara*, because the shells are less abundant (Fig. 3). *Pisidium* $\delta^{18}$O values are relatively stable between 500 and 456 cm, fluctuating between ~8% and ~9%. A gradual depletion to ~10% is visible between 432 and 420 cm. The $\delta^{18}$O values become slightly enriched in the upper 15 cm of the record. *Pisidium* $\delta^{13}$C values fluctuate around ~6% between 500 and 480 cm, and around ~7% between 474 and 456 cm depth. Around 430 cm depth $\delta^{13}$C values become gradually depleted. The uppermost 12 cm show fluctuations between ~7% and ~8% (Fig. 3).

Chronology

The chronology is constrained by 11 $^{14}$C dates on terrestrial plant macrofossils (Table 3) and geochemically identified tephra shards at 411–412 cm depth (Table 4) from the Askja...
1875 eruption (Mohn, 1878). This was the only tephra in the sequence that provided enough material for identification. All tephra shards were confined to one sample, with a concentration of ~15 shards cm\(^{-2}\) wet sediment. This indicates that reworking, bioturbation or downward migration at this level was limited. It was only possible to analyse six shards due to the low concentration of tephra. Two of these were outliers, possibly with an origin in the Katla volcanic system (Table 4). The age model was constructed with the IntCal04 atmospheric calibration curve (Reimer et al., 2004) and the Bayesian software Bpeat (Blaauw and Christen, 2005; Blaauw et al., 2007), using the following prior assumptions: (i) accumulation was approximately linear within sections (in order to allow for many changes in accumulation rate, we applied this to 11 sections, or the number of dated levels minus one); (ii) the accumulation rate probably varied between 10 and 50 cm\(^{-1}\) a \(-1\) (AlpaMean 30, AlphaStd 15, Epsilon 2); (iii) hiatus between sections was considered unlikely; and (iv) prior outlier probabilities for all \(^{14}C\) dates were 5%. The calendar age of the Askja 1875 tephra was set at 75 +10 \(-10\) 72.34 0.79 12.11 3.34 0.09 0.72 2.61 3.22 2.41 0.16 0.09 97.13 Askja-1875

Table 4  Major oxide percentages in tephra from Blektjärnen compared with analyses of the Askja-1875 tephra detected at other sites in Sweden and Norway (Bergman et al., 2004; Pilcher et al., 2005; Borgmark and Wastegård, 2008)

<table>
<thead>
<tr>
<th>Lab. no.</th>
<th>Depth (cm)</th>
<th>Material</th>
<th>(^{14}C) age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ua-33388</td>
<td>421–423</td>
<td>Betula catkin bracts and seed</td>
<td>985 ± 30</td>
</tr>
<tr>
<td>Ua-34567</td>
<td>428–430</td>
<td>Betula catkin bracts and seed</td>
<td>665 ± 40</td>
</tr>
<tr>
<td>Ua-34568</td>
<td>434–436</td>
<td>Betula catkin bracts and seeds</td>
<td>1835 ± 40</td>
</tr>
<tr>
<td>Ua-33389</td>
<td>446–448</td>
<td>Betula catkin bracts</td>
<td>2245 ± 30</td>
</tr>
<tr>
<td>Ua-33390</td>
<td>451–453</td>
<td>Betula catkin bracts and Pinus needles</td>
<td>2310 ± 30</td>
</tr>
<tr>
<td>Ua-33391</td>
<td>463–465</td>
<td>Betula catkin bracts and Pinus needle</td>
<td>2485 ± 30</td>
</tr>
<tr>
<td>Ua-34569</td>
<td>472–473</td>
<td>Betula catkin bracts and Pinus needle</td>
<td>2725 ± 40</td>
</tr>
<tr>
<td>Ua-34570</td>
<td>482–483</td>
<td>Betula catkin bracts</td>
<td>3005 ± 40</td>
</tr>
<tr>
<td>Ua-33392</td>
<td>486–488</td>
<td>Betula catkin bracts and Pinus needle</td>
<td>3450 ± 45</td>
</tr>
<tr>
<td>Ua-34571</td>
<td>493–495</td>
<td>Betula catkin bracts and seed</td>
<td>3310 ± 40</td>
</tr>
<tr>
<td>Ua-33393</td>
<td>499–500</td>
<td>Betula catkin bract and Pinus needle</td>
<td>3935 ± 55</td>
</tr>
</tbody>
</table>

Discussion

Modern lake hydrology

The lake is infilled by groundwater seepage and direct precipitation, direct outflow is small although some water is lost from the outflow pipe and there is likely to be some groundwater seepage. The water samples from Lake Blektjärnen show relatively stable \(^{18}O\) values of around ~10% from April to October. The lower \(^{18}O\) value of ~11% from May is probably due to the influence of isotopically \(^{18}O\)-depleted snowmelt during the spring thaw (Fig. 2). The lake water \(^{18}O\) is ~3% enriched when compared to the groundwater and does not lie on the GMWL (Fig. 2). In contrast, the stream Gravbäcken has \(^{18}O\) values comparable to groundwater and lies on the GMWL at the intercept with the LEL. Gravbäcken water is therefore likely to be derived mostly from groundwater, and its position at the point of interception of the GMWL and LEL suggests it has values close to the mean weighted precipitation (Fig. 2). \(^{18}O\) values for the other lakes in the study area that have both inflows and outflows (Table 1) were close to the GMWL in May 2008, which indicates that they are probably continually flushed. However, all the lakes are influenced by summer evaporation as they have more positive \(^{18}O\) values in September and lie on the LEL (Fig. 2). The difference between \(^{18}O\) and \(^{2}H\) in the water of Lake Blektjärnen, as compared to the other sampled lakes and streams, shows that it is more strongly affected by evaporation and is not flushed by winter fresh water as the other lakes seem to be (except Lake Vitsjön). The most likely reason for this difference is the larger volume of Lake Blektjärnen (Table 1). A comparison between \(^{18}O\) values in Lake Blektjärnen and \(^{18}O\) in precipitation, which has been regularly monitored (1975–1980) at Bredkälen (400 m a.s.l.; 63° 50’ N, 15° 18’ E; ~130 km north-northeast of Lake Blektjärnen) and Forslund (192 m a.s.l.; 60° 05’ N, 13° 47’ E; ~430 km to the south) show that lake water \(^{18}O\) is more stable throughout the ice-free season compared to \(^{18}O\) in precipitation (Fig. 5), which suggests a relatively long residence time for the lake water, at
least more than 1 year. Thus the modern lake water data for Lake Blektjärnen show that the $\delta^{18}O$ values of lake water are mainly controlled by the balance between evaporation and input of precipitation, which is expressed as the evaporation to input ratio ($E/I$).

Past changes in Chara and Pisidium $\delta^{18}O$ and $\delta^{13}C$  

$\delta^{18}O$ values of Chara and Pisidium depend on the temperature and isotopic composition of the lake water. An increase in water temperature results in lower $\delta^{18}O$ due to mineral–water fractionation of $\sim -0.24\%_{o}^{} C$ $^{-1}$ (Craig, 1965). This effect is counteracted by contrasting isotopic change in meteoric water due to changes in condensation temperature, which is $\sim +0.6\%_{o}^{} C$ $^{-1}$ (Dansgaard, 1964), assuming the Dansgaard relationship for northwestern Europe. Therefore, if temperature increases by 1°C the $\delta^{18}O$ of the carbonates change by +0.36% (−0.24% + 0.6%) (Leng and Marshall, 2004). Calculated equilibrium calcite values (in V-PDB) using mean air temperatures as estimates for water temperatures (Livingstone and Lotter, 1998) and lake water $\delta^{18}O$ compositions of −10 to −12% in V-SMOW (Fig. 6) show that, despite a constant lake water $\delta^{18}O$ value, relatively enriched equilibrium calcite can be yielded if it is formed when temperatures are lower. As expected, relatively depleted equilibrium calcite will be precipitated if calcite is precipitated when temperatures are relatively higher. The isotopic composition of Lake Blektjärnen water is determined by the isotopic composition and amount of input water and evaporation (as described above). Shifts in the isotopic composition of the precipitation reflect changes in regional temperatures and precipitation patterns that follow upon changes in atmospheric circulation dynamics. The change of the isotopic composition of lake water due to evaporation can be very significant, often swapping any per mil change in $\delta^{18}O$ due to temperature.

All these effects need to be considered when comparing Chara and Pisidium $\delta^{18}O$ records because of the difference in the actual length of their respective growth season. Pisidium $\delta^{18}O$ values are probably influenced by lower lake temperatures and more depleted (spring–autumn) lake water. This is because of their longer active season that lasts from late May until early November when the mean air temperature is ca 8°C,

Figure 4  Grey-scale graph of the computed age model. Dark-grey areas correspond to sections where the chronology is well constrained, while light-grey sections indicate higher uncertainty. The age model is constrained by 11 $^{14}C$ dates (indicated by stars) and the Askja-1875 tephra (indicated by a black dot) and was constructed with the IntCal04 calibration curve (Reimer et al., 2004) and the Bayesian software Bpeat (Blauw and Christen, 2005; Blauw et al., 2007) using prior assumptions (see text).

Figure 5  Precipitation $\delta^{18}O$ values measured at Bredkålen and Forshult (1975–1980) compared to the lake water samples of Lake Blektjärnen (presented in Table 2). The data for Bredkålen and Forshult were obtained from the GNIP/WMO database (2008).

Figure 6  y-Axis indicates calculated equilibrium calcite $\delta^{18}O$ values (V-PDB) depending on the lake water temperature (x-axis) and isotopic composition of the lake water (V-SMOW, bold lines). Mean air temperatures, ~8°C during late May to early November and ~13°C for June–July, are used as estimates for water temperatures. The measured Chara (black circles) and Pisidium (grey circles) $\delta^{18}O$ values are indicated to the left in the graph. A $\delta^{18}O$ offset of ~0.8‰ for aragonite in Pisidium shells is removed in the figure, since it is independent of temperature (von Grafenstein et al., 1999; Kim et al., 2007). Equilibrium calcite values were calculated using $^C_{\text{calcite}} = 13.8 - 4.586 C - 8w + 0.0862w^2$ (Leng and Marshall, 2004), where $\delta c = \text{carbonate} \delta^{18}O$ (V-PDB), and $\delta w = \text{water} \delta^{18}O$ (V-SMOW).
whereas Chara mainly photosynthesise during June–July when the mean air temperature is ~13°C (Fig. 6) (cf. Hammarlund et al., 2002). This difference of 5°C corresponds to a change of ~1.2‰ in δ18O and probably explains some of the difference between the Chara and Pisidium δ18O records. The isotopic composition of the lake water will also be more negative early in the season due to the influence of 18O-depleted snowmelt, which would further deplete the δ18O of Pisidium.

The cycling of carbon in lakes is complex and involves several steps where fractionation can occur, which complicates the interpretation of carbon isotopic signals. Dissolved inorganic carbon (DIC) in a lake contains a number of carbon species (Kelts and Hsu, 1978) and the δ13C in the DIC pool can vary by several per mil during a year due to contribution from sources including soil-derived CO2 (δ13C ~−25‰; Hoefs, 2004), dissolution of local bedrock (δ13C ~−2 to +2‰; Sturkell et al., 1998), aquatic production (discrimination against 13C by photosynthesising plants; Hollander and McKenzie, 1991), deposition and breakdown of organic material (deposition removes carbon from the system and breakdown releases 13C-enriched CO2; e.g. Dettman et al., 1999; Teranes et al., 1999; Myrbo and Shapley, 2006). During the summer months when lakes are actively evaporating, the lake water also exchanges CO2 with the isotopically heavier atmospheric CO2, resulting in δ13C enrichment in DIC when residence times are longer (Li and Ku, 1997). The covariance often seen between δ18O and δ13C in lacustrine carbonates is commonly attributed to evaporation and atmospheric exchange, which often occur concurrently.

Chara algae convert bicarbonate, HCO3−, into two CO2 molecules by proton pumping (McConnaughey, 1991). Kinetic fractionation occurs as the lighter molecule is preferentially used for photosynthesis and the heavier is used to precipitate calcite (McConnaughey, 1991; McConnaughey and Falk, 1991; Hammarlund and Lemdahl, 1994; Hammarlund et al., 1997). von Grafenstein et al. (2000) suggested a kinetic effect on Chara δ13C of ~4‰, compared to the δ13C composition of DIC. For Pisidium, however, it has been suggested that they build their shells in or close to isotopic equilibrium with DIC in water (Stuiver, 1968; Fritz and Poplawski, 1974; McConnaughey et al., 1997; von Grafenstein et al., 1999, 2000). The recorded difference between mean δ13C values in Chara (~−2.5‰) and Pisidium (~−6.5‰) from Lake Blektjärnen of ~4‰ is consistent with the previously suggested offsets for kinetic effects in Chara, assuming that Pisidium precipitates δ13C in equilibrium with DIC (Fritz and Poplawski, 1974; Hammarlund et al., 1997; von Grafenstein et al., 1999, 2000).

Overall, the Lake Blektjärnen isotope record shows similar δ18O and δ13C trends (Figs 3 and 7). We argue that this is because increased evaporation and enhanced vapour exchange led to preferential loss of lighter isotopes, which resulted in elevated values of δ18O and δ13C during periods with relatively drier climate (Talbot, 1990; Li and Ku, 1997). The correlation coefficient for covariance is large (r = 0.54) between δ18O and δ13C values in Chara, indicating that past changes in the isotopic composition of Lake Blektjärnen in the summer is controlled to a large degree by variation in the E/I ratio. If so, more negative δ18O and δ13C values would imply more humid conditions. The Pisidium records display small covariance (r = 0.22) between δ18O and δ13C values, which might be explained to some extent by their relatively longer active season and different habitat. A long season has implications for the δ13C compositions as Pisidium experiences variable δ13C values due to seasonally changing rates of productivity and decomposition in the lake. Also the Pisidium δ13C composition is likely to be more readily affected by oxidation of organic matter at the sediment–water interface because of their preferred habitat (and burrowing) in deeper

**Figure 7** (A) Comparison of sediment carbon content (% TOC, CaCO3 and residue) and δ18O and δ13C in Chara and Pisidium raw data (dots and thin line) and three-point running mean (thick black line) vs. calendar years BP. Four intervals of humidity changes inferred from Lake Blektjärnen records are indicated: dark grey denotes relatively high humidity between ca. 4000–3000 and 1000–50 cal. a BP; and light grey indicates relatively dry conditions between ca. 4400–4000 and 2500–1000 cal. a BP.
sediments where decomposition processes often elevate the concentration of $^{13}$C-depleted CO$_2$.

**Palaeoclimatic significance**

Prior to 4000 cal. a BP

$\text{Chara } \delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values are relatively high between ca. 4400 and 4000 cal. a BP. Given the strong evaporation dependence of Lake Blektjärnen we suggest that the $E/I$ ratio (the balance between evaporation and input water) was relatively high due either to low precipitation or higher temperatures, or a combination of these factors (Fig. 7). Pollen-based temperature reconstructions show that climate was warmer in Scandinavia from ca. 8000 to ca. 4000 cal. a BP (Seppä et al., 2005; Antonsson and Seppä, 2007). A warmer climate could have favoured the aquatic productivity illustrated by the relatively high TOC content (Fig. 7).

Between ca. 4000 and 3000 cal. a BP

Isotope minima in $\text{Chara } \delta^{18}\text{O}$ and $\delta^{13}\text{C}$ occur at ca. 3500 cal. a BP; the negative trend begins around 4000 cal. a BP (Fig. 7). We suggest that precipitation increased, suppressing evaporation (which increases $\delta^{18}\text{O}$) and atmospheric equilibration (which increases $\delta^{13}\text{C}$) through input of $^{18}$O-depleted rainwater and shortened lake water residence time (lower $E/I$ ratio). Somewhat cooler summer conditions (<0.5°C) have been inferred based on chironomids (Velle et al., 2005) and pollen records (Seppä et al., 2009) at this time. Lower temperatures probably changed the isotopic composition of precipitation towards more negative $\delta^{18}\text{O}$ values; however, temperature alone could not have caused the isotopic shift of 1‰ in $\text{Chara } \delta^{18}\text{O}$ because a lowering of as much as 3°C would be required to account for the $\delta^{18}\text{O}$ trend (assuming +0.36‰ °C$^{-1}$; Leng and Marshall, 2004).

Isotope minima have also been recorded at ca. 3500 cal. a BP in the $\delta^{18}\text{O}$ carbonate record from Lake Igelsjön (Hammarlund et al., 2003; Jessen et al., 2005), in the $\delta^{18}\text{O}$ cellulose record from Lake Spåme (located only ~60 km west of Lake Blektjärnen) (St Amour, 2009) and in the $\delta^{18}\text{O}$ diatom record from Lake Vuolep Allakasjaure, northern Sweden (Rosqvist et al., 2004) (Fig. 8). Lake Spåme and Lake Vuolep Allakasjaure are both high-altitude through-flow lakes and the isotopic composition of the lake waters are therefore mainly influenced by the amount and seasonal distribution of rainfall and the isotopic composition of the lake waters are therefore mainly influenced by the amount and seasonal distribution of rainfall and the isotopic composition of the lake waters (Jonsson et al., 2009; St Amour, 2009; Jonsson et al., 2010). Geochronological and vegetation data from Lake Igelsjön (Hammarlund et al., 2003; Jessen et al., 2005) further support the

Figure 8  Comparison of $\text{Chara } \delta^{18}\text{O}$ three-point running mean values with previously published $\delta^{18}\text{O}$ carbonate record from Lake Igelsjön (Hammarlund et al., 2003) with revised chronology (Jessen et al., 2005), carbonate $\delta^{18}\text{O}$ values from Lake Tibetanus (five-point running mean) (Rosqvist et al., 2007), aquatic cellulose $\delta^{18}\text{O}$ from Lake Spåme (St Amour, 2009) and diatom $\delta^{18}\text{O}$ from Lake Vuolep Allakasjaure (Rosqvist et al., 2004). Lake Blektjärnen and Lake Igelsjön are evaporative and thus reflect changes in $E/I$ ratio. Lake Tibetanus is mainly groundwater fed and reflects changes in isotopic composition of mean annual precipitation, whereas the isotopic composition of the lake waters in Lake Spåme and Lake Vuolep Allakasjaure mainly reflect the amount and seasonal distribution of precipitation. A diatom $\delta^{18}\text{O}$ value of +25‰ indicates larger contribution of relatively $^{18}$O-depleted precipitation, whereas a value of +27‰ indicates larger contribution of relatively $^{18}$O-enriched precipitation (Jonsson et al., 2010). The marked areas indicate depleted $\delta^{18}\text{O}$ values inferred from these lakes indicating wetter/cooler conditions around 3500 cal. a BP, and the onset of the successive depletion trend in $\delta^{18}\text{O}$ values around 1750 cal. a BP inferred from the records from Lake Blektjärnen. Note the different scales.
inference that there was a major shift towards wetter and/or cooler climate at this time in southern Sweden and evidence for a glacier advance is reflected in the geochemical record in Lake Vuolep Allakasjaure (Rosqvist et al., 2004). The similar isotope response of the proxy records in these environments suggests that the change was significant and regional. Today increased humidity in Scandinavia results from an intensified westerly air flow, and we therefore suggest that zonal flow was intensified and was the dominating atmospheric circulation pattern during the period.

Unfortunately, there are periods with no Chara encrustations, and therefore the isotopic record is incomplete between ca. 3000 and 2500 cal. a BP (Fig. 7). Growing or preservation conditions must have changed, possibly due to a climate shift. Increased aquatic productivity due to warmer summers could have decreased light penetration, which in turn inhibited photosynthesis in Chara. The increased aquatic productivity could also have resulted in increased decomposition, which dissolved Chara calcite through elevated CO₂ levels (Dean, 1999).

Between ca. 2500 and 1000 cal. a BP

Values for Chara δ¹⁸O and δ¹³C are relatively enriched between ca. 2500 until 1000 cal. a BP, indicating that the E/I ratio increased compared to the previous period, either due to decreased input of winter/spring precipitation, higher temperatures and a relatively larger contribution of more positive summer precipitation, or a combination of these factors (Fig. 7). Again, a change in δ¹⁸O forced by temperature alone seems unlikely as an increase of several degrees would be required. Reconstructions based on chironomids and pollen reveal relatively stable temperatures (Velle et al., 2005; Seppä et al., 2009). Therefore we argue that the winter/spring and summer climate must have been drier and the lake water residence time longer to allow evaporation and atmospheric equilibration to enrich the lake water in δ¹⁸O and δ¹³C respectively. Increased evaporation during this time period can also be inferred from the Lake Igelsjön isotope data (Fig. 8) (Hammarlund et al., 2003). Drier summers are probably associated with a dominance of an anticyclonic circulation pattern (Seppä et al., 2009) and we suggest that this forced the higher isotope values through this period.

From 1750 cal. a BP onwards we note that both the Chara and Pisidium isotope values (for Pisidium until 700 cal. a BP only) become progressively more negative (Fig. 7). A negative trend at this time has also been detected isotope records from northern Sweden (Fig. 8) (Shemesh et al., 2001; Rosqvist et al., 2007; Jonsson et al., 2010), again showing a common response to atmospheric forcing. This suggests that climate became wetter even at these relatively more continental sites (i.e. at Lake Blektjärnen, Lake Tibetanus and Lake 850 (Shemesh et al., 2001) not included in Fig. 8). The steadily decreasing δ¹⁸O values in Lake Igelsjön from ca 3000 cal. a BP onwards (Hammarlund et al., 2003) suggest that south Sweden possibly was influenced by increased strength of zonal flow already from this time.

After ca. 1000 cal. a BP

The E/I ratio in Lake Blektjärnen remained low after ca. 1000 cal. a BP, suppressing δ¹⁸O and δ¹³C in the lake water. A decrease in the δ¹⁸O of precipitation is expected as temperatures were decreasing at this time (to ~0.5°C lower compared to 1961–1990 average temperature; Moberg et al., 2005) and compared to the Holocene mean (Velle et al., 2005). However, this change is too small to account for the relatively large shift detected in Chara δ¹⁸O. Therefore it is likely that climate was generally humid especially prior to ca. 500 cal. a BP and during the last 100 a. Humid conditions during the last 1000 a were also inferred from the Lake Igelsjön data (Hammarlund et al., 2003). The isotope records from Lake Tibetanus and Lake Spåme also show a negative trend over the past 1000 a, again indicating a common response to regional shifts in circulation (Fig. 8). Wetter conditions in northern Europe, caused by a persistent positive North Atlantic Oscillation (NAO) mode, have been reconstructed for the period 1000–500 cal. a BP (Trouet et al., 2009).

The Chara δ¹⁸O values are slightly enriched after ca. 500 cal. a BP, until ca. 100 cal. a BP, suggesting that climate was drier (Fig. 8). Enriched carbonate δ¹⁸O values are also seen at this time in the Lake Igelsjön (Hammarlund et al., 2003) and Lake Tibetanus (Rosqvist et al., 2007) records (Fig. 8). This suggests that climate was both dry (our data) and cool (Moberg et al., 2005; Velle et al., 2005). Drier conditions in northern Europe during this period were also inferred from reconstructed weaker NAO conditions (Trouet et al., 2009).

The most negative value in the Lake Blektjärnen record occurs at AD ca. 1900, after which values increase again. A similar isotope minimum occurred at Lake Tibetanus at this time (Rosqvist et al., 2007), indicating that the isotope hydrology of these lakes responded to the large climate shifts that occurred at the end of the Little Ice Age in northern Fennoscandia (Fig. 8).

Conclusions

Stable isotopes on Chara calcite and Pisidium shells in Lake Blektjärnen in central Sweden are used to reconstruct past changes in E/I ratio over the last ca. 4400 a. Modern lake water isotope data show that Lake Blektjärnen has a relatively high E/I ratio, which is probably the result of relatively high summer temperatures, enriched summer precipitation and relatively small contribution of depleted winter/spring precipitation. The relatively high Chara δ¹⁸O and δ¹³C values between 4400 and 4000 cal. a BP suggest that conditions may have been similar to today. From the low Chara δ¹⁸O and δ¹³C values between 4400 and 3000 cal. a BP, especially around 3500 cal. a BP, we infer that precipitation increased and temperatures decreased. Relatively enriched Chara δ¹⁸O and δ¹³C values between 2500 and 1000 cal. a BP indicate that climate became drier and warmer, probably as a result of dominance of an anticyclonic atmospheric circulation. However, a depletion trend starts after ca. 1750 cal. a BP, which has also been detected in several other δ¹³C records (carbonate and diatom) in Sweden, suggesting increasingly wetter conditions. Our data show that climate was wetter and probably cool between ca. 1000 and 500 cal. a BP and at the end of the 19th century, i.e. at the end of the Little Ice Age. Between ca. 500 and 100 cal. a BP summers were probably both dry and cool. Our results show the potential of using lacustrine stable isotope data to reconstruct past changes in humidity during summer (Chara) and during the ice-free season (Pisidium) at a continental site. Such information is crucial for the identification of past shifts in atmospheric circulation patterns.

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