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Low-frequency and high-frequency changes in temperature and effective humidity during the Holocene in south-central Sweden: implications for atmospheric and oceanic forcings of climate

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Abstract An integrated use of independent palaeoclimatological proxy techniques that reflect different components of the climate system provides a potential key for functional analysis of past climate changes. Here we report a 10,000 year quantitative record of annual mean temperature (T_{ann}), based on pollen-climate transfer functions and pollen-stratigraphical data from Lake Flarken, south-central Sweden. The pollen-based temperature reconstruction is compared with a reconstruction of effective humidity, as reflected by a δ^{18}O record obtained on stratigraphy of lacustrine carbonates from Lake Igelsjön, c. 10 km from Lake Flarken, which gives evidence of pronounced changes in effective humidity. The relatively low T_{ann}, and high effective humidity as reflected by a low evaporation/inflow ratio suggest a maritime early Holocene climate (10,000–8,300 cal year BP), seemingly incompatible with the highly seasonal solar insolation configuration. We argue that the maritime climate was due to the stronger-than-present zonal flow, enhanced by the high early Holocene sea-surface temperatures in the North Atlantic. The maritime climate mode was disrupted by the abrupt cold event at 8,200 cal year BP, followed at 8,000 cal year BP by a stable Holocene Thermal Maximum. The latter was characterized by T_{ann} values about 2.5°C higher than at present and markedly dry conditions, indicative of stable summertime anti-cyclonic circulation, possibly corresponding with modern blocking anticyclonic conditions. The last 4,300 year period is characterized by an increasingly cold, moist, and unstable climate. The results demonstrate the value of combining two independent palaeoclimatic proxies in enhancing the reliability, generality, and interpretability of the palaeoclimatic results. Further methodological refinements especially in resolving past seasonal climatic contrasts are needed to better understand the role of different forcing factors in driving millennial-scale climate dynamics.

Introduction

The relative mildness of the climate in Scandinavia and elsewhere in northern Europe has traditionally been attributed largely to the North Atlantic oceanic circulation and associated meridional energy transport in the eastern North Atlantic (Rahmstorf 2000). However, the direct influence of the North Atlantic oceanic circulation on the climate of northern Europe was questioned by Seager et al. (2002) who couple the mild winters of northern Europe to the westerly airflow and advection of heat from the Atlantic irrespective of the strength of the meridional oceanic energy transport. One way to examine the influence of the oceanic forcing on the climate of Scandinavia is to use palaeoclimatological proxies to investigate potential correlations between past climatic changes of the continental regions and dynamics of the North Atlantic. Sediment records from the Nordic Seas give evidence of millennial-scale trends in sea-surface temperatures (SST) (Koç et al. 1993; Klitgaard-Kristensen et al. 2001; Birks and Koç 2002; Calvo et al. 2002; Marchal et al. 2002; Risebrobakken et al. 2003), and various records from the eastern North Atlantic reflect long-term variability in the production of North Atlantic deep water (NADW), documenting potential changes in the intensity of the Atlantic meridional overturning circulation (AMOC) (Bianchi and McCave 1999; Keigwin and Boyle 2000; Oppo et al. 2003; Hall et al. 2004). More transient, episodic perturbations in NADW production and North Atlantic circulation may

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have occurred during the early post-glacial as a result of a number of freshwater pulses from the proglacial lakes of the melting Laurentide ice sheet (Alley et al. 1997; Barber et al. 1999; Clark et al. 2001, 2002; Fisher et al. 2002; Teller et al. 2002; Broecker 2003; Nesje et al. 2004). On the basis of the strong influence of SST and the North Atlantic circulation on the climate of Europe during modern and historical times (Rodwell et al. 1999; Sutton and Hodson 2003), it can be hypothesized that low- and high-frequency changes in this important oceanic forcing mechanisms have induced millennial- and centennial-scale changes in the atmospheric circulation across Scandinavia, and that these perturbations can be detected by means of palaeoclimatological reconstructions.

Proxy climate indicators preserved in lake sediments provide a means to reconstruct past climatic patterns and, when examined with high temporal resolution, may detect potential abrupt changes in the atmospheric circulation. Often such reconstructions are based on a single palaeoclimatic proxy method or focus on specific climatic variables, usually temperature. However, in order to provide a more coherent picture of past atmospheric circulation dynamics, it is necessary to use a combination of proxy techniques, which reflect different components of the climate system. Stable isotope records obtained from calcareous lake sediments have proved useful for reconstruction of temporal changes in lacustrine water balance, thus providing evidence of past changes in effective humidity (e.g. Talbot 1990; Wolfe et al. 2001). On the basis of Holocene stable carbon-isotope and oxygen-isotope records of lacustrine carbonates at Lake Igelsjön, south-central Sweden, Hammarlund et al. (2003) demonstrated that the period 8,000–4,000 cal year BP (years before AD 1950) was characterized by a relatively dry and stable climate, whereas the late Holocene experienced more humid and variable climatic conditions. In order to generate a more complete assessment of the palaeoclimatological changes in the region and to provide an independent appraisal of the stable isotope records, we carried out a quantitative annual mean temperature (T_{ann}) reconstruction based on detailed pollen-stratigraphical data from Lake Flarken, a small lake ca. 10 km from Lake Igelsjön. The 5.7-m sediment sequence, covering the last 12,000 years, was originally analysed for pollen, diatoms, and geochemistry by Digerfeldt (1977). We applied a recently compiled pollen-climate calibration model, specifically designed for T_{ann} reconstructions in Scandinavia, to the Holocene pollen record from Lake Flarken. The aim of this paper is to present the new temperature record, which is the first of its kind from southern Sweden, and to use the combined records of temperature, effective humidity, and inferred vegetation history to analyse past climate dynamics in this part of Europe, which is presently experiencing a varying influence of Atlantic air-masses at interannual to decadal time-scales. Possible couplings of the observed centennial to millennial variations in atmospheric circulation to oceanic forcings are discussed.

Study area

The two sites under study are situated in the province of Västergötland in south-central Sweden (Fig. 1). Climatologically, the study region is located in the boundary zone between the oceanic West coast and the continental East coast of southern and central Sweden. The T_{ann} of the Climate Normals Period 1961–1990 at the closest meteorological station is 5.9°C. As a result of a steep gradient, the annual precipitation of 700–750 mm is about 30% less than at the coast, 150–200 km West of the study area (Fig. 1). The maximum rainfall period of the year is July-September. Biogeographically, the study area is situated in the northern part of the southern coniferous forest region, termed the Boreo-Nemoral zone (Sjörs 1967).

Lake Flarken (58°33′N, 13°40′E, 108 m a.s.l.) is located in an area of archaic gneiss with a gently undulating surface, which is covered by a thin and discontinuous layer of sandy or silty till. The soil is poor in lime and basic minerals. Lake Flarken is a shallow (0.9 m), partly over-grown polyhumic lake with a slightly elongated shape (ca. 300 by 600 m). The telmatic and aquatic vegetation is well developed with abundant reed beds and submerged macrophytes. The lake is surrounded by southern-Boreal vegetation typical of the region, with predominantly mixed forests of pine (*Pinus sylvestris*) and spruce (*Picea abies*). Birch (*Betula pendula*, *B. pubescens*) is the dominant broad-leaved tree and alder (*Alnus incana*, *A. glutinosa*) is also common. The nemoral, thermophilous broad-leaved trees elm (*Ulmus glabra*), lime (*Tilia cordata*), oak (*Quercus robur*,*Q. petraea*), hazel (*Corylus avellana*) and ash (*Fraxinus excelsior*) occur locally at climatologically and edaphically suitable sites. Beech (*Fagus sylvatica*) and hornbeam (*Carpinus betuloides*) are absent as their northern distribution limits are located ca. 100 km southwest and ca. 200 km South of the study region, respectively.

Lake Igelsjön (58°28′N, 13°44′E, 111 m a.s.l.) is a small lake (ca. 50 by 70 m), located 10 km South of Lake Flarken (Fig. 1). Its geological and topographic setting was described in detail by Hammarlund et al. (2003).

Methods

Sampling and pollen analysis

A 5.7-m sediment sequence from Lake Flarken was sampled and analysed for pollen and spores in 1974 (Digerfeldt 1977). Pollen samples were prepared with a standard KOH, HF, and acetolysis procedure (Moore et al. 1991). A total of 114 pollen samples were analysed

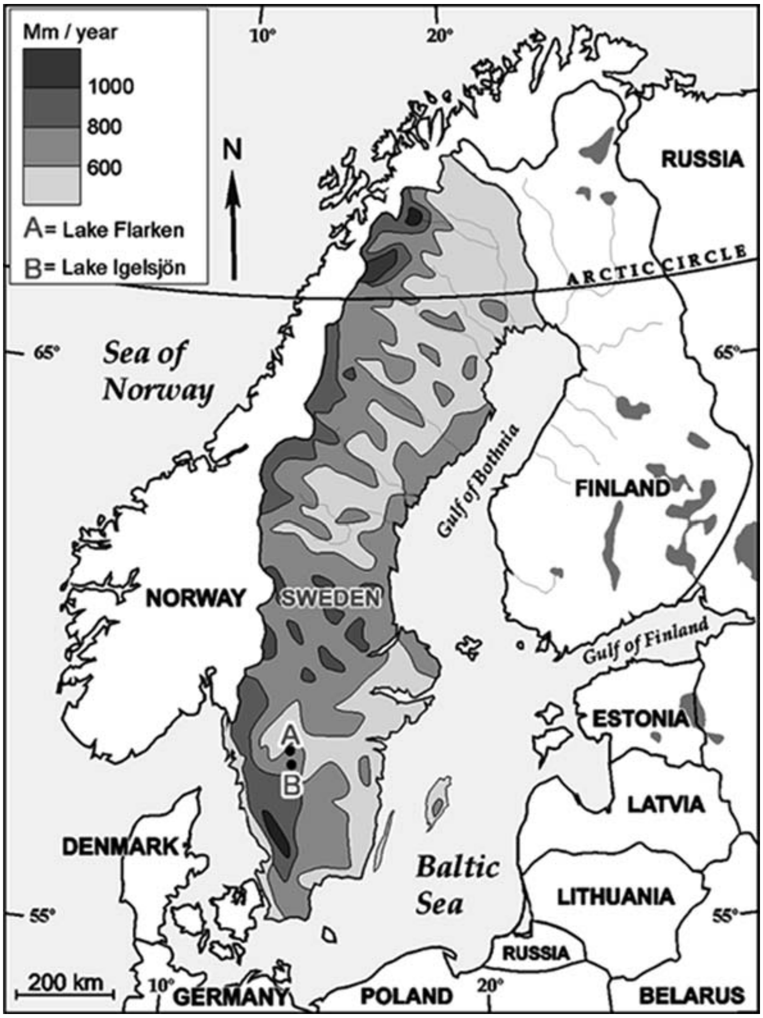


Fig. 1 The location of the study region. Isolines of the mean annual precipitation (mm) are indicated by *dashed lines*

from the core and a minimum of 1,000 terrestrial pollen and spore grains were counted in each sample. Percentages of the terrestrial pollen and spore taxa were calculated from their total sum. The pollen diagram was constructed with the TILIA and TILIA.GRAPH software (Grimm 1990).

Quantitative annual mean temperature reconstruction

Quantitative environmental reconstructions based on fossil biological data require the use of mathematical transfer functions (ter Braak 1987) that express past values of the environmental variable of interest as a function of the fossil biological data selected for the purpose (Birks 1995). The generation of transfer functions for biological data requires a collection of modern surface samples that are mathematically correlated with modern climate to produce a calibration set or model. Here the transfer functions were derived from a North European pollen-climate calibration set. This model is based on top surface sediment samples of small to medium-sized lakes and includes 113 samples from Finland, 24 samples from Estonia (Seppä et al. 2004), and 37 new samples from Sweden. All samples were selected, collected, and analysed by standardised criteria (see Seppä et al. 2004). The transfer functions were developed using weighted averaging partial least squares (WA-PLS) regression, a non-linear, unimodal regression and calibration technique commonly used in quantitative environmental reconstructions (ter Braak and Juggins 1993; Birks 1998; Birks and Seppä 2004). WA-PLS was implemented by the program CALIBRATE (S. Juggins and C.J.F ter Braak, unpublished program). In total, 104 terrestrial pollen and spore types were included in the model, with their values transformed to square-roots in order to stabilize the variance and to maximize ‘the signal to noise’’ ratio (Prentice 1980).

The numerical performance of the calibration model was tested by means of leave-one-out cross-validation or jack-knifing, where the modern T_{ann} is reconstructed n times using a calibration set of the size $n-1$, omitting the sample from the site for which the modern T_{ann} is reconstructed or “predicted” (ter Braak and Juggins 1993; Birks 1995). The results of the cross-validation test are shown in Table 1. In comparison to other corresponding calibration sets (see Seppä and Bennett 2003; Birks and Seppä 2004), they indicate a relatively high

Table 1 Summary performance statistics of the pollen-climate calibration set used for the T_{ann} reconstruction

Number of sites	173
Temperature gradient	−4.1–7.1°C
Temperature range	11.2°C
Number of taxa	104
r^2 between predicted and modern temperature	0.88
Root mean square error of prediction (RMSEP)	0.95°C
Maximum bias	2.1°C
RMSEP as % of the gradient length	8.5%

All the pollen surface sample sites are small- to medium size lakes in Finland, Estonia, and Sweden, selected on consistent criteria (Seppä et al. 2004). r^2 and RMSEP describe the statistical performance of the calibration model, evaluated by the leave-one-out cross-validation procedure

performance (low RMSEP, high r^2) of the pollen-climate calibration model used in the current study. The transfer functions were applied to the 114 fossil pollen assemblages of the Lake Flarken sediment sequence to generate quantitative estimates of past T_{ann} values. Sample-specific errors of the reconstructed values were generated by Monte-Carlo simulation (199 simulations), using the WA-PLS program of ter Braak and Juggins (1993).

Radiocarbon dating and age-depth model

The sediment sequence was dated by means of 13 conventional radiocarbon datings obtained on bulk sediment samples. The dates were calibrated with the CALIB 4.3 program (Stuiver and Reimer 1993), using the bidecadal tree-ring data set (set A) of the INTCAL98 calibration curve (Stuiver et al. 1998). A 10-sample smoothing of the calibration curve was applied in order to avoid multiple intersections. The age-depth model for the sediment sequence was derived by applying a third-order polynomial function to the calibrated dates, and by assuming a modern (−25 cal year BP) age for the core top.

Stable isotope analyses

The procedures of carbon and oxygen-isotope analysis of lacustrine carbonates extracted from the sediment sequence of Lake Igelsjön were reported by Hammarlund et al. (2003). The hydrological setting of the lake, with continuous closed-basin conditions, led to a pronounced covariance between δ^{18}O and δ^{13}C of bulk carbonates precipitated mainly as a consequence of summer-time photosynthesis in *Chara* algae. This means that both isotopic records show strong responses to major variations in effective humidity with time through changes in lake-water evaporation/inflow ratio and equilibration with atmospheric CO_2, respectively, during the ice-free season (Hammarlund et al. 2003). However, as δ^{18}O is influenced to a lesser degree than δ^{13}C by processes not directly related to climate, such as aquatic productivity, the former record was chosen to represent Holocene palaeohydrological change in the region for comparison with the temperature reconstruction from Lake Flarken. As a result of a new series of radiocarbon dates, further details of changing sedimentation rates were obtained and applied here, giving evidence of a significantly higher age (maximum difference ca. 400 years) in the interval of 4,500–3,300 cal year BP as compared to the age model presented by Hammarlund et al. (2003).

Results

The age-depth model of Lake Flarken, based on 13 calibrated radiocarbon dates (Table 2), reflects rather stable sedimentary conditions in the lake and a gradually changing accumulation rate during the last 12,000 years (Fig. 2). The T_{ann} record of Lake Flarken is shown in Fig. 3. As discussed by Hammarlund et al. (2003), the hydrological status of Lake Igelsjön was influenced by the local palaeogeographical evolution of the study area in response to glacio-isostatic rebound during the

Table 2 Radiocarbon dates of the Lake Flarken sediment sequence (Digerfeldt 1977)

Lab no	Depth (cm)	δ^{13}C	Age (^{14}C year BP)	Age (cal year BP) (1 SD)
Lu-1040	20–25	−28.3	1,000 ± 50	940 (960–910)
Lu-1039	65–70	−27.6	2,470 ± 55	2,650 (2,710–2,390)
Lu-1038	125–130	−29.4	4,070 ± 60	4,540 (4,610–4,460)
Lu-1037	180–185	−29.6	4,520 ± 65	5,270 (5,300–5,040)
Lu-1036	235–240	−30.0	5,390 ± 70	6,210 (6,270–6,130)
Lu-1035	295–300	−29.9	6,130 ± 70	6,990 (7,170–6,900)
Lu-1034	345–350	−30.8	6,590 ± 75	7,470 (7,550–7,430)
Lu-1033	395–400	−30.8	7,370 ± 80	8,180 (8,240–8,070)
Lu-1032	445–450	−30.2	8,060 ± 85	9,010 (9,060–8,830)
Lu-1031	465–470	−28.9	8,210 ± 85	9,170 (9,300–9,040)
Lu-1030	515–520	−26.0	8,960 ± 90	10,160 (10,200–9,920)
Lu-1083	535–540	−20.5	9,720 ± 95	11,170 (11,210–11,090)
Lu-1029	565–570	−16.7	10,330 ± 100	12,220 (12,620–11,930)

All dates are conventional radiocarbon dates obtained on bulk sediment samples

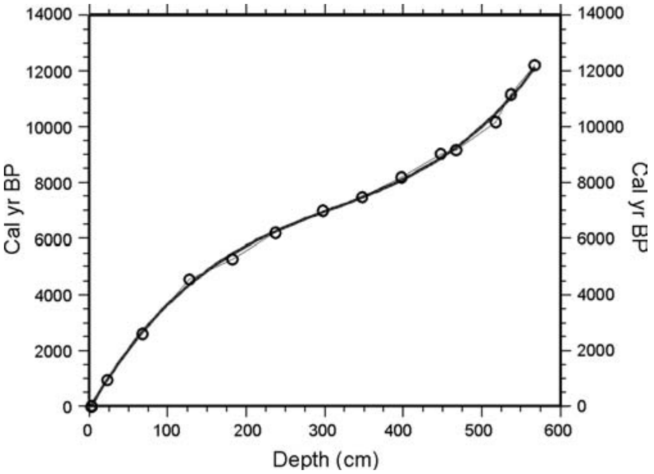


Fig. 2 The age-depth model of Lake Flarken, based on 13 calibrated radiocarbon dates (Table 2). The model was developed by fitting a third-order polynomial curve to the dates and by assuming a modern age for the sediment core top

earliest ca. 1,500 years part of the Holocene, thus confounding the climate-related palaeohydrological response of the lake at this stage. Hence, the following palaeoclimatic interpretation based on reconstructions of T_{ann} and δ^{18}O-inferred effective humidity (Fig. 4) is restricted to the time period after 10,000 cal year BP.

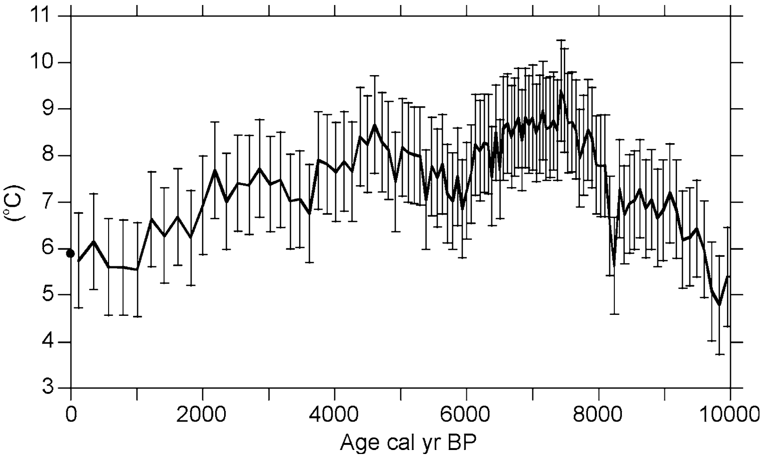
Climate reconstructions

The beginning of the study period is characterized by a rising trend of T_{ann}, which stabilizes around 7.0°C at 9,000–8,300 cal year BP (Fig. 3). The δ^{18}O record shows relatively low values, suggesting that the evaporation/inflow ratio was low but increasing at 10,000–8,300 cal year BP (Fig. 4). The rising trend of T_{ann} was punctuated by a sudden cooling of ca. 1.5°C at 8,300 cal year BP at Lake Flarken, which can be correlated to a pronounced decrease in δ^{18}O values at Lake Igelsjön (Fig. 4). These changes, indicating the onset of a cold and humid event of at least 200 years, probably correspond to the 8,200 year cold event identified in the Greenland ice cores (e.g. Alley et al. 1997).

A marked climatic recovery is recorded by rapidly rising T_{ann} values to 8.0–9.0°C at ca. 8,100 cal year BP and by an equally distinct increase in δ^{18}O at ca. 8,000 cal. BP. The slight apparent offset in timing of these changes can be considered as a result of dating uncertainties. The subsequent warm period lasted until a rapid cooling at ca. 4,300 cal year BP, hence forming the Holocene thermal maximum (HTM) in the study region, which correlates with elevated evaporation/inflow ratios brought about by low effective humidity as suggested by high δ^{18}O values at Lake Igelsjön (Fig. 4). The period of inferred warmth and dryness at ca. 8,000–4,300 cal year BP broadly coincides with a phase of generally low lake levels in southern Sweden (Digerfeldt 1988). Although the records of T_{ann} and inferred effective humidity are generally stable, the period is punctuated by a phase of lower T_{ann} at 6,100–5,400 cal year BP (Fig. 4). As this apparent relative cooling cannot be connected to any known climate event in Scandinavia, it is likely that it was caused by local, non-climatic variability in the pollen record.

A steady post-HTM decline of T_{ann}, which is fairly well correlated to the distinct decrease in δ^{18}O at Lake Igelsjön, began at about 4,300 cal year BP, followed by a gradual decline towards the present state. The δ^{18}O record (Fig. 4) and especially the δ^{13}C record of Lake Igelsjön (Hammarlund et al. 2003) contain a number of rapid changes superimposed on the generally decreasing trend. These wiggles suggest rapid hydrological changes, often within 100 years, during the last ca. 4,000 years in general, but especially during a transient phase in the period of 4,600–3,400 cal year BP, separating two different climate modes (Hammarlund et al. 2003). The absence of directly correlative changes in the T_{ann} reconstruction at this stage suggests that the observed changes in effective humidity, with distinctly declining δ^{18}O values centred at 4,400 and 4,100–4,000 cal year BP, respectively, may have been less strongly coupled to summer temperature than in the case of the cold event at

Fig. 3 Annual mean temperature reconstruction from Lake Flarken for the last 10,000 years (*black line*). The *grey* bars indicate 95% sample-specific error envelopes, generated by Monte-Carlo simulation. The modern T_{ann} at the site is 5.9°C, which is the same as reconstructed by the model. The *black dot* indicates the modern annual mean temperature at the site



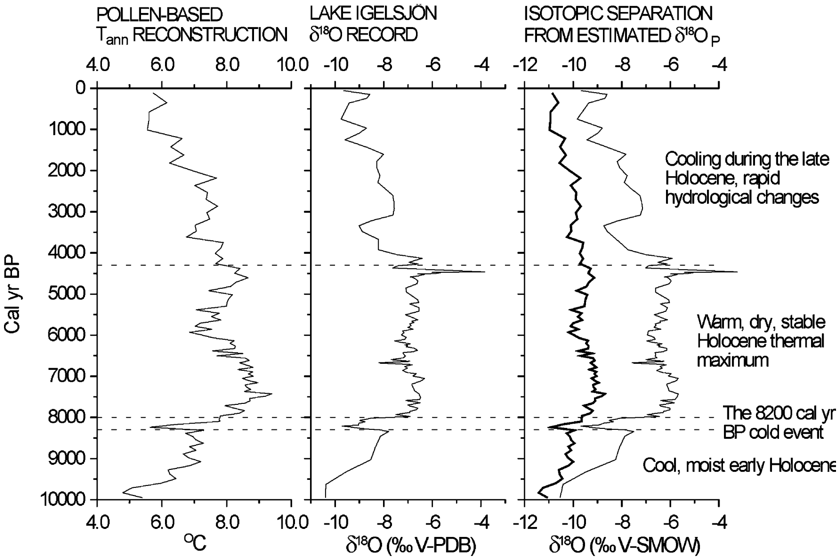


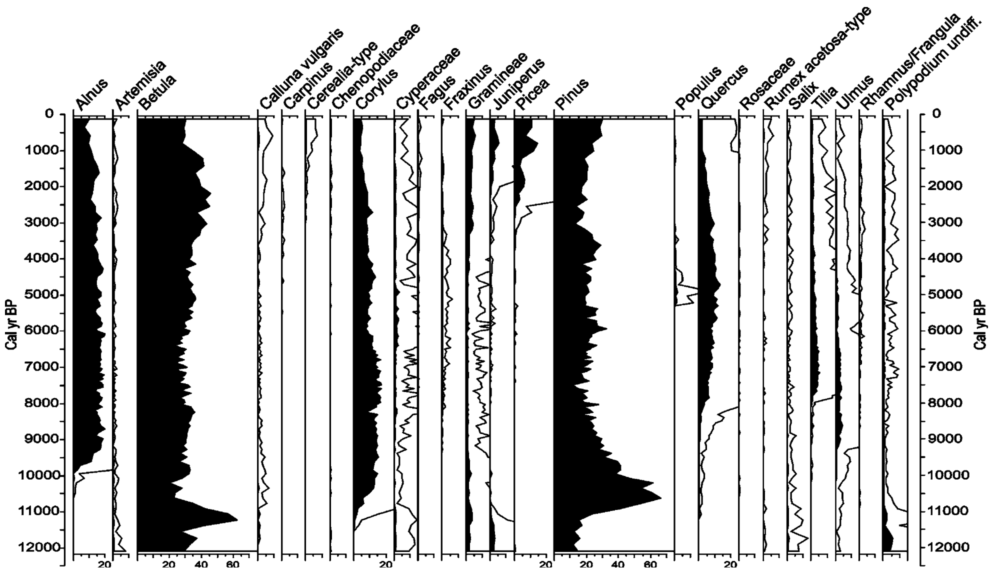
Fig. 4 Comparison of the T_{ann} record from Lake Flarken (*left-hand panel*) with the carbonate $\delta^{18}O$ record from Lake Igelsjön (*middle panel*; Hammarlund et al. 2003) during the last 10,000 years. The distance between the two lakes is about 10 km. A tentative estimate of changes in the oxygen–isotope composition of regional precipitation ($\delta^{18}O_P$) and groundwater recharge to Lake Igelsjön is indicated by the *bold line* in the *right-hand panel*, as inferred from the modern spatial relationship between T_{ann} and $\delta^{18}O_P$ (Rozanski et al. 1992). The *thin line* represents inferred variations in the oxygen–isotope composition of summer-time ambient lake-water ($\delta^{18}O_L$) at Lake Igelsjön, after accounting for equilibrium fractionation effects on carbonate $\delta^{18}O$ (c. −0.25‰/°C; Craig 1965; Friedman and O'Neil 1977) related to changing lake-water temperature as derived from the T_{ann} record. The changing isotopic separation between $\delta^{18}O_P$ and $\delta^{18}O_L$ reflects variations in evaporation/inflow ratio of the basin related to changes in summer-time effective humidity. The inferred main palaeoclimate patterns are indicated on the right

8,200 cal year BP. However, insufficient dating control of the Lake Flarken record precludes a more detailed analysis of these relationships.

Pollen record

Of the temperate deciduous tree species, *Corylus* and *Ulmus* were present at their respective maximum Holocene values well before 8,000 cal year BP (Fig. 5). In contrast, *Quercus* and *Tilia* occurred at trace values clearly below their present-day levels at this stage, although the reconstructed T_{ann} at 9,000–8,300 cal year BP was at least 1.0°C higher than at present. The cold event at 8,200 cal year BP is reflected in the pollen stratigraphy by an abrupt and distinct decline in *Corylus* and to lesser extent in *Ulmus* and *Alnus*, while there was a marked increase in *Betula* (Fig. 5). The onset of the HTM at about 8,000 cal year BP is reflected by rising values of *Tilia*,*Fraxinus*, and *Quercus*. Assuming that the post-glacial immigration of tree species took place in approximate dynamic equilibrium with climate (Prentice et al. 1991; Davis and Shaw

Fig. 5 A simplified pollen percentage diagram from Lake Flarken, showing the 24 most common or important pollen and spore types. The total number of pollen samples is 114 (Digerfeldt 1977)



2001; Post 2003; Shuman et al. 2004), the population dynamics of these tree species during the HTM can be explained by a major change in the atmospheric circulation pattern as suggested by independent stable isotope data from Lake Igelsjön. *Corylus* and *Ulmus*, the temperate deciduous species that were abundant before 8,000 cal year BP, require long growing seasons but are relatively sensitive to frost and, along with *Alnus*, have a low drought-tolerance (Hintikka 1963; Skre 1979; Prentice and Helmisaari 1991). Their high values in the pollen record prior to 8,300 cal year BP may therefore reflect relatively humid and oceanic climatic conditions during the early Holocene. *Tilia* and *Quercus* are more continental in their modern distributions ranges (Hultén 1971; Dahl 1998) and climatic tolerances, being less sensitive to drought but generally requiring higher mid-summer temperatures than *Corylus* and *Ulmus* (Hintikka 1963; Pigott and Huntley 1978; Skre 1979; Pigott 1981; Prentice and Helmisaari 1991). Hence, their absence or infrequent occurrence before 8,300 cal year BP likely resulted from too low mid-summer temperatures and their subsequently rising values were probably connected to the shift towards predominantly dry and warm conditions at about 8,000 cal year BP.

The cooling at about 4,300 cal year BP is mostly inferred from decreasing values of *Corylus* and *Quercus* and from increasing values of *Pinus* and *Betula*. *Picea*, which is currently one of the dominant tree species in the region, was established at ca. 2,500 cal year BP. The western distribution limit of *Picea abies* in Scandinavia corresponds closely to the −1.5°C mean January isotherm, possibly due to the detrimental influence of snowless conditions and repeated freeze–thaw cycles that characterize the winters in western Europe (Prentice and Helmisaari 1991; Sykes et al. 1996; Dahl 1998; Bradshaw et al. 2000). Consequently, the late-Holocene expansion of *Picea* in southern and central Sweden is usually attributed to increasingly cold and snow-rich winters during the late-Holocene (Tallantire 1972; Giesecke and Bennett 2004). As *Picea* favours moister soil conditions as compared to *Pinus*, its southward expansion was probably related to the gradual late-Holocene increase in effective humidity as recorded at Lake Igelsjön. Although Lake Flarken was originally selected for this investigation on the basis of forested surroundings and assumed minor long-term human impact (Digerfeldt 1977), the increasing values of *Juniperus* and Cerealia-type during the last 3,000 years reflect the regional spread and intensification of agricultural human impact on forests in the study region (Fig. 5).

Discussion

Validation of the Lake Igelsjön palaeohumidity record

The new pollen-based reconstruction of annual mean temperature from Lake Flarken provides a means for independent assessment of the validity of the Lake Igelsjön δ^{18}O record as a reflection primarily of changing effective humidity through variations in summer-time evaporation/inflow ratio of the basin as proposed by Hammarlund et al. (2003). Theoretical modern relationships can be used for estimation of the magnitude of hydrological over-printing on lake-water and carbonate δ^{18}O as compared to other potential forcing factors. These include primarily (1) changes in the oxygen-isotope composition of precipitation ($\delta^{18}O_P$) and thereby recharging groundwater and lake-water ($\delta^{18}O_L$); and (2) changes in summer-time lake-water temperature affecting the oxygen-isotope fractionation during calcite formation by *Chara* photosynthesis.

As demonstrated by von Grafenstein et al. (1998, 1999), the spatial pattern and long-term trends in $\delta^{18}O_P$ are largely coherent and apparently strongly related to annual mean temperature across northern Europe and the North Atlantic, with a lacustrine record from southern Germany closely matching Greenland ice-core data during the last c. 10,000 years. Although considerable temporal deviations from this relationship in response to the changing atmospheric circulation have been observed for the earliest millennia of the Holocene in Scandinavia (Hammarlund et al. 2002), the sensitivity of the Lake Igelsjön δ^{18}O record to changing atmospheric temperature can be tested by applying the regression equation for modern European observations ($\delta^{18}O_P = (0.59 \pm 0.08)T - 14.24$) as presented by Rozanski et al. (1992) to the Lake Flarken T_{ann} reconstruction. This relationship, which is in good agreement with the inferred temporal $\delta^{18}O_P$-temperature gradient proposed by von Grafenstein et al. (1998), produces a hypothetical $\delta^{18}O_P$ record for the study area that may account for about 40% of the Holocene variability in carbonate δ^{18}O at Lake Igelsjön (Fig. 4). The credibility of this approach for modern conditions in the study area is demonstrated by the excellent match between the uppermost inferred annual mean $\delta^{18}O_P$ value (c. −10.8‰) and monitored δ^{18}O of groundwater during all seasons and lake-water during ice-covered conditions (Hammarlund et al. 2003).

Changes in the oxygen-isotope composition of ambient lake-water ($\delta^{18}O_L$) at Lake Igelsjön during the ice-free season can also be tentatively derived from the T_{ann} record on the assumption of approximately equal long-term changes in annual mean air temperature and summer-time lake-water temperature during the Holocene. Such a consistency seems reasonable on the basis of modern spatial air–temperature relationships in southern Sweden (Vedin 1995) and the small volume of the lake. An inferred record of $\delta^{18}O_L$ is displayed in Fig. 4, based on compensation for the effect of changing lake-water temperature on the oxygen-isotope fractionation during calcite formation, assuming a slight constant kinetic isotope enrichment effect in *Chara* algae as compared to equilibrium conditions (Hammarlund et al. 1999, 2002) and a sensitivity of c. −0.25‰/°C (Craig 1965; Friedman and O'Neil 1977) to temporal deviations from modern temperature conditions as derived from T_{ann} data. As the capacity of the inflowing groundwater to adjust to prevailing air temperatures was probably greater during times of prolonged residence time, i.e. primarily at c. 8,000–4,300 cal year BP, the temperature-related displacement of $\delta^{18}O_L$ towards higher numerical values as compared to carbonate $\delta^{18}O$ may be slightly overestimated in other parts of the record. The inferred $\delta^{18}O_L$ data were anchored to the V-SMOW scale based on the observed coupling of modern *Chara* $\delta^{18}O$ values of c. $-9‰$ (V-PDB) to corresponding measured $\delta^{18}O_L$ values of c. $-9‰$ V-SMOW during early summer when *Chara* photosynthesis is at its maximum (Mörner and Wallin 1977). Temperature estimates for the data-points of the Lake Igelsjön $\delta^{18}O$ record were derived by interpolation between the nearest T_{ann} data in the Lake Flarken reconstruction.

As revealed by substantial temporal variations in $\delta^{18}O_L$ independent of $\delta^{18}O_P$, which can only be attributed to changing evaporation/inflow ratios of the basin, changing hydrology is the single most important process determining the observed variations in $\delta^{18}O$ at Lake Igelsjön, accounting for c. 60% of the variability in spite of being subdued by temperature effects. Parts of the long-term trends, however, are clearly influenced by changes in $\delta^{18}O_P$ that to some extent resemble those observed in southern Germany (von Grafenstein et al. 1998). Considerably enhanced isotopic separation as compared to present-day conditions, most likely reflecting increased effective humidity in the study area, were recorded at c. 8,000–4,000 cal year BP, with corresponding patterns of lower magnitude at c. 9,000–8,300 and c. 3,300–1,500 cal year BP. A brief episode of significantly lowered isotopic separation occurred at c. 8,300–8,000 cal year BP.

Long-term climate dynamics

Comparison of the present results with prior terrestrial records of temperature and humidity from Scandinavia and adjacent regions reveals a general conformity of major Holocene climatic trends. As early as 1924, von Post (1924, 1925) presented plant macrofossil evidence according to which the early-Holocene vegetation in central Sweden was characterized by a number of indicator species, notably *Cladium mariscus*, suggesting mild winters and long but relatively cool summers, typical of a predominantly oceanic climate. During the mid-Holocene, these species were replaced by other indicator species such as *Trapa natans*, associated with warmer and drier summer conditions and, therefore, with more continental climatic conditions (von Post 1925). This interpretation has later been supported by records of lake-level variations in central and southern Sweden (Digerfeldt 1988) and elsewhere in northern Europe (Harrison et al. 1993; Yu and Harrison 1995). Similarly, quantitative (Hammarlund et al. 2002; Heikkilä and Seppä 2003; Seppä and Poska 2004) and qualitative (Dahl and Nesje 1996; Nesje et al. 2001; Hammarlund et al. 2003) temperature reconstructions based on independent proxy techniques from Fennoscandia and the Baltic region indicate roughly parallel trends in temperature and humidity, with inferred early-Holocene temperatures higher than at present but lower than during the HTM. In most of these records, the HTM dates to about 8,000–4,000 cal year BP.

The regionally consistent nature of these palaeoclimatic patterns suggests that the individual records are not significantly influenced by local non-climatic factors or by potential inherent biases associated with various proxy techniques. Consequently, the major reconstructed changes in T_{ann} at Lake Flarken and the palaeohydrological development at Lake Igelsjön can be assessed in terms of such climatological features that are the main drivers of modern spatial gradients and temporal variability of temperature, precipitation, and effective humidity in the study region. Due to the geographical location on the eastern seaboard of the North Atlantic, the dominant climatic situation in southern Scandinavia is strongly dependent on the relative strength of the two major atmospheric circulation modes, the westerly or zonal airflow, associated with migratory cyclones, and the anticyclonic blocking. The shifting dominance of these broad-scale atmospheric circulation patterns greatly affects the weather patterns in Scandinavia and drives both short-term and decadal-scale climatic variability (Johannessen 1970; Chen and Hëllström 1999; Chen 2000; Werner et al. 2000; Marshall et al. 2001; Jacobeit et al. 2003). Especially, winter temperature variations are mostly caused by changes in the dominant ambient atmospheric flow pattern with a westerly component usually associated with positive temperature anomalies and high precipitation, whereas anticyclonic conditions can cause subsidence and give rise to greater losses of radiative energy and weak exchange with the surrounding areas, leading to extremely low temperatures (Chen and Hellström 1999; Chen 2000; Junge and Stephenson 2003). In general, autumn, winter, and spring temperatures in northern Europe correlate positively with the intensity of the western airflow (Kozuchowski et al. 1992; Jönsson and Bärring 1994; Chen and Hellström 1999; Junge and Stephenson 2003). In summer, however, the advection of maritime air brings in rainy and cloudy weather conditions with below-average temperatures. Summer temperatures in Scandinavia are therefore negatively correlated with western zonal flow indices, and the temperature pattern in general is less affected by the atmospheric circulation over the North Atlantic (Jönsson and Bärring 1994; Chen and Hellström 1999; Jacobeit et al. 2001).

Given the lack of reliable proxy techniques that would permit detailed analysis of seasonal contrasts of past climates, any model for the early Holocene seasonality is preliminary and speculative. Nevertheless, the conformity of the stable isotope and pollen data presented here suggests that the dominant atmospheric circulation mode in south-central Sweden at 10,000–8000 cal year BP was characterized by a strong and persistent zonal flow leading to mild winters and predominantly humid conditions. A distinct change towards drier climatic conditions took place at about 8,000 cal year BP, reflected by higher evaporation/inflow ratios (Fig. 4), and lower lake levels (Digerfeldt 1988; Almquist-Jacobson 1995). In association with elevated reconstructed T_{ann} values and the expansion of tree species requiring high mid-summer temperatures, this suggests a change towards a summer-time circulation situation which was less strongly influenced by the zonal flow. The modern atmospheric circulation analogue, which may correspond to the reconstructed pattern, is associated with blocking anticyclonic conditions during the summer. Under such conditions, the persistent high-pressure cell located over northern Europe prevents moist Atlantic air masses from reaching Scandinavia and the zonal flow is replaced by meridional flow carrying warm air from the South or southeast (Rex 1950; Johannessen 1970; Lupo et al. 1997). Depending on the strength and persistence of the anticyclone, the associated warm and dry weather pattern can lead to characteristic "indian summers" in Scandinavia (Lupo et al. 1997). The decrease in reconstructed T_{ann} in combination with increased effective humidity inferred from the δ^{18}O record at about 4,300 cal year BP (Fig. 4) suggests a sudden break-up of the predominantly stable anticyclonic conditions, followed by a further, gradual cooling towards the present. The last 1,000 years represent the coldest period since c. 9,500 cal year BP, and it is likely that lowered evaporation/inflow ratios and rising lake levels were caused by decreased evaporation in response to the general cooling.

The proposed theory of millennial-scale changes in atmospheric circulation patterns must identify a mechanism by which the atmospheric system can be triggered to change from one state to another. The glacial–interglacial cycle is associated with the astronomic insolation theory but the long-term Holocene trends in annual, summer, and winter insolation (Berger and Loutre 1991; Crucifix et al. 2002) cannot solely explain the observed changes in atmospheric circulation patterns. Given the current coupling of the North Atlantic SST and the intensity of the zonal flow (Lau 1997; Rodwell et al. 1999; Sutton and Hodson 2003), associations between the inferred climatic shifts in south-central Sweden and a potential oceanic forcing can be searched for in proxies for SST in the eastern North Atlantic. In general, the palaeoceanographic evidence indicates high SST during the early-Holocene, with maximum reconstructed values (2.0–4.0°C above the present) dating to about 10,000 to 7,000 cal year BP, depending on the proxy used and the location of the study site (Koç et al. 1993; Klitgaard-Kristensen et al. 2001; Calvo et al. 2002; Marchal et al. 2002; Birks and Koç 2002; Hald et al. 2003). The mid-Holocene to late-Holocene is characterized by gradually decreasing SST and associated attenuation of the Norwegian Current and the inflow of Atlantic surface water into the Arctic Ocean (Birks and Koç 2002). We therefore argue that the relatively oceanic climate in south-central Sweden during the early Holocene was related to more vigorous AMOC and higher SST in the eastern North Atlantic, mediated by strong zonal flow across Scandinavia, and that the transition toward the drier part of the HTM at about 8,000–7,000 cal year BP was predominantly induced by declining SST and associated weakening of the influence of the zonal flow. Regional coherence across Scandinavia of such a development is demonstrated by data from northernmost Sweden. Hammarlund et al. (2002) proposed a successive decline in the influence of maritime air masses on the distal side of the Scandes Mountains during the earliest millennia of the Holocene, based on the changing relations between δ^{18}O of precipitation and pollen-inferred July mean air temperature.

The 8,200 cal year BP cold event

Our new data on the rapid, transient cooling at about 8,200 cal year BP in south-central Sweden adds to the increasing body of evidence documenting the nature and extent of the 8,200 cal year BP event, and can improve our understanding of the causal mechanisms behind it. The explanation usually favoured for the event is a catastrophic meltwater pulse from the glacial Lakes Agassiz and Ojibway at about 8,500 cal year BP, which may have led to a transient freshening of North Atlantic surface waters and a weakening or a shutdown of the AMOC (Barber et al. 1999; Keigwin and Boyle 2000). Some studies, however, have questioned the role of the freshwater pulse as a cause of the event (Hu et al. 1999; Dean et al. 2002), predominantly due to the lack of evidence from the marine realm of a major reduction of NADW formation, which would be primordial for a weakening of the AMOC (Keigwin and Boyle 2000; Clark et al. 2001; Weaver and Hillaire-Marcel 2004). The recent high-resolution reconstructions of the occurrence and amplitude of this cold event in Scandinavia, and even further East in the Boreal Zone of Europe (Fig. 6), demonstrate its widespread extent in northern Europe, distal to the North Atlantic Current, where the relative mildness of climate is critically dependent on the influence of the westerlies and the advection of warm maritime air in winter. Hence, the accumulating evidence from northern Europe supports the hypothesis that the sudden and strong climatic changes associated with the 8,200 cal year BP event were caused by a weakening and subsequent recovery of the winter-time zonal flow in response to an abrupt perturbation of the AMOC and associated rapid changes in SST of the North Atlantic. However, the summer climate was probably characterized by increased humidity, and thus persistence of the zonal circulation mode, as inferred from geochemical evidence of a lake-level rise at Lake Igelsjön (Hammarlund et al. 2003) and from the inferred decrease in the separation between $\delta^{18}O_P$ and $\delta^{18}O_L$ (Fig. 4).

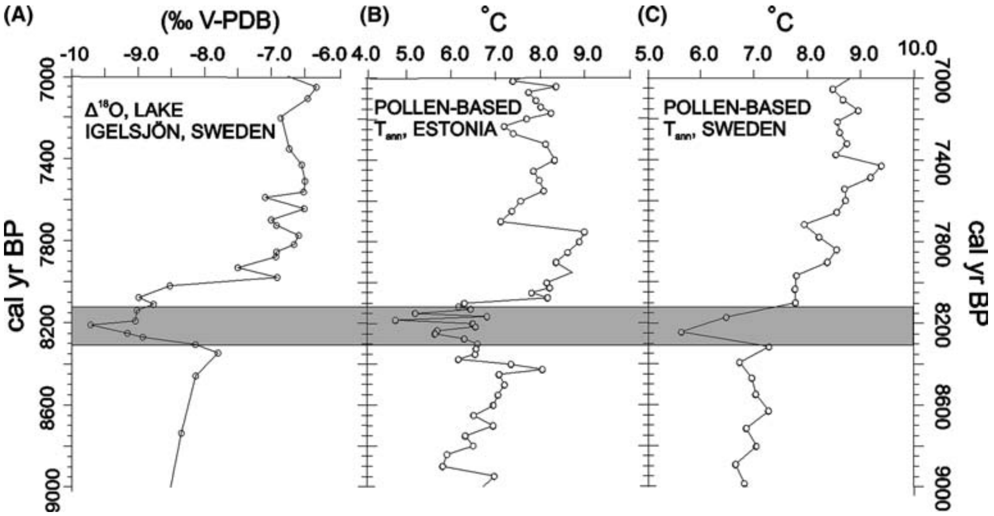


Fig. 6 Enlargements of the three independent climate reconstructions covering the cold event at 8,200 cal year BP. **a** The δ^{18}O record from Lake Igelsjön (Hammarlund et al. 2003), **b** the pollen-based T_{ann} reconstruction from Lake Rouge in Estonia (Veski et al. 2004), **c** the reconstructed T_{ann} from Lake Flarken, Sweden. The time-scale of Lake Rouge is based on a floating varve chronology anchored to a calendar-year time-scale by correlation of the palaeomagnetic secular variation curve with data from Lake Nautajärvi in Finland (Ojala and Tiljander 2003). The cumulative error is 1–2% (Veski et al. 2004). The time-scales of Lake Flarken and Lake Igelsjön are based on independent radiocarbon datings

Provided that the 8,200 cal year BP event was caused by a perturbation of the AMOC, this palaeoclimatic feature provides an important opportunity to investigate climatic and environmental responses in northern Europe to such perturbations, and to use the reconstructed responses to validate those simulated by various climate models. In order to study the mechanisms behind the 8,200 cal year BP cold event, a global atmosphere-sea-ice-ocean model simulation was carried out by Renssen et al. (2001). The simulation suggests that a freshwater pulse of 0.75 Sv during 20 years results in a weakening of the AMOC during 320 days and an associated cooling of 1.0–5.0°C over the adjacent continents, and the simulation by Vellinga and Wood (2002) suggest a cooling of 1.0–2.0°C in central and southern Scandinavia due to the weaker zonal air flow as a result of lowered SST in the North Atlantic. The duration and amplitude of the simulated cooling is therefore consistent with the reconstructed 1.0–1.5°C cooling at Lake Flarken (Fig. 6). As a result of the stronger influence of the zonal air flow on winter climate than on summer climate (Chen and Hellström 1999), the models suggest maximum cooling in winter and a 1–2 month extension of the snow-cover season in northern Europe (Vellinga and Wood 2002). This is consistent with the pollen-stratigraphical data from Lake Flarken (Fig. 5), exhibiting a particularly pronounced decline in *Corylus*, which is a predominantly oceanic thermophilous tree species requiring a long growing seasons and warm early springs. There is, however, an apparent difference between the reconstructed and simulated hydrological response in central Scandinavia. The strong zonal flow is associated with wetter-than-normal conditions in Scandinavia (Rodwell et al. 1999; Marshall et al. 2001) and the model simulations consequently indicate a marked decrease in the precipitation giving rise to drier conditions during the 8,200 cal year BP event (Vellinga and Wood 2002). Although this may seem to contradict with the stable isotope evidence from Lake Igelsjön, indicating a general increase in effective humidity (Fig. 4), it is likely that the possible reduction of precipitation was compensated for by a more pronounced decrease in the summer temperature, which resulted in reduced evaporation.

Conclusions

The combined use of palaeoclimatic proxies reflecting different components of the climate system, such as those utilized in this study, can help to generate more comprehensive climate reconstructions. However, in order to assess the fundamental forcings of the reconstructed palaeoclimatic patterns, it is necessary to identify the underlying causative processes sustaining and changing the climate patterns. For this purpose, it is essential to examine the patterns and processes of the contemporary climate and weather and to use these as analogues of inferred dynamics of past climates. This approach is particularly justified in Scandinavia due to the great temporal climatic variability (Johannessen 1970) and the strong coupling between climate and the dominant atmospheric circulation mode, as documented by analyses of long-term climate records and atmospheric circulation indices (Chen 1999; Marshall et al. 2001; Slonosky et al. 2001). However, the long-term climatological investigations also demonstrate that the circulation–climate relationships may not remain stationary when the period of investigation is extended further into the historical past (Jacobeit et al. 2001;

Sutton and Hodson 2003). On millennial time scales and under boundary conditions different from the modern situation, such non-stationarities are likely to be even more significant. Therefore, the adopted approach of modern analogues can at best be applied on an approximate level and probably becomes more ambiguous towards the early Holocene with progressively non-analogous boundary conditions.

In general, the independent records of annual mean temperature and effective humidity in south-central Sweden show coherent long-term trends. Consistent evidence exists of enhanced zonal circulation and predominantly humid conditions during the early-Holocene, replaced by a stable period of warm and dry conditions during the HTM, at about 8,000–4,300 cal year BP, probably due to the increasing influence of blocking anticyclonic circulation during the summer. The abrupt end of the HTM at 4,300 cal year BP in south-central Sweden agrees in general with other climate reconstructions from Boreal regions in Europe. Numerous proxy records from the eastern seaboard of the North Atlantic suggest a progressive shift towards cooler and/or wetter climatic conditions, initiated slightly before or around 4,000 cal year BP. These include records of peat humification (Granlund 1932; Gunnarsson et al. 2003), lake-level variations (Digerfeldt 1988; Plunkett et al. 2004), mountain glacier status (Dahl and Nesje 1996; Nesje et al. 2001), speleothem δ^{18}O composition (Lauritzen and Lundberg 1999; McDermott et al. 2001), alpine tree-limit fluctuations (Kullman and Kjällgren 2000; Hammarlund et al. 2004), and quantitative temperature variations inferred from biological transfer functions (Heikkilä and Seppä 2003; Seppä and Poska 2004). Thus, a growing body of evidence suggests that the HTM came to a sudden end adjacent to the North Atlantic, probably as a result of a threshold response of the dominant atmospheric circulation mode to changes in oceanic and astronomical forcings and a subsequent cessation of the stable anticyclonic climatic conditions. Another picture emerging from the present data in conjunction with other recent palaeoclimate records from northern Europe concerns the cause and nature of the 8,200 cal year BP cold event. The increasing evidence of the amplitude, its geographical extent in northern Europe, and in particular, the abrupt start and end of the event suggest rapid threshold responses of the zonal flow to a sudden and strong change in a major forcing factor. These seem inconsistent with a suggested weak-forcing scenario or more regional atmospheric re-organizations as causes of the event (Dean et al. 2002). Although there is currently no deep-sea evidence for a shutdown of AMOC during the 8,200 cal year BP event, we conclude that the evidence from Scandinavia supports the argument that the cause of this prominent climatic perturbation must be searched for in high-resolution marine records.

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References

Alley RB, Mayewski PA, Sowers T, Stuiver M, Taylor KC, Clark PU (1997) Holocene climatic instability: a prominent, widespread event 8,200 year ago. Geology 25:483–486

Almquist-Jacobson H (1995) Lake-level fluctuations at Ljustjärnen, central Sweden and their implications for the Holocene climate of Scandinavia. Palaeogeogr Palaeoclimatol Palaeoecol 118:269–290

Barber DC, Dyke A, Hillaire-Marcel C, Jennings AE, Andrews JT, Kerwin MW, Bilodeau G, McNeely R, Southon J, Morehead MD, Gagnon J-M (1999) Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes. Nature 400:344–348

Berger A, Loutre MF (1991) Insolation values for the climate of the last 10 million years. Q Sci Rev 10:297–317

Bianchi GG, McCave IN (1999) Holocene periodicity in North Atlantic climate and deep-ocean flow south of Iceland. Nature 397:515–517

Birks CJA, Koç N (2002) A high-resolution diatom record of late-quaternary sea-surface temperatures and oceanographic conditions from the eastern Norwegian Sea. Boreas 31:323–344

Birks HJB (1995) Quantitative palaeoenvironmental reconstructions. In: Maddy D, Brew JS (eds) Statistical modeling of quaternary science data, Technical Guide 5. Quaternary Research Association, Cambridge, pp 161–254

Birks HJB (1998) Numerical tools in quantitative palaeolimnology—progress, potentialities, and problems. J Paleolimnol 20:301–332

Birks HJB, Seppä H (2004) Pollen-based reconstructions of late-Quaternary climate in Europe—progress, problems, and pitfalls. Acta Palaeobotanica 44:317–334

Bradshaw RHW, Holmqvist BH, Cowling SA, Sykes MT (2000) The effects of climate change on the distribution and management of *Picea abies* in southern Scandinavia. Can J For Res 30:1992–1998

Broecker WS (2003) Does the Trigger for Abrupt Climate Change Reside in the Ocean or in the Atmosphere? Science 300:1519–1522

Calvo E, Grimalt J, Jansen E (2002) High resolution $U^{K}{}_{37}$ sea surface temperature reconstruction in the Norwegian Sea during the Holocene. Q Sci Rev 21:1385–1394

Chen D (2000) A monthly circulation climatology for Sweden and its application to winter temperature case study. Int J Climatol 20:1067–1076

Chen D, Hellström C (1999) The influence of the North Atlantic Oscillation on the regional temperature variability in Sweden: spatial and temporal variations. Tellus 51A:505–516

Clark PU, Marshall SJ, Clarke GKC, Hostetler SW, Licciardi JM, Teller JT (2001) Freshwater forcing of abrupt climate change during the last glaciation. Science 293:283–287

Clark PU, Pisias NG, Stocker TS, Weaver AJ (2002) The role of the Atlantic thermohaline circulation in abrupt climate change. Nature 415:863–869

Craig H (1965) The measurement of oxygen isotope palaeotemperatures. In: Tongiorgi E (ed) Stable isotopes in oceanographic studies and palaeotemperatures. Consiglio Nazionale delle Ricerche, Pisa, pp 161–182

Crucifix M, Loutre M-F, Tulkens P, Fichefet T, Berger A (2002) Climate evolution during the Holocene: a study with an Earth system model of intermediate complexity. Clim Dyn 19:43–60

Dahl E (1998) The phytogeography of Northern Europe. Cambridge University Press, Cambridge, p 297

Dahl SO, Nesje A (1996) A new approach to calculating Holocene winter precipitation by combining glacier equilibrium-line altitudes and pine-tree limits: a case study from Hardangerjøkulen, central southern Norway. Holocene 6:381–398

Davis MB, Shaw RG (2001) Range shifts and adaptive responses to quaternary climate change. Science 292:673–679

Dean W, Forester RM, Platt Bradbury J (2002) Early Holocene change in atmospheric circulation in the Northern Great Plains. An upstream view of the 8.2 ka cold event. Q Sci Rev 21:1763–1775

Digerfeldt G (1977) The Flandrian development of Lake Flarken. Regional vegetation history and palaeoclimatology. University of Lund, Department of Quaternary Geology, Report 13

Digerfeldt G (1988) Reconstruction and regional correlation of Holocene lake-level fluctuations in Lake Bysjön, South Sweden. Boreas 17:165–182

Fisher TG, Smith DG, Andrews JT (2002) Preboreal oscillation caused by a glacial Lake Agassiz flood. Q Sci Rev 21:873–878

Friedman I, O'Neil JR (1977) Compilation of stable isotope fractionation factors of geochemical interest. In: Chapter KK (ed) Data of geochemistry, 6th edn. United States Geological Survey Professional Paper 440-KK, Washington DC

Giesecke T, Bennett K (2004) The Holocene spread of *Picea abies* (L.) Karst. in Fennoscandia and adjacent areas. J Biogeogr 31:1523–1548

von Grafenstein U, Erlenkeuser H, Müller J, Jouzel J, Johnsen S (1998) The cold event 8200 years ago documented in oxygen isotope records of precipitation in Europe and Greenland. Clim Dyn 14:73–81

von Grafenstein U, Erlenkeuser H, Brauer A, Jouzel J, Johnsen S (1999) A mid-European decadal isotope-climate record from 15,500 to 5000 years B.P. Science 284:1654–1657

Granlund E (1932) De svenska högmossarnas geologi. Sveriges Geologiska Undersökning C 373. Å rsbok 26:1–193

Grimm EC (1990) TILIA and TILIA.GRAPH. PC spreadsheet and graphics software for pollen data. INQUA Working Group on Data-Handling Methods. Newsletter 4:5–7

Gunnarsson BE, Borgmark A, Wastegård S (2003) Holocene humidity fluctuations in Sweden inferred from dendrochronology and peat stratigraphy. Boreas 32:347–360

Hald M, Husum K, Vorren TO, Grøsfjeld K, Jensen HB, Sharapova A (2003) Holocene climate in the subarctic fjord Malangen, northern Norway: a multi-proxy study. Boreas 32:543–559

Hall IR, Bianchi GG, Evans JR (2004) Centennial to millennial scale Holocene climate-deep water linkage in the North Atlantic. Q Sci Rev 23:1529–1536

Hammarlund D, Edwards TWD, Björck S, Buchardt B, Wohlfarth B (1999) Climate and environment during the Younger Dryas (GS-1) as reflected by composite stable isotope records of lacustrine carbonates at Torreberga, southern Sweden. J Q Sci 14:17–28

Hammarlund D, Barnekow L, Birks HJB, Buchardt B, Edwards TWD (2002) Holocene changes in atmospheric circulation recorded in the oxygen-isotope stratigraphy of lacustrine carbonates from northern Sweden. Holocene 12:339–351

Hammarlund D, Björck S, Buchardt B, Israelson C, Thomsen, CT (2003) Rapid hydrological changes during the Holocene revealed by stable isotope records of lacustrine carbonates from Lake Igelsjön, southern Sweden. Q Sci Rev 22:353–370

Hammarlund D, Velle G, Wolfe BB, Edwards TWD, Barnekow L, Bergman J, Holmgren S, Lamme S, Snowball I, Wohlfarth B, Possnert G (2004) Palaeolimnological and sedimentary responses to Holocene forest retreat in the Scandes Mountains, west-central Sweden. Holocene 14:862–876

Harrison SP, Prentice IC, Guiot J (1993) Climatic control on Holocene lake-level changes in Europe. Clim Dyn 8:189–200

Heikkilä M, Seppä H (2003) A 11,000 yr palaeotemperature reconstruction from the southern boreal zone of Finland. Q Sci Rev 22:541–554

Hintikka V (1963) Über das Grossklima einiger Pflanzenareale in zwei Klimakoordinatensystemen dargestellt. Ann Bot Soc Zool Bot Fenn Vanamo 34:1–63

Hu FS, Slawinski D, Wright HE Jr, Ito E, Johnson RG, Kelts KR, McEwan RF, Boedigheimer A (1999) Abrupt changes in North American climate during early Holocene times. Nature 400:437–440

Hultén E (1971) Atlas of the distribution of vascular plants in Northwestern Europe. 2nd edn. Kartografiska institutionen, Stockholm

Jacobeit J, Jönsson P, Bärring L, Beck C, Ekström M (2001) Zonal indices for Europe 1780–1995 and running correlation with temperature. Clim Change 48:219–241

Jacobeit J, Wanner H, Luterbacher J, Beck C, Philipp A, Sturm K (2003) Atmospheric circulation variability in the North-Atlantic-European area since the mid-seventeenth century. Clim Dyn 20:341–352

Johannessen RW (1970) The Climate of Scandinavia. In: Wallén CC (ed) Climates of Northern and Western Europe. World Survey of Climatology, volume 5 (Editor in Chief: H.E. Landsberg). Elsevier, Amsterdam, pp 23–80

Jönsson P, Bärring L (1994) Zonal index variations, 1899–1992: links to air temperature in southern Scandinavia. Geogr Ann 76A:207–219

Junge MM, Stephenson DB (2003) Mediated and direct effects of the North Atlantic Ocean on winter temperatures in northwest Europe. Int J Climatol 23:245–261

Keigwin LD, Boyle EA (2000) Detecting Holocene changes in thermohaline circulation. Proc Natl Acad Sci USA 97:1343–1346

Klitgaard-Kristensen D, Sejrup HP, Haflidason H (2001) The last 18 kyr fluctuations in Norwegian Sea surface conditions and implications for the magnitude of climate change: Evidence from the North Sea. Paleoceanography 16:455–467

Koç N, Jansen E, Haflidason H (1993) Paleoceanographic reconstructions of surface ocean conditions in the Greenland, Iceland and Norwegian seas through the last 14 ka based on diatoms. Q Sci Rev 12:115–140

Kozuchowski K, Wibig J, Maheras P (1992) Connections between air temperature and precipitation and the geopotential height of the 500 hPa level in a meridional cross-section in Europe. Int J Climatol 12:343–352

Kullman L, Kjällgren L (2000) A coherent postglacial tree-limit chronology (*Pinus sylvestris* L.) for the Swedish Scandes: aspects of paleoclimate and 'recent warming', based on megafossil evidence. Arctic Antarctic Alpine Res 32:419–428

Lau NC (1997) Interaction between global SST anomalies and the mid-latitude atmospheric circulation. Bull Am Meteorol Soc 78:21–33

Lauritzen SE, Lundberg J (1999) Calibration of the speleothem delta function: an absolute temperature record for the Holocene in northern Norway. Holocene 9:659–669

Lupo AR, Oglesby RJ, Mokhov II (1997) Climatological features of blocking anticyclones: a study of Northern Hemisphere CCM1 model blocking events in present-day and double CO_2 concentration atmospheres. Clim Dyn 13:181–195

Marchal O, Cacho I, Stocker TF, Grimalt JO, Calvo E, Martrat B, Shackleton N, Vautravers M, Cortijo E, van Kreveld S, Andersson C, Koç N, Chapman M, Sbaffi L, Duplessy JC, Sarnthein M, Turon J-C, Duprat J, Jansen E (2002) Apparent long-term cooling of the sea surface in the northeast Atlantic and Mediterranean during the Holocene. Q Sci Rev 21:455–483

Marshall J, Kushnir Y, Battisti D, Chang P, Czaja A, Dickson R, Hurrell J, McCartney M, Saravan R, Visbeck M (2001) North Atlantic climate variability: phenomena, impacts and mechanisms. Int J Climatol 21:1863–1898

McDermott F, Mattey DP, Hawkesworth C (2001) Centennial-scale holocene climate variability revealed by a high-resolution speleothem $\delta^{18}O$ record from SW Ireland. Science 294:328–1331

Moore PD, Webb JA, Collinson, MA (1991) Pollen analysis. Blackwell, Oxford, p 216

Mörner NA, Wallin B (1977) A 10,000-year temperature record from Gotland, Sweden. Palaeogeogr Palaeoclimatol Palaeoecol 21:113–138

Nesje A, Matthews JA, Dahl SO, Berrisford MS, Andersson C (2001) Holocene glacier fluctuations and winter-precipitation changes in the Jostedalsbreen region, western Norway, based on glaciolacustrine sediment records. Holocene 11:267–280

Nesje A, Dahl SO, Bakke J (2004) Were abrupt Lateglacial and early-Holocene climatic changes in northwestern Europe linked to freshwater outbursts to the North Atlantic and Arctic Oceans? Holocene 14:299–310

Ojala AE, Tiljander M (2003) Testing the fidelity of sediment chronology: comparison of varve and paleomagnetic results from Holocene lake sediments from central Finland. Q Sci Rev 22:1787–1803

Oppo, DW, McManus JF, Cullen JL (2003) Deepwater variability in the Holocene epoch. Nature 422:277–278

Pigott CD (1981) Nature of seed sterility and natural regeneration of Tilia cordata near its northern limit in Finland. Ann Bot Fenn 18:255–263

Pigott CD, Huntley JP (1978) Factors controlling the distribution of Tilia cordata at the northern limits of its geographical range. I. Distribution in North-West England. New Phytol 81:429–441

Plunkett GM, Whitehouse NJ, Hall VA, Brown DM, Baillie MGL (2004) A precisely-dated lake level rise marked by diatomite formation in northeastern Ireland. J Q Sci 19:3–7

von Post L (1924) Ur de sydsvenska skogarnas regionala historia under post-arktisk tid. Geologiska Föreningen i Stockholm Förhandlingar 46:83–128

von Post L (1925) Gotlandsagen (Cladium mariscus R Br.) i Sveriges postarktikum. Ymer 30:295–312

Post E (2003) Climate-vegetation dynamics in the fast lane. Trends Ecol Evol 18:551–553

Prentice IC (1980) Multidimensional scaling as a research tool in Quaternary palynology: a review of theory and methods. Rev Palaeobot Palynol 31:71–104

Prentice IC, Helmisaari H (1991) Silvics of north European trees: compilation, comparisons and implication for forest succession modelling. For Ecol Manage 42:79–93

Prentice IC, Bartlein PJ, Webb T III (1991) Vegetational and climate change in eastern North America since the last glacial maximum. Ecology 72:2038–2056

Rahmstorf S (2000) The thermohaline ocean circulation: a system with dangerous thresholds? Clim Change 46:247–256

Renssen H, Goosse H, Fichefet T, Campin J-M (2001) The 8.2 kyr BP event simulated by a global atmosphere-sea-ice-ocean model. Geophys Res Lett 28:1567–1570

Rex DF (1950) Blocking action in the middle troposphere and its effect upon regional climate: II. The climatology of blocking action. Tellus 2:275–301

Risebrobakken B, Jansen E, Andersson C, Mjelde E, Hevrøy K (2003) A high-resolution study of Holocene paleoclimatic and paleoceanographic changes in the Nordic Seas. Paleoceanography 18(1017):1–14

Rodwell MJ, Rodwell DP, Folland CK (1999) Oceanic forcing of the wintertime North Atlantic oscillation and European climate. Nature 398:320–323

Rozanski K, Araguas-Araguas L, Gonfiantini R (1992) Relation between long-term trends of oxygen-18 isotope composition of precipitation and climate. Science 258:981–985

Seager R, Battisti DS, Yin J, Gordon N, Naik N, Clement AC, Cane MA (2002) Is the Gulf Stream responsible for Europe's mild winters? Q J R Meteorol Soc 128:2563–2586

Seppä H, Bennett KD (2003) Quaternary pollen analysis: recent progress in palaeoecology and palaeoclimatology. Progr Phys Geogr 27:580–611

Seppä H, Poska A (2004) Holocene annual mean temperature changes in Estonia and their relationship to solar insolation and atmospheric circulation patterns. Q Res 61:22–31

Seppä H, Birks HJB, Odland A, Poska A, Veski S (2004) A modern pollen-climate calibration set from northern Europe: testing and developing a tool for palaeoclimatological reconstructions. J Biogeogr 31:251–267

Shuman B, Newby P, Huang Y, Webb III T (2004) Evidence for the close climatic control of New England vegetation history. Ecology 85:1297–1310

Sjörs H (1967) Nordisk Växtgeografi. Scandinavian University Books, Stockholm, p 229

Skre O (1979) The regional distribution of vascular plants in Scandinavia with requirements for high summer temperatures. Norwegian J Bot 26:295–318

Slonosky VC, Jones PD, Davies TD (2000) Variability of the surface atmospheric circulation over Europe, 1774–1995. Int J Climatol 20:1875–1897

Slonosky VC, Jones PD, Davies TD (2001) Atmospheric circulation and surface temperature in Europe from the 18th century to 1995. Int J Clim 21:63–75

Stuiver M, Reimer PJ (1993) Extended ^{14}C data base and revised CALIB 3.2 ^{14}C calibration program. Radiocarbon 35:215–230

Stuiver M, Reimer PJ, Bard E, Beck JW, Burr GS, Hughen KA, Kromer B, McCormac G, van der Plicht J, Spurk M (1998) 1998 INTCAL98 radiocarbon age calibration, 24,000–0 cal BP. Radiocarbon 40:1041–1083

Sutton RT, Hodson DLR (2003) Influence of the Ocean on North Atlantic Climate Variability 1871–1999. J Clim 16:3296–3313

Sykes MT, Prentice IC, Cramer W (1996) A bioclimatic model for the potential distribution of northern European tree species under present and future climates. J Biogeogr 23:203–233

Talbot MR (1990) A review of the palaeohydrological interpretation of carbon and oxygen isotopic ratios in primary lacustrine carbonates. Chem Geol (Isotope Geosci Sect) 80:261–279

Tallantire P (1972) The regional spread of spruce (*Picea abies* (L)Karst.) within Fennoscandia: a reassessment. Norwegian J Bot 19:1–16

Teller JT, Leverington DW, Mann JD (2002) Freshwater outbursts to the oceans from glacial Lake Agassiz and climate change during the last deglaciation. Q Sci Rev 21:879–887

ter Braak CJF (1987) Calibration. In: Jongman RHG, ter Braak CJF, van Tongeren OFR (eds) Data analysis in community and landscape ecology. Pudoc, Wageningen, pp 78–90

ter Braak CJF, Juggins S (1993). Weighted averaging partial least squares regression (WA-PLS): an improved method for reconstructing environmental variables from species assemblages. Hydrobiologia 269/270:485–502

Vedin H (1995) Air temperature. In: Raab B, Vedin H (eds) Climate, lakes and rivers. Swedish Meteorological and Hydrological Institute, Norrköping, pp 44–57

Vellinga M, Wood RA (2002) Global climatic impacts of a collapse of the Atlantic thermohaline circulation. Clim Change 54:251–267

Veski S, Seppä H, Ojala AEK (2004). Cold event at 8200 yr B.P. recorded in annually laminated lake sediments in eastern Europe. Geology 32:681–684

Weaver AJ, Hillaire-Marcel C (2004) Global warming and the next ice age. Science 304:400–402

Werner PC, Gerstengarbe F-W, Fraedrich K, Oesterle H (2000) Recent climate change in the North Atlantic/European sector. Int J Climatol 20:463–471

Wolfe BB, Edwards TWD, Elgood RJ, Beuning KRM (2001) Carbon and oxygen isotope analysis of lake sediment cellulose: methods and applications. In: Last WM, Smol JP (eds) Tracking environmental changes using lake sediments. Physical and geochemical methods, vol 2. Kluwer, Dordrecht, pp 373–400

Yu G, Harrison SP (1995) Holocene changes in atmospheric circulation patterns as shown by lake status changes in northern Europe. Boreas 24:260–268