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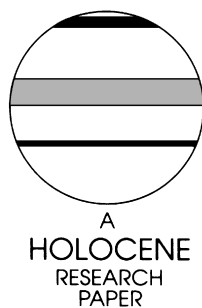
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# Holocene climatic change reconstructed from diatoms, chironomids, pollen and near-infrared spectroscopy at an alpine lake (Sjuodjijaure) in northern Sweden

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**Abstract:** The results of a multiproxy study reconstructing the climate history of the last 9300 years in northern Sweden are presented. It is based on diatom, chironomid and pollen analyses, as well as near-infrared spectroscopy (NIRS), of a radiocarbon dated sediment core from Sjuodjijaure (67°22'N, 18°04'E), situated 100 m above tree-line in the Scandes mountains. Mean July air temperature was reconstructed using transfer functions established for the region. The biological proxies show significant changes in composition during the Holocene and the inferred temperatures all follow the same general trend. For the period between about 9300 to 7300 cal. BP the reconstructions should be interpreted with caution due to the lack of convincing modern analogues in the training set. However the reconstruction suggest that July temperature was on average about the same as today, with several rapid short-term cold and warm periods. Cold periods were dated to about 8500, 8200 and 7600 cal. years BP and a warm period to about 7700 cal. BP. About 7300 cal. BP, a major shift to a warmer climate occurred. Pine migrated into the area, which was previously covered with birch forest. From the mid-Holocene until today the sediment record suggests a descending tree-limit and a gradual lowering of July temperature.

**Key words:** Holocene climate, lake sediments, northern Sweden, pollen, chironomid, diatom, near-infrared spectroscopy.

## Introduction

Plant and animal remains preserved in lake sediments can be used for retrospective reconstruction of climate during the Holocene. Lakes situated at ecotonal boundaries, such as around the tree-line, are of particular interest for climate reconstructions

because a small change in climate can cause large biotic changes (MacDonald *et al.*, 1993; Körner, 1998).

The Sarek National Park in the Scandes mountain range of northern Sweden is part of the World Heritage Site Lapponia and is one of Europe's largest wilderness areas (9400 km<sup>2</sup>). There is a steep climatic gradient in the area and within 15 km the vegetation changes from coniferous forest (*Picea abies* and *Pinus sylvestris*) to subalpine areas dominated by mountain birch (*Betula pubescens* ssp. *tortuosa*) through dwarf-shrub

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heaths (e.g., *Betula nana*, *Vaccinium* spp. and *Empetrum nigrum*) and up into low- and mid-alpine tundra with little or no soil and a sparse vegetation of mosses and lichens. The tree-limit is situated at about 700 m above sea level and consists of mountain birch. The area has low human impact with low levels of atmospheric pollution.

Northern Scandinavia provides the opportunity to compare results from a variety of palaeoclimatological proxies, e.g., tree-rings (Briffa *et al.* 1990; Zetterberg *et al.*, 1996; Eronen *et al.*, 1999), glacier advances (Karlén, 1976; Nesje *et al.*, 1994; Matthews and Karlén, 1992), tree megafossils (Karlén, 1976; Kullman, 1995; 1999; Eronen and Huttunen, 1993), pollen (Berglund *et al.*, 1996; Barnekow, 1999), varved sediments (Pettersson, 1999), oxygen isotopes of lacustrine carbonates (Hammarlund and Edwards, 1998) and mineral magnetism and particle-size distribution (Snowball and Sandgren, 1996).

For quantitative reconstructions of climate using subfossils such as pollen, chironomids and diatoms in sediment cores, so-called transfer functions must be used, i.e., numerical models of the relationships between subfossils in surface sediments and corresponding climatic data from a series of lakes situated along a major climate gradient (Birks, 1995; 1998). To obtain reliable reconstructions, it is advantageous to work in an area with low human impact, and to use transfer functions established from lakes in the study region.

A multiproxy approach is important (Birks *et al.*, 2000). Organisms may respond to climate with different timelags, and climate and other environmental factors may produce similar signals, for example both climate and land use can change the pollen signal. Pollen analysis is a commonly accepted method for reconstructing past changes in vegetation and thus indirectly past climate change (e.g., Birks, 1981; Huntley and Prentice, 1988; Prentice *et al.*, 1991; Barnekow, 1999). Several studies have also shown strong statistical relationships between present-day air/water temperature and diatom (Pienitz *et al.*, 1995; Vyverman and Sabbe, 1995; Lotter *et al.*, 1997; Weckström *et al.*, 1997; Rosén *et al.*, 2000b) and chironomid assemblages (Walker *et al.*, 1991; Olander *et al.*, 1999). Recently, relationships between near-infrared spectra of surface sediments from lakes and July air temperature and catchment vegetation have also been demonstrated (Rosén *et al.*, 2000a). Near-infrared spectroscopy (NIRS) is a rapid and non-destructive technique that measures attributes of the chemical composition of organic materials (Korsman *et al.*, 1992; 1999; Malley *et al.*, 1996; 1999; Nilsson *et al.*, 1996; Dabakk *et al.*, 1999).

Although several studies of vegetation and climate change using pollen analysis have been made in the north Swedish mountains (Sonesson and Lundberg, 1974; Berglund *et al.*, 1996; Barnekow, 1999), this study from Sjuodjijaure in the Sarek National Park is the first study in Sweden that combines pollen, chironomids, diatoms and NIRS and uses a transfer-function approach to reconstruct quantitatively July air temperatures during the Holocene.

## Material and methods

Sjuodjijaure (unofficial name, 67°22'N, 18°04'E) is a small (6 ha), shallow (maximum depth 4.2 m), headwater lake situated on granite and syenite. It is situated at 826 m above sea level, about 100 m above present tree-line, and is surrounded by mountains, which reach 1500–2000 m above sea level. The lake is situated in an U-shaped valley with a gentle slope up to the lake that would allow vegetation to migrate a relatively long distance even with a small change in climate. It is an oligotrophic clear-water lake with a pH of about 6.3. Duration of ice cover extends from October to June and present-day mean July air temperature is

9.8°C. This value is extrapolated and corrected for altitude from a nearby climate station using an adiabatic lapse rate of 0.57°C 100 m<sup>-1</sup> (Laaksonen, 1976).

In spring 1996, a 255 cm long sediment core was collected, using a Russian corer and a gravity corer (HTH Teknik, Vårvägen 37, SE-951 49 Luleå), from the deepest part of the lake. Samples were taken at 5 cm intervals except for particularly critical periods where every centimetre was analysed (1 cm = c. 40 years).

For diatom preparation and taxonomy, see Rosén *et al.* (2000b). Chironomid preparation and analysis included sediment deflocculation in 10% KOH and sieving on a 50 µm mesh. All head capsules were picked at 20 × magnification and mounted on slides in Euparal (Wiederholm and Eriksson, 1979). Head capsules were identified at 100–400 × magnification using keys by Pankratova (1970), Hofmann (1971), Sæther (1975; 1976), Wiederholm (1983) and Schmid (1993).

Pollen preparation included sediment digestion with 5% KOH followed by hydrofluoric acid treatment and acetolysis (Moore *et al.*, 1991). The samples were stained with safranin, and mounted in silicone oil. About 500–600 pollen grains were counted per sample. Identifications follow Moore *et al.* (1991). For critical determinations, modern reference material was used.

Sample preparation and analysis for NIRS follow Rosén *et al.* (2000a). <sup>14</sup>C dating of terrestrial macrofossils and bulk sediment samples were performed using accelerator mass spectrometry (AMS) (Ångström Laboratory, Box 534, SE-751 21 Uppsala). <sup>14</sup>C dates were transformed to calibrated years BP (cal. BP) (i.e., AD 1950) following Stuiver and Reimer (1993). Age-depth modelling was made using generalized additive models by Heegaard and Birks (unpublished data). Only dates from terrestrial macrofossils were included in the modelling.

Correspondence analysis (CA) was used to explore temporal changes in diatom and chironomid composition. Two analyses were made: (i) samples from all levels to assess major changes during the entire core; and (ii) samples from 7100 cal. yr BP to present to explore trends during a period with minor changes in assemblage composition. Sample scores from Sjuodjijaure were compared with sample scores from the 52-lake training set to assess how downcore diatom assemblages compare to diatom composition in surface sediments from lakes with different catchment vegetation today. For this comparison, five-sample running means from Sjuodjijaure core were used. All ordinations were performed with CANOCO 3.12 (ter Braak, 1991).

Diatom, chironomid and pollen diagrams were made using TILIA 2.0 and TILIA GRAPH 1.25 (Grimm, 1993). The program ZONE 1.2 (Juggins, 1991; Lotter and Juggins, 1991) was used to detect major changes in the fossil assemblages using constrained optimal sum of squares partitioning (Birks and Gordon, 1985). The broken-stick model was used to test if the proposed zonations were statistically significant (Jolliffe, 1986; Jackson, 1993; Bennett, 1996).

Species optima and tolerances to July temperature were estimated using Gaussian logit regression (GLR) (ter Braak and Looiman, 1986; Birks, 1995). The statistical significance of each optimum was assessed using a hierarchical series of response models using the Huisman-Olff-Fresco program written by J. Oksanen (HOF 2.2, Huisman *et al.*, 1993). We report optima of taxa only if they have a statistically significant fit from both the GLR and the HOF analysis. An estimated optimum outside the sampled gradient in the training set is indicated by < (below) and > (beyond) the sampled gradient.

Analogue matching using squared chi-squared distance as the dissimilarity measure was used to assess if the fossil diatom, chironomid and pollen assemblages have good analogues in the modern training sets. A total of 99 permutations were used to assess the approximate statistical significance of the dissimilarity coefficients. Fossil samples were considered good analogues if

they lay within the 5% percentile. Analogue matching using squared chi-squared distance was also used to infer gross-scale changes in vegetation. The lakes in the training set were classified on the basis of the main catchment vegetation into conifer-forest lakes, mountain-birch lakes or alpine lakes. The sum of all squared chi-squared distances between training-set lakes and downcore samples was calculated. Lakes with the lowest sum of squared chi-squared distance were considered the best analogues. Squared chi-squared distances for the five best analogues from each vegetation class were compared with each other to infer changes in past vegetation. The program ANALOG 1.6 was used for analogue matching (Birks *et al.*, 1990).

Transfer functions were developed from the same region as Sjuodjijaure. For details about the diatom transfer function and a map of the training-set lakes, see Rosén *et al.* (2000b) and for NIRS see Rosén *et al.* (2000a). For chironomid-based temperature reconstructions, a weighted average model with inverse deshrinking (Birks *et al.*, 1990) was used on a 40-lake training set ( $R_{\text{jack}}^2 = 0.44$ , root mean square error of prediction based on leave-one-out jack-knifing (RMSEP) =  $1.02^\circ\text{C}$  (18.5% of gradient). Lakes with fewer than 50 head capsules in the samples were excluded from the transfer function. For pollen, a one component weighted averaging partial least squares regression model using square-root transformed pollen percentages from 55 lakes, was selected as the minimal adequate model ( $R_{\text{jack}}^2 = 0.33$ , RMSEP =  $1.20^\circ\text{C}$ ; 22.2% of the gradient). Identical statistical procedures were used to develop the diatom, chironomid and pollen transfer functions (Rosén *et al.*, 2000b) and made using CALIBRATE 0.81 (Juggins and ter Braak, 1993). Sample specific errors were estimated using program WAPLS 1.0 (Juggins and ter Braak, 1995). The surface sample from Sjuodjijaure was not included in the training sets. See Birks (1995; 1998) for statistical details of the transfer functions, model evaluation by leave-one-out cross-validations and sample-specific error.

The reconstructed July temperatures at Sjuodjijaure were corrected for Holocene isostatic land-uplift following the procedure of Dahl and Nesje (1996). A land-uplift gradient of  $0.3 \text{ m km}^{-1}$  (Sørensen *et al.*, 1987) and the sea-level curves of Kjemperud (1981), Sveian and Olsen (1984) and Møller (1987) were used to model Holocene isostatic uplift in the Sarek mountains (S.O. Dahl, personal communication). The resulting land-uplift curve can then be used to adjust the reconstructed temperatures by applying a standard adiabatic lapse rate of  $0.57^\circ\text{C } 100 \text{ m}^{-1}$  (Laaksonen, 1976). A similar adjustment for land uplift was made by Barnekow (1999).

## Results

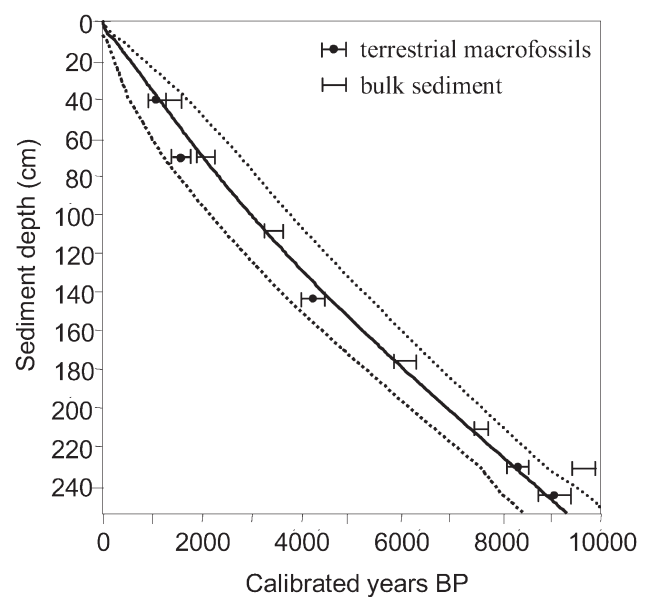
### Sediment dating and stratigraphy

Results of AMS dating are presented in Table 1 and Figure 1. Bulk samples gave consistently older ages (170–1300 years) in the three levels where both macrofossils and bulk sediment were dated. This is a well-known phenomenon (reservoir effect) that causes problems in dating lake sediments with few terrestrial macrofossils, such as Sjuodjijaure and other mountain lakes (Barnekow *et al.*, 1998).

Loss-on-ignition (LOI) analysis shows lowest values and largest variability (3–19%) during the early Holocene (255–210 cm, *c.* 9300–7300 cal. BP) (Figure 8). The non-organic fraction is mainly derived from minerogenic matter. Between 210 and 15 cm (*c.* 7300–400 cal. BP), the LOI is relatively constant (14–19%) and the non-organic fraction is mainly derived from diatoms (Thompson *et al.*, 2000). Because of a shortage of sediment the top 15 cm were not analysed for LOI.

**Table 1** Radiocarbon dates from Lake Sjuodjijaure (calibrated ages are within  $2\sigma$ )

Material	Sediment depth (cm)	Dates ( $^{14}\text{C}$ yr BP)	Calibrated age (yr BP)
Terrestrial macrofossil	39.5–40	$1360 \pm 160$	1550–940
Bulk sediment	40–41	$1535 \pm 65$	1540–1300
Terrestrial macrofossil	70	$1700 \pm 160$	1810–1400
Bulk sediment	70–71	$2150 \pm 70$	2330–1940
Bulk sediment	107–108	$3265 \pm 65$	3630–3360
Terrestrial macrofossil	143	$3835 \pm 70$	4420–3990
Bulk sediment	175–176	$5300 \pm 75$	6280–5910
Bulk sediment	210–211	$6800 \pm 70$	7700–7480
Bulk sediment	230–231	$8620 \pm 80$	9850–9440
Terrestrial macrofossil	231	$7615 \pm 110$	8560–8130
Terrestrial macrofossil	244	$8135 \pm 75$	9360–8730



**Figure 1** Calibrated  $^{14}\text{C}$  dates ( $2\sigma$ ) of terrestrial macrofossils and bulk sediment samples, and an age-depth model based on terrestrial macrofossils ( $2\sigma$ ).

### Diatom, chironomid and pollen assemblages

Six statistically significant zones for diatoms, eight for chironomids and five for pollen were found (Figures 2–4). Although zone boundaries vary slightly, three common major periods can be distinguished:

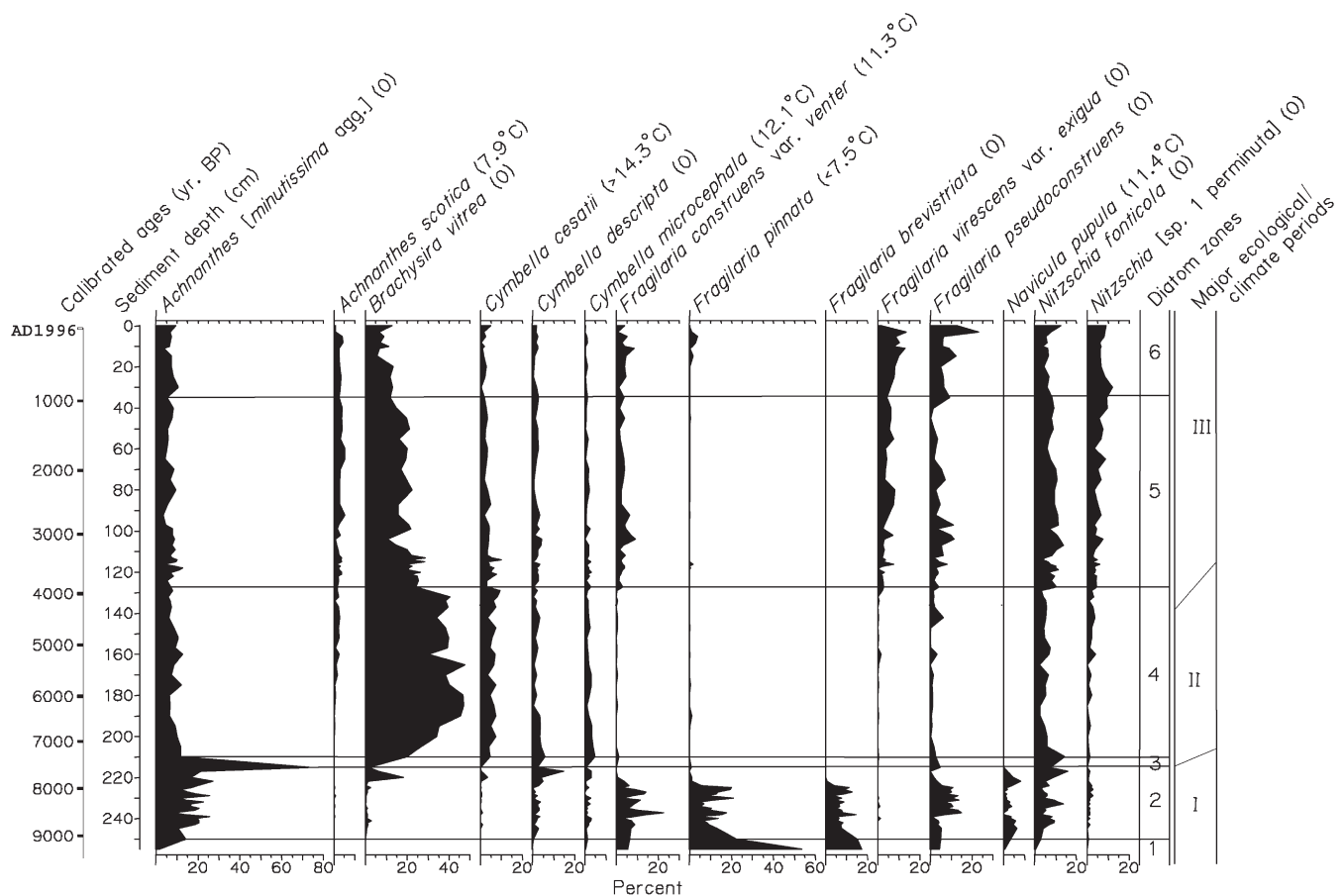
Period I (early Holocene) 255 to  $210 \pm 5$  cm, *c.* 9300 to  $7300 \pm 200$  cal. BP;

Period II (mid-Holocene)  $210 \pm 5$  to  $127 \pm 9$  cm, *c.*  $7300 \pm 200$  to  $3900 \pm 300$  cal. BP;

Period III (late Holocene)  $127 \pm 9$  to 0 cm, *c.*  $3900 \pm 300$  to AD 1996.

July air temperature optima for the most common taxa are presented in Figures 2–4.

A total of 201 diatom taxa were identified in the core and most are benthic (Figure 2). *Fragilaria* spp. and *Achnanthes* [*minutissima* agg.] dominate in the early Holocene. At the transition between the early and mid-Holocene *Achnanthes* [*minutissima* agg.] shows a major peak (74%). The mid-Holocene has a very different flora compared to the early Holocene. *Achnanthes* [*minutissima* agg.] declines, and *Brachysira vitrea* as well as different species of *Cymbella* are most common. During the late



**Figure 2** Percentage diatom diagram from Sjuodjjaure plotted against sediment depth. The first column shows modelled, calibrated ages. The two last columns show statistically significant diatom zones and major ecological/climate periods. Temperatures within brackets are statistically significant July air temperature optima for the species. An optimum below the gradient in the training set is indicated by < and beyond the gradient by > and (0) indicates no statistically significant optimum. Only the most common diatom taxa are shown.

Holocene, *Achnanthes scotica* (low temperature optimum) and different species of *Fragilaria* increase. Interestingly the 'cold' species *Fragilaria pinnata* var. *pinnata*, which is almost absent since 7300 cal. BP, appears again in seven samples between 20 and 3 cm (c. 500 cal. BP to a few decades ago), but is absent again in the surface sample.

Among the chironomids, 26 taxa were identified (Figure 3). The early Holocene has a highly variable chironomid composition with rapid changes between 'cold' and 'warmer' taxa, e.g., *Corynocera ambigua*, *Corynocera oliveri*-type, *Chironomus anthracinus*-type and *Procladius* spp. The mid-Holocene is more stable with a higher frequency of 'warmer' taxa. It starts with a rapid increase of 'warm' taxa like *Psectrocladius septentrionalis*-type and *Pentaneurini* spp. During the Late Holocene, *Paratanytarus* spp. and *Heterotrissocladius brundini* increase. Interestingly, the 'cold' species *Corynocera oliveri*-type, which was almost absent since the early Holocene, increases towards the present and shows a peak of 18% around 250 cal. BP.

During the early Holocene, *Betula* pollen is most frequent in the oldest part, and values decline (Figure 4). Pine pollen occurs with low frequencies at first, and gradually becomes more abundant. *Alnus* pollen is also present, along with pollen of shrubs such as *Salix* and *Juniperus*, and pollen of *Corylus/Myrica*. The first *Picea* pollen appears in this period. Pollen of Gramineae and a variety of herbaceous plants as well as fern spores are common. The pollen assemblage reflects a partly open birch-forest vegetation.

In the mid-Holocene, *Betula* declines and *Pinus* gradually becomes more abundant. In general, the pollen composition reflects a transition from an initially more open vegetation

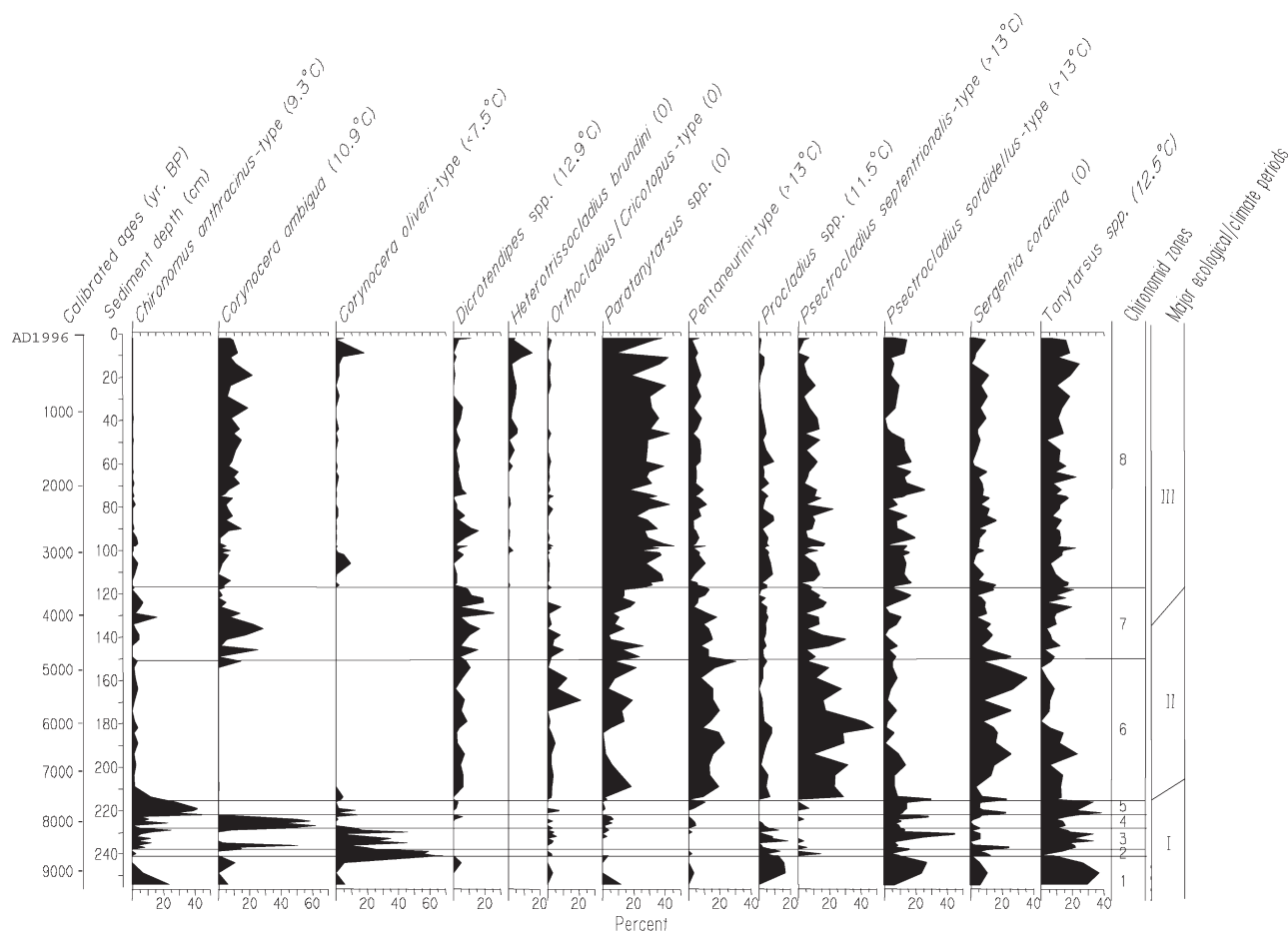
characterized by shrubby birch vegetation into a vegetation type with a gradually increasing presence of *Pinus*. *Picea* pollen occurs more regularly, and *Alnus* pollen gradually decreases in abundance. Pollen of *Empetrum* and other Ericaceae types gradually increases in frequency.

In the late Holocene *Pinus* and *Alnus* pollen decrease gradually, and *Picea* pollen increases in abundance. *Rumex acetosa* and *R. acetosella* become more frequent, along with Cyperaceae pollen. Ferns spores are less common than before in the later part of the period. Although tree pollen still dominates the pollen assemblage, the gradual decrease of arboreal pollen relative to non-arboreal pollen suggests that the local vegetation was becoming more open. Interestingly, pollen of *Linnaea borealis*, which only occurred with one pollen grain in the 55-lake training set and is considered as a forest species, occurs in six samples between 221 and 35 cm (c. 7800–900 cal. BP).

In the most recent part of Period III (30–0 cm, c. 800–0 cal. BP) *Pinus* pollen decreases markedly and Gramineae, Cyperaceae and *Rumex* values increase. Pine most probably disappeared from the area, and the local vegetation changed into the rather open, shrubby birch community that is present today.

### Correspondence analysis (CA) and modern analogue matching

Correspondence analysis (CA) confirms that there were major shifts in the diatom and chironomid assemblages around 7500–7100 cal. BP (215–205 cm) (Figure 5). The sample scores (multiplied by 100) on CA axis 1 decline for diatoms from 40 to –50 and for chironomids from 126 to –70. CA of the assemblages for the period between 7100 cal. BP and the present shows



**Figure 3** Percentage chironomid diagram from Sjuodjijaure plotted against sediment depth. The first column shows modelled, calibrated ages. The two last columns show statistically significant chironomid zones and major ecological/climate periods. Temperatures within brackets are statistically significant July air temperature optima for the taxa. An optimum below the gradient in the training set is indicated by < and above the gradient by > and (0) indicates no statistically significant optimum. Only the most common chironomid taxa are shown.

a consistently decreasing trend in sample scores for diatoms and chironomids, with a relatively larger between-sample variation for chironomids. Interestingly, the most recent diatom sample, corresponding to approximately the last 10 years, has a relatively high sample score.

Modern analogue matching for diatoms is good (5% percentile limit) for 23 out of 28 samples between 9300 and 7100 cal. BP. From 7100 cal. BP until today, all samples have good analogues. For chironomids, three out of 31 samples have good analogues between 9300 and 7100 cal. BP, whereas 67 out of 70 samples have good analogues between 7100 cal. BP and the present. For pollen, there are no good analogues for the period 9300–3900 cal. BP, and 26 out of 50 samples between 3900 cal. BP and the present have good analogues.

A comparison of CA scores from Sjuodjijaure, based on diatoms, with scores from lakes in the training set, shows that samples from the early Holocene (*c.* 9300–7300 cal. BP) have similar scores as surface sediments from lakes in birch forest today, indicating a similar diatom composition (Figure 6). During this period, the best analogues are with birch-forest lakes (Figure 7). During the mid-Holocene (*c.* 7300–4900 cal. BP), the best analogues are lakes with conifers and mixed conifer/birch forest. The sample scores are also similar to conifer-forest lakes. From *c.* 4900 until *c.* 1000 cal. BP, the best analogues are still conifer and mixed conifer/birch forest lakes, but good matches were found for one birch-forest lake and one alpine lake. The sample scores show the closest affinity with conifer-forest lakes. During the last *c.* 1000 years, the best analogues changed to birch-forest and alpine lakes. Sample scores from *c.* 1000 cal. BP to today fall in the range of all three vegetation types.

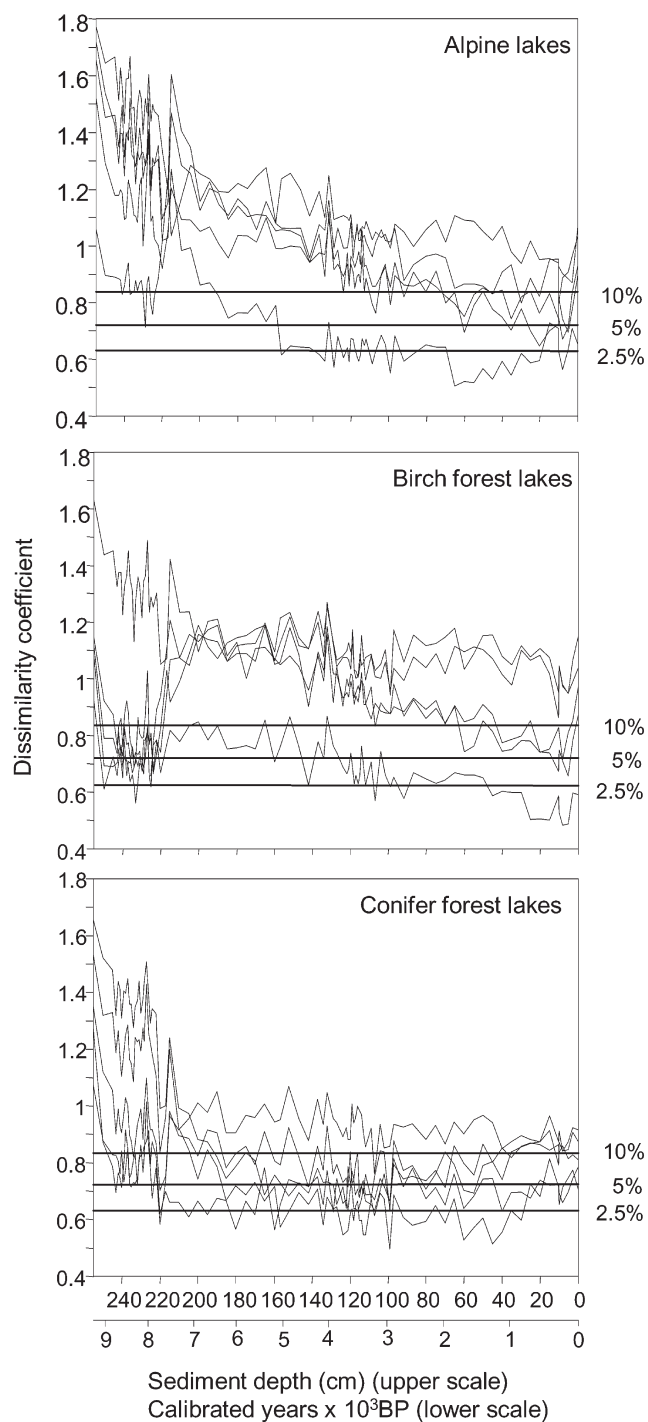
### Inferred July air temperatures

The inferred mean July air temperatures based on pollen, chironomid and diatom assemblages show a generally similar picture for the Holocene (Figure 8). Figure 9 shows a detailed comparison between diatom- and chironomid-based temperatures to facilitate the interpretation of Period I.

#### Period I: early Holocene

Diatoms, chironomids, pollen and NIRS suggest July air temperatures similar to today but with some short-term fluctuations (values should be reduced by *c.* 0.6°C to account for land uplift). Cold events were reconstructed at: *c.* 8500 cal. BP (238–235 cm) from diatoms (a decline of *c.* 0.6°C) and chironomids (*c.* 1.3°C); *c.* 8200 cal. BP (232–228 cm) as inferred from diatoms (*c.* 0.5°C) and chironomids (*c.* 0.6°C), whereas pollen suggests a decrease of 0.8°C and a subsequent increase of 1.7°C. The sample resolution for NIRS is too low to assess such short-term variability. From *c.* 8000 to *c.* 7700 cal. BP (226 to 218 cm), diatoms (increase of 1.0°C), pollen (1.8°C) and NIRS (0.4°C) suggest increasing summer temperatures. The pollen-based temperature starts to increase about 100 years later than diatoms and NIRS. In contrast to other proxies, chironomids suggest a decrease of 1.4°C for the period 7900–7700 cal. BP. However, chironomids show the highest sample-specific errors for that period during the whole Holocene. A short cooling event is indicated by diatoms (decline of *c.* 1.1°C) and chironomids (0.9°C) *c.* 7600 cal. BP (217–215 cm) and LOI decreases at the same time. The pollen-based temperature also starts to decrease (216 cm) and continues to decrease until 7100 cal. BP (205 cm).





**Figure 7** Dissimilarity coefficients (DC) between diatom assemblage composition from surface-sediment samples in the training set and downcore assemblages from Sjuodjijaure (analogue matching). DCs are based on squared chi-squared distances. The five best modern analogues from each of the classes conifer-forest lakes, birch-forest lakes and alpine lakes are shown. The early Holocene shows best analogues with modern birch-forest lakes, and the mid-Holocene with conifer- and mixed conifer/birch-forest lakes. During the late Holocene, analogue matching for modern alpine and birch-forest lakes becomes better and the analogues matching with conifer-forest lakes decrease during the last 35 cm (*c.* 900 cal. BP) of sediment. 0 corresponds to the coring date AD 1996.

### Period III: late Holocene

From *c.* 3900 cal. BP until today for pollen, and from *c.* 3100 cal. BP until today for diatoms, inferred temperatures are about the same as present. The chironomid-inferred July temperature continues to suggest higher temperatures than today with a slight decreasing trend towards present day. NIRS-inferred temperature

suggest *c.* 1.5°C higher temperature than today until about 900 cal. BP when the reconstructed temperature decreases to about the same level as today. The reconstructed July temperature from the top sample for each proxy is 9.9°C for diatoms (0 cm below sediment surface), 10.7°C for chironomids (3 cm), 9.8°C for pollen (0 cm) and 9.7°C for NIRS (15 cm). Present-day July temperature is estimated to be 9.8°C.

Between-sample variation in temperatures based on chironomids was high during the early Holocene and high for pollen during the whole Holocene. The sample-specific errors for inferred mean July air temperature vary between 0.9 and 1.1°C for diatoms, 1.0–1.2°C for chironomids, 1.3–1.7°C for pollen. Statistical methods for estimating sample specific errors for the OSC filtering technique for NIRS are not yet available. Therefore, one must assess reliability on test set predictions (Rosén *et al.*, 2000a). The interpretation of the sample-specific prediction errors is uncertain because of the strong auto-correlation and non-independence of individual samples in stratigraphical time-series (Birks, 1998). Emphasis is placed here on consistent trends within and between the different reconstructed records rather than a strict adherence to  $\pm 1.1^\circ\text{C}$  between adjacent samples.

Correlations between the reconstructed temperatures from diatoms, chironomids, pollen and NIRS for the whole Holocene sequence are highest between chironomids and NIRS ( $r = 0.92$ ) and lowest between pollen and NIRS ( $r = 0.32$ ) (Table 2). For the period from 7300 cal. BP until today, correlations increase for all combinations except for chironomids and NIRS, and the highest correlation is between diatoms and chironomids ( $r = 0.84$ ) and diatoms and pollen ( $r = 0.83$ ). The lowest correlation is between NIRS and pollen ( $r = 0.45$ ).

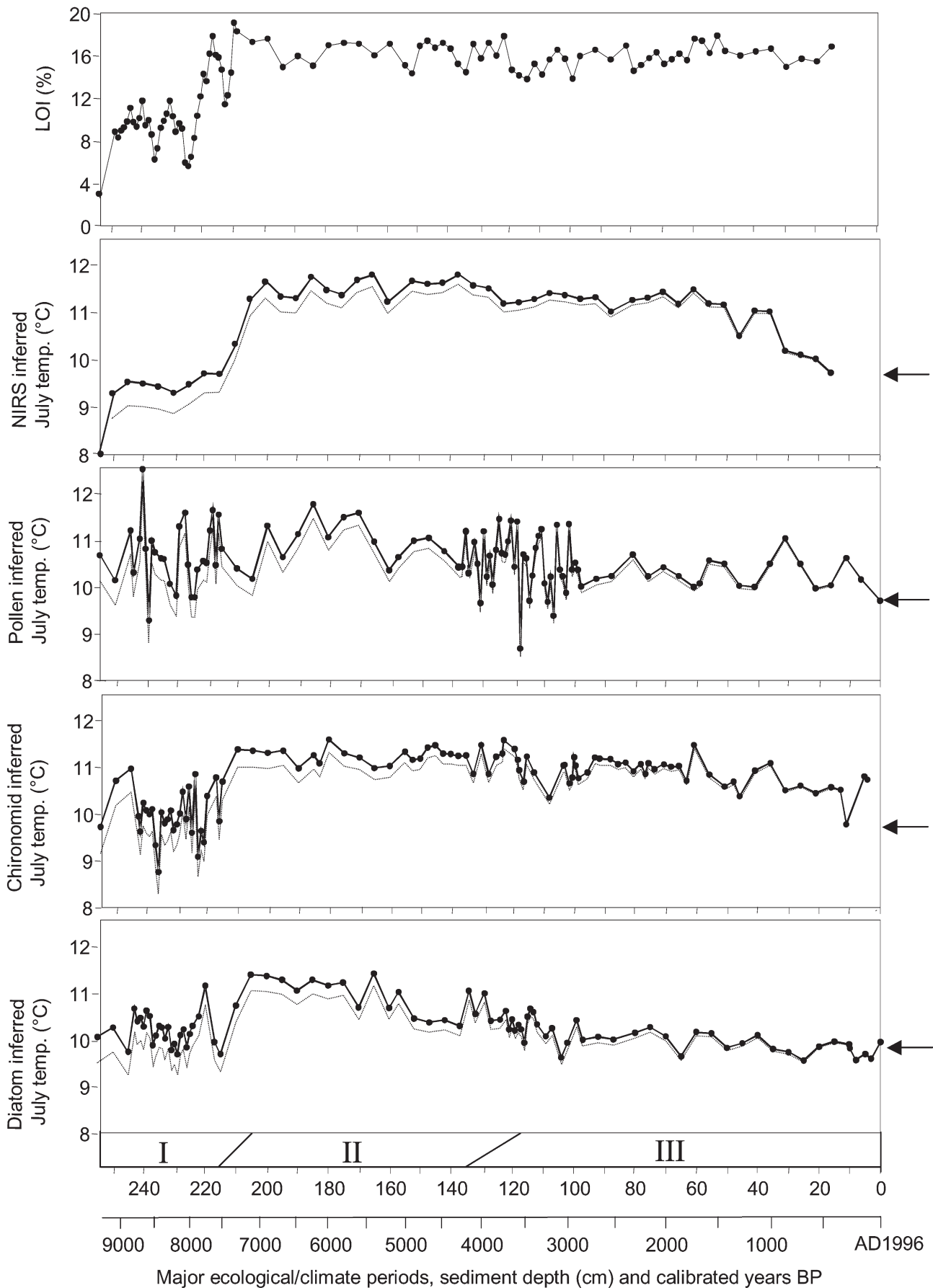
## Discussion

### Assessment of the different climatic reconstructions

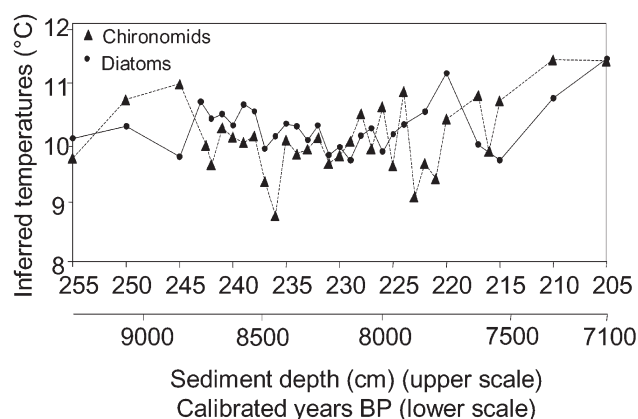
The correlation between the July air temperatures based on diatoms, chironomids, pollen and NIRS varies from poor (NIRS-pollen) to good (NIRS-chironomids). The differences are hardly surprising, since different proxies respond to climate with different timelags and July air temperature is not the sole factor controlling biological assemblage composition and the sediment properties that give the NIR signal. The diatom transfer function used for July air temperature is statistically independent of lakewater pH, alkalinity, total organic carbon (TOC) and maximum lake depth ( $P = 0.01$ ) (Rosén *et al.*, 2000b) and the chironomid transfer function is statistically independent of TOC ( $P = 0.05$ ) and lake depth ( $P = 0.01$ ). However, July air temperature is a variable that is correlated to several climate-related factors, such as summer water temperature (Livingstone and Lotter, 1998), length of growing season, vegetation cover, duration of ice cover, precipitation, mixing of the water column, UV-radiation, hypolimnion anoxia, nutrients, silica and grazing (Livingstone and Lotter, 1998; Walker, 1987; Walker *et al.*, 1991; Pienitz *et al.*, 1995; Lotter *et al.*, 1999; Smol, 1988; Smol *et al.*, 1991; Wetzell, 1983; Servant-Vildary *et al.*, 1992; Vinebrooke and Leavitt, 1996). Thus, the diatom, chironomid and pollen assemblages and the NIR signal may all be influenced by some of these temperature-related variables. One basic assumption of all work involving transfer functions in quantitative palaeoecology is that ‘... the environmental variable to be reconstructed is, or is linearly related to, an ecologically important variable in the system of interest’ (Birks *et al.*, 1990). However, since no variable is perfectly linearly related to July air temperature and as the proxies may be sensitive to different combinations of the above-mentioned variables, the inferred temperatures will inevitably vary between the proxies.

The response time to climate change might also be different





**Figure 8** Mean July air temperatures inferred from diatoms, chironomids, pollen and near-infrared spectroscopy (NIRS), and results of loss-on-ignition (LOI) measurements, in a 9300-year sediment core from Sjuodjijaure. Ages are calibrated years BP. Dotted line indicates inferred July air temperatures corrected for land uplift. Arrows show the present temperature at the lake. Numbers I-III indicate the major ecological/climate periods.



**Figure 9** Mean July air temperature inferred from diatoms and chironomids for the period 255–205 cm (from c. 9300 to 7100 cal. BP).

**Table 2** Correlation coefficients for the comparison of July air temperatures inferred from diatoms, chironomids, pollen and near-infrared spectrometry (NIRS). The correlation coefficients were calculated for the whole sediment sequence (255–0 cm) and for 210–0 cm, respectively. Correlations were based on five-sample running mean values for each proxy. Only levels analysed for all proxies were included in the calculations

	r (255–0 cm)	r (210–0 cm)
Diatoms/chironomids	0.53	0.84
Diatoms/pollen	0.79	0.83
Diatoms/NIRS	0.35	0.58
Pollen/chironomids	0.48	0.70
Pollen/NIRS	0.32	0.45
Chironomids/NIRS	0.92	0.79

between proxies. Due to the longer lifespan of terrestrial vegetation (especially trees), pollen may respond more slowly than diatoms, chironomids and NIRS (Birks, 1981). Diatoms are extremely abundant and ecologically diverse, and their short life-span and fast migration rates enable them to respond quickly to environmental change (MacDonald *et al.*, 1993; Lotter *et al.*, 1999).

Modern analogues in the early Holocene are good for diatoms but poor for chironomids and pollen. High minerogenic input in combination with birch forest around the lake in the early Holocene is uncommon in the Scandes mountains today. This may explain the poor modern analogue situation for chironomids and pollen. The inferred temperatures should therefore be interpreted with caution during the early Holocene due to the lack of convincing modern analogues (Birks *et al.*, 1990). From c. 7300 cal. BP until the present, the reconstructed values are probably more reliable as the analogues are considerably better. There are good analogues for all diatom samples and only three of 70 chironomid samples are outside the 5% percentile. Analogues for pollen are poor until 3900 cal. BP but considerably better after 3900 cal. BP to the present.

The poor analogues for pollen are probably due to long-distance transport of pollen, which decreases the palynological distinction between forest and alpine areas (e.g., Anderson *et al.*, 1991). The predictive ability of the pollen transfer function is lower for July air temperature above tree-line compared to below tree-line.

Overall, the results of the different proxies show relatively consistent patterns in the reconstructed temperatures. However, it is important not to over-interpret the results and to remember that the uncertainties in the chronology are large (Table 1). Only a few levels have been dated and even though they are based on

terrestrial macrofossils there are uncertainties about the time it takes for the macrofossil to enter the sediment. A general problem with all  $^{14}\text{C}$  dates is the error inherent in the dating method, and there are errors associated with the age-depth model (about 100–150 years).

### Early Holocene (9300–7300 cal. BP)

Inferred July air temperatures were about the same as today, but with several rapid changes between cold and warmer periods. Most of the short-term variations lie within the sample-specific errors of each reconstruction method. However, events can be identified with more confidence when they are replicated by two or more proxies at the same time. Diatoms and chironomids indicate rapid cooling and a subsequent warming of 0.6–1.7°C at about 8500 and 7600 cal. BP. LOI shows simultaneously decreasing values. At about 8200 cal. BP, pollen indicates a cooling of 0.8°C and a subsequent warming of 1.7°C and LOI decreases. Diatoms and chironomids infer only a small decrease of 0.5–0.6°C at this same time. The sample resolution for NIRS is too coarse to reconstruct short-term variability. Diatoms, pollen and NIRS indicate that a rapid warming of 0.4–1.8°C took place, beginning about 8000 cal. BP. Simultaneously, LOI values change from their Holocene minima values to almost their highest values during the Holocene. In contrast, chironomids suggest a decrease of 1.4°C for the period 7900–7700 cal. BP. These discrepancies can be due to different responses to changes in the ecosystem or to statistical uncertainties in the reconstructions. The chironomid-inferred temperatures show the highest sample-specific errors for the whole Holocene.

The non-organic fraction in the early Holocene is mainly minerogenic (Thompson *et al.*, 2000). Possible explanations for the low LOI values are high snow accumulation (Snowball *et al.*, 1999) before 8000 cal. BP in combination with unstable soils after deglaciation or a low production of organic material. Both pollen and indirectly diatoms indicate that birch grew locally in the drainage area. Mountain birch is competitive in regions with fairly cold, humid, snow-rich conditions and variable climate on unstable soils (Hämet-Ahti, 1963; Kallio and Mäkinen, 1978; Kullman, 1981).

These results are in good agreement with several previous studies, which suggest that the early-Holocene climate in northern and western Fennoscandia was of a humid and oceanic character, with a birch tree-limit higher than present (e.g., Yu and Harrison, 1995; Seppä, 1996; Berglund *et al.*, 1996; Dahl and Nesje, 1996; Hammarlund and Edwards, 1998; Barnekow, 1999; Seppä and Weckström, 1999). However, the rather low temperatures suggested in our study contrast with studies of Kullman (1995; 1999), who found tree megafossils of pine well above present tree-line from the same period, which suggest warmer summers. It is possible that our reconstructions are affected by snowfields, soil formation and high minerogenic influx during the early Holocene, which may depress the inferred temperatures, and our results for this time should therefore be interpreted with caution.

The inferred cooling and drop in LOI at about 8500 cal. BP corresponds well with the wettest phase during the Holocene at c. 8500–8300 cal. BP, as inferred from glacier fluctuations at Hardangerjøkulen in western Norway (Dahl and Nesje, 1996). In contrast to our study, they infer higher temperatures during this period.

Considerable evidence exists for a cold climatic event centred around 8200 cal. BP in the North Atlantic region, which this study also supports. The diatom-inferred temperature from Tsuolbma-javri in Finland shows a drop at this time (Korhola *et al.*, 2000) and there are indications for a decline in the pine-tree limit in the Scandes (Kullman, 1995; Karlén, 1976), a glacier advance in northern Sweden and southern Norway (Karlén, 1976; Dahl and Nesje, 1996), increased accumulation of minerogenic material in

northern Sweden (Snowball *et al.*, 1999), and a notable  $\delta^{18}\text{O}$  minimum in Greenland ice cores at  $8210 \pm 30$  cal. BP (Johnsen *et al.*, 1992; Alley *et al.*, 1997).

In agreement with our study, there are indications of low winter precipitation and the disappearance of glaciers in central southern Norway and warm summer temperatures in the Scandes mountains at around 8000 cal. BP (Kullman, 1995; Dahl and Nesje, 1996). The inferred drop in temperature at 7600 cal. BP coincides with an advance of the Hardangerjøkulen (Nesje *et al.*, 1994).

### Mid-Holocene (7300–3900 cal. BP)

The results indicate a major shift in climate *c.* 7300 cal. BP. Diatom, chironomid and NIRS records suggest a temperature increase of 1.5–1.7°C towards a Holocene maximum. The correspondence analysis results confirm the large change in assemblage composition of diatoms and chironomids. LOI also increases. The pollen-inferred temperature possibly shows a timelag compared to diatoms, chironomids and NIRS. Diatoms suggest a decreasing trend in temperatures from *c.* 7100 cal. BP and pollen a decreasing trend from 6200 to 3900 cal. BP, whereas chironomids and NIRS suggest more constant values throughout this period. Chironomid composition shows a significant change around 4900 cal. BP (Figure 3), which may indicate major changes in the lake ecosystem. Both pollen and diatom assemblages suggest a mixture of pine and birch in the drainage area. During the mid-Holocene, the non-organic fraction of the sediment consists mainly of diatom frustules (Thompson *et al.*, 2000) which together with the higher and more stable LOI values as well as an altitudinal rise of pine suggests more stable soils, less snow accumulation and a more continental climate compared to the early Holocene.

Several studies indicate high summer temperatures with some short-term fluctuations in Fennoscandia during this mid-Holocene period. Diatom-inferred July temperature from Tsuolbmajavri shows a peak at 6200 cal. BP, which is later than in our study, and a drop around 7200 and 4200 cal. BP (Korhola *et al.*, 2000). The discrepancy may be due to chronological uncertainties or different developments of the drainage area, which may override the climate signal. During the mid-Holocene there is an increased abundance of pine pollen and macrofossils in lake sediments (Berglund *et al.*, 1996; Barnekow, 1999; Seppä and Weckström, 1999), a high, but decreasing, altitudinal limit for tree megafossils (Karlén, 1976; Kullman, 1995) and evidence for glacier retreat (Karlén, 1976; Nesje and Kvamme, 1991). The oldest pine remains used for dendrochronology in northern Fennoscandia are from *c.* 7500 cal. BP (Zetterberg *et al.*, 1996). Oxygen isotope records of lacustrine carbonate suggest increasing continentality from *c.* 10000 to 6300 cal. BP (Hammarlund and Edwards, 1998). From *c.* 5100 to 4500 cal. BP there are several indications for decreasing temperature and glacier advances (e.g., Karlén, 1976; Nesje and Kvamme, 1991; Kullman, 1995; Dahl and Nesje, 1996; Barnekow, 1999; Seppä and Weckström, 1999).

### Late Holocene (3900 cal. BP to AD 1996)

Pollen, diatoms and chironomids show significant compositional changes at 4200, 3900 and 3600 cal. BP, respectively. A main feature is the increasing frequency of *Picea* pollen. Inferred temperatures from diatoms and pollen change from a decreasing trend to more stable temperatures, whereas chironomids, NIRS and LOI continue to suggest rather constant temperatures. The non-organic part of the sediment continues to mainly reflect the abundance of diatom frustules (Thompson *et al.*, 2000). Both pollen and diatoms infer a mixed forest of conifers and birch, which gradually becomes more open. Furthermore, *Linnaea borealis*, which is considered a forest species and only occurred with one pollen grain in the 55-lake training set, occurred in six samples between 221 and 35 cm (*c.* 7800–900 cal. BP). The pollen record changes from poor to good analogues at *c.* 3900 cal. BP, which suggests

that the vegetation developed into types that exist in northern Sweden today, but at lower altitudes than Sjuodjijaur. At 900 cal. BP, the NIRS suggests a cooling, whereas pollen suggest that an open shrubby birch community developed, which persists today around the lake. Such a decrease in inferred temperature at around 900 cal. BP is not reconstructed by diatoms or chironomids. However, diatom composition changes significantly at 900 cal. BP and the best analogues change simultaneously from a conifer/birch forest lake to a birch forest and alpine lake. The 'Little Ice Age' (*c.* 400 to 100 BP), recorded from glaciers, tree megafossils and tree-ring data (Nesje and Kvamme, 1991; Karlén, 1976; Kullman, 1995) is not a conspicuous feature in the reconstructed July temperature curves from Sjuodjijaur. However, the diatom *Fragilaria pinnata* var. *pinnata*, which in the training set is most common in high-altitude lakes and was almost absent since the early Holocene, increases in six samples towards the present (*c.* 400–50 cal. BP) and is absent again in the surface sample. Similarly the 'cold' chironomid taxon *Corynocera oliveri*-type increases towards the present (*c.* 800–30 cal. BP) and shows a peak of 18% at 250 cal. BP.

A colder climate with some short-term fluctuations is indicated during the past *c.* 4000 years by a lowering of the pine tree-limit (Kullman, 1995; Barnekow, 1999; Eronen *et al.*, 1999), glacier advances (Nesje and Kvamme, 1991; Snowball and Sandgren, 1996) and increased erosion (Snowball *et al.*, 1999). Diatom-inferred temperatures from Tsuolbmajavri show only small changes with slightly higher temperatures between 2000 and 1000 cal. BP and a drop in temperature around 400 cal. BP (Korhola *et al.*, 2000). Dendrochronology and varved sediment studies suggest a major change in climate with very few pine trees and increased minerogenic influx around 2200 cal. BP (Eronen *et al.*, 1999; Petterson, 1999). This is not a major feature in our data. From 1000 cal. BP there is evidence for cooling (Matthews and Karlén, 1992; Seppä and Weckström, 1999).

## Conclusions

This study illustrates that diatoms, chironomids, pollen, near-infrared spectroscopy (NIRS) and loss-on-ignition (LOI) in lake sediments can yield valuable information about past climate. The inferred mean July air temperatures based on four proxies show a generally similar picture. The early Holocene shows some rapid changes in climate, the mid-Holocene indicates warmer temperatures, and the late Holocene lower temperatures. To assess consistency in the reconstructions on a regional scale, detailed palaeoecological analysis of additional long sediment cores from mountain lakes are needed.

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