Rapid hydrological changes during the Holocene revealed by stable isotope records of lacustrine carbonates from Lake Igelsjön, southern Sweden

Dan Hammarlund*a,*, Svante Björcka, Björn Buchardtb, Carsten Israelsonc, Charlotte T. Thomsenb

a Quaternary Geology, Department of Geology, Lund University, Tornav. 13, S-223 63 Lund, Sweden
b Geological Institute, University of Copenhagen, Øster Voldg. 10, DK-1350 Copenhagen K, Denmark
c National Institute of Radiation Hygiene, Knapholm 7, DK-2730 Herlev, Denmark

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Abstract

A Holocene sediment sequence from Lake Igelsjön, south central Sweden, was studied by stable oxygen- and carbon-isotope analyses of different carbonate components. The deposit, which covers the time-span from ca 11,500 cal BP to the present, was laid down in a small, kettle-hole lake, the hydrological balance of which is presently dominated by groundwater flow. Isotopic records obtained on bulk carbonates originating mainly from summer-produced, calcitic algal encrustations exhibit several rapid shifts of more than 2%, likely reflecting pronounced hydrological variations. Corresponding isotopic data obtained on calcitic gastropod opercula from parts of the profile show subdued responses to major climatic shifts, probably related to an extended calcification season. The isotopic records were complemented by studies of modern isotope hydrology, and our interpretations are based on a simplistic climate-hydrology model in which variations in groundwater generation within the lake catchment produce changes in groundwater level and related adjustments of lake level and surface/volume ratio of the basin during the ice-free season. Assumed periods of decreased lake volume in a relatively dry climate (low lake level) are characterised by enrichment in 18O and 13C resulting from increased evaporation/inflow ratio and atmospheric equilibration, respectively. In clear contrast to this situation, intervals of more humid climatic conditions give rise to increased lake volume (high lake level), possibly surface overflow, and relatively depleted isotopic ratios. Relatively humid conditions, which may correlate to a wide-spread cooling event recorded by various proxies across the North Atlantic region, are indicated by distinct isotopic shifts at ca 8300 and 8000 cal BP, bracketing a period of 18O-depletion. The period between ca 8000 and 4000 cal BP was characterised by relatively dry and stable climatic conditions, whereas the subsequent part of the Holocene experienced a more humid and variable climate following marked and coherent depletions in 18O and 13C at ca 4000 cal BP.

1. Introduction

Regional climate variability and sub-Milankovitch climate variations have become topics of great interest. In this respect, the Holocene is probably the best candidate for such studies; the possibilities of obtaining well-dated records from this period are exceptional and Holocene records may be found in most regional settings and climate zones. Variations in moisture availability caused by changing precipitation and evaporation are important aspects of Holocene climate change, although sometimes overlooked in palaeoclimatic research focusing to a greater extent on past temperatures. The hydrological balance of lakes may respond sensitively to changes in net precipitation and humidity. Based on several reconstructions of past lake levels through detailed lithostratigraphic and vegetational studies of lake sediments, the Holocene paleohydrological development of southern Sweden is relatively well known (Digerfeldt, 1988, 1997; Harrison...
and Digerfeldt, 1993; Almquist-Jacobson, 1995). In order to complement these records, which do not allow reconstruction of short-term fluctuations, we have performed a study of Holocene climate variations based on high-resolution records of stable oxygen- and carbon-isotopes from a carbonate-rich sediment succession deposited in a small lake in south central Sweden. The aim of the study is to detect and date changes in the stable isotope composition of different carbonate components of the sediments, and to analyse these data in the light of modern isotope hydrology of the lake. Thus, temporal changes in water balance and relative estimates of temperature and seasonality, potentially responsible for the observed trends and isotopic offsets can be evaluated. We also try to relate and compare our isotopic records with other types of studies, mainly glacier fluctuations in the Scandes Mountains, to achieve a more holistic view of the Holocene climatic, and especially hydrological, development of southern Scandinavia. The strong climatic influence of the North Atlantic Drift on this maritime-continental border region makes it a potential tracer region for disturbances in ocean circulation during the Holocene (cf. Bond et al., 1997), which can place these isotopic data in an even wider context.

Oxygen- and carbon-isotope ratios in lacustrine carbonates can be used to infer climate changes through the influence of several processes within the climate system, one of which is the hydrological budget of the lake under study. Lakes with short residence times, i.e. low ratios of lake/catchment area maintain the isotopic characteristics of the recharging water (e.g. von Grafenstein et al., 1996). On the other hand, significant enrichment in the heavy isotopes—$^2$H and $^{18}$O in water, $^{13}$C in dissolved inorganic carbon (DIC)—occurs in lake waters subject to more extensive and prolonged exposure to evaporation and atmospheric exchange, respectively, thus reflecting catchment water balance (e.g. Gibson et al., 1993; von Grafenstein et al., 2000). Temporal changes in the influence of these processes resulting from variations in catchment hydrology can be traced by isotopic analyses of lacustrine carbonates ($\delta^{13}$C and $\delta^{18}$O), and related palaeohydrological implications were reviewed by Talbot (1990) and re-examined by Li and Ku (1997). As the first Holocene stable isotope record of its kind from Scandinavia, the present study of a hydrologically sensitive lake is based on oxygen- and carbon-isotope analyses of two specific carbonate components, algal encrustations and gastropod opercula, representing calcification during different seasons of the year. This approach, which has previously been applied to Late Weichselian lake sediments in southern Sweden (Hammarlund and Keen, 1994; Hammarlund and Lemdahl, 1994; Hammarlund et al., 1999), yields additional details of the Holocene climatic development in the region.

2. Site description

Lake Igelsjön is situated in the northeastern part of the province of Västergötland in south central Sweden (58°28′N, 13°44′E; Fig. 1), at an elevation of 111 m a.s.l. The lake is located in an area of predominantly glaciofluvial deposits within the Middle Swedish endmoraine zone which is associated with a glacial readvance during the Younger Dryas stadial (Björck et al., 1988). The glacial deposits are underlain by Cambrian sandstone whereas the nearby residual mountain, Mount Billingen, consists of Cambro-Ordovician alum shales and limestones intruded by younger dolerites. The small, roundish lake is ca 70 m long and 50 m wide, and has a gently undulating bottom-surface topography with water depths varying between 1.5 and 2.5 m (Table 1). The surface catchment area is ca

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Table 1

<table>
<thead>
<tr>
<th>Measured/estimated parameter</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment area</td>
<td>ca 320,000 m²</td>
</tr>
<tr>
<td>Lake area</td>
<td>ca 2500 m²</td>
</tr>
<tr>
<td>Maximum water depth</td>
<td>ca 2.5 m</td>
</tr>
<tr>
<td>Lake volume</td>
<td>ca 5000 m³</td>
</tr>
<tr>
<td>Groundwater input (estimated)</td>
<td>ca 3.6 l/s</td>
</tr>
<tr>
<td>Residence time (estimated)</td>
<td>ca 20 days</td>
</tr>
<tr>
<td>Maximum water temperature</td>
<td>ca 20 °C</td>
</tr>
<tr>
<td>Period of ice cover</td>
<td>Late Nov.–March</td>
</tr>
<tr>
<td>pH (July 1999)</td>
<td>7.1</td>
</tr>
</tbody>
</table>

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Fig. 1. Map of southern Scandinavia showing the location of the study area.
0.32 km² (Fig. 2) but surface run-off to the lake is very limited. Sub-surface groundwater dominates input to
the lake and the average residence time is estimated to ca 20 days based on modern groundwater formation within
the catchment. A slightly larger lake of the same character and equal elevation ca 500 m to the east is
connected to Lake Igelsjön through an artificial canal that was excavated through an intervening peatland
during the early 20th century. At present-day climatic conditions there is no surface outflow from the lakes and
the threshold of the catchment is situated at ca 114 m a.s.l. The hummocky landscape surrounding the site is
occupied mainly by kame deposits (sands and gravels) laid down during the late Younger Dryas deglaciation
(12,000–11,500 cal BP). Further details of local geology

3. Methods

3.1. Fieldwork and subsampling

Sediment cores were collected from the ice in the central part of the lake in January 1997 at an
approximate water depth of 2.2 m, using 1 m long Russian peat samplers, 7.5 and 10 cm in diameter. The
cracking peat sequence was described in detail in the field (Table 2). The uppermost part of the
sequence, which consists of very loose gyttja, was sampled with a simple gravity corer. After correlation
of a sequence of over-lapping core segments in the laboratory the profile was contiguously subsampled into
122 sections, 30–180 mm thick, taking into account lithostratigraphic boundaries. Minor aliquots were used
for analyses of total carbon and calcium carbonate contents and stable isotope analyses of bulk carbonates.
In the interval of 7.19–5.06 m below the water surface samples of bulk carbonates were collected at higher
stratigraphic resolution before subsampling into sections, with samples ranging in thickness from 5 to
20 mm. For radiocarbon dating and extraction of carbonate macrofossils for additional stable isotope
analyses the remaining parts of the 122 sections were carefully washed through a 200 μm sieve and the residue
was examined under a binocular microscope.

3.2. Lithology and carbonate mineralogy

Total carbon content (TC) of the sediments was determined by combustion at 1150°C in pure oxygen
with subsequent detection of carbon dioxide by infrared absorption photometry in an Eltra-Metalyt unit (preci-
sion better than ±1%). The calcium carbonate content (CaCO₃) was measured by sodium hydroxide titration
to neutral pH after dissolution of 0.5 g of sample in 0.5 M hydrochloric acid and boiling for 20 min (preci-
sion better than ±0.5%). The organic carbon content (OC) was calculated as OC = TC − 12/100.
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analyses. The records of OC, CaCO$_3$, and $R$ are given as percentages of total dry weight in Fig. 4. The mineralogical composition of carbonates from selected sediment samples was determined by X-ray diffraction analysis using Cu-$\alpha$ radiation in a Philips PW 3710 diffractometer.
3.3. Radiocarbon dating

Delicate macroscopic remains of terrestrial and emergent aquatic plants, mostly determined to species level (Table 3) were sampled from the sieve residue at 22 levels and radiocarbon dated by accelerator mass spectrometry (AMS) at the Tandem Laboratory, Uppsala University (Ua) and at the radiocarbon laboratory, Department of Geology, Lund University (LuA), respectively. Six of the radiocarbon dates (labelled “LuA” in Table 3) were obtained from the core collected in 1997, whereas the remaining 16 dates (labelled “Ua” in Table 3) were obtained from a nearly identical core collected at the same position in 1996. The two cores were readily correlated on the basis of lithostratigraphic characteristics. The numerous radiocarbon dates in the interval of 4.80–7.30 m were carried out for comparison with an independent chronology obtained by thermal ionisation mass spectrometry (TIMS) U–Th dating of this part of the sediment sequence (Israelson et al., 1997). Apart from reported radiocarbon ages, the chronological terminology in the following text is based on calendar-year ages before 1950 (cal BP) as derived by calibration of radiocarbon ages against the IntCal98 calibration curve (Stuiver et al., 1998) using the CALIB 4.1 software. The calibrated ages reported here thus differ slightly from the data given by Israelson et al. (1997), which were related to the 1996 datum year based on the IntCal93 calibration curve (Stuiver and Reimer, 1993).

3.4. Stable isotope analyses

For oxygen- and carbon-isotope analyses of bulk carbonates, sediment samples were freeze-dried and homogenised. Samples of Chara sp. calcitic encrustations (each consisting of 5–15 mg) and calcitic opercula of Bithynia tentaculata gastropods (each consisting of generally 15–25 opercula) were collected after sieving of contiguous stratigraphic sections within core intervals, where these materials occur as macroscopic remains. All bulk sediment samples and most of the carbonate macrofossil samples were processed on a preparation line described by Buchardt (1977). Apart from reported radiocarbon ages, the chronological terminology in the following text is based on calendar-year ages before 1950 (cal BP) as derived by calibration of radiocarbon ages against the IntCal98 calibration curve (Stuiver et al., 1998) using the CALIB 4.1 software. The calibrated ages reported here thus...
Table 3
Radiocarbon dates

<table>
<thead>
<tr>
<th>Sample depth (m)</th>
<th>Lab. no.</th>
<th>Material analysed</th>
<th>Weight (mg)</th>
<th>Reported age (14C yr BP)</th>
<th>Calibrated age (mid-intercept) (cal BP)</th>
<th>Calibrated age (2σ Interval)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.42–3.49</td>
<td>LuA-4467</td>
<td>Nym., Bet., Que.</td>
<td>2.8</td>
<td>1180 ± 100</td>
<td>1065</td>
<td>925–1293</td>
</tr>
<tr>
<td>4.04–4.10</td>
<td>LuA-4468</td>
<td>Nym., Bet., Aln.</td>
<td>5.6</td>
<td>2000 ± 90</td>
<td>1936</td>
<td>1724–2294</td>
</tr>
<tr>
<td>4.88–4.90</td>
<td>Ua-11219</td>
<td>Nym.</td>
<td>1.0</td>
<td>3070 ± 150</td>
<td>3287</td>
<td>2853–3632</td>
</tr>
<tr>
<td>4.90–4.95</td>
<td>Ua-11220</td>
<td>Nym., Til., Bet.</td>
<td>1.3</td>
<td>2995 ± 170</td>
<td>3182</td>
<td>2757–3625</td>
</tr>
<tr>
<td>4.97–5.00</td>
<td>Ua-11190</td>
<td>Nym., Til., Bet., Car.</td>
<td>5.2</td>
<td>3445 ± 210</td>
<td>3691</td>
<td>3212–4281</td>
</tr>
<tr>
<td>5.04–5.07</td>
<td>Ua-11188</td>
<td>Nym., Aln., Bet.</td>
<td>1.5</td>
<td>3195 ± 190</td>
<td>3431</td>
<td>2887–3686</td>
</tr>
<tr>
<td>5.18–5.24</td>
<td>Ua-11221</td>
<td>Nym., Aln.</td>
<td>3.0</td>
<td>3580 ± 160</td>
<td>3869</td>
<td>3469–4405</td>
</tr>
<tr>
<td>5.42–5.48</td>
<td>Ua-11222</td>
<td>Nym., Bet.</td>
<td>3.5</td>
<td>3935 ± 140</td>
<td>4412</td>
<td>3932–4827</td>
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<tr>
<td>5.65–5.70</td>
<td>Ua-11189</td>
<td>und.</td>
<td>2.0</td>
<td>4735 ± 220</td>
<td>5553</td>
<td>4848–5925</td>
</tr>
<tr>
<td>5.85–5.91</td>
<td>Ua-11223</td>
<td>Til., Bet.</td>
<td>1.2</td>
<td>4410 ± 180</td>
<td>5020</td>
<td>4453–5579</td>
</tr>
<tr>
<td>6.04–6.10</td>
<td>Ua-11224</td>
<td>Nym., Bet.</td>
<td>0.8</td>
<td>5430 ± 260</td>
<td>6230</td>
<td>5612–6780</td>
</tr>
<tr>
<td>6.22–6.26</td>
<td>Ua-11108</td>
<td>Bet.</td>
<td>1.8</td>
<td>6320 ± 240</td>
<td>7252</td>
<td>6662–7661</td>
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<tr>
<td>6.30–6.35</td>
<td>Ua-11193</td>
<td>Nym., Bet., Pin.</td>
<td>19.0</td>
<td>9220 ± 270</td>
<td>10,316</td>
<td>9561–11,181</td>
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<tr>
<td>6.62–6.68</td>
<td>Ua-11225</td>
<td>Bet., Aln., und.</td>
<td>1.0</td>
<td>6660 ± 320</td>
<td>7676</td>
<td>7321–8151</td>
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<tr>
<td>6.88–6.92</td>
<td>Ua-11226</td>
<td>Bet., Aln.</td>
<td>n.d.</td>
<td>7370 ± 170</td>
<td>8175</td>
<td>7840–8450</td>
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<tr>
<td>6.97–7.05</td>
<td>Ua-11191</td>
<td>Bet., Pin.</td>
<td>12.0</td>
<td>8670 ± 140</td>
<td>9575</td>
<td>9431–10,169</td>
</tr>
<tr>
<td>7.13–7.18</td>
<td>Ua-11227</td>
<td>Nym., Bet., Ulm.</td>
<td>1.8</td>
<td>7660 ± 230</td>
<td>8412</td>
<td>7977–9027</td>
</tr>
<tr>
<td>7.28–7.33</td>
<td>Ua-11228</td>
<td>Bet., Aln., Pin.</td>
<td>2.0</td>
<td>7525 ± 190</td>
<td>8352</td>
<td>7957–8969</td>
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<tr>
<td>7.74–7.81</td>
<td>Ua-4469</td>
<td>Bet., Pin.</td>
<td>3.0</td>
<td>8880 ± 100</td>
<td>10,063</td>
<td>9560–10,222</td>
</tr>
<tr>
<td>8.11–8.20</td>
<td>Ua-4470</td>
<td>Bet., Emp., und.</td>
<td>3.0</td>
<td>9520 ± 130</td>
<td>11,029</td>
<td>10,425–11,195</td>
</tr>
<tr>
<td>8.85–8.92</td>
<td>Ua-4471</td>
<td>Bet., Emp.</td>
<td>ca 2.5</td>
<td>8680 ± 210</td>
<td>9586</td>
<td>9155–10,235</td>
</tr>
<tr>
<td>9.17–9.35</td>
<td>Ua-4472</td>
<td>Dry.</td>
<td>ca 1.0</td>
<td>9490 ± 140</td>
<td>10,714</td>
<td>10,287–11,188</td>
</tr>
</tbody>
</table>

Nym. = fruits of Nymphaea alba, Bet. = fruits and/or catkin scales of Betula pubescens, Que. = bud scales of Quercus robur, Aln. = fruits and/or catkin scales of Alnus glutinosa, Til. = fruits of Tilia cordata, Car. = fruits of Carex sp., Pin. = seeds of Pinus sylvestris, Ulm. = fruits of Ulmus glabra, Emp. = seeds of Empetrum nigrum, Dry. = leaf fragments of Dryas octopetala, und. = undetermined terrestrial macrofossils, n.d. = weight not determined.

analytical reproducibility for δ13C and δ18O is better than ±0.03‰ and ±0.07‰, respectively. The results are expressed as δ-values (per mil deviations from the V-PDB standard) by calibration against laboratory standards, thus ensuring compatibility of results obtained from different laboratories.

Modern water samples collected from the lake and its vicinity during the period of 1996–1999 (Table 4) were analysed for 18O/16O ratios at the Ice Core Laboratory, Niels Bohr Institute for Astronomy, Geophysics and Physics, University of Copenhagen, and for 2H/1H ratios at the Geological Institute, University of Copenhagen using the Zn-reduction method as described by Coleman et al. (1982). The results are related to the V-SMOW standard with an analytic reproducibility of ±0.02‰ and ±3‰ on the δ-scales for δ18O and δ2H, respectively.

4. Sediment description and chronology

The sediment succession was divided into 12 lithostratigraphic units (Table 2) with depths (9.55–2.20 m) related to the water surface of the lake. Apart from a basal silt layer (unit 1), the lowermost 1.2 m of the profile (units 2–4) consists of greyish calcareous gyttja with a varying proportion of silt. Above ca 8.3 m algal-rich calcareous gyttjas and calcareous algal gyttjas prevail, characterised by distinct colour alterations and laminations ranging in thickness from millimetres or less to several centimetres. The content of minerogenic material (R) is negligible in units 5–8 with the exception of a distinct peak at ca 7.1 m (unit 6). In units 9–12 slightly higher R values prevail (Fig. 4). Bands of brownish algal gyttja with a reduced content of calcareous matter occur at ca 7.1, 6.2, 5.2, 5.1, 4.8 m, and at ca 4.4–4.2 m. The uppermost 1-m part of the succession (unit 12) consists of loose, brownish calcareous gyttja. Restricted amounts of macroscopic shells of molluscs such as Bithynia tentaculata, Valvata cristata, Valvata piscinalis, and Pisidium sp. occur in units 7–12. Based on X-ray diffraction analysis, carbonates in the bulk sediment samples used for isotopic analyses were identified as exclusively low-Mg calcite. No other carbonate minerals were detected. Abundant mm-sized, tubular encrustations formed on the stems of Chara sp. and at ca 7.1 m (unit 6). In units 9–12 slightly higher R values prevail (Fig. 4). Bands of brownish algal gyttja with a reduced content of calcareous matter occur at ca 7.1, 6.2, 5.2, 5.1, 4.8 m, and at ca 4.4–4.2 m. The uppermost 1-m part of the succession (unit 12) consists of loose, brownish calcareous gyttja. Restricted amounts of macroscopic shells of molluscs such as Bithynia tentaculata, Valvata cristata, Valvata piscinalis, and Pisidium sp. occur in units 7–12. Based on X-ray diffraction analysis, carbonates in the bulk sediment samples used for isotopic analyses were identified as exclusively low-Mg calcite. No other carbonate minerals were detected. Abundant mm-sized, tubular encrustations formed on the stems of Chara sp.

The 22 radiocarbon dates are compiled in Table 3. A calendar-year age–depth model for the sediment succession based on these dates, which closely agrees with the U/Th chronology reported by Israelson et al. (1997) for the interval of 4.80–7.30 m, is shown in Fig. 5. Two of
the radiocarbon dates clearly yielded too high ages in relation to adjacent dates and the assumed time-depth curve. These dates (UA-11193 and 11191) were both obtained on samples partly consisting of undetermined wood remains and/or relatively coarse terrestrial macrofossils that could have sustained in the catchment soil for some time before being deposited in the lake. The lowermost date suggests that the sedimentation was initiated shortly after the Pleistocene-Holocene transition. However, the presence of abundant seeds of Empetrum nigrum and leaf fragments of Dryas octopetala in the lower part of unit 2 (Table 3) gives evidence of a treeless environment during the deposition of the oldest sediments. This type of vegetation can be characterised by loose gyttjas, the sedimentation rate, with minimum values of 0.3 mm/yr in the upper part of unit 7, may be partly related to post-depositional compaction. In the upper part of the sequence, characterised by loose gyttjas, the sedimentation rate increased again to 1.1 mm/yr.

5. Results and interpretations of the stable isotope analyses

5.1. Modern isotope hydrology

To investigate the modern hydrological balance of the lake and its relation to the Holocene isotopic records, oxygen- and hydrogen-isotope data were obtained on...
modern water samples from the study area. Groundwater samples collected near the lake show only minor changes in isotopic composition over the year, with \( \delta^{18}O \) values ranging from \(-10.8\%\) to \(-10.2\%\) (Table 4; Fig. 6). The subdued seasonal variations point to a relatively large recharge area and extensive mixing of groundwater in the aquifer supplying water to the lake. Close correspondence with the weighted annual mean value of precipitation (\(-10.7\%\)) observed at Torsö (50 m a.s.l.; ca 40 km north of Lake Igelsjön (Figs. 1 and 3B)) suggests that the isotopic ratio of groundwater is inherited from the average of the seasonal isotopic range of precipitation that typically occurs in the region. Lake-water samples collected during the winter plot close to the groundwater samples, which indicates that regional groundwater dominates input to the lake during most of the ice-covered season (December–February). During other parts of the year the lake-water isotopic composition exhibits substantial variations with an \( \delta^{18}O \) amplitude of at least 3.5\%. These changes are likely related to input of isotopically depleted snowmelt during the spring (March–April) and isotopic enrichment caused by evaporation from the lake-water surface during the rest of the ice-free season (May–November). On a hydrogen-/oxygen-isotope cross-plot (Fig. 6) all groundwater samples as well as lake-water samples from January, March, and April plot close to the global meteoric water line (Craig, 1961), whereas lake-water samples from May to July fall along a local evaporation line with a slope near 5 as expected for water bodies affected by evaporation (Craig and Gordon, 1965). These results suggest that the water body is affected by a well-developed evaporative isotopic enrichment in spite of the rather short residence time (ca 20 days or less) as estimated from catchment size and meteorological data. Surface run-off from the catchment and direct precipitation seems to have no major impact on the isotopic composition of lake water during the ice-free season.

5.2. Stable isotope records of carbonates

Oxygen- and carbon-isotope records have been obtained from three different types of carbonate samples. These include bulk carbonates \( (\delta_{\text{Sed}}; \ 129 \) samples in the interval of 9.55–2.20 m), Chara sp.
encrustations ($\delta_{\text{Cha}}$; 28 samples in the interval of 9.50–7.13 m), and Bithynia tentaculata opercula ($\delta_{\text{Bit}}$; 73 samples in the interval of 6.54–2.20 m). Based on distinct shifts, prevailing trends, and consistent levels in these parameters the studied sediment sequence has been divided into five isotopic zones (IG-1–IG-5) as shown in Fig. 4. The different isotopic parameters within the respective zones are described and interpreted in detail below.

The isotopic records exhibit several rapid and extensive shifts and the major trends are broadly similar for $\delta^{18}$O and $\delta^{13}$C, although no strong mutual correlations exist across the record as a whole (Fig. 7). This suggests that the isotopic composition of carbonates is controlled mainly by hydrology rather than lake-water temperature or changes in the isotopic composition of input water (cf. Talbot, 1990). Short-term fluctuations are likely related to variations in evaporation/inflow ratio ($\delta^{18}$O) and atmospheric exchange ($\delta^{13}$C), respectively, through changes in lake volume and residence time. Lake waters that have undergone evaporation exhibit systematic enrichment in 18O (Craig and Gordon, 1965; Gibson et al., 1993), and an increase in evaporation/inflow ratio (prolonged residence time) also increases the extent to which lake-water DIC is isotopically equilibrated with atmospheric carbon dioxide, which leads to enrichment in $^{13}$C (Turner et al., 1983). These hydrological processes have profound consequences for the isotopic signatures of lacustrine carbonates precipitating in closed-basin lakes with high evaporation/inflow ratios (e.g. Talbot and Kelts, 1990).

Thus, we propose a simplistic climate-isotope hydrology model to explain the major variations in $\delta^{18}$O and $\delta^{13}$C with time, in which changes in catchment hydrology and lake level are coupled to net precipitation and groundwater level of the local unconfined aquifer (Fig. 8). In order to achieve a better understanding of the fairly complex relationships between the different variables, the data set has been analysed with multivariate statistical techniques, performed with the CANOCO programme (Ter Braak, 1988). These statistical runs verified the model described below. In Fig. 9 the $\delta_{\text{Sed}}$ records are displayed against a calendar-year age scale.

5.2.1. Zone IG-1: 9.55–8.29 m (ca 11,500–10,700 cal BP)

This zone represents the initial ca 800-year period of the Holocene lake history, which at least in its earliest phase, immediately following the deglaciation, was characterised by sparse terrestrial vegetation and unstable soils highly susceptible to erosion. This is evidenced by the initially high content of minerogenic
material (residue) in the sediments (Fig. 4). Therefore, deposition of detrital carbonates derived from glacial deposits in the catchment has to be considered at this stage as a potentially complicating process at the interpretation of isotopic records obtained on bulk carbonates (Hammarlund and Buchardt, 1996).
However, based on several independent lines of evidence, any major influence of this process on the $\delta_{\text{Sed}}$ records can be dismissed. Firstly, samples of unweathered glacial deposits from the lake catchment (Fig. 2) exhibit no measurable content of calcium carbonate, consistent with observations by Lundqvist et al. (1931) of glaciofluvial deposits in the Lerdala area with exclusively crystalline clasts or Palaeozoic material confined to sandstone and alum shale particles. Secondly, samples of the local Ordovician limestone that crops out on the slopes of Mount Billingen exhibit $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values in the ranges of ca $-7\%$o to $-6\%$o and ca $+1\%$o to $+2\%$o, respectively (B. Buchardt, unpublished data). Samples of bulk carbonates in the lowermost part of the sequence are consistently depleted in $^{18}\text{O}$ by ca 5% as compared to the expected oxygen-isotope composition of any such detrital carbonates, which points to an endogenic origin (Fig. 7). In addition, the isotopic data obtained on Chara encrustations are generally in good agreement with the respective $\delta_{\text{Sed}}$ data even in the most minerogenic-rich, basal part of the profile (Fig. 4). This consistency, which is valid for the entire part of the profile in which individual Chara encrustations could be identified and subsampled (units 1–5), demonstrates that the records of $\delta_{\text{Sed}}$ were obtained on calcite originating mainly from photosynthesis in Chara algae.

Within the studied sequence, minimum values of $\delta^{18}\text{O}_{\text{Sed}}$ around $-11.5\%$o were recorded in zone IG-1. The ca 2%o lower values recorded in zone IG-1 as compared to surface-sediment samples may be related either to more $^{18}\text{O}$-depleted precipitation, lower evaporation/inflow ratio, higher lake-water temperature, or a combination of these factors. In addition, during its early history the lake may to some extent have been influenced by $^{18}\text{O}$-depleted melt-water from bodies of stagnant glacier ice in the catchment (Björck and Digerfeldt, 1986).

The record of $\delta^{13}\text{C}_{\text{Sed}}$ exhibits a pronounced decreasing trend from ca $+2\%$o to $-3\%$o which was most likely brought about by the successive establishment of terrestrial vegetation and related soil development in the lake catchment. The rapid post-glacial immigration of plants as a response to warming at the onset of the Holocene resulted in a succession from herb-dominated, discontinuous vegetation to forest, initially dominated...
successive depletion with time in 13C of DIC in the study area (Björck and Digerfeldt, 1984). As discussed by Hammarlund et al. (1997) on the basis of a similar carbon-isotope record from northern Sweden, this development leads to increased release of 13C-depleted carbon dioxide from soil respiration and successive depletion with time in 13C of DIC in groundwater and lakes. As stated previously, unit 4 can be assumed to have been reworked from the lower part of unit 2, which means that the anomalously high values of δ13C in the upper part of zone IG-1 are not directly related to environmental change.

5.2.2. Zone IG-2: 8.29–7.19 m (ca 10,700–8400 cal BP)

Within this zone a distinct increase in δ18O sed was recorded, and if this change is explained exclusively by lake-water temperature it would require a temperature decrease of more than 10°C during the summer (Craig, 1965). This is highly unlikely based on other proxy records such as regional pollen data which show no signs of a cooling at this stage (Digerfeldt, 1977). A slight increase in organic carbon content and persistently very high values of carbonate content would rather suggest increased aquatic productivity and at least maintained lake-water temperatures. Slightly higher values of δ13C sed as compared to the upper part of zone IG-1 also point to increased photosynthetic activity in the lake, giving rise to 13C-enrichment of DIC (McKenzie, 1985). An enrichment in 18O in precipitation and hence in groundwater feeding the lake could have contributed to the observed increase in δ18O sed, as well as an increase in evaporation/inflow ratio brought about by a general decrease in net precipitation. Such a hydrological development (i.e. towards lowered lake level; Fig. 8) may also be related to the rather extensive isostatic rebound at this stage leading to successive isolation of the local glaciofluvial aquifer from the nearby sea, and thus a general lowering of the groundwater table (Björck and Digerfeldt, 1986).

5.2.3. Zone IG-3: 7.19–6.90 m (ca 8400–8000 cal BP)

This narrow zone is characterised by rapid and extensive isotopic shifts. The pronounced decrease in δ18O sed at 7.11 m is assumed to reflect mainly a decrease in evaporation/inflow ratio of the basin related to increased net precipitation (Fig. 8). The 18O-depletion coincides with a significant peak in minerogenic residue (unit 6) which is interpreted as an increase in catchment erosion in response to elevated lake-level and possibly enhanced run-off. The associated increase in suspension load probably resulted in decreased light penetration and deteriorated conditions for Chara photosynthesis as indicated by the decrease in carbonate content and disappearance of macroscopic Chara encrustations. The enhanced input of nutrients in the form of siliciclastic material likely also induced an increase in phytoplankton production, which explains the distinct increase in δ13C sed accompanied by increased organic content in the lower part of the zone. Subsequent to the increase in catchment erosion and lake productivity the aquatic system adapted to the altered hydrological balance, and a substantial decrease in evaporation/inflow ratio can be inferred also from lowered δ13C sed values, although slightly delayed as compared to the decrease in δ18O sed. The 13C-depletion reflects an increase in the supply of groundwater with relatively 13C-depleted DIC in relation to DIC in isotopic equilibrium with atmospheric carbon dioxide (Fig. 8). The absence of an isotopic response to input of any potential detrital carbonates is evidenced by the clearly asynchronous changes in the oxygen- and carbon-isotope records in relation to the peak in minerogenic residue of unit 6 (cf. Zone IG-1 above).

5.2.4. Zone IG-4: 6.90–5.22 m (ca 8000–4000 cal BP)

Based on very distinct isotopic shifts to higher levels in the records of δ13C sed at the IG-3/IG-4 zone boundary, a return to, and even manifestation of the hydrological conditions that prevailed in zone IG-2 can be assumed. The record of δ18O sed exhibits rather stable values around −7‰ throughout the zone which may suggest that steady-state conditions in terms of evaporative enrichment in 18O were obtained (cf. Lister et al., 1991), following a short-lasting intervening period of relatively rapid through-flow and lowered evaporation/inflow ratio in zone IG-3. The ca 3‰ higher values of δ13C sed as compared to the upper part of zone IG-2 probably partly reflect higher aquatic productivity and increased phytoplankton production as evidenced by a general increase in organic carbon content. However, the general covariance with corresponding trends observed in δ18O sed from zone IG-3 and upwards through the profile suggests that hydrology rather than aquatic productivity was the main factor controlling δ13C of DIC and limnic carbonates. Further evidence of this relationship is given by δ13C data obtained on bulk organic material from parts of the sediment succession (Thomsen, 2000), showing parallel isotopic shifts as compared to the δ13C sed record. Periods of 13C-depletion are generally associated with lithological changes (increased organic carbon content and decreased carbonate content). Such episodes (e.g. at ca 6.2 m) were likely associated with increased nutrient supply caused mainly by elevated lake level during the summer, thus reflecting increased humidity (Fig. 8).

The records of δ18O bit, which extend upwards from ca 6.5 m (Fig. 4), are broadly parallel with corresponding δ18O sed data, although with consistent offsets (Fig. 7). As suggested by concentric growth increments, calcification of Bithynia tentaculata opercula takes place during the entire part of the year when the organisms are active, interrupted by periods of winter hibernation (T. von Proschwitz, personal communication). As precipitation
of Chara encrustations (represented by the $\delta^{18}$O$_{\text{Sed}}$ record) occurs mainly during the early part of the summer (cf. Mörner and Wallin, 1977), the higher values of $\delta^{18}$O$_{\text{Bit}}$ can be assumed to reflect lower lake-water temperatures on average across extended active seasons as compared to Chara photosynthesis. The more extensive, corresponding offset between the two $\delta^{13}$C records (5.2–7.0‰) is caused partly by kinetic carbon-isotope fractionation related to proton pumping during assimilation of bicarbonate in Chara algae (McConnaughey, 1991). This effect has been demonstrated previously by Hammarlund et al. (1997, 1999). However, the consistently high values of $\delta^{13}$C$_{\text{Sed}}$ are probably to a large extent related to isotopic exchange with atmospheric carbon dioxide (Turner et al., 1983) as a result of the prevailing water balance conditions (i.e. relatively high evaporation/inflow ratios).

5.2.5. Zone IG-5: 5.22–2.20 m (ca 4000 cal BP to present)

Following a distinct decrease in $\delta^{18}$O$_{\text{Sed}}$ at the IG-4/IG-5 transition, relatively large variations were recorded within zone IG-5, indicating considerable changes in evaporation/inflow ratio of the basin. However, superimposed on these fluctuations is a general depletion in $^{18}$O with time, which suggests a long-term change from the predominant mode of lake contraction that prevailed in zone IG-4 to prolonged periods of increased lake volume and possibly surface outflow (Fig. 8). A general increase in precipitation, likely causing enhanced slope erosion, is also indicated by higher values of minerogenic residue in the upper part of the profile. In addition, the $\delta^{18}$O$_{\text{Sed}}$ record may to a lesser extent have been influenced by changes in lake-water temperature, although a decrease in summer lake-water temperature during the later part of the Holocene (e.g. Mörner and Wallin, 1977) would have counteracted the observed carbonate $^{18}$O-depletion. On the other hand, a general depletion in $^{18}$O of precipitation, perhaps in combination with a relative increase in winter precipitation, could have contributed to the recorded trend. However, the interpretation in terms of an over-riding hydrology-driven response is supported by the general decrease in $\delta^{13}$C$_{\text{Sed}}$ which indicates increased lake volume, decreased evaporation/inflow ratio, and successively more humid climatic conditions.

As opposed to the situation in the preceding zone, the records of $\delta_{\text{Bit}}$ exhibit general trends that have no counterparts in the corresponding $\delta_{\text{Sed}}$ data. This is most likely related to differences in isotopic characteristics of the lake water between the specific seasons of the year during which precipitation of the respective carbonate components occurred. Whereas, relatively high values of $\delta^{18}$O$_{\text{Sed}}$ in zone IG-4 reflect precipitation of Chara encrustations in lake water subject to $^{18}$O-enrichment due to enhanced evaporation/inflow ratios during the summer, this process did not affect average lake-water $\delta^{18}$O to the same extent during the extended season of shell formation of Bithynia tentaculata (cf. Fig. 6). Within zone IG-5 a general decrease in evaporation/inflow ratio, influencing mainly lake-water $\delta^{18}$O during the summer, led to a successively decrease in $\delta^{18}$O$_{\text{Sed}}$ while the record of $\delta^{18}$O$_{\text{Bit}}$ was largely unaffected by this hydrological change. A corresponding response related to seasonal differences in $\delta^{13}$C of DIC is evident from rather stable values of $\delta^{13}$C$_{\text{Bit}}$ across the IG-4/IG-5 transition as compared to the distinct long-term decrease in $\delta^{13}$C$_{\text{Sed}}$. These observations suggest that pronounced lake contraction developed on a seasonal basis during parts of the lake history (mainly zone IG-4), with minimum lake volume and maximum lake-level drawdown during the summer.

Based on comparisons between measured or estimated temperatures at the bottom of the lake (Table 4) and corresponding values inferred from surface-sediment $\delta^{18}$O of carbonates and modern lake-water $\delta^{18}$O (Craig, 1965), possible disequilibrium precipitation can be assessed for the analysed components (Fronval et al., 1995). Average lake-water $\delta^{18}$O for the ice-free season during calcification of Bithynia is probably in the range of $-10$‰ to $-9$‰ V-SMOW (Fig. 6). Although large variations were recorded in the uppermost part of the profile, the use of a $\delta^{18}$O$_{\text{Bit}}$ value of $-6.5$‰ V-PDB results in a bottom-water temperature range of ca +5°C to +8.5°C. This estimate is in good agreement with local mean annual air temperature ($+5.9$°C) and expected temperature of regional groundwater, which may point to equilibrium precipitation as commonly assumed for mollusks (Fritz and Poplawski, 1974). A similar exercise for $\delta^{18}$O$_{\text{Sed}}$ (ca $-9$‰ V-PDB) within a lake-water $\delta^{18}$O-range of $-9.5$‰ to $-8.5$‰ V-SMOW during the summer (mainly June) yields temperatures near the bottom of the lake during precipitation of Chara calcite of ca +16°C to +20°C. These relatively high values suggest that bicarbonate assimilation in Chara algae may be associated with a slight kinetic fractionation effect, giving rise to $^{18}$O-enrichment in calcitic encrustations (cf. Hammarlund et al., 1999).

6. Discussion

The major variations in hydrological balance of Lake Igelsjön inferred from the isotopic records were likely associated with changes in groundwater and lake-water levels of several metres (Fig. 8). The altitudinal difference between the present-day lake level, representing exclusively groundwater exchange, and the threshold of the basin is ca 3 m. Although, the available data do not provide unambiguous evidence for surface outflow across the threshold at any stage, or other absolute measures of lake level, the assumed hydrological
fluctuations must have been extensive and most likely related to regional changes in climate. Therefore, other available records of climatic humidity for the Holocene should be considered for comparison. In Fig. 9 the isotopic records are compared with a reconstruction of Holocene variations in sediment limit from Lake Bysjön (Digerfeldt, 1988), ca 300 km to the south (see Fig. 1). As shown by Digerfeldt (1988) and Harrison and Digerfeldt (1993) based on a compilation of similar studies from several other sites, the Lake Bysjön record is a representative proxy for long-term, lake-level variations in southern Sweden caused by changes in net precipitation. The curve is based on detailed sediment-stratigraphic and pollen-analytical studies of lake sediments along transects across bathymetrical gradients, and the approach exploits the assumption that lake levels and sediment limits of small lakes situated in areas of highly permeable glaciofluvial deposits respond sensitively to climatically induced variations in regional groundwater levels (Digerfeldt, 1988). Comparison is also made with a glaciation record for the Jostedalsbreen area in the Scandes Mountains of southern Norway (Nesje et al., 2001), ca 500 km NW of Lake Igelsjön (Fig. 9). This record, which is based on variations in organic content of three proglacial lacustrine sequences, is assumed to reflect changes in glacier mass-balance as a result of winter precipitation and summer temperature. Thus, if our simplistic climate-isotope hydrology model is valid for major responses of catchment water balance to regional hydrological changes (Fig. 8), mutual trends in these two independent climate records should be visible in the oxygen- and carbon-isotope ratios as suggested by low values of $\delta^{18}O_{\text{sed}}$ at this stage. However, by ca 9000 cal BP the influence of these environmental conditions on the hydrological balance of the lake had probably ceased.

A correlation of the lithological and isotopic excursions in the interval of ca 8300–8000 cal BP (zone IG-3) with the widely recognised, so-called 8200-yr event seems highly probable although the dating control does not allow for a definite coupling to a mutual climatic forcing (cf. Bennett, 2002). This event, originally identified as a distinct depletion in $^{18}O$ of Greenland ice-cores (Johnsen et al., 1992; Grooves et al., 1993; Alley et al., 1997), has been attributed to a major meltwater discharge that retarded the North Atlantic thermo-haline circulation (Barber et al., 1999; Renssen et al., 2001). Its climatic consequences have generally been recorded as a 200–400 yr period of cooling, mainly affecting summer conditions in the North Atlantic region. Such a development has been demonstrated independently based on several different proxies (Klitgaard-Kristensen et al., 1998; Nesje and Dahl, 2001; Tinner and Lotter, 2001; Snowball et al., 2002), including a record of $\delta^{18}O$ obtained on limnic ostracods from southern Germany (von Grafenstein et al., 1998). The assumed increase in net precipitation at Lake Igelsjön, as inferred from lowered values of $\delta^{18}O_{\text{sed}}$, is thus consistent with a regional lowering of summer temperature and a related decrease in evaporation (cf. Tinner and Lotter, 2001). A short, contemporary period of cooling is indicated by decreased frequencies of broad-leaved trees in the regional pollen record from Lake Flarken, ca 10 km north of Lake Igelsjön (Digerfeldt, 1977). Indeed, the Lake Bysjön record (Fig. 9) shows evidence of increased net precipitation at this stage, although the duration of the lake-level high-stand clearly exceeds what would be expected if it reflects the North Atlantic perturbation at ca 8200 cal BP. However, it should be noted that the methodology used for sediment-limit reconstruction may overestimate the chronological extension of lake-level high-stands due to subsequent erosional phases (Digerfeldt, 1988). Additional palaeoclimatic evidence of the 8200-yr event in Scandinavia is provided by a pronounced re-advance of mountain glaciers in southern Norway, the “Finse event”, which has been attributed mainly to decreased summer temperature (Dahl and Nesje, 1996; Nesje et al., 2001). The lack of any significant increase in winter precipitation as inferred from the Norwegian glaciolacustrine records (Nesje et al., 2001) may suggest that the observed depletion in $^{18}O$ of limnic carbonates at Lake Igelsjön was related to palaeohydrology may be slightly modified by the effects of varying precipitation isotopic composition and lake-water temperature ($\delta^{18}O$) and aquatic productivity ($\delta^{13}C$), respectively. Individual periods and specific aspects of the Holocene climatic development in the region are discussed below.

6.1. The early Holocene (ca 11,500–8000 cal BP)

Lake status records from several sites in southern Sweden exhibit a pattern of consistent low-stands during the late Preboreal, culminating around 10,500 cal BP (Fig. 9; Harrison and Digerfeldt, 1993). The absence of any isotopic enrichment prior to ca 9000 cal BP that would reflect a corresponding water-level lowering at Lake Igelsjön, may be explained by the proximity of the site to the Preboreal sea. Following deglaciation the sea protruded into Lake Långn, situated only a few km north of Lake Igelsjön (Fig. 2), and this former marine bay was not isolated from the sea by glacio-isostatic rebound until ca 11,000 cal BP (Björck and Digerfeldt, 1986). The coastal setting probably decreased the regional groundwater gradient, which may have impeded any lake-level lowering and reduction of lake volume. Furthermore, the proximity to the sea during the early Holocene may also have led to a locally more maritime climate and relatively low evaporation/inflow ratios as suggested by low values of $\delta^{18}O_{\text{sed}}$ at this stage.
6.2. The mid-Holocene (ca 8000–4000 cal BP)

The termination of the Finse event coincides with a major reduction of glacial activity in the Scandes Mountains as a consequence of elevated summer temperature, conditions that prevailed until ca 4000 cal BP (Dahl and Nesje, 1996; Nesje et al., 2001). Such a scenario can also be invoked to explain the substantial isotopic enrichments at ca 8000 cal BP, which suggest that the water balance of Lake Igelsjön responded to drier and warmer summer conditions (Fig. 8). This climatic mode, implying a general lake-level lowering, seems to have persisted during a period of ca 4000 yr, without any major fluctuations in the isotopic records. During this interval the regional vegetation of southern Sweden was dominated by stable climax forests with several warmth-demanding species (Digerfeldt, 1977; Lagerås, 1996), which suggests that the inferred hydrological status of the lake was caused mainly by relatively high summer temperatures rather than low amounts of precipitation, although the two processes likely interacted (cf. Dahl and Nesje, 1996). A brief period of increased net precipitation, perhaps related to lowered summer temperature, is indicated at ca 6700 cal BP, although the extent and regional significance of this temporary shift is difficult to assess. A mid-Holocene interval of relatively low net precipitation, partly due to high summer temperatures, is consistent with elevated tree-limits and retraction of mountain glaciers in the Scandes Mountains (Kullman, 1995; Dahl and Nesje, 1996; Karlén and Kuylenstierna, 1996; Nesje et al., 2001). According to Granlund (1932), an additional recurrence surface (RY3), dated to ca 2500 cal BP, reflects a second significant increase in humidity as a result of increased precipitation in combination with lowered temperature. This climatic shift is also indicated in the isotopic records as distinct depletions in 18O and 13C at ca 4.5 m (Figs. 4 and 9). It is noteworthy that several details of the Norwegian record of glacier fluctuations subsequent to reformation of the Jostedalsbreen ice cap around 6000 cal BP (Nesje et al., 2001) are reproduced by second-order variations in the isotope stratigraphies at Lake Igelsjön. This correlation, which is particularly strong with the 813C record (Fig. 9), lends increased credibility to these independent data sets as sensitive and regionally significant palaeohydrological proxies. As indicated by rather dramatic shifts in the isotopic records from Lake Igelsjön, in combination with considerably increased variability (Figs. 4 and 9), much of this change in climate may have occurred relatively rapidly within a few 100 years shortly after 4000 cal BP. Independent evidence of such a shift between distinct climate modes, involving also decreased climate stability, has been presented by Anderson et al. (1998) and Snowball et al. (1999). Both studies postulate an abrupt climatic change at ca 3700 cal BP, identified as decreased peat humification in Scotland and increased soil erosion in northern Sweden, respectively. Processes within the climate system itself, independent of orbital forcing, have to be invoked to explain these observations, although the main climatic parameter responsible for the inferred increase in net precipitation is unclear (increasing precipitation, decreasing temperature, or a
combination of both). A major change in the atmospheric circulation pattern over Northwest Europe seems to have taken place at about this time, perhaps as a result of a weakening of North Atlantic thermohaline circulation as indicated by declining sea-surface temperatures and salinity, (Duplessy et al., 1992; Koç and Jansen, 1994). Bond et al. (1997) identified increased ice rafting in the North Atlantic at ca 4200 cal BP (event no. 3). However, according to INTCAL98 (Stuiver et al., 1998) it is one of the few Holocene Bond events that do not correlate with major shifts towards increased atmospheric $^{14}$C content, and therefore it is possibly not related to neither decreased solar forcing or disturbed ocean ventilation. It may, however, be related to a general change in circulation patterns caused by decreased summer insolation at mid- to high northern latitudes. In fact, only three times during the last 100 ka has insolation been lower than during the last 4000 yr (Berger, 1978), and perhaps a critical climatic threshold for the Northern Hemisphere was passed around 4000 cal BP.

7. Concluding remarks

The isotopic records from Lake Igelsjön provide evidence of several rapid changes in net precipitation during the Holocene, the most extensive of which occurred between 8300 and 8000 cal BP and around 4000 cal BP, respectively. These climatic shifts, which affected large parts of northern and central Europe, were probably related to large-scale rearrangements of atmospheric circulation patterns. For example, the widely recorded cooling shortly before 8000 cal BP, with inferred records of lowered growth-season temperatures distributed from northern Sweden to Switzerland (Snowball et al., 2002; Tinner and Lotter, 2001), seems to be associated with an increase in effective moisture of equally regional significance. This pattern suggests a southward displacement of the Polar Front across most of the North Atlantic region, giving rise to cooler summers and drastically altered cyclonic pathways, preferentially during winter seasons. A general cooling accompanied by decreased snow accumulation in Greenland (Alley et al., 1997) suggests an expansion of the Polar high-pressure vortex and an associated steepening of the temperature and pressure gradients in the North Atlantic region (von Grafenstein et al., 1998). This pattern probably induced a strong zonal atmospheric flow with enhanced cyclonic activity across the seaboard of Northwest Europe, perhaps contributing to expansion of mountain glaciers in southern Norway (Dahl and Nesje, 1996) and increased spring snow-melt in northern Sweden (Snowball et al., 2002). Summer conditions may also have been characterised by increased precipitation, although the increased humidity was related mainly to lowered temperatures (cf. Tinner and Lotter, 2001).

As compared to the early Holocene perturbations discussed above, the boundary conditions influencing the climatic development at 4000–3500 cal BP differed substantially in terms of the absence of remnant Laurentian ice-caps and a markedly altered orbital configuration. However, a coupling of the abrupt increase in effective moisture at this stage to some analogous, but hitherto unresolved, ocean-atmosphere forcing seems highly probable. The shift towards more humid and variable climatic conditions recorded at Lake Igelsjön at ca 4000 cal BP correlates well with the onset of mild and wet winter conditions as inferred from glaciolacustrine deposits in Norway (Nesje et al., 2001). This change, which was attributed to a prevailing weather regime characterised by a positive North Atlantic Oscillation index, thus demonstrates the regional character of the enhanced moisture flux across the Scandinavian Peninsula during the later part of the Holocene.

Our results demonstrate the usefulness of isotopic data obtained on sediments from hydrologically sensitive lakes as proxies for variations in moisture regime, and may thus serve as inspiration for similar studies elsewhere. Further details, such as the relation of a relatively humid climate during the 8200 yr event to a probable temperature decline, as well as the regional significance of second-order changes in the inferred record of net precipitation, will have to be explored by additional studies based on similar approaches. Complementary information on long-term dynamics of the ocean-atmosphere circulation during the Holocene may be gained by reconstruction of the isotopic composition of ambient precipitation as proposed by Rozanski et al. (1997) based on $\delta^{18}$O records from open-basin lakes (e.g. Edwards et al., 1996; von Grafenstein et al., 1998; Hammarlund et al., 2002). This type of information may to some extent be incorporated in the $\delta^{18}$O$_{sed}$ records from Lake Igelsjön, although effectively masked by hydrological alteration.

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References


