Increased aridity during the early Holocene in West Greenland inferred from stable isotopes in laminated-lake sediments

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Abstract

Palaeoclimatic inferences from the Greenland ice cores suggest that Holocene climate was relatively uniform. The ice core records primarily reflect hemispheric temperature-related climate processes whereas lakes tend to reflect regional scale climatic variability. Stable isotopes in closed-basin lakes are sensitive to changes in effective precipitation. Here we report stable isotope evidence ($\delta^{18}$O and $\delta^{13}$C records from authigenic calcite in laminated lake sediments) from two oligosaline, closed-basin lakes in southern West Greenland (Søndre Strømfjord). The stable isotope profiles indicate a dynamic early to mid-Holocene climate as a strongly negative precipitation-evaporation balance from $\sim$7000 to 5600 cal yr BP lowered lake levels throughout the region. This interpretation of the stable isotope data is supported by a survey of modern lake-water isotopic composition and fossil shorelines around many closed-basin saline lakes which indicate higher lake levels in the past. The increased aridity during the early Holocene resulted from a shift in regional circulation patterns in the Davis Straits–Baffin Bay area. Enhanced stability of the West Greenland depression and the situation of a regional trough over the Søndre Strømfjord area caused weakened westerly airflow and strengthened outflow (i.e. winds blowing off the ice sheet), resulting in reduced precipitation in the region. Decreased precipitation, coupled with higher insolation, probably caused the negative precipitation-evaporation balance.

1. Introduction

The need for high-quality records of Holocene climate is crucial to our understanding of the possible driving processes and for defining natural scales of climatic variability (Steig, 1999). In contrast to the long-term ($10^{5}$ years) environmental variability recorded by the Greenland ice cores (Johnsen et al., 1995), the Holocene record is relatively uniform with a few notable exceptions such as the 8200 cal yr BP cooling event (Alley et al., 1997). Direct measurements of borehole temperatures, however, indicate a gradual 2–3°C cooling after 5000 cal yr BP (Dahl-Jensen et al., 1998). There is also a need for long-term records of changing precipitation patterns to match the growing database of Holocene palaeotemperature reconstructions. Such records may be derived from lake sediments, which are, an important complement to the ice core data. Moreover, the ice core records primarily reflect stratospheric and hemispheric climate processes. Stable isotopes and biotic-based estimates of temperature and aridity derived from lake sediments (Battarbee, 2000; Leng and Marshall, 2004) broaden our understanding of how climate has varied and provide regional-scale climate inferences. The latter are becoming increasingly important for model validation as GCMs are downscaled to provide palaeoclimatic reconstructions at ecologically relevant spatial scales (Hostetler et al., 2000).

The area around Søndre Strømfjord (Fig. 1) is the widest ice-free margin of Greenland and exhibits a strong climatic gradient from the dry, continental interior close to the ice-margin to the slightly more maritime conditions at the coast (Hasholt and Søgaard, 1978). Sediment records from lakes in this region (Anderson and Bennike, 1997; Willemse and Törnqvist, 1999; Bennike, 2000) provide an important means of understanding the changing environmental conditions in the area between the Greenland ice sheet and the Baffin Bay–Davis Strait. Although majority of the lakes along Søndre Strømfjord are oligotrophic and dilute (Anderson et al., 1999, 2001), the best known lakes are the oligosaline systems (Williams, 1991). The
combination of closed-basins with low precipitation and high rates of evaporation during the summer (Hasholt and Søgaard, 1978) means that lake-water salinity is enhanced above the regional average (Anderson et al., 2001). Elsewhere closed-basin saline lakes have been utilised extensively as palaeoclimate indicators (Fritz, 1996). The oligosaline lakes along Søndre Strømfjord are characterised by laminated sediments with a high calcite content (Anderson et al., 2000). Biologically mediated calcite precipitation in low-Arctic lakes occurs during the short summers when higher temperatures and light availability result in enhanced primary productivity from algae and submerged macrophytes. Calcite production and its isotopic signature will thus be weighted towards a seasonally specific signal that is controlled directly by the length of the ice-free period. Factors influencing the $\delta^{18}O$ and $\delta^{13}C$ value of lake-water in closed basins are relatively well understood (Talbot, 1990; Li and Ku, 1997; Leng and Marshall, this volume). In general, the higher $\delta^{18}O$ values in West Greenland lakes are indicative of lower precipitation and/or higher evaporation (i.e., low effective precipitation–evaporation) (Leng and Anderson, 2003). The $\delta^{13}C$ derived from bicarbonate in the lake water depends on several local factors. Under certain conditions it is a measure of biological productivity, although it can also be influenced by exchange with atmospheric CO$_2$ in arid environments (cf. Mckenzie, 1985).

Here, we present stable isotope records ($\delta^{18}O$ and $\delta^{13}C$) from laminated sediments from two closed-basin lakes near the head of Søndre Strømfjord (Kangerlussuaq) in West Greenland that allow us to evaluate the effective precipitation record in this area from the early to mid-Holocene.

2. Study area

The area around the head of Søndre Strømfjord in West Greenland (≈67°N 55°W, Fig. 1) has relatively uniform vegetation (dwarf shrub-tundra) and geology (granodioritic gneiss). The climate today is low-Arctic continental with a mean annual temperature of $-6^\circ$C and low average annual precipitation (<150 mm yr$^{-1}$), most of which occurs mainly during July and August. Surface runoff is limited and largely confined to the spring thaw, although most snow sublimates rapidly at the end of the winter period (April–May). The majority of the lakes in the area are oligotrophic, dilute systems (Brodersen and Anderson, 2002) but closer to the ice-sheet there are also numerous oligosaline lakes (Williams, 1991; Anderson et al., 2001).

The cores used in this study were taken from two meromictic, oligosaline lakes situated ≈40 km west of...
the present-day ice margin, close to the head of the fjord (Sondre Strømfjord; Greenlandic = Kangerlussuag) (Fig. 1). The area is considered to be ice-free from about 7500 cal yr BP (van Tateno et al., 1996). The study lakes, SS6 and Braya Sø (SS4) are located at ca 150 m asl, well above the marine limit for this area (ca 60 m). The salinity of these lakes is from locally derived salts (including a strong aeolian input) that have been concentrated by evaporation (Anderson et al., 2001). The salinity is not the result of the trapping of seawater as with many other Arctic saline lakes (Ouellet et al., 1989). SS6 (conductivity: 3300 μS cm⁻¹) has a surface area of 21 ha and a maximum depth of ~12 m. During periods of high water level it may be intermittently connected to Limnesø, a larger oligosaline lake. A small, freshwater lake (SS7; conductivity 220 μS cm⁻¹) drains into SS6. Braya Sø (conductivity: 2600 μS cm⁻¹) has a surface area of 73 ha and a maximum depth of 23 m. It has no outflow, but two smaller lakes drain into it for a short period during the early summer.

2. Methods

2.1. Modern lake water isotopic composition

The modern lake water from SS6 collected during the open water period between 1998 and 2000 has $\delta^{18}O$ values that varied between −9.7‰ (September 2000) and −11.3‰ (May 1999). Two samples were collected during 1998 which gave $\delta^{18}O$ values of −10.7‰ (June 1998) and −10.2‰ (September 1998). Water from SS4 was collected only once a year from 1998 to 2000 and had $\delta^{18}O$ values which ranged from −7.5‰ (June 1998) to −10.0‰ (May 1999) (Leng and Anderson, 2003).

The two water collections from SS6 during 1998 suggest that seasonal evaporative loss of the lighter isotope during the period of greatest potential for evaporation that year (the lakes are normally frozen between mid-late September and early June) was minimal. However, the range in values for both lakes suggests that the balance between input and evaporation changes from year to year. The calculated oxygen isotope mean weighted value for precipitation (−19‰) is depleted relative to all the modern lake waters suggesting a significant current trend towards evaporative concentration in the latter (Leng and Anderson, 2003).

3. Results and discussion

4.1. The oxygen-isotope record

$\delta^{18}O_{\text{calcite}}$ values at SS6 are highly variable in the lower section of the core (prior to 4300 cal yr BP; Zones 2 and 3) (Fig. 2) and range from −12‰ to +3‰. The present-day isotopic composition of lake water can be used to calculate the composition of $\delta^{18}O_{\text{calcite}}$ that,
presumably, is precipitating in the lakes today. The calculated \( \delta^{18}O \) can be compared with the \( \delta^{18}O_{\text{calcite}} \) data from the core and as a result environmental conditions in the past can be compared with those occurring today. If we assume maximum photosynthesis occurs during the warmest month (July), when the lake temperature is approximately 15°C, and the modern day \( \delta^{18}O_{\text{lakewater}} \) of -10.4% (average of lake water data from

![Graph showing % carbonate and organics, 14C yrs, and δ13C for lakes Braya So (SS4 upper section) and SS6 (lower section).](image-url)
1998 to 2000), calcite precipitated in isotopic equilibrium with the modern water would have a \( \delta^{18}O_{\text{calcite}} \) value of \(-10.2\%\) using Hays and Grossman’s (1991) fit of O’Neil et al.’s (1996) experimental data. The values of calcite in the sediment of SS6 are mostly isotopically heavier, but span the range between \(-11.2\%\) and \(+2.9\%\). Therefore, it is reasonable to conclude that the calcite precipitated in SS6 was in water that was isotopically heavier due to evaporative loss of \( ^{16}O \) in Zones 2 and 4. In Zones 1 and 3, the \( \delta^{18}O_{\text{calcite}} \) values are variable but some points are similar or lower than the calculated modern \( \delta^{18}O_{\text{calcite}} \) which would suggest periodic conditions then were similar (and at times wetter) to those of today. It is unusual that the \( \delta^{18}O \) values from Zone 4 (which represents the past ca 3500 years) are generally higher than the calculated \( \delta^{18}O \) for the modern day lake. However, the present Russian cores do not include sedimentation up to the present due to loss of material during collection, although preliminary analyses of Kaakj cores which include the most recent sediments indicate that \( \delta^{18}O \) values are similar to those at the top of the Russian cores for both lakes. Reasons for the discrepancy between the core values and estimated \( \delta^{18}O_{\text{calcite}} \) values are unclear. One alternative explanation may be that the calcite precipitation occurs under the ice: increased salinisation of polar lakes is well known due to the thick ice cover and expulsion of salts from the ice during freeze-up. This can cause substantial increases in conductivity and result in the precipitation of calcite at low temperatures. Alternatively, delays in the break-up of lake ice cover may have an effect. Today, much of the evaporation occurs in late-June to early July (spring time) under nearly cloudless skies and as the lakes warm rapidly. Delays in ice melt are related to cooler springs and there is a corresponding reduction in mean summer lake water temperatures (Anderson and Brodersen, unpublished data).

During the period represented by Zones 1 and 3, SS6 was probably an open lake system and likely to have been connected to Limnaesø. An extremely rapid change in the \( \delta^{18}O \) from \(-8\%\) to \(+3\%\) (Zone 2), that started around 7100 cal yr BP (Fig. 3) and predates the clay band at 140 cm by \(~\)1.5 cm (Fig. 2), suggests a marked arid phase that resulted in substantial lake level lowering. This arid interval resulted in the positive \( \delta^{18}O \) values (up to \(+3\%) at SS6; from \(-7\%) to \(-1\%) at Brayas Sø. \( \delta^{18}O \) values in Zone 4 fluctuate around a mean of \(-6\%) and indicate a relatively stable late Holocene climate (after 4300 cal yr BP) (Fig. 3). Notable deviations between 40 and 60 cm (mid-Zone 4) (\(~\)1800–2900 cal yr BP) suggest short intervals of wetter conditions.

Changes in the \( \delta^{18}O \) profiles from Brayas Sø are less pronounced than in SS6 (Fig. 2), presumably due to its greater volume of water (by a factor of 5–6). The larger volume effectively acts as a buffer, delaying and subduing lake-water isotope response to changing effective precipitation. It is possible, however, to identify similar features in \( \delta^{18}O \) profiles from both lakes. In contrast to SS6, which is intermittently connected to Limnaesø, Brayas Sø is today, isolated from nearby lakes. It is evident, however, from the lacustrine deposits which are exposed today on the saddle between Brayas Sø and Hunde Sø that these two lakes were once connected (Fig. 1). These deposits suggest that the lake level has dropped by at least \(~\)5 m from its highest stand. The highest \( \delta^{18}O \) value at Brayas Sø (\(-1\%)\) occurs at 120 cm (\(~\)7100 cal yr BP) and is synchronous with the clay band and lake level lowering (Fig. 2), as at SS6. These changes are possibly associated with the lowering of the lake from the period when it was connected with Hunde Sø.

4.2. The carbon-isotope record

Variations in \( \delta^{13}C \) values can also be indicative of climate, in that the \( ^{13}C/^{12}C \) ratio changes in response to...
algal productivity and atmospheric CO$_2$ exchange (McKenzie, 1985), although they may also reflect changes in soil productivity. $\delta^{13}$C$_{TCO_2}$ values in water from surficial soils and the seasonally active melt layer entering lake SS6 in the summer months, must be depleted in $^{13}$C due to isotopically light CO$_2$, liberated by the decay of terrestrial organic matter in the soil. On an average, terrestrial derived C3 organic matter has mean $\delta^{13}$C values between $-22\%$ and $-34\%$ (O'Leary, 1995). Isotopically light CO$_2$ enters soil waters and shallow groundwaters by dissolution, forming carbonic acid, which dissociates almost completely into bicarbonate, carbonate and hydrogen ions. At pH values of $\sim 9$ (representative of the present-day lake), HCO$_3^-$ is the dominant carbon species in lake water. HCO$_3^-$ in equilibrium with CO$_2$ has $\delta^{13}$C values $\sim 10\%$ higher than CO$_2$ at $15^\circ$C (Romanek et al., 1992), the mean lake water July temperature so HCO$_3^-$ derived solely from soil CO$_2$ with $\delta^{13}$C of between $-34\%$ and $-22\%$ should have $\delta^{13}$C values of ca $-24\%$ to $-12\%$. Equilibrium precipitation of calcite from bicarbonate has a $\delta^{13}$C value $\sim 1\%$ higher (Barlow et al., 1997). The measured values for $\delta^{13}$C should, therefore, be between $-23\%$ and $-11\%$ if the carbon was derived solely from terrestrial sources. The $\delta^{13}$C values in Zones 1 and 3 at SS6 mostly fall within this range and have a corresponding depleted $\delta^{18}$O similar to modern meteoric water values. High $\delta^{18}$O values in Zones 2 and 4 correspond with high $\delta^{13}$C. The latter values suggest that the dissolved bicarbonate pool is not only derived from the saturated zone but has an isotopically heavier carbon isotope source as well, and that the proportion of terrestrially derived organic carbon must account for only a small amount of the bicarbonate pool.

There are two possibilities that may account for the higher $\delta^{13}$C values. They may reflect partial equilibration of the bicarbonate in the near-surface waters by atmospheric CO$_2$ exchange (Ussowski and Hoefs, 1990; Andrews et al., 1993). This scenario is only likely if the lake waters had considerably longer residence times during which lake water evaporation and exchange with the atmospheric CO$_2$ occurred. At SS6, this process was probably dominant in Zone 2 (Fig. 2) where the enriched $\delta^{18}$O indicates that the climate was distinctly more arid and lake levels were lower. In Zone 4, (ca $<4300$ cal yr BP; Fig. 2) there is a notable increase in organic matter, and to a lesser extent calcite, coincident with high $\delta^{13}$C values. It is likely that the higher organic content (Fig. 2) associated with high $\delta^{13}$C values are the result of enhanced productivity, which resulted from increased algal productivity. During this time the increased biomass would extract proportionally larger amounts of $^{12}$C, leaving the aqueous HCO$_3^-$ pool enriched in $^{13}$C. Since $^{15}$C would be released during oxidation of organic matter, this process would normally require higher sedimentation rates to bury the organic matter or permanent anoxic bottom water that slow the rate of organic matter oxidation. Today, both lakes have anoxic hypolimnia, and the distinctive nature of the laminated sediments and the presence of purple sulphur bacterial pigments (S. McGowan unpublished) indicates the presence of stable and anoxic bottom waters.

A few features in $\delta^{13}$C profiles can be clearly identified in both lakes (despite the overall difference in the values). One are the low values in the early Holocene (Zone 1), however, the timing of the increase is offset. This may be due to inaccuracies in the chronologies or may indicate that Braya Sø responded faster to environmental change. The second feature is the decrease during Zone 3, although it is much smaller in Braya Sø. There is also a short-lived oscillation in both records at the beginning of Zone 4. Four negative oscillations in $\delta^{13}$C occur between 20 and 60 cm depth (1600–3000 cal yr BP) in SS6 (see Fig. 3) which suggest a series of rapid, short lived, changes in the lake’s overall carbon budget, possibly indicating periodic wetter conditions.

With the exception of the earliest part of the record, there is quite good agreement in the timing of features identified in both lakes (Fig. 3). The estimated errors for any individual date are substantial, probably due to reservoir effects associated with the bulk dates (Table 1) (see also McGowan et al., 2003). The agreement between the lake profiles is, therefore, well within the range of possible error and suggests that the lakes responded synchronously to regional climate changes. The Zone 3–4 boundary dates to 4244 cal yr BP in SS6 and 4180 cal yr BP in Braya Sø, while ages for the Zone 2–3 boundary are 5700 and 5594 cal yr BP for SS6 and Braya Sø, respectively. The greatest discrepancy, however, occurs in the basal sections of the profiles (> 7000 cal yr BP) and is primarily due to the lack of a proper basal date at Braya Sø (Fig. 3).

### 4.3. Hydrologic links

The isotope records from these low-Arctic, oligosaline lakes reflect the changing precipitation–evaporation balance in this area through the mid- to late-Holocene. Importantly, temperature effects on the isotopic composition in this area are minimal. The temperature dependency of $\delta^{18}$O is small ($<1\%$/$^\circ$C) which means that there would have to be lake water temperature changes that are unduly unrealistic to account for the observed changes in $\delta^{18}$O seen at both lakes. The synchronous changes (Fig. 3) recorded in the SS6 and Braya Sø sediments suggest that they are reflecting regional process. The lakes are $\sim 3$ km apart and their catchments are not connected, effectively ruling out in-lake processes. The effect of groundwater processes, which can have a major influence on isotopic
composition in more temperate lakes, is limited in this area by local geology and permafrost. The presence of fossil shorelines around the two study lakes (Anderson et al., 2001) also suggests that they have contracted in both area and volume and hence become chemically concentrated since their formation (ca 7500–8500 cal yr BP). Importantly, SS6 and Braya Sø are not isolated examples. There is physical evidence of lake level lowering throughout the region (Fig. 1), supporting the conclusion that at the regional scale climate in this area was substantially drier during the period B 8000–4300 cal yr BP than it is today.

Supporting evidence for major changes in the early Holocene in this area are also provided by diatom-inferred conductivity records from the same lakes (McGowan et al., 2003). Diatom-inferred conductivity indicates that the lakes were initially fresh (conductivity <400 μS cm⁻¹) but increased to >2000 μS cm⁻¹ ca 5000 cal yr BP (McGowan et al., 2003). Following a rapid increase in conductivity across the period of clay band deposition, the diatom record also suggests a distinct wetter phase between ~5000 and 4000 cal yr BP (in both lakes) when conductivity values dropped to below 500 (McGowan et al., 2003). This is in good agreement with the increase in runoff inferred from the δ¹³C profile (Zone 3) and the decrease in δ¹⁸O values in SS6 between 5300 and 4000 cal yr BP (Fig. 3).

### 4.4. Palaeoclimatic implications

In general, the climate of southern West Greenland during the early- to mid-Holocene was more arid than today. The evidence for alternating wet-dry periods suggests that regional climate was quite dynamic in the early- to mid-Holocene (Steig, 1999), perhaps representing interplay between the changing mass of the Greenland ice sheet and ocean processes in the North Atlantic. The data presented here for variable effective P:E may indicate that the relationship between the Greenland high and the North Atlantic low (Barlow et al., 1997) fluctuated more substantially prior to B 4300 cal yr BP than it does today. The ice-free area in West Greenland would have been at its maximum (B 200 km) in this period (6500 cal yr BP) (van Tatentove et al., 1996), the ice sheet being at least B 20 km west of its present location, while the Sukkertoppen ice cap (to the southwest; see Fig. 1) would have been substantially smaller if not totally absent. More locally, the stronger “outflow situation” (i.e. winds blowing off the ice sheet) in the Søndre Strømfjord area may have led to stronger cyclonic conditions in the region. The associated depression, the Baffin trough, (which today parallels the outer coast) creates predominantly east-south-easterly winds and hence drier conditions at the head of the fjord as well blocking the transport of moist air masses.
from the southwest. The overall result would have been lower precipitation and increased evaporation. The isotopic signals recorded in the early-Holocene mainly reflect this reduced summer precipitation but also intense evaporation (for example the increase in δ18O from −8% to +2% at SS6 ~ 7100–7800 cal yr BP). The evaporation was presumably a combination of higher water temperatures due to the higher summer insolation (which increases evaporation), increased windiness and low relative humidity. Present day studies have suggested that higher temperatures over West Greenland are associated with a more westward location of the Baffin trough and weaker subpolar westerlies (Barlow et al., 1997). Despite the dating uncertainties encountered in this study, these results show that isotope analysis has enormous potential in achieving seasonally specific information in Arctic lakes. In particular, the identification of arid phases in the lake sediment record provides complementary information to the temperature inferences derived from the Greenland ice-cores.

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