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The Holocene 2002; 12; 481

DOI: 10.1191/0959683602hl559rp

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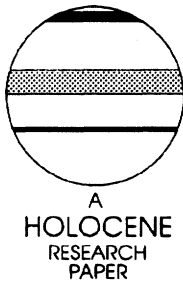
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Quantitative multiproxy assessment of long-term patterns of Holocene environmental change from a small lake near Abisko, northern Sweden

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Received 2 July 2001; revised manuscript accepted 14 December 2001



Abstract: Quantitative reconstructions are made of Holocene changes in climatic and environmental conditions from analyses of pollen, chironomids and diatoms in identical stratigraphic levels of a sediment core from Vuoskkujävi (68°20'43 N, 19°06'00 E, 348 m a.s.l.) near Abisko in northern Sweden (Lapland). Transfer functions, based on regional calibration sets, are applied to reconstruct Holocene patterns in mean July air temperature (using all three indicators), mean January air temperature (pollen), annual precipitation (pollen) and lakewater pH (diatoms). During periods with 'good' fit to the modern calibration sets all mean July air-temperature inferences based on the three proxy indicators reveal a general trend of decreasing temperature: pollen-inferred mean July air temperature shows a decrease of c. 1.1°C since 7500 cal. yrs BP; the chironomids show a decrease of c. 1.2°C since the early Holocene; whereas the diatoms show a decrease of c. 1.5°C since 6000 cal. yrs BP. Pollen-inferred mean January air temperature indicates that winters may have been warmer by c. 3.0°C during the early Holocene, followed by a gradual cooling until 8500 cal. yrs BP (c. 1.0°C warmer than today) and a subsequent warming until 7000 cal. yrs BP (c. 2.0°C warmer than today). Since 7000 cal. yrs BP, a gradual cooling towards the present-day values is inferred. According to the pollen, annual precipitation may have been considerably higher during the early Holocene than today (c. +150 mm) and increased until 7000 cal. yrs BP (c. +320 mm). Since 7000 cal. yrs BP, annual precipitation decreased continuously towards present-day values. Diatom-inferred pH trends show that natural acidification of c. 0.5 pH units followed deglaciation; present-day values were reached c. 5000 cal. yrs BP. The early Holocene is identified as a problematic time period for the application of modern calibration sets, as diatoms show 'poor' fit to the calibration set from 10 600 to 6000 cal. yrs BP, pollen from 10 600 to 7500 cal. yrs BP, and chironomids from 10 250 to 10 000 cal. yrs BP. Compared with estimates from the COHMAP GCM model, mean July air-temperature inferences based on biological proxies at Vuoskkujävi suggest a more moderate decrease in temperature over the past 9000 years.

Key words: Pollen, chironomids, diatoms, Subarctic, Lapland, precipitation, pH, temperature, multiproxy approach, quantitative inferences, weighted averaging partial least squares (WA-PLS), Holocene.

Introduction

Global warming appears to be amplified at high latitudes, where the temperature over the last 30 years has increased more than elsewhere (Chapman and Walsh, 1993; Serreze *et al.*, 2000). Altered patterns of temperature and precipitation lead, among other things, to a pronounced reduction in the duration of snow and ice cover, with corresponding shifts in hydrologic processes and erosion (Weller and Lange, 1999). Impacts of such changes on terrestrial and aquatic biota in high latitudes are manifold. Vegetation benefits from a prolonged growing season, which may alter species composition. Biological production in lakes is affected by warming through earlier ice breakup in spring and delayed freeze-up dates in autumn (Smol, 1988). Unfortunately, instrumental climatic records are short and sparse in high latitudes and, thus, limit our understanding of spatial and temporal patterns of low frequency, natural climate variability (Rind and Overpeck, 1993). As a consequence, palaeoecological records of terrestrial (e.g., pollen, tree-rings) and aquatic (e.g., diatoms, chironomids) biota are important in quantifying and assessing past climatic changes and are one possibility of overcoming the lack of instrumental climate records from high latitudes (e.g., MacDonald *et al.*, 2000).

In this study, we use three different biological proxy indicators (pollen, chironomids and diatoms) and loss-on-ignition (LOI) analyses of lake sediments to provide an overall assessment of the Holocene environmental history at Lake Vuoskkujávri (hereafter referred to as 'Vuoskkujávri') in northern Sweden. This multiproxy approach may lead to more reliable conclusions than quantitative statements based on only a single proxy indicator, as shown for example in western Norway (Birks *et al.*, 2000) and in Switzerland (Ammann *et al.*, 2000). The pollen record is a widely accepted method of inferring past vegetation composition, and we use pollen to infer quantitatively past changes in mean July and January air temperature and annual precipitation (e.g., Birks, 1981; Huntley and Prentice, 1988). We use subfossil remains of chironomid larvae (non-biting midges) to infer past changes in mean July air temperature (e.g., Lotter *et al.*, 1997; Olander *et al.*, 1999; Brooks and Birks, 2000a; 2000b). Temperature reconstructions using chironomids have been applied for the Lateglacial (e.g., Brooks and Birks, 2000b), but Holocene reconstructions in Subarctic environments are relatively rare and, thus, require further assessment (Battarbee, 2000; Rosén *et al.*, 2001). We also use sedimentary diatom assemblages to quantify changes in lake-water pH and mean July air temperature. Diatoms are widely regarded as a reliable proxy for quantitative inferences of lake-water pH and acidification (Birks *et al.*, 1990; Renberg *et al.*, 1993), but their potential as temperature indicators continues to be met with some scepticism (Anderson, 2000; Battarbee, 2000). However, recent studies from northern Fennoscandia suggest that diatom records provide reliable estimates of past fluctuations in mean July air temperature (Korhola *et al.*, 2000b; Rosén *et al.*, 2001). All quantitative palaeoenvironmental inferences in this study are based on modern calibration sets (e.g., Birks, 1995; 1998) that include entire biological assemblages instead of indicator species (Birks, 1981). Present-day ecological parameters (e.g., optimum) of each biological taxon for particular environmental variables are estimated and then applied to fossil assemblages, under the basic assumption that the taxon's environmental requirements have remained unchanged during the time period of interest (Birks *et al.*, 1990). Additionally, loss-on-ignition analysis of sediments may provide a proxy for changes in lake productivity and is a useful method to detect major environmental disruptions (e.g., Willemsen and Törnqvist, 1999; Nesje and Dahl, 2001).

In addition to applying a multiproxy approach as an attempt to improve our understanding of palaeoenvironmental changes in northern Scandinavia, a second objective of this study was to assess the reliability of quantitative palaeoclimatic inferences based on pollen, chironomids and diatoms. To do this, we identified problematic time periods for quantitative inferences during the Holocene using a multivariate statistical approach that compared the 'fit' (*sensu* Birks *et al.*, 1990) of fossil assemblages and modern calibration-set assemblages to the variable of interest. Additionally, we compared quantitative inferences based on our multiproxy methods at Vuoskkujávri with the palaeoecological evidence that has been carried out at nearby sites in the Abisko region, including plant macrofossils and pollen in Holocene sediments (Sonesson, 1974; Küttel, 1984; Berglund *et al.*, 1996; Barnekow, 1999), tree megafossils (Kullman, 1999), oxygen-isotope records (Berglund *et al.*, 1996; Shemesh *et al.*, 2001; Hammerlund *et al.*, 2002) and sedimentological and mineral magnetic studies (Snowball, 1996; Snowball and Sandgren, 1996). Because some of the results from these investigations are contradictory, further independent and critically assessed evidence is needed to provide an improved overall picture of Holocene environmental change in northern Sweden. Except for the study by Rosén *et al.* (2001) in the Sarek Mountains, no multiproxy study has yet been performed on one sediment core from northern Sweden, and neither chironomids nor diatoms have previously been used for quantitative palaeoecological inferences in the Abisko region. Vuoskkujávri provides an ideal setting for palaeoenvironmental studies, as it is located at a high latitude, near the tree-limit (e.g., Lotter *et al.*, 1999) and at a sensitive climatic boundary that is controlled by alternating influences of air masses from Atlantic and Arctic origins (Shemesh *et al.*, 2001). Thus, relatively small climatic shifts may have resulted in detectable changes in palaeoenvironmental indicators.

Study site

Vuoskkujávri (68°20'43 N, 19°06'00 E, 348 m a.s.l.) is located 10 km east of the Abisko village and about 200 km north of the Arctic Circle. Lake elevation is only 7 m above the present-day lake level of Torneträsk (341 m a.s.l.), a 70 km long lake that dominates the local landscape (Figure 1). Vuoskkujávri is located on crystalline bedrock (Caledonian); its catchment also includes granite, dolomite, syenite and quartzite with limestone lenses (Kulling, 1964). The lake has two major inlets originating from nearby hillslopes and one outlet into Torneträsk. The surface area is 0.68 km² and the catchment covers an area of 11.2 km². The maximum depth is 18 m and the lake includes several basins varying considerably in depth. Lakewater pH is 6.9 and the alkalinity is 302 meq/L. The current fish population is dominated by Arctic charr (*Salvelinus alpinus*). By spatial interpolation from nearby climate stations, present-day annual precipitation and mean July and January temperatures are estimated as 308 mm, 12.0°C and -12.4°C, respectively (A. Odland, personal communication). The lake is normally ice-covered from November to May.

Vuoskkujávri is surrounded today by mountain birch forest (*Betula pubescens* ssp. *tortuosa*) with an understorey of ericaceous dwarf shrubs and herbs such as *Cornus suecica*, but the present-day northern tree-limit of Scots pine (*Pinus sylvestris*) is located only 10 km east of the lake. In addition, there is an isolated pine population about 10 km to the west of the lake in the Abisko valley that might have been connected with the population east of Vuoskkujávri in the past (Sonesson and Lundberg, 1974). Major impacts within the catchment occurred in the beginning of the twentieth century with railway construction, and road construction in 1980. Before these events, the catchment was rela-

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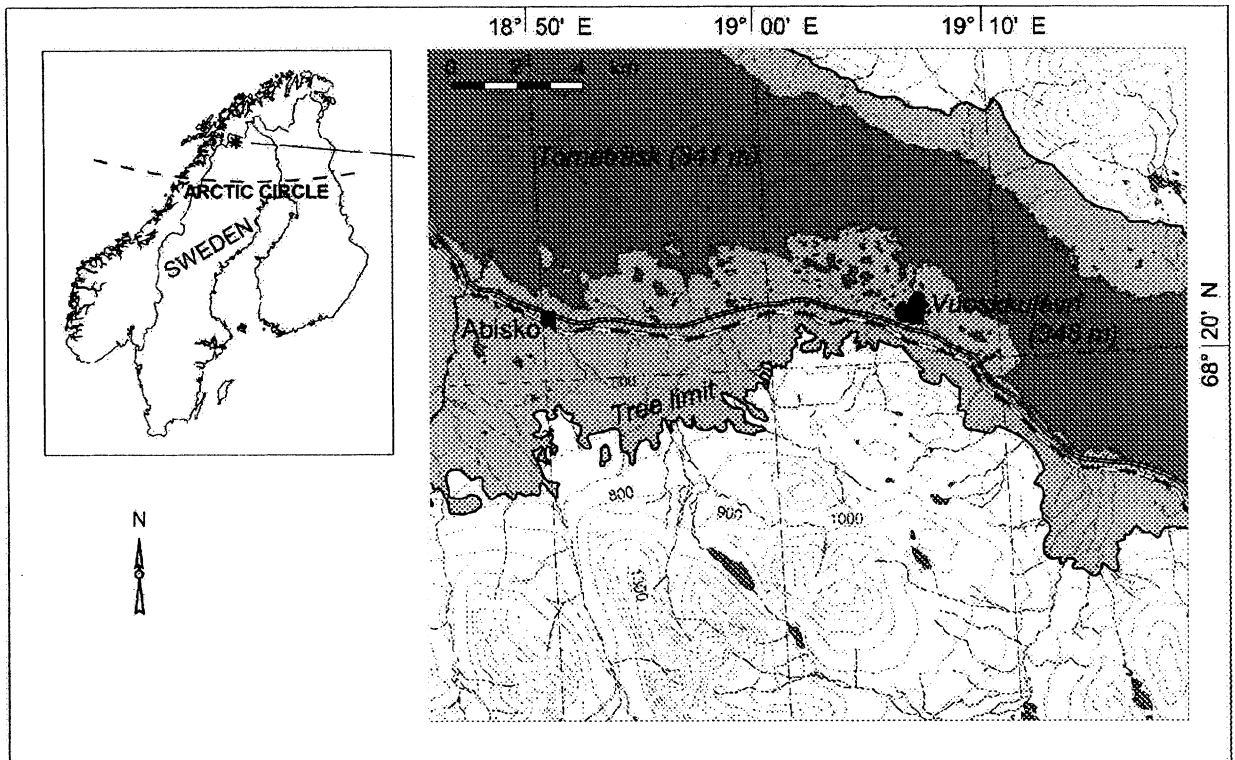


Figure 1 Map showing the location of Vuokskujävi. The present-day tree-limit shown is formed by mountain birch (*Betula pubescens* ssp. *tortuosa*).

tively inaccessible and human impact was probably limited to activities by Saami people.

Materials and methods

Fieldwork

Vuokskujävi was sampled in July 1994 as one of seven sites along the Kiruna-Lofoten transect from Kiruna (Sweden) to Vesterålen (Norway) (Birks and Peglar, unpublished data). A 5 cm diameter modified Livingstone piston corer (Wright, 1967) was used to collect a core from the deep-water region (6 m) of the southeastern basin. The less-consolidated surface sediments (top 25 cm) were cored using a modified Kajak gravity corer (Renberg, 1991). The overlapping sediment segments (total core length = 2.47 m) were correlated by depth, as the loss-on-ignition values did not reveal any changes that could be used for core correlation.

Laboratory analysis and sample preparation

Samples for all proxy indicators (pollen, chironomids and diatoms) and LOI were removed from identical stratigraphic levels, allowing sample-by-sample comparison between the different proxy indicators. Analyses were performed on 1 cm thick sediment intervals positioned 4 cm apart, except in the oldest part of the sequence (834–848 cm) where analyses were performed on 1 cm thick sediment intervals positioned 2 cm apart to achieve higher resolution during the initial establishment of terrestrial vegetation. A total of 67 samples was analysed from the core.

The loss-on-ignition (LOI) of the sediment was estimated using a standard procedure (Peglar *et al.*, 1989). One cm³ of wet sediment was dried at 105°C overnight and then burned for six hours at 550°C. The LOI of the sediment was calculated as the percentage dry weight loss after ignition.

Pollen samples were prepared using method B of Berglund and Ralska-Jasiewiczowa (1986) and mounted in 2000 cS silicone oil.

A known weight of tablets containing a known concentration of *Eucalyptus* pollen was added to each sample prior to preparation to allow estimation of pollen and spore concentrations. At least 500 pollen grains and spores were counted at a magnification of $\times 400$, $\times 1000$ for critical examination, and identified to the lowest possible taxonomic level using keys (Birks, 1973; Moore *et al.*, 1991; Punt *et al.*, 1976–95) and an extensive modern pollen reference collection.

For chironomid analysis, 3–5 ml of wet sediment were deflocculated overnight in a 10% KOH solution and then sieved using a 100 μ m mesh. Head capsules were hand-picked, dehydrated in ethanol 99% and mounted with their mouthpart upward on microscopic slides in Euparal®. If possible, a minimum of 120 head capsules was identified in each sample. Taxonomic identifications were based mainly on Wiederholm (1983). Members of the *Tanytarsini* tribe were divided into taxonomic types using Brooks *et al.* (1997) and unpublished taxonomic descriptions by S.J. Brooks. In cases where head capsules were split in two, two halves were taken to represent one unit.

Diatom preparation was carried out using standard methods including digestion with 30% H₂O₂ as described by Battarbee (1986), applying a preparation technique for large sample sets (Renberg, 1990). Cleaned diatom samples were dried onto coverslips and permanently mounted onto microscope slides using Naphrax®. Identifications of at least 400 diatom valves in each sample follow the guidelines of the SWAP project and Krammer and Lange-Bertalot (1986–91). Diatom concentrations were estimated using microspheres (Battarbee and Kneen, 1982).

Dating and depth-age modelling

Small bulk-sediment samples for AMS radiocarbon dating were pretreated at the Laboratory for Radiocarbon Dating in Trondheim (NO) and measured at the Ångström Laboratory in Uppsala. The dates were calibrated into calendar years BP (Table 1) using CALIB 3.0.3.c, method A, and the bidecadal data set (Stuiver

Table 1 The bulk-sediment samples from Vuoskujärvi used for ^{14}C AMS dating. The depth includes the water-column (601 cm)

Lab. number	Depth (cm)	$\delta^{13}\text{C}$ (‰)	^{14}C age BP (1 sd)	Cal. age BP (1 sd)
TUa-1225A	633.5–634.0	-33.7	1760 ± 85	1760–1560
TUa-1226A	657.5–658.0	-32.1	2375 ± 80	2470–2330
TUa-1227A	679.5–680.0	-31.4	3010 ± 80	3315–3060
TUa-1228A	705.5–706.0	-31.2	4205 ± 95	4860–4570
TUa-1229A	729.5–730.0	-31.0	5020 ± 80	5890–5665
TUa-1230A	749.5–750.0	-32.1	5560 ± 80	6430–6290
TUa-1231A	781.5–782.0	-30.8	6835 ± 105	7710–7550
TUa-1232A	801.5–802.0	-30.1	7470 ± 100	8350–8130
TUa-1233A	835.5–836.0	-30.0	9065 ± 120	10 270–9950
TUa-1234A	846.0–850.0	-31.4	9075 ± 100	10 290–9895

and Reimer, 1993). The depth-age modelling was performed using generalized additive modelling.

Zonation and stratigraphical assessment by DCA

Stratigraphic changes in composition of pollen, chironomid and diatom assemblages were zoned using optimal partitioning using sum-of-squares criteria (Birks and Gordon, 1985). The number of significant zones was assessed by comparison with the broken-stick model (Bennett, 1996) and the statistically significant zones are presented (Figure 2).

All the biological proxy data were analysed by detrended correspondence analysis (DCA) using the program CANOCO (version 4.0) (ter Braak and Smlauer, 1998) to detect the major trends in the data and to assess the compositional turnover in each indicator group (Figure 3). For these purposes, the data were square-root transformed to stabilize their variances and rare taxa were downweighted.

Calibration sets and transfer functions

The quantitative inferences are based on surface-sediment calibration sets. The calibration set for pollen includes 191 lakes distributed over the whole of Norway and northern Sweden, covering broad gradients in temperature and precipitation. The calibration sets for chironomids and diatoms include the same 100 lakes, which are distributed regionally over northernmost Sweden (Larocque *et al.*, 2001; Bigler and Hall, 2002). The statistical relationship between the organisms and the environmental variable of interest determined whether linear or unimodal-based models should be applied (ter Braak, 1987; 1995; Birks, 1995). Therefore, we tested all taxa of the three groups of proxy indicators (i.e., pollen, chironomids and diatoms) statistically for their response models to the environmental variable of interest using a hierarchical set of response models (Birks *et al.*, 1990) fitted by generalized linear modelling implemented by the HOF program (version 2.2, unpublished program by J. Oksanen). The results suggest that models based on a combination of linear and unimodal responses are appropriate for the proxy indicators. The inference model selection is to some extent subjective (Birks, 1998), and in the present study we used an inference procedure based on unimodal response models (i.e., weighted averaging partial least squares, WA-PLS) (ter Braak and Juggins, 1993) for calibrating July temperature. The same technique based on unimodal responses was chosen for January temperature (pollen), precipitation (pollen) and pH (diatoms).

We developed transfer functions and summarized them in terms of the coefficient of determination between observed and predicted values (r^2) and prediction error, i.e., root mean square error

of prediction (RMSEP), both estimated on the basis of leave-one-out cross-validation (Birks, 1995). For July temperature, pollen, chironomid and diatom transfer functions resulted in r^2 of 0.54, 0.65 and 0.70 whereas the RMSEP was 1.03°C, 1.13°C and 0.96°C respectively. The January temperature-pollen transfer function yielded r^2 of 0.74 and RMSEP of 2.57°C, whereas the precipitation-pollen transfer function resulted in r^2 of 0.68 and RMSEP of 417 mm. A relatively strong transfer function was established for diatom-based pH inference, with r^2 of 0.77 and RMSEP of 0.19 pH units. Complete details of model selection and the summary statistics of each transfer function are given elsewhere; for chironomids by Larocque *et al.* (2001), for diatoms by Bigler and Hall (2002) and for pollen by Birks *et al.* (unpublished data).

Quantitative reconstructions and their evaluation

Palaeoenvironmental reconstructions were calculated using WA-PLS regression and calibration within the computer program CALIBRATE (version 0.81, unpublished program by S. Juggins and C.J.F. ter Braak). Sample specific error estimates (Figure 4) were calculated using the computer program WA-PLS (version 1.0, unpublished program by S. Juggins and C.J.F. ter Braak). Due to uncertainties in estimating glacio-isostatic land-uplift as a function of time, our reconstructions are not corrected for glacio-isostatic land-uplift. However, the regional glacio-isostatic land-uplift is estimated to be about 100 m since deglaciation (Møller, 1987).

The environmental reconstructions were evaluated using two approaches. First, to provide an indication of how well a fossil assemblage was represented in the modern calibration set, we calculated the proportion of taxa from each fossil assemblage represented in the modern calibration set (Birks, 1998) (Figure 2, b and c). Second, canonical correspondence analysis (CCA) of the modern and the fossil data was carried out with the environmental variable of interest (e.g., July temperature) as the sole constraining variable to assess the fit of the fossil assemblages to the environmental variable of interest (Birks *et al.*, 1990). We used the residual distance (square residual length, SqRL) of the modern samples as a criterion of fit. Fossil samples with a high residual distance from the environmental variable axis have a 'poor' fit to that variable. The fossil samples are added passively to this axis and any fossil sample with a residual distance equal to or larger than the residual distance of the extreme 10% of the calibration set samples is considered to have a 'poor' fit to the environmental variable (Birks *et al.*, 1990). This method allows an assessment of how well the composition of the fossil assemblage fits into the modern calibration sets, but does not *sensu stricto* evaluate whether inferred values accurately reflect past conditions. Fossil assemblages with poor 'fit' may provide accurate estimates of an environmental variable, and assemblages with good 'fit' may not always provide accurate estimates. Consequently, we use the criterion of 'fit' as a guide to whether fossil assemblages contain abundances of taxa with relatively weak or strong relationships to the variable being reconstructed.

Statistically optimal LOESS smoothers (locally weighted regression) were selected by cross-validation using S-PLUS to highlight the major long-term 'signal' in the quantitative reconstructions (Birks, 1998). For the July temperature reconstructions, the polynomial degree and span of the smoothers differ substantially between pollen (degree = 2, span = 0.7), chironomids (degree = 1, span = 1.0) and diatoms (degree = 1, span = 0.2). The January temperature reconstruction is smoothed with a polynomial degree of 2 and a span of 0.5, whereas the precipitation and the pH reconstruction are smoothed with a degree of 1 and spans of 0.6 (precipitation) and 0.2 (pH), respectively (Figure 4).

(a)
Vuoskujávri
 Selected pollen & spore percentages
 Analyst: Sylvia M. Peglar

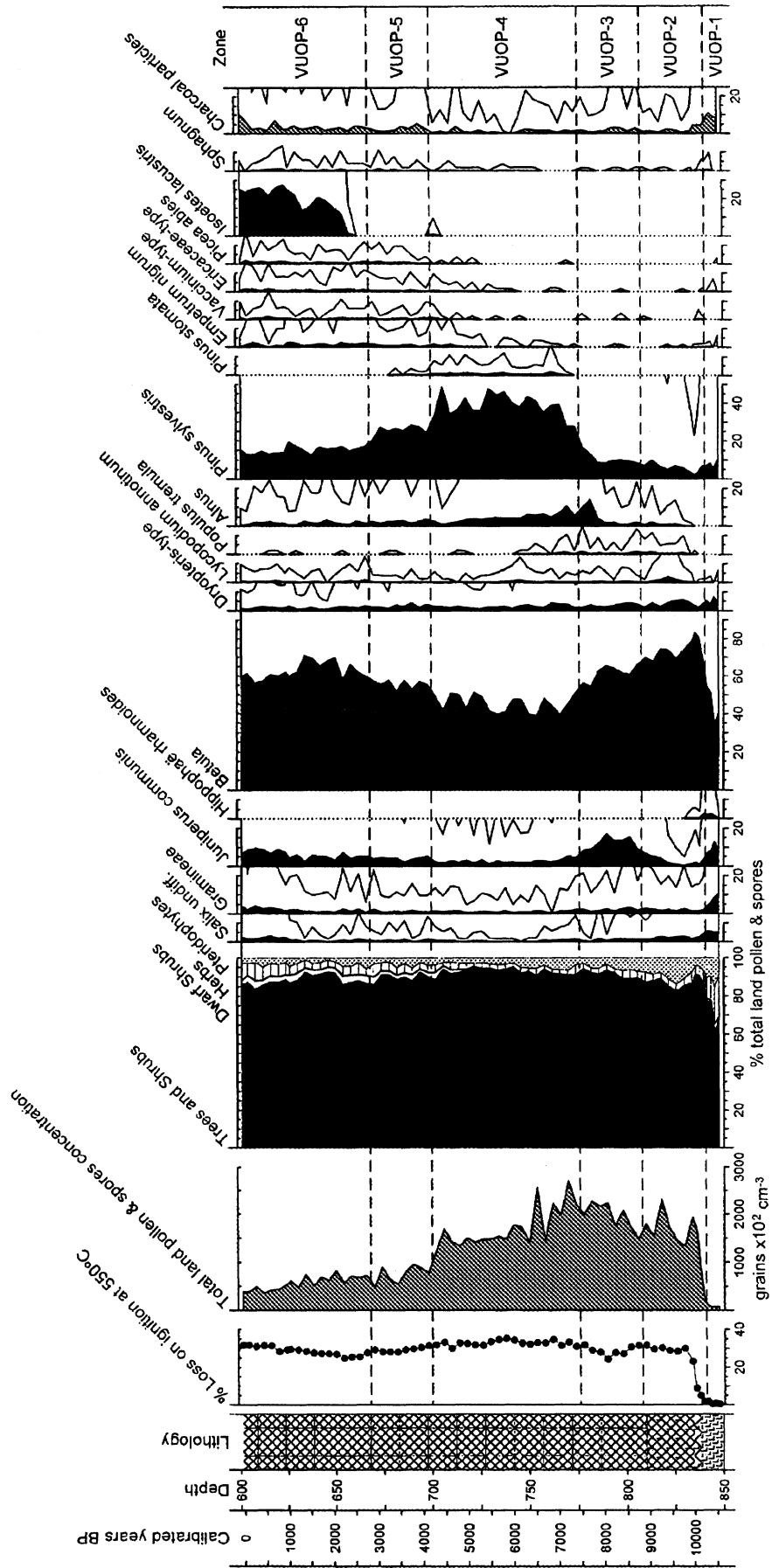


Figure 2 Biostratigraphical record of selected (a) pollen, (b) chironomid and (c) diatom taxa. The scales at the bases of the diagrams give percentages for the black silhouettes; unshaded silhouettes are exaggerated $\times 10$ scale.

(b)
Vuoskujávri
 Selected chironomid head capsule percentages
 Analyst: Isabelle Larocque

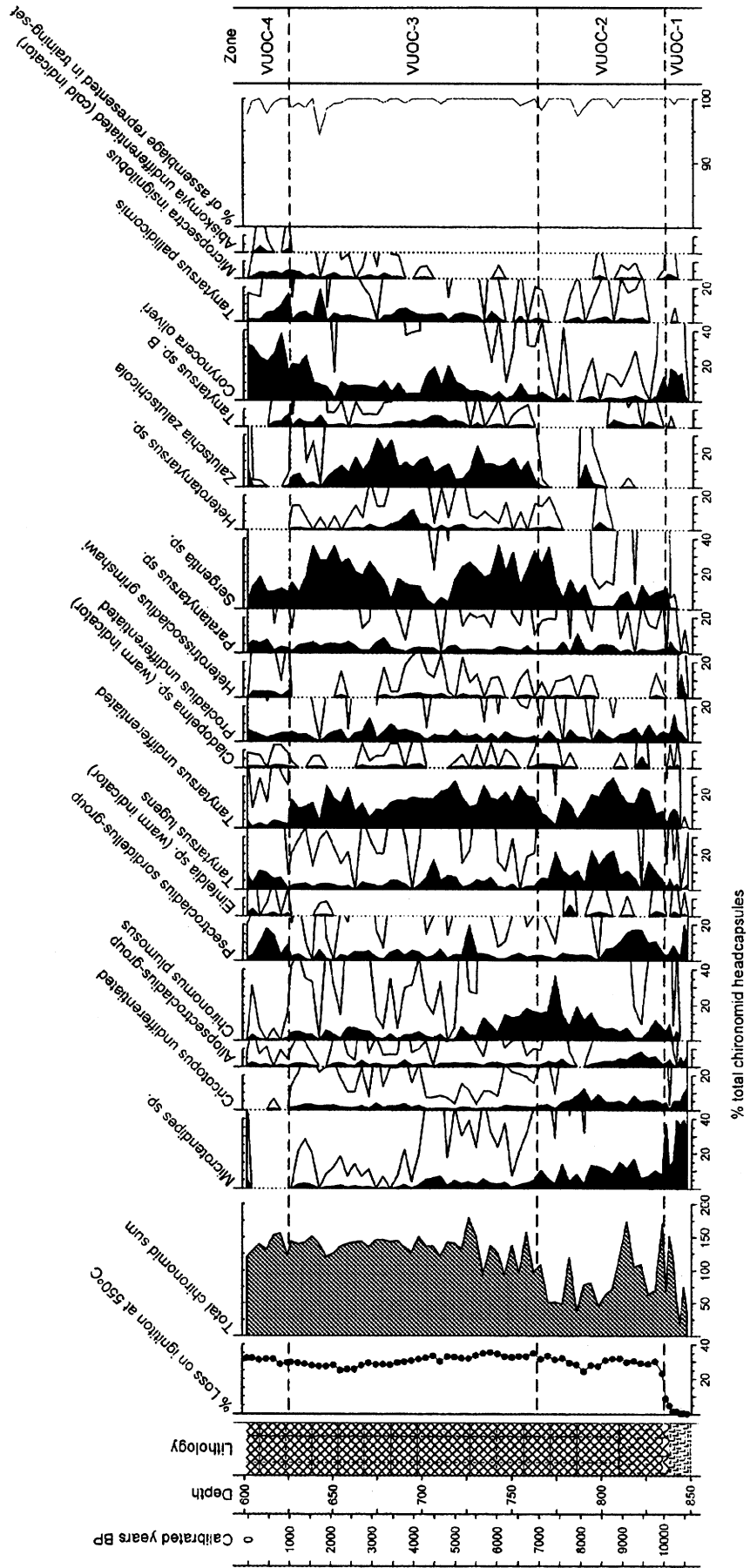


Figure 2 Continued.

(c)
Vuoskujávri
 Selected diatom percentages
 Analyst: Christian Bigler

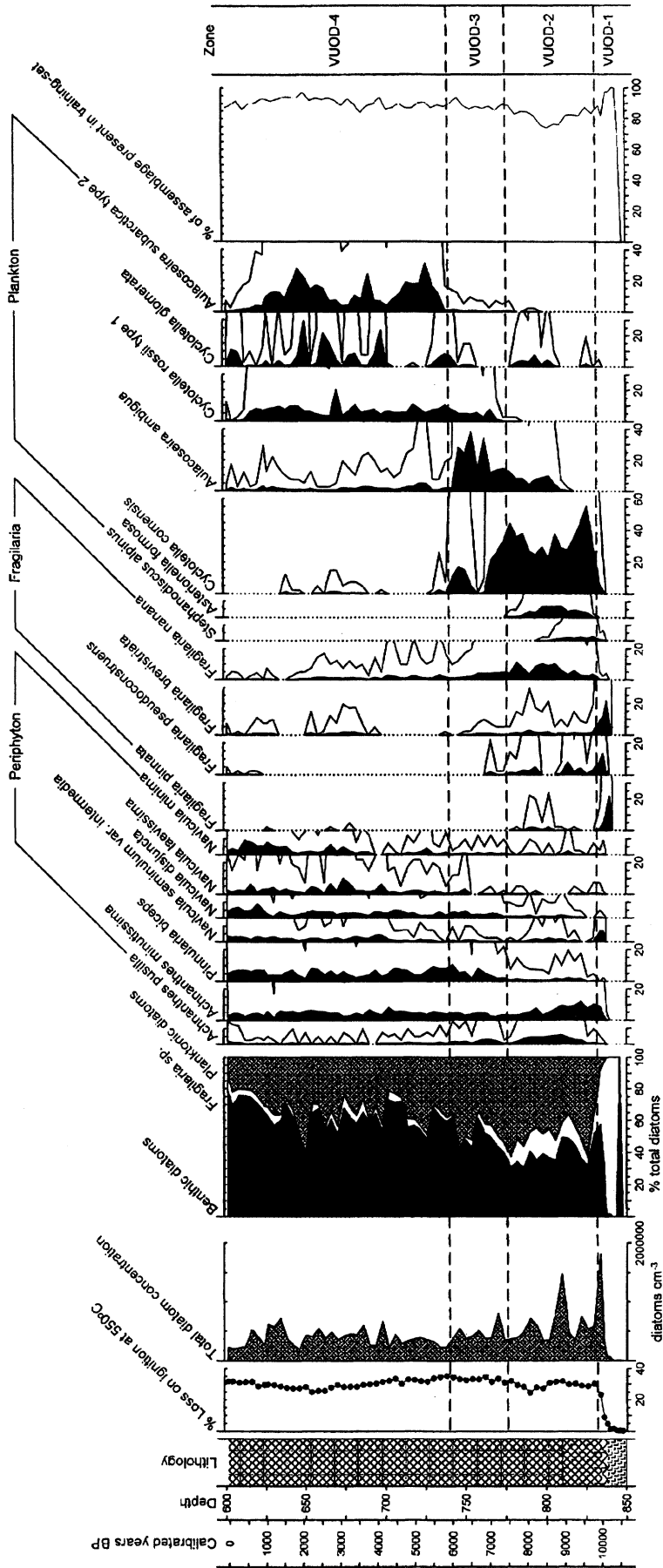


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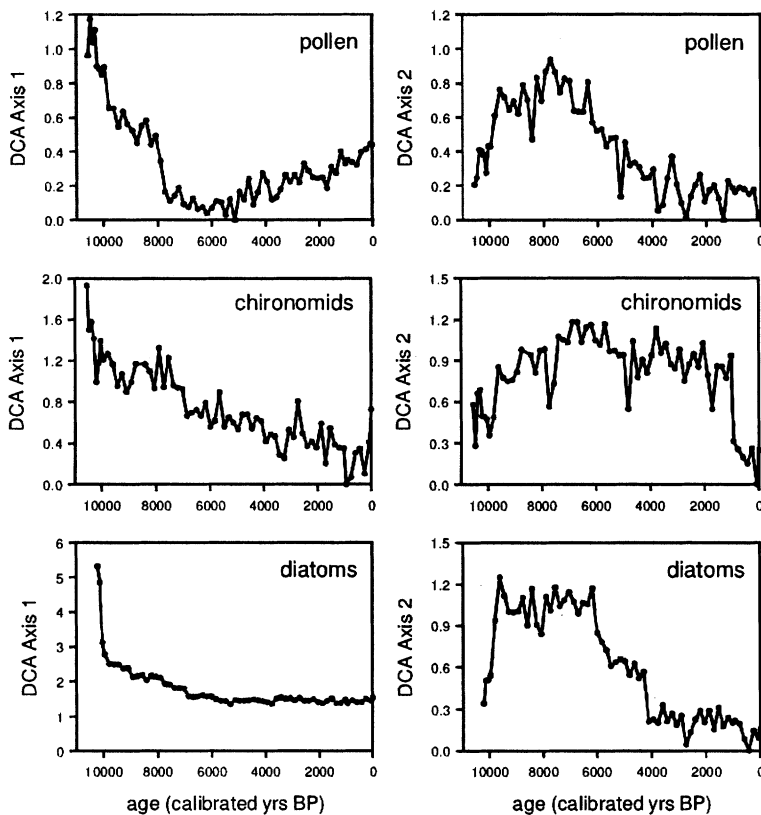


Figure 3 DCA plots of the sample scores (standard deviations of compositional change) on the first two axes for pollen, chironomids and diatoms, indicating the compositional changes in each proxy indicator group. The DCA scores explain a significant amount of variance in the data sets, with the exception of the second diatom axis that was not statistically significant. The percentage of the total variance represented by each axis is as follows: pollen DCA axis 1 = 15.7%, pollen DCA axis 2 = 8.4%, total inertia = 0.61; chironomid DCA axis 1 = 16.3%, chironomid DCA axis 2 = 7.8%, total inertia = 0.82; diatom DCA axis 1 = 27.9%, diatom axis 2 = 4.4%, total inertia = 1.86.

Results

Biostratigraphical records

Overall, the zonation of pollen, chironomids and diatoms consistently identify two major transitions during the Holocene. The first transition occurs at 10 000 cal. yrs BP and coincides with the onset of organic sedimentation (Figure 2). Both chironomid and diatom stratigraphies show a significant zone boundary at 10 000 cal. yrs BP, whereas the pollen zone boundary occurs c. 250 years earlier. The concentrations of each of our three palaeoecological indicators, as well as the loss-on-ignition values (<5%), are markedly lower in sediments older than 10 000 cal. yrs BP, which is consistent with an overall sparse vegetational cover and low aquatic production (Figure 2).

The second major transition occurs around 7500–7000 cal. yrs BP and coincides with the establishment of Scots pine (*Pinus sylvestris*) within the catchment of Vuoskkujävi and a major shift in the diatom composition (see below). Interestingly, the corresponding zone boundary for chironomids is delayed until 7000 cal. yrs BP (Figure 2). Individual biostratigraphical records of pollen, chironomids and diatoms are summarized in the next three sections and selected taxa are presented in Figure 2.

Pollen and spores (Figure 2a)

After deglaciation, at c. 10 600 cal. yrs BP, a relatively open vegetation grew around the lake, dominated by herbs, ferns and shrubs such as *Hippophaë rhamnoides*, *Juniperus communis*, *Salix* and *Betula* (Figure 2a). At c. 10 200 cal. yrs BP, rather open *Betula* woodland became established (zone VUOP-2) with some *Populus tremula*, *Salix* and ferns (*Dryopteris*-type). At the begin-

ning of zone VUOP-3 (8800 cal. yrs BP), *Juniperus communis* pollen increases with concomitant decreases in herbs and ferns as the *Betula* woodland thickened and juniper formed an extensive understorey. Towards the top of zone VUOP-3, *Alnus* (probably *Alnus incana*) pollen values increase, suggesting its growth close to the site. *Pinus sylvestris* pollen values rapidly increase at the zone VUOP-3/VUOP-4 boundary (7500 cal. yrs BP), and the presence of pine stomata throughout zone VUOP-4 suggests that *Pinus* grew locally near the lake. At the beginning of zone VUOP-5 (4200 cal. yrs BP), *Pinus* pollen decreases and pine stomata become rare and then disappear, marking the retreat of *Pinus* from the lake's catchment. *Betula* and dwarf ericaceous shrub pollen (*Empetrum nigrum*, *Vaccinium*-type, *Ericaceae*-type) increase as open *Betula* woodland with a dwarf-shrub understorey replaced the *Betula/Pinus* woodland. There is only a minimal increase in fern spores, suggesting that this was a drier type of *Betula* woodland than earlier in the Holocene. *Picea abies* pollen values suggest that spruce had migrated and expanded into northern Sweden (although not locally) by c. 4000 cal. yrs BP. *Sphagnum* spores also increase, suggesting an expansion of bogs in the region. In zone VUOP-6, there are further increases in dwarf-shrub taxa and an abrupt increase in *Isoetes lacustris* spores, an aquatic pteridophyte, suggesting some major change in the lake. Towards the top of the sequence (starting 1000 cal. yrs BP), herb pollen increases, probably reflecting opening of the woodland in the area, possibly as a result of Saami people and reindeer herding and grazing.

The pollen DCA scores show a major change at 7500 cal. yrs BP consistent with the zonation (Figure 3). On the first DCA axis, the sample scores change from a sharply decreasing towards a

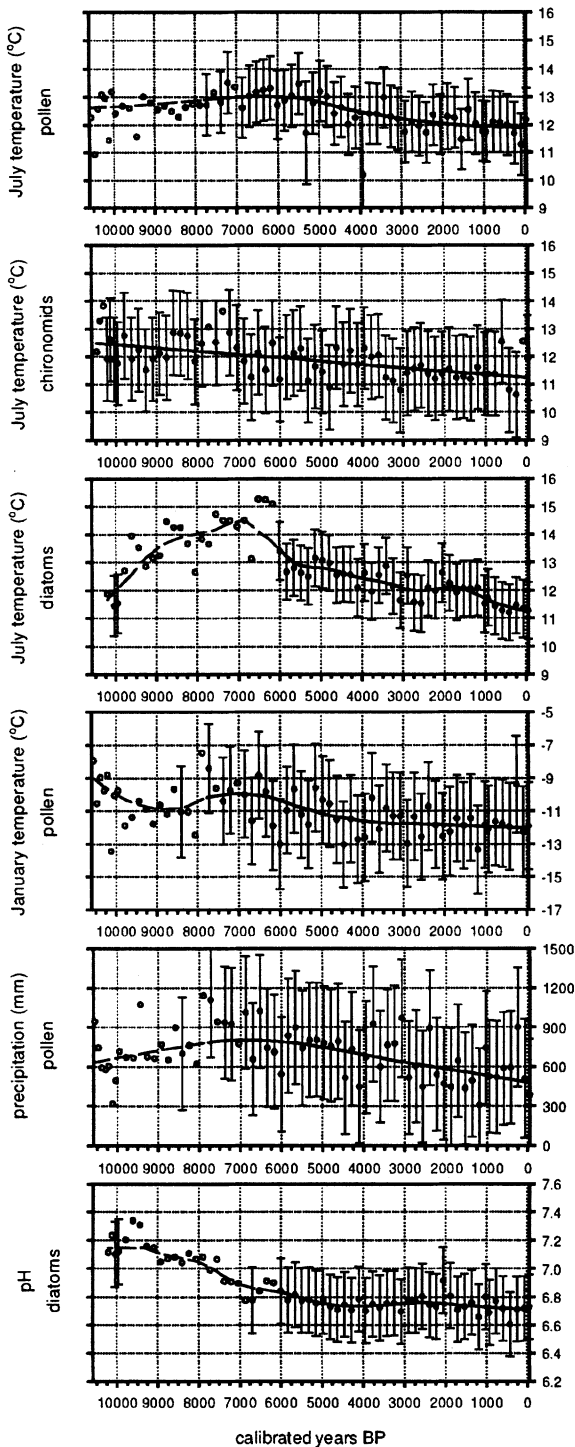


Figure 4 Quantitative reconstructions of mean air temperature (January, July), precipitation and pH based on pollen, chironomids and diatoms with sample specific error estimates (WA-PLS). Open circles in the reconstructed July air temperature indicate fossil assemblages that have a 'poor' fit and sample specific errors are not shown. A statistically optimal LOESS smoother was applied to highlight the signal and trends; for the span and polynomial degree of each smoother, see 'Materials and methods' section in the text.

gently increasing trend, whereas the scores on the second DCA axis change from increasing to decreasing values.

Chironomids (Figure 2b)

The chironomid stratigraphy is divided into four statistically significant zones. The first chironomid assemblage zone (VUOC-1; 10 600–10 000 cal. yrs BP) coincides with low LOI values, suggesting that the organic content of sediments may be an important factor for chironomid larvae (Olander *et al.*, 1999; Larocque *et al.*, 2001). *Microtendipes* (up to 40%), *Corynocera oliveri* (up to 20%), *Psectrocladius sordidellus*, undifferentiated *Psectrocladius* (up to 20%) and *Heterotrissocladus grimshawi* (up to 15%) dominate the assemblage in zone 1, but the composition is highly variable with adjacent sediment samples showing marked increases and decreases in the relative abundances of several taxa. Of these taxa, *H. grimshawi* has been established as an indicator of cold-water, deep-lake environmental conditions (Korhola *et al.*, 2000a; Larocque *et al.*, 2001). All other taxa are widely distributed in the regional Swedish calibration set, but *Corynocera oliveri* is mentioned as a cold-water taxon in Norway (Brooks and Birks, 2000a) and in Finland (Olander *et al.*, 1999), while *Microtendipes* is often regarded as a warm-water taxon (Brooks *et al.*, 1997; Smith *et al.*, 1998; Brooks and Birks, 2000a). Here, taxa with affinity for warmer conditions seem to be replaced by taxa preferring colder conditions at the end of the zone. Chironomid zone VUOC-2 (10 000–7000 cal. yrs BP) coincides with a rapid increase in LOI to stable Holocene values of 30–35% of dry sediment mass. The onset of VUOC-2 coincides with marked declines in the percent abundance of *Microtendipes* and *Corynocera oliveri*. *Tanytarsus lugens* and undifferentiated *Tanytarsus* dominate within the zone, in association with *Sergentia*, *Microtendipes*, *Psectrocladius* and *Cricotopus*. Interestingly, the warm-indicator *Einfeldia* is present, but at relatively low abundance and it exhibits marked fluctuations in relative abundance. The third chironomid zone (VUOC-3; 7000–1000 cal. yrs BP) is dominated by *Zalutschia zalutschicola*, undifferentiated *Tanytarsus*, *Sergentia* and *Corynocera oliveri*. *Zalutschia zalutschicola* is not continuously present within the two previous zones but it accounts for up to 30% total head capsules within this zone. *Zalutschia zalutschicola*, *Sergentia* and *Corynocera oliveri* all prefer a colder mean July air temperature (Larocque *et al.*, 2001) and a temperature decrease might have allowed the establishment of *Zalutschia* during that period, which coincides with the decrease of the warm-indicator *Chironomus plumosus* that dominates the interphase between the zones. There was probably some competition between the two cold-indicators *Zalutschia zalutschicola* and *Corynocera oliveri* (Larocque *et al.*, 2001), as indicated by their reciprocal relationship where increases in one taxon coincide with decreases in the other. *Microtendipes*, a warm-water indicator, and *Cricotopus* were less abundant compared to the previous zone. The fourth zone (VUOC-4), from 1000 cal. yrs BP to the present, was characterized particularly by the appearance of the cold-indicator *Abiskomyia*, which was previously absent from the Holocene record. Interestingly, the warm-indicator *Einfeldia* also occurs at low relative abundance in the same samples. *Einfeldia* is present within zones VUOC-1, -2 and -4, but is absent in zone 3. Furthermore, the assemblage is characterized by marked increases in *Psectrocladius sordidellus*-group, *Tanytarsus lugens* and *Corynocera oliveri*, whereas the proportions of undifferentiated *Tanytarsus*, *Zalutschia zalutschicola* and *Sergentia* decrease. *Microtendipes* and *Cricotopus* almost disappear.

The chironomid sample scores on the first DCA axis show a long-term decreasing trend. Interestingly, the second axis shows a major change in compositional turnover at 1000 cal. yrs BP, which is consistent with the numerical zonation results.

Diatoms (Figure 2c)

The initial diatom assemblage zone (VUOD-1; 10 600–10 000 cal. yrs BP) is characterized by low concentrations of diatom

frustules. The assemblage is dominated by small *Fragilaria* species including *F. pinnata*, *F. pseudoconstruens* and *F. brevistriata*, which is typical of early-Holocene records in Fennoscandia (e.g., Korhola *et al.*, 2000b). This pioneering diatom flora was quickly replaced after 10 000 cal. yrs BP (VUOD-2) by a mainly planktonic flora, dominated by *Cyclotella comensis*. The small planktonic species such as *Cyclotella comensis* bloom in northern Scandinavia, preferably during the autumn overturn (Rautio *et al.*, 2000). *Aulacoseira ambigua*, *Fragilaria nanana* and *Achnanthes minutissima*, that can occupy both planktonic and benthic habitats, are also relatively abundant in assemblages of zone VUOD-2 (10 000–7500 cal. yrs BP). Interestingly, *Asterionella formosa* and *Stephanodiscus alpinus*, two planktonic species indicative of mesotrophic to eutrophic conditions, appear only in VUOD-2 and contribute 5–10% of the diatom sum. The subsequent zone, VUOD-3 (7500–6000 cal. yrs BP), is characterized by the disappearance of

Stephanodiscus alpinus and *Asterionella formosa*, declining abundances of *Cyclotella comensis*, increased relative abundance of *Aulacoseira ambigua* and the first appearance of *Cyclotella rossii* type 1. Within zone 3, the pioneering *Fragilaria* species almost disappear completely, even though the relative abundances of benthic diatoms increase (e.g., *Pinnularia biceps*). The most recent diatom zone (VUOD-4) covers almost 6000 years and no major changes occur within that period. The onset of the zone is characterized by a sharp decline in the abundance of *Aulacoseira ambigua*, which dominates the previous zone and a corresponding increase in *Aulacoseira subarctica* type 2. *Cyclotella glomerata* is continuously present throughout zone 4 and displays marked fluctuations in relative abundance, to as much as 20% of the assemblage in some samples.

The sample scores on the first DCA axis indicate that the diatoms experienced the most dramatic compositional change during the earliest part of the Holocene. The pattern of the sample scores on the second DCA axis is generally similar to that of pollen, but the second DCA axis of the diatom record is, in contrast to the pollen and chironomids, not statistically significant as assessed by comparison with the broken-stick model (Legendre and Legendre, 1998).

Evaluation of environmental reconstructions

Representation of fossil assemblages in the modern calibration data sets

The fossil pollen assemblages are in general well represented in the modern calibration set. Between 99.35 and 100% of the fossil assemblages are present in the calibration set, or 90 out of 96 taxa recorded in the Holocene sediment sequence of Vuoskujärvi. The poorest representation (0.65–0.5% of taxa not present in the calibration set) occurs between 10 600 and 10 400 cal. yrs BP.

For chironomids, taxa in the modern calibration set account for at least 95% of the fossil assemblages (Figure 2b), except for one sample (646 cm; sediment depths indicate distance from water surface). In terms of taxa, 46 out of 54 are present in the modern calibration set.

Compared to the other proxies, the fossil diatom assemblages are relatively poorly represented in the calibration set. In general, modern calibration data are available for 80–90% of each fossil assemblage (Figure 2c). The poorest representation is recorded during VUOD-2 (10 000–7500 cal. yrs BP), where only 70–85% of the assemblages are represented. Overall, 120 of the 179 recorded fossil diatom taxa are present in the modern calibration set.

Assessing the fit of fossil samples to the calibration set by CCA

Using the assessment of the residual distance (SqRL) to the first CCA axis with July temperature as the sole constraining variable, we identified samples, or in some cases whole time periods, with 'poor' fit to July temperature (Figure 4). Twenty-two pollen samples (848–786 cm, 778 cm, 766 cm) have a 'poor' fit to July temperature, suggesting that the reconstruction period 10 600–7500 cal. yrs BP is problematical. The same samples similarly have a 'poor' fit to January temperature and to annual precipitation. These 'poor' fits result largely from the fossil pollen assemblages having no strong modern analogues in terms of similar relative pollen and spore abundances in the modern calibration set.

For the chironomid inference model, six samples with a 'poor' fit to July temperature are identified (Figure 4). The three oldest samples where chironomid remains are found (846 cm, 844 cm and 842 cm) showed 'poor' fit to July temperature, suggesting that the early Holocene (before 10 300 cal. yrs BP) is a problematic time period for chironomid-based quantitative temperature reconstructions. In addition, two samples between 8000 and 7000 cal. yrs BP (782 cm and 774 cm, respectively) and a sample close to the sediment surface (604 cm), all suggesting relatively high temperatures, show a 'poor' fit to July temperature.

Diatom assemblages show, with the exception of two samples around 10 000 cal. yrs BP (836 and 834 cm respectively), a 'poor' fit to July temperature before 6000 cal. yrs BP (Figure 4). Most of the samples even reveal a 'very poor' fit (Birks *et al.*, 1990) to July temperature with a residual distance higher than 5% of the extreme calibration-set lakes. Nearly the same samples as for July temperature also show a 'poor' fit to lakewater pH. Consequently, diatom-based inferences must be considered as tentative before 6000 cal. yrs BP. The reason for the 'poor' fit to temperature is mainly the unique composition of the planktonic diatom assemblage before 6000 cal. yrs BP which contain species that are not present in the modern calibration set.

Environmental reconstructions

In this study, our interpretations focus mainly on the long-term, smoothed trends, rather than on inferences from individual data points (Figure 4). Individual 1 cm thick sediment samples generally integrate several decades and, thus, exclude an interpretation in terms of short-term environmental change.

July temperature (pollen, chironomids, diatoms)

The smoothed pollen-based July temperature reconstruction reveals a temperature during the early Holocene that was probably 0.7°C above the present-day value (Figure 4). The reconstruction subsequently shows a continuously increasing trend until 6500 cal. yrs BP, when the highest temperatures are reconstructed to 1.1°C above the present-day value. Warmest temperatures occur in individual samples between 7500 and 5500 cal. yrs BP, and correspond to samples with high relative abundances of *Pinus* pollen. Since 6500 cal. yrs BP, July temperature tended to decrease towards present-day values (Figure 4).

The smoothed chironomid-inferred July temperature shows a linear decreasing temperature over the whole Holocene period, with highest individual values occurring before 7000 cal. yrs BP. The chironomid inferences suggest a decrease of 1.2°C since the early Holocene. Overall, the chironomids exhibit the greatest variability of inferred temperatures and the highest sample specific errors, compared to inferences based on pollen or diatoms (Figure 4).

Diatoms infer that temperatures during the early Holocene were probably slightly warmer than today, with peak mean July temperatures, 3.0°C above the present day, occurring 7000 cal. yrs

BP (Figure 4). Since 7000 cal. yrs BP, the inferred temperatures decreased, with greatest changes occurring between 7000 and 6000 cal. yrs BP. However, diatom inferences before 6000 cal. yrs BP may not be reliable, as the fossil assemblages reveal a 'poor' fit to temperature. Since 6000 cal. yrs BP, a gradual temperature decrease of 1.5°C is recorded (Figure 4), which is slightly more than is inferred from either pollen or chironomids.

A comparison of the three indicators is limited to the last 6000 years, when all proxy-based reconstructions show a 'good' fit to July temperature. Overall, all indicators reconstruct a cooling trend over the last 6000 years, with inferred-temperature declines ranging from 0.8 to 1.5°C. The present-day mean July temperature at Vuoskkujávri (12.0°C) is estimated accurately by the pollen and chironomid assemblages, whereas the diatoms underestimate it by 0.8°C; an error that is still within the prediction error of the inference model. All the smoothed values underestimate the present-day temperature by between 0.1 and 0.8°C.

January temperature (pollen)

The January temperature reconstruction is based on the pollen record only and the reconstruction for 10 600–7500 cal. yrs BP must be regarded as tentative because fossil pollen assemblages exhibit 'poor' fit. January temperatures may have been considerably warmer (+3.0°C) during the early Holocene than today. Cooler winter temperatures followed the early Holocene, reaching a relative minimum at 8500 cal. yrs BP with only 1.0°C warmer winters than today. From 8500 cal. yrs BP, the winter temperatures increased until 7000 cal. yrs BP, when mean January temperature reached a relative maximum 2.0°C above present-day values. Since 7000 cal. yrs BP, winter temperatures have tended to cool towards present-day values. A marked cooling trend occurred between 6500 and 4000 cal. yrs BP, whereas inferred January temperatures have remained relatively constant during the past 4000 years. The modern pollen assemblage overestimates the present-day mean January temperature by 0.4°C.

Precipitation (pollen)

Pollen analyses tentatively suggest that annual precipitation was higher throughout the Holocene than it is today. During the early Holocene, precipitation may have been 150 mm higher than today. Inference shows increasing precipitation from the early Holocene until 7000 cal. yrs BP, when precipitation was highest (320 mm above modern values). Since 7000 cal. yrs BP, the pollen record suggests a drying trend towards present-day conditions, although intersample variability is relatively high. Vuoskkujávri is subjected to orographic effects that make the surroundings of Abisko one of the driest places in Sweden (Alexandersson *et al.*, 1991). The precipitation inference model used has relatively high sample specific errors (>400 mm), that exceed even the current amount of annual precipitation (~300 mm). However, the sample specific errors are not extreme when compared with the wide range of precipitation covered by the modern calibration set (300–3540 mm; Birks *et al.*, unpublished data).

Lakewater pH (diatoms)

Diatom-inferred lakewater pH trends suggest that Vuoskkujávri underwent a gradual, long-term pattern of natural acidification of c. 0.5 pH units during the Holocene from slightly alkaline conditions immediately after deglaciation (7.2 pH units) to a relatively constant pH of 6.7 since c. 5000 cal. yrs BP. Based on the reconstructed pH values, there are no signs of major pH changes related to changes in land-use patterns or impacts by reindeer herding that could increase alkalinity via erosion of unweathered catchment bedrock during the last 1000 years.

Discussion

The Vuoskkujávri record

Past vegetation patterns and pine immigration

The extensive establishment of Scots pine (*Pinus sylvestris*) around Vuoskkujávri, based on the stomatal record, occurred at c. 7500 cal. yrs BP. Vuoskkujávri (348 m a.s.l.) is geographically located between two lakes investigated by Barnekow (1999), i.e., Lake Latteluokta (370 m a.s.l.) and Badsjön (400 m a.s.l.), where pine immigration according to the macrofossil record started at 8300 and 7600 cal. yrs BP, respectively. The regional immigration pattern of Scots pine in the Abisko region based on pollen, macrofossils (needles) and stomata is consistent, as the pollen percentage and influx values at all three lakes are low before the continuous needle or stomatal record, suggesting that Scots pine was not growing locally. However, this is in contrast to tree megafossil finds in the southern Swedish Scandes (Kullman and Kjällgren, 2000) and in particular at the shore of a small lake at 999 m a.s.l. on Mount Njulla (Kullman, 1999), only a few kilometres from Vuoskkujávri. Wood remains of considerable size of *Pinus*, *Alnus* and *Betula* were found at this high-altitude lake, suggesting a climate that could support tree growth soon after deglaciation and in the early Holocene with *Pinus* growing at an elevation of 500 m and *Betula* 350 m above present-day tree-limit. However, as no *Pinus* needles were found and the pollen influx values were low at this high-altitude lake (Barnekow, 1999), both of which are indicators for a local presence, we suggest that if *Pinus* was growing locally at high altitude it was as relatively rare, isolated individuals, perhaps confined to a few locally favourable sites.

Past aquatic ecosystems

The diatom record provides reliable quantitative temperature reconstructions only since 6000 cal. yrs BP. For the period prior to 6000 cal. yrs BP, fossil assemblages had 'poor' fit and lacked good modern analogues, indicating that the boundary conditions of our regional calibration-set lakes were exceeded. Nevertheless, the stratigraphical record in Vuoskkujávri allows some conclusions beyond the calibration-set approach. The changes in life form (benthic versus planktonic diatoms) probably reflect changes in length of ice cover and prevailing water-column mixing regimes, similar to those recorded in a small lake in the Swiss Alps (Lotter and Bigler, 2000). In order to bloom and reproduce, planktonic diatoms are dependent on turbulent mixing in the water-column and they benefit from a long period without ice cover. In addition, the amount of light, lake depth and thermal structure, including the depth and stability of the thermocline, may affect the occurrence of planktonic diatoms. In Vuoskkujávri, we find indirect evidence for prolonged ice-free season from 10 000 to 6000 cal. yrs BP, as the ratio of planktonic to benthic diatoms was highest during these first four millennia of the Holocene. Interestingly, modest abundances of *Stephanodiscus alpinus* and *Asterionella formosa*, planktonic taxa indicative of meso- to eutrophic conditions, are consistent with elevated nutrient supplies probably derived from a relatively easily erodable catchment with sparse, open vegetation as well as prolonged ice-free periods. The suggested pattern with longer ice-free periods is supported, to some extent, by the presence of chironomid head capsules of the genus *Einfeldia*. Considered as a warm-water indicator in the regional calibration set (Larocque *et al.*, 2001), *Einfeldia* already occurred during the early Holocene and until 7500 cal. yrs BP. It is completely absent during the mid-Holocene, but reappears continuously at 1000 cal. yrs BP.

Chironomid assemblage change at 1000 cal. BP

A major transition occurred in the chironomid assemblage at 1000 cal. yrs BP. The fact that, for example, profundal cold-indicators such as *Heterotrissocladius grimshawi* (Korhola *et al.*, 2000a) and *Micropsectra insignilobus* (Itkonen *et al.*, 1999) increase while littoral cold-indicators such as undifferentiated *Tanytarsus* decrease suggests that these changes might not be related only to temperature. Beside temperature, the shift from littoral to profundal taxa could be caused by other factors such as lakewater oxygen level, nutrients, fish predation pressure or decreases in the availability of littoral habitats (e.g., macrophyte beds). Greater oxygen availability is suggested by the increase of profundal taxa such as *Heterotrissocladius grimshawi* (Clerk *et al.*, 2000), *Micropsectra insignilobus* and *Abiskomyia*. At the same time, taxa typical of mesotrophic lakes with relatively low oxygen levels decrease, such as *Sergentia* (Schnell *et al.*, 1994; Guilizzoni *et al.*, 1996), *Tanytarsus* (Itkonen *et al.*, 1999; Clerk *et al.*, 2000) and *Chironomus* (Quinlan *et al.*, 1998; Little and Smol, 2000). Although chironomid larvae have been found in fish guts, indicating that they are a food choice for fish, very few studies have investigated the effect of fish on chironomid assemblages. Taxa preferring greater oxygen availability have been shown to occur in lakes where fish communities are introduced, although the assemblages varied from one lake to the other (Johnson *et al.*, 1990). As the history of the fish population of Vuoskkujávri is unknown, any effect of fish on the chironomid assemblage resulting from possible fish introductions by Saami people remains speculative. However, a change from littoral to profundal taxa that prefer higher oxygen levels suggests that the oxygen level increased and could be the controlling factor for the chironomid assemblage change at 1000 cal. yrs BP.

Palaeoclimate in the Abisko region: temperature patterns

Comparison of July temperature as inferred by different proxies at Vuoskkujávri

The taxonomic composition and abundance of biological communities are usually determined by complex interactions among several environmental and biotic factors. As a consequence, the reconstruction of a single environmental variable (e.g., mean July air temperature) from taxonomic changes in fossil assemblages involves considerable simplification of the complex interactions between individual taxa and their environment (Birks, 1981; 1995). To minimize the introduction of errors arising from such potential oversimplifications, palaeoecologists rely increasingly on quantitative inferences developed from multiproxy sources (Ammann *et al.*, 2000; Birks *et al.*, 2000). However, multiproxy approaches are fraught with their own set of challenges and limitations. For example, proxies from both terrestrial and aquatic ecosystems are likely to react in different ways to the same climatic and environmental changes due to differences in the effect of direct and indirect control factors, timelags and other complex feedback mechanisms.

The quantitative mean July air temperature reconstructions based on pollen, chironomids and diatoms at Vuoskkujávri are no exception when sample-by-sample comparisons are performed. However, when the general trends are compared, the three proxy indicators show a remarkably consistent agreement during the past 6000 years. The cooling of mean July temperature over this time period is consistent among all the proxy indicators. The magnitude of cooling differs to some extent among the proxies (0.8–1.5°C), but considering the magnitude of the prediction errors associated with the inference models ($\pm 1^\circ\text{C}$) this difference is well within the precision of our models. These findings emphasize the value of multiproxy studies that are able to confirm results based on one proxy indicator, and therefore lead to a more reliable and consist-

ent picture of long-term palaeoenvironmental reconstructions (Birks *et al.*, 2000).

During the period since deglaciation until 6000 cal. yrs BP, the different proxy indicators for mean July air temperatures are not in as close agreement as during the remainder of the Holocene. Pollen and diatoms exhibit 'poor' fit and infer a moderate temperature increase, whereas chironomids infer a moderate temperature decrease. This pattern is partly reflected in the compositional turnover of each proxy indicator group, as assessed by DCA analysis (Figure 3). Patterns of DCA sample scores for pollen and diatoms show good agreements, especially on the second DCA axis, while chironomids show a markedly different pattern (Figure 3). For pollen, the DCA scores on the first axis shows the greatest changes at the same time period as when the 'poor' fit to the calibration set starts (7500 cal. yrs BP). For diatoms, a similar change in the DCA scores occurs simultaneously with the start of the 'poor' fit to the calibration set at 6000 cal. yrs BP, but instead on DCA axis 2.

Inconsistencies between different proxy groups within the early-Holocene record from Vuoskkujávri illustrate that the calibration-set approach is not always straightforward. Several factors could be responsible for inconsistencies among multiple proxies. Fossil assemblages may exceed the boundary conditions of the present-day calibration sets, which lead to no modern-analogue (i.e., 'poor' fit) situations (Birks, 1998). Additionally, certain environmental variables might have strongly regulated the biological assemblages in Vuoskkujávri in the past but play a less important role today, and vice versa. For example, the presence of the planktonic diatom species *Stephanodiscus alpinus* and *Asterionella formosa* suggests that elevated nutrient concentrations influenced diatom-community composition from 10 000 to 7500 cal. yrs BP, but nutrient concentrations do not appear to be a significant factor determining the distribution and abundance of diatoms within the modern calibration set (Bigler and Hall, 2002). Also, the marked decrease of lakewater pH during the early Holocene might have influenced the diatom distribution to a greater extent than during the past 5000 years of relatively stable inferred pH. Moreover, several environmental variables may have interacted in unique combinations in the past, resulting in the development of biological assemblages that no longer exist. Mainly, the period after glacial retreat with ongoing pedogenesis in the lake catchment and increased precipitation during the early Holocene may have led to unique environmental conditions and interactions that affected each proxy-indicator group differently. Also, migrational and other response lags might have been different for terrestrial (pollen) and aquatic (diatoms, chironomids) organisms. As a consequence, even quantitative multiproxy environmental reconstructions may provide both consistencies and contradictions (Ammann and Oldfield, 2000). Regardless of the cause, evidence from this study indicates that the palaeoenvironmental inferences are problematic during the early Holocene period at Vuoskkujávri, due to 'poor' fit of fossil assemblages to environmental gradients included within the modern calibration set. Comparison of the 'fit' of fossil assemblages to modern relationships between biota and the reconstructed variable appears to provide a useful criterion for evaluating the reliability of quantitative inferences. This method highlights that quantitative inferences are likely to be unreliable during 10 600–6000 cal. yrs BP based on diatoms, during 10 600–7500 cal. yrs BP based on pollen, and during 10 600–10 300 cal. yrs BP based on chironomids. These periods correspond to the problematic early Holocene when previous palaeoenvironmental studies show the greatest disagreement (see below). Despite these problems, the calibration-set approach still remains one of the most powerful approaches for palaeoenvironmental reconstructions currently available. Using several proxies instead of one proxy indicator might compensate to some degree for limitations based on an incomplete coverage

of the past and present ecological requirements of the taxa within the modern calibration sets.

Comparison with temperature reconstructions from nearby sites

The temperature reconstruction presented here from Vuoskkujávri is the first to combine several aquatic and terrestrial biological proxy indicators from a single sediment core using samples from identical stratigraphic levels in the Abisko region of northern Sweden. The long-term temperature reconstruction at Vuoskkujávri, specifically the mean July air temperature decrease of 0.8–1.5°C since 6000 cal. yrs BP, is consistent with studies from other sites near Abisko. Based on pollen and plant macrofossil records from six lakes in the Abisko surroundings, the mean annual temperature during the mid-Holocene was estimated to be c. 1.5–2.0°C warmer, followed by a trend to a colder climate (Barnekow, 1999), a magnitude of cooling that is similar to our inferences from Vuoskkujávri. Further independent, consistent evidence comes from sedimentological investigations of lakes in the Kårsa Valley, a side valley to the main Abisko Valley, suggesting that the Kårsa glacier was absent during the early and mid-Holocene but reformed 3250 cal. yrs BP (Snowball and Sandgren, 1996; Snowball, 1996). Interestingly, both the chironomids and diatoms imply a considerable cooling starting at c. 3500 cal. yrs BP, when individual data points instead of the smoothed curves are considered (Figure 4). In contrast, the pollen record shows only minor changes at that time. The evidence from the Kårsa Valley supports the estimated temperature trends in Vuoskkujávri and suggests that the last four millennia were the coolest millennia of the entire Holocene.

Similar to our observations from the Vuoskkujávri record, other studies from the Abisko region show considerable differences in temperatures before 6000 cal. yrs BP. According to tree megafossil findings at 999 m a.s.l., summer temperature during the early Holocene was an estimated c. 3.0° warmer than today (uncorrected for glacio-isostatic land-uplift) (Kullman, 1999). This estimate is consistent with evidence from nearby Lake 850, where the temperature decrease associated with the oxygen-isotope record was suggested to be c. 2.5–4.0°C since the early Holocene (Shemesh *et al.*, 2001). However, the Vuoskkujávri record does not suggest values of this magnitude.

Within northern Fennoscandia, very few studies have used the same methodological approach as described in this paper, and a detailed regional comparison inevitably requires more data. A similar study applying pollen, chironomids and diatoms was carried out in the Sarek Mountains, 150 km south of Abisko (Rosén *et al.*, 2001). Regular organic sedimentation started in the investigated alpine-tundra lake (Sjuodjijaur; 826 m a.s.l.) at 7100 cal. yrs BP which is considerably later than at Vuoskkujávri. Before the start of a regular organic sedimentation, palaeoclimatic interpretation at Sjuodjijaur is also rather speculative. Since 7100 cal. yrs BP, the temperature decrease suggested by Rosén *et al.* (2001) is comparable to the values at Vuoskkujávri. Reconstructions from both sites consistently show gradually decreasing temperature inferences for all proxy indicators. Interestingly, the diatom record at Sjuodjijaur reveals the greatest temperature decrease (1.7°C since 7100 cal. yrs BP) of all proxies, whereas the pollen-inference estimates the lowest temperature decrease (1.0°C since 7100 cal. yrs BP) of all the proxies, a pattern that is consistent with Vuoskkujávri.

A record of diatom-inferred mean July air temperature from Lake Tsuolbmajavri in northern Finland reveals very minor changes over the entire Holocene period. Inferred July temperature oscillated between 10.3 and 11.1°C with the warmest period around 6200 cal. yrs BP and the coolest at 4000 cal. yrs BP (Korhola *et al.*, 2000b). Consistent with the record from the Finnish site, the diatom record from Vuoskkujávri suggests that the

warmest summers of the entire Holocene period occurred between 6500 and 6000 cal. yrs BP even though the Vuoskkujávri diatom inference shows a 'poor' fit to temperature, which makes any comparisons tentative. However, the estimated temperature changes at Lake Tsuolbmajavri are considerably smaller than at Vuoskkujávri, and the cold phase around 4000 cal. yrs BP at Lake Tsuolbmajavri is not as pronounced in Vuoskkujávri. Minor environmental changes according to chironomids and pollen were similarly recorded in sediments from Alanen Laanjärvi close to Kiruna, a lake that is situated east of the Scandes and influenced more by continental climate (Heinrichs *et al.*, unpublished data). It seems that lakes situated east of the Scandinavian mountain range such as Lake Tsuolbmajavri and Alanen Laanjärvi are less sensitive to climatic change than sites within the mountain range, possibly because these sites lie outside the range of boundary changes between Atlantic and Arctic air masses. Instead, we hypothesize that the influences of continental climatic regimes have prevailed over the entire Holocene at these sites (Birks and Peglar, unpublished data).

A major factor confounding the temperature reconstruction over the Holocene is glacio-isostatic land-uplift. Since 9000 cal. yrs BP, land has been uplifted by c. 100 m, with most of it occurring during the early Holocene (Møller, 1987). Applying the general lapse rate for Fennoscandia of 0.57°C/100 m (Laaksonen, 1976), the natural cooling effect due to land-uplift alone is estimated to be 0.6°C since the early Holocene. The quantitative reconstructions from Vuoskkujávri (Figure 4) and the mentioned values within the discussion section are not, however, corrected for glacio-isostatic land-uplift, but glacio-isostatic land-uplift appears to account for a considerable proportion of the inferred long-term pattern of Holocene temperature change.

Palaeoclimate in the Abisko region: precipitation patterns

The pollen-inferred precipitation from Vuoskkujávri suggests more oceanic conditions during the early Holocene than today, with a shift towards drier conditions after 7000 cal. yrs BP. However, due to 'poor' fit of fossil assemblages, the reconstruction is rather tentative before 7500 cal. yrs BP. Independent evidence from oxygen-isotope studies in the Abisko region supports this reconstructed precipitation pattern. A carbonate-rich sediment core from nearby Lake Tibetanus shows exponentially decreasing $\delta^{18}\text{O}_{\text{sed}}$ values during the Holocene (Berglund *et al.*, 1996; Hammarlund *et al.*, 2002), whereas the record from Lake 850 based on oxygen isotopes extracted from deposited diatom shells ($\delta^{18}\text{O}_{\text{di}}$) reveals a more gradual decrease during this period (Shemesh *et al.*, 2001). Based on oxygen-isotope measurements, the current precipitation around Abisko originates equally from relatively enriched Atlantic air masses and relatively depleted Arctic air masses (Shemesh *et al.*, 2001). Changes in the isotopic composition not only reflect shifts in temperature (Dansgaard, 1964) but also indicate a shift in the predominating air masses (e.g., Hammarlund *et al.*, 2002). Consequently, both sedimentary records of oxygen isotopes are consistent with increasing influence of Arctic air masses carrying more depleted moisture to the Abisko region throughout the Holocene. Both studies assume in general a reduction in the amount of annual precipitation since the early Holocene, which is consistent with the pollen-inferred precipitation record at Vuoskkujávri (Shemesh *et al.*, 2001; Hammarlund *et al.*, 2002). Additional evidence for reduced precipitation after 6000 cal. yrs BP is recorded near to Vuoskkujávri in a small lake (Badsjön), where a lake-level lowering of 1.0–1.5 m took place between 6350 and 4500 cal. yrs BP (Barnekow, 2000). This reduction in the amount of annual precipitation could have triggered the expansion of *Pinus sylvestris* that began at Vuoskkujávri around 7500 cal. yrs BP. A shift to more continental climatic conditions and decreasing precipitation in connection with soil

maturation may have improved the growing conditions for *Pinus*. The same process was also suggested in a more regional context by Seppä and Hammarlund (2000), where the transgressive expansion of *Pinus* within northern Fennoscandia was related to the oxygen-isotope record from Lake Tibetanus.

To summarize, oxygen isotopes (Shemesh *et al.*, 2001; Hammarlund *et al.*, 2002) and inferred lake-level changes (Barnekow, 2000) support the general trend from more oceanic to more continental conditions as inferred in Vuoskkujävi from the pollen-based transfer functions. Although the pollen-inferred values are variable, long-term patterns reconstruct a trend towards drier conditions since at least 7000 cal. yrs BP (Figure 4).

Comparison to model simulations (COHMAP simulations)

The COHMAP community attempted to compare and validate results obtained from general circulation models (GCM) covering the last 18 000 years, using numerous well-dated palaeoecological data (COHMAP members, 1988). The approach provides one way of evaluating the mechanisms of climatic change. Based on the earth-sun geometry and Milankovitch cycles, a gradually decreasing seasonality can be expected with lower solar radiation during summer and increased radiation during winter months since the early Holocene (Bradley, 1999). The COHMAP model estimates were calculated at 3000-year intervals, so our record from Vuoskkujävi covered the last three time slices (3000, 6000 and 9000 cal. yrs BP) only. At 9000 and 6000 cal. yrs BP, the COHMAP model suggests stronger westerlies from the Atlantic to the Eurasian continent and considerably warmer temperatures than today (by 2–4°C) due to increased insolation. Since 6000 cal. yrs BP, a gradual decrease in the westerlies and in temperature was suggested, mainly due to the reduction of the ice sheets and the overall insolation. The COHMAP models are supported by diatom-inferred sea-surface conditions from the Greenland Sea, the Iceland Sea and the Norwegian Sea (Koç and Jansen, 1993).

Inferences based on diatoms, chironomids and pollen in this study at Vuoskkujävi suggest a more moderate decrease in temperature than suggested by the COHMAP GCM model. For diatoms, the decrease in temperature was 1.5°C since 6000 cal. yrs BP, whereas the pollen and chironomid inferences suggest a decrease in temperature of 1.1 and 1.2°C, respectively, which is an underestimate compared to the COHMAP model simulations. However, the precipitation pattern with increased precipitation and stronger westerlies during the early Holocene (e.g., 9000 and 6000 cal. yrs BP) is in good agreement with the pollen-inferred precipitation patterns.

Acknowledgements

The study was financed by the Norwegian NFR (Grant no. 454.88/001), the Environment and Space Research Institute (MRI) in Kiruna through CIRC and the Nordic Arctic Research Programme POLARCLIM project. We are grateful to Hilary Birks, Nigel Cameron and Viv Jones for help with fieldwork. We acknowledge Steinar Gulliksen and Göran Possnert for the radiocarbon datings, Arvid Odland for the modern climate estimates, Einar Heegaard for the depth-age modelling and the LOESS cross-validations and Karin Aune for preparing Figure 1.

References

Alexandersson, H., Karlström, C. and Larsson-McCann, S. 1991: Temperature and precipitation in Sweden 1961–1990. Reference normals. SMHI-report No 81, Norrköping, 88 pp.

- Ammann, B. and Oldfield, F. 2000: Rapid-warming project. *Palaeogeography, Palaeoclimatology, Palaeoecology* 159(3–4), 3 pp.
- Ammann, B., Birks, H.J.B., Brooks, S.J., Elcher, U., von Grafenstein, U., Hofmann, W., Lemdahl, G., Schwander, J., Tobolski, K. and Wick, L. 2000: Quantification of biotic responses to rapid climatic changes around the Younger Dryas – a synthesis. *Palaeogeography, Palaeoclimatology, Palaeoecology* 159 (Special Issue), 313–47.
- Anderson, N.J. 2000: Diatoms, temperature and climatic change. *European Journal of Phycology* 35, 307–14.
- Barnekow, L. 1999: Holocene vegetation dynamics and climate changes in the Torneträsk area, northern Sweden. PhD thesis, Quaternary Geology, Lund, 30 pp.
- 2000: Holocene regional and local vegetation history and lake-level changes in the Torneträsk area, northern Sweden. *Journal of Paleolimnology* 23, 399–420.
- Battarbee, R.W. 1986: Diatom analysis. In Berglund, B.E., editor, *Handbook of Holocene palaeoecology and palaeohydrology*, Chichester: John Wiley, 527–70.
- 2000: Palaeolimnological approaches to climate change, with special regard to the biological record. *Quaternary Science Reviews* 19, 107–24.
- Battarbee, R.W. and Kneen, M.J. 1982: The use of electronically counted microspheres in absolute diatom analysis. *Limnology and Oceanography* 27, 184–89.
- Bennett, K.D. 1996: Determination of the number of zones in a biostratigraphical sequence. *New Phytologist* 132, 155–70.
- Berglund, B.E. and Ralska-Jasiewiczowa, M. 1986: Pollen analysis and pollen diagrams. In Berglund, B.E., editor, *Handbook of Holocene palaeoecology and palaeohydrology*, Chichester: John Wiley, 455–84.
- Berglund, B.E., Barnekow, L., Hammarlund, D., Sandgren, P. and Snowball, I.F. 1996: Holocene forest dynamics and climate changes in the Abisko area, northern Sweden – the Sonesson model of vegetation history reconsidered and confirmed. *Ecological Bulletins* 45, 15–30.
- Bigler, C. and Hall, R.I. 2002: Diatoms as indicators of climatic and limnological change in Swedish Lapland: a 100-lake calibration-set and its validation for paleoecological reconstructions. *Journal of Paleolimnology*, 27, 97–115.
- Birks, H.H., Battarbee, R.W. and Birks, H.J.B. with contributions by Bradshaw, E.G., Brooks, S.J., Duigan, C.A., Jones, V.J., Lemdahl, G., Peglar, S.M., Solem, J.O., Solhøy, I.W. and Stalsberg, M.K. 2000: The development of the aquatic ecosystem at Kråkenes Lake, western Norway, during the late-glacial and early-Holocene – a synthesis. *Journal of Paleolimnology* 23, 91–114.
- Birks, H.J.B. 1973: *Past and present vegetation of the Isle of Skye: a palaeoecological study*. London: Cambridge University Press, 415 pp.
- 1981: The use of pollen analysis in the reconstruction of past climates: a review. In Wigley, T.M.L., Ingram, M.J. and Farmer, G., editors, *Climate history: studies in past climates and their impact on man*, Cambridge: Cambridge University Press, 111–38.
- 1995: Quantitative paleoenvironmental reconstructions. In Maddy, D. and Brew, J.S., editors, *Statistical modelling of Quaternary science data*, Cambridge: Quaternary Research Association XII, 161–254.
- 1998: Numerical tools in paleolimnology – progress, potentialities, and problems. *Journal of Paleolimnology* 20, 307–32.
- Birks, H.J.B. and Gordon, A.D. 1985: The analysis of pollen stratigraphical data. Zonation. In Birks, H.J.B. and Gordon, A.D., *Numerical methods in Quaternary pollen analysis*, London: Academic Press, 289 pp.
- Birks, H.J.B., Line, J.M., Juggins, S., Stevenson, A.C. and ter Braak, C.J.F. 1990: Diatoms and pH reconstruction. *Philosophical Transactions of the Royal Society London B* 327, 263–78.
- Bradley, R.S. 1999. *Paleoclimatology – reconstructing climates of the Quaternary*. San Diego: Academic Press, 613 pp.
- Brooks, S.J. and Birks, H.J.B. 2000a: Chironomid-inferred late-glacial and early-Holocene mean July air temperatures for Kråkenes Lake, western Norway. *Journal of Paleolimnology* 23, 77–89.
- 2000b: Chironomid-inferred Late-glacial air temperatures at Whitrig Bog, southeast Scotland. *Journal of Quaternary Science* 15, 759–64.
- Brooks, S.J., Mayle F.E. and Lowe, J.J. 1997: Chironomid-based Late-glacial climatic reconstruction for southeast Scotland. *Journal of Quaternary Science* 12, 161–67.
- Chapman, W.L. and Walsh, J.E. 1993: Recent variations of sea ice and air temperatures in high latitudes. *Bulletins of the American Meteorological Society* 74, 33–47.
- Clerk, S., Hall, R., Quinlan, R. and Smol, J.P. 2000: Quantitative infer-

- ences of past hypolimnetic anoxia and nutrient levels from a Canadian Precambrian shield lake. *Journal of Paleolimnology* 23, 319–36.
- COHMAP Members** 1988: Climatic changes of the last 18,000 years: observations and model simulations. *Science* 241, 1043–52.
- Dansgaard, W.** 1994: Stable isotopes in precipitation. *Tellus* 16, 436–68.
- Guilizzoni, P., Marchetto, A., Lami, A., Cameron, N.G., Appleby, P.G., Rose, N.L., Schnell, Ø.A., Bellis, C.A., Giorgis, A. and Guzzi, L.** 1996: The environmental history of a mountain lake (Lago Paione Superiore, Central Alps, Italy) for the last c. 100 years: a multidisciplinary, paleolimnological study. *Journal of Paleolimnology* 15, 245–64.
- Hammarlund, D., Barnekow, L., Birks, H.J.B., Buchardt, B., and Edwards, T.W.D.** 2002: Holocene changes in atmospheric circulation recorded in the oxygen-isotope stratigraphy of lacustrine carbonates from northern Sweden. *The Holocene* 12, 339–51.
- Huntley, B. and Prentice, I.C.** 1988: July temperatures in Europe from pollen data 6,000 years before present. *Science* 241, 687–90.
- Itkonen, A., Marttila, V., Meriläinen, J.J. and Salonen, V.-P.** 1999: 8000-year history of palaeoproductivity in a large boreal lake. *Journal of Paleolimnology* 21, 271–94.
- Johnson, M.G., Kelso, J.R.M., McNeil, O.C. and Morton, W.B.** 1990: Fossil midge association and the historical status of fish in acidified lakes. *Journal of Paleolimnology* 3, 113–27.
- Koç, N. and Jansen, E.** 1993: Paleooceanographic reconstructions of surface ocean conditions in the Greenland, Iceland and the Norwegian Sea through the last 14-ka based on diatoms. *Quaternary Science Reviews* 12, 115–40.
- Korhola, A., Olander, H. and Blom, T.** 2000a: Cladoceran and chironomid assemblages as quantitative indicators of water depth in subarctic Fennoscandian lakes. *Journal of Paleolimnology* 24, 43–54.
- Korhola, A., Weckström, J., Holmström, L. and Erästä, P.** 2000b: A quantitative climatic record from diatoms in northern Fennoscandia. *Quaternary Research* 54, 284–94.
- Krammer, K. and Lange-Bertalot, H.** 1986–91: Bacillariophyceae 1–4 Teil. In Ettl, H., Gerloff, J., Heynig, H. and Mollenhauer, D., editors, *Süßwasserflora von Mitteleuropa*, Stuttgart/New York: Gustav Fischer Verlag.
- Kulling, O.** 1964: Översikt över norra Norrbottensfjällens kaledonberggrund. *Sveriges geologiska undersökning* 19, 166 pp.
- Kullman, L.** 1999: Early Holocene tree growth at a high elevation site in the northernmost Scandes of Sweden (Lapland): a palaeobiogeographical case study based on megafossil evidence. *Geografiska Annaler* 81A, 63–74.
- Kullman, L. and Kjällgren, L.** 2000: A coherent postglacial tree-limit chronology (*Pinus sylvestris* L.) for the Swedish Scandes: aspects of paleoecology and 'recent warming', based on megafossil evidence. *Arctic, Antarctic, and Alpine Research* 32, 419–28.
- Küttel, M.** 1984: Vuolep Allakasjaure – eine pollenanalytische Studie zur Vegetationsgeschichte der Tundra in Nordschweden. *Festschrift Welten, Diss. Bot.* 72, 191–212.
- Laaksonen, K.** 1976: The dependence of mean air temperatures upon latitude and altitude in Fennoscandia (1921–1950). *Annales Academiae Scientiarum Fennicae* 119 (Series AIII), 5–19.
- Larocque, I., Hall, R.I. and Grahn, E.** 2001: Chironomids as indicators of climate change: a 100-lake training-set from a subarctic region of northern Sweden (Lapland). *Journal of Paleolimnology* 26, 307–22.
- Legendre, P. and Legendre, P.** 1998: *Numerical ecology* (second English edition). Amsterdam: Elsevier, 853 pp.
- Little, J.L. and Smol, J.P.** 2000: Changes in fossil midge (Chironomidae) assemblages in response to cultural activities in a shallow, polyimnetic lake. *Journal of Paleolimnology* 23, 207–12.
- Lotter, A.F. and Bigler, C.** 2000: Do diatoms in the Swiss Alps reflect the length of ice-cover? *Aquatic Sciences* 62, 125–41.
- Lotter, A.F., Birks, H.J.B., Hofmann, W. and Marchetto, A.** 1997: Modern diatom, cladocera, chironomid, and chrysophyte cyst assemblages as quantitative indicators for the reconstruction of past environmental conditions in the Alps. I. Climate. *Journal of Paleolimnology* 18, 395–420.
- Lotter, A.F., Pienitz, R. and Schmidt, R.** 1999: Diatoms as indicators of environmental change near Arctic and Alpine treeline. In Stoermer, E.F. and Smol, J.P., editors, *The diatoms – applications to the environmental and earth sciences*, Cambridge: Cambridge University Press, 205–26.
- MacDonald, G.M., Felzer, B., Finney, B.P. and Forman, S.L.** 2000: Holocene lake sediment records of Arctic hydrology. *Journal of Paleolimnology* 24, 1–14.
- Møller, J.J.** 1987: Shoreline relation and prehistoric settlement in northern Norway. *Norsk Geografisk Tidsskrift* 41, 45–60.
- Moore, P.D., Webb, J.A. and Collinson, E.** 1991: *Pollen analysis*. Oxford: Blackwell Scientific.
- Nesje, A. and Dahl, S.O.** 2001: The Greenland 8200 cal. yr BP event detected in loss-on-ignition profiles in Norwegian lacustrine sediment sequences. *Journal of Quaternary Science* 16, 155–66.
- Olander, H., Birks, H.J.B., Korhola, A. and Blom, T.** 1999: An expanded calibration model for inferring lakewater and air temperatures from fossil chironomid assemblages in northern Fennoscandia. *The Holocene* 9, 279–94.
- Peglar, S.M., Fritz, S.C. and Birks, H.J.B.** 1989: Vegetation and land-use history at Diss, Norfolk, UK. *Journal of Ecology* 77, 203–22.
- Punt, W. et al.**, editors, 1976–95: *The Northwest European Pollen Flora*, vols. I–VII. Amsterdam: Elsevier, 265 pp.
- Quinlan, R.J., Smol, J.P. and Hall, R.I.** 1998: Quantitative inferences of past hypolimnetic anoxia in south-central Ontario lakes using fossil midges (Diptera: Chironomidae). *Canadian Journal of Fisheries and Aquatic Sciences* 55, 587–96.
- Rautio, M., Sorvari, T. and Korhola, A.** 2000: Diatom and crustacean zooplankton communities, their seasonal variability, and representation in the sediment of subarctic lake Saanajärvi. *Journal of Limnology* 59, 81–96.
- Renberg, I.** 1990: A procedure for preparing large sets of diatom slides from sediment cores. *Journal of Paleolimnology* 4, 87–90.
- 1991: The HON-Kajak sediment corer. *Journal of Paleolimnology* 6, 167–70.
- Renberg, I., Korsman, T. and Birks, H.J.B.** 1993: Prehistoric increases in the pH of acid-sensitive Swedish lakes caused by land-use changes. *Nature* 362, 824–26.
- Rind, D. and Overpeck, J.** 1993: Hypothesized causes of decade-to-century-scale climate variability: climate model results. *Quaternary Science Reviews* 12, 357–74.
- Rosén, P., Segerström, U., Eriksson, L., Renberg, I. and Birks, H.J.B.** 2001: Climate change during the Holocene as recorded by diatoms, chironomids, pollen and near-infrared spectroscopy (NIRS) in a sediment core from an alpine lake (Sjuodjjaure) in northern Sweden. *The Holocene* 11, 551–62.
- Schnell, Ø.A., Fjellheim, A. and Raddum, G.G.** 1994: Invertebrates – past and present – AL:PE – acidification of mountain lakes: palaeolimnology and ecology. In Wathne, B.M. and Patrick, S.T., editors, *AL:PE Report*, Oslo: Norwegian Institute for Water Research (NIVA), 67–71.
- Seppä, H. and Hammarlund, D.** 2000: Pollen-stratigraphical evidence of Holocene hydrological change in northern Fennoscandia supported by independent isotopic data. *Journal of Paleolimnology* 24, 69–79.
- Serreze, M.C., Walsh, J.E., Chapin, F.S., Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W.C., Morison, J., Zhang, T. and Barry, R.G.** 2000: Observational evidence of recent change in the northern high-latitude environment. *Climatic Change* 46, 159–207.
- Shemesh, A., Rosqvist, G., Rietti-Shati, M., Rubensdotter, L., Bigler, C., Yam, R. and Karlén, W.** 2001: Holocene climatic change in Swedish Lapland inferred from an oxygen-isotope record of lacustrine biogenic silica. *The Holocene* 11, 447–54.
- Smith, M.J., Pelatt, M.G., Walker, I.R. and Mathewes, R.W.** 1998: Post-glacial changes in chironomid communities and inferred climate near treeline at Mount Stoyoma, Cascade Mountains, southwestern British Columbia, Canada. *Journal of Paleolimnology* 20, 277–93.
- Smol, J.P.** 1988: Paleoclimate proxy data from freshwater arctic diatoms. *Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie* 23, 837–44.
- Snowball, I.F.** 1996: Holocene environmental change in the Abisko region of northern Sweden recorded by the mineral magnetic stratigraphy of lake sediments. *GFF* 118, 9–17.
- Snowball, I. and Sandgren, P.** 1996: Lake sediment studies of Holocene glacial activity in the Kårsa valley, northern Sweden: contrasts in interpretation. *The Holocene* 6, 367–72.
- Sonesson, M.** 1974: Late Quaternary forest development of the Torneträsk area, north Sweden. 2. Pollen analytical evidence. *OIKOS* 25, 288–307.
- Sonesson, M. and Lundberg, B.** 1974: Late Quaternary forest development of the Torneträsk area, north Sweden. 1. Structure of modern forest ecosystems. *OIKOS* 25, 121–33.
- Stuiver, M. and Reimer, P.J.** 1993: Extended ¹⁴C data base and revised CALIB 3.0 ¹⁴C age calibration program. *Radiocarbon* 35, 215–30.
- ter Braak, C.J.F.** 1987: Ordination. In Jongman, R.H.G., ter Braak, C.J.F.

and van Tongeren, O.F.R., editors, *Data analysis in community and landscape ecology*, Cambridge: Cambridge University Press, 91–173.

— 1995: Non-linear methods for multivariate statistical calibration and their use in palaeoecology: a comparison of inverse (k-nearest neighbours, partial least squares and weighted averaging partial least squares) and classical approaches. *Chemometrics and Intelligent Laboratory Systems* 28, 165–80.

ter Braak, C.J.F. and 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.

ter Braak, C.J.F. and Smilauer, P. 1998: *Canoco for Windows: software for Canonical Community Ordination (version 4)*. Ithaca, NY: Microcomputer Power.

Walker, I.R., Smol, J.P., Engstrom, D.R. and Birks, H.J.B. 1991: An assessment of Chironomidae as quantitative indicators of past climatic change. *Canadian Journal of Fisheries and Aquatic Sciences* 48, 975–87.

Weller, G. and Lange, M. 1999: Impacts of global climate change in the Arctic regions. Tromsø: IASC Report, 59 pp.

Wiederholm, T. 1983: Chironomidae of the Holarctic region, keys and diagnoses: Part 1 – Larvae. *Entomologica scandinavica Supplement* 19, 457 pp.

Willemse, N.W. and Törnqvist, T.E. 1999: Holocene century-scale temperature variability from West Greenland lake records. *Geology* 27, 580–84.

Wright, H.E. 1967: A square-rod piston sampler for lake sediments. *Journal of Sedimentology and Petrology* 37, 975–76.