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Late-Quaternary summer temperature changes in the northern-European tree-line region

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Abstract

We present two new quantitative July mean temperature (T_{jul}) reconstructions from the Arctic tree-line region in the Kola Peninsula in north-western Russia. The reconstructions are based on fossil pollen records and cover the Younger Dryas stadial and the Holocene. The inferred temperatures are less reliable during the Younger Dryas because of the poorer fit between the fossil pollen samples and the modern samples in the calibration set than during the Holocene. The results suggest that the Younger Dryas T_{jul} in the region was 8.0–10.0°C, being 2.0–3.0°C lower than at present. The Holocene summer temperature maximum dates to 7500–6500 cal yr BP, with T_{jul} about 1.5°C higher than at present. These new records contribute to our understanding of summer temperature changes along the northern-European tree-line region. The Holocene trends are consistent in most of the independent records from the Fennoscandian–Kola tree-line region, with the beginning of the Holocene thermal maximum no sooner than at about 8000 cal yr BP. In the few existing temperature-related records farther east in the Russian Arctic tree line, the period of highest summer temperature begins already at about 10,000 cal yr BP. This difference may reflect the strong influence of the Atlantic coastal current on the atmospheric circulation pattern and the thermal behaviour of the tree-line region on the Atlantic seaboard, and the more direct influence of the summer solar insolation on summer temperature in the region east of the Kola Peninsula.
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Keywords: Pollen; Kola Peninsula; Transfer function; Younger Dryas; Holocene

Introduction

The northern tree line is controlled by a few critical climatic parameters, and its past movements can provide a basis for assessing paleoclimatic trends at high latitudes. Winter temperatures can be important for tree growth and tree-line location in the oceanic climatic regions (Crawford et al., 2003; Crawford and Jeffree, 2004), but in more continental regions the main determinants for the location of the conifer tree line are climatic parameters associated with growing-season conditions, such as mean growing degree days, the duration of the growing season, and mean temperature of the warmest month (Tuhkanen 1993; Sveinbjornsson, 2000; Grace et al., 2002; Körner, 2006). The sensitivity of the tree line to summer temperature changes is important from the viewpoint of paleoclimatic reconstructions because it permits the construction of transfer functions for specifically determined climatic parameters such as July mean temperature. Thus, quantitative summer temperature reconstructions based on pollen, chironomid, and diatom data, for example, have been widely generated in the northern tree-line regions (e.g. Rosén et al., 2001; Seppä and Birks, 2001, 2002; Andreev et al.

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2004; Bjune et al., 2004; Kerwin et al., 2004; Larocque and Hall, 2004; Ilyashuk et al., 2005; Solovieva et al., 2005; Caseldine et al., 2006; Weckström et al., 2006).

Although still relatively sparse, quantitative summer temperature reconstructions from the Fennoscandian tree-line zone have provided evidence for generally consistent patterns of Holocene climate change. Pollen-based July mean temperature reconstructions have, along with other climatic proxy methods, shown a relatively clearly defined Holocene thermal maximum (HTM) at 8000 to 4000 calibrated radiocarbon years before present (cal yr BP), the onset of Holocene neoglaciation at 4000 cal yr BP and a gradual cooling towards the present (Seppä and Birks, 2001, 2002; Davis et al., 2003). This differs from the results obtained farther east in the northern Russian tree-line region. There the plant megafossil and macrofossil data show that the northern conifer forest limit reached its northernmost post-glacial position already roughly at 10,000–9000 cal yr BP (Krementski et al., 1998; MacDonald et al., 2000b; Paus et al., 2003; Väliranta et al., 2006), suggesting that high summer temperatures in the east were reached 1000–2000 yr earlier than in northern Fennoscandia and in closer correspondence with summer insolation peak in the early Holocene (CAPE Project members, 2001; MacDonald et al., 2000a,b). However, the paleoclimatic records are still sparse in the region and are totally lacking from large parts of the European Russian Arctic. Any comprehensive understanding of Holocene summer temperature changes in northern Europe requires additional paleoclimatic records with good time resolution and wider geographical coverage.

For resolving the summer temperature pattern in northern Europe, a key region is the Kola Peninsula, located between Fennoscandia and the Russian Arctic. Here we present two new pollen-based July mean temperature reconstructions from the tree-line region on the northern coast of the central Kola Peninsula. We combine these new records with existing records from the Fennoscandian tree line in order to assess the geographical consistency of the reconstructed paleoclimatic features along this west-to-east transect. An essential climatic feature of this transect is the influence of the Norwegian Current and associated high coastal sea surface-water temperature (SST). The winter ice-free sea leads to higher winter, spring, and autumn temperatures in the adjacent continent and promotes the growth of trees at higher latitudes than at the corresponding latitudes further east. Thus, in addition to the main forcing factors such as solar insolation, the paleoclimatic patterns in the region may have been influenced by Holocene changes in ocean current patterns and SST, providing a link to the paleoceanographic records obtained from the northern Norwegian Sea and the Barents Sea region.

Materials and methods

New quantitative climate reconstructions were developed from pollen records obtained from two small lakes located in the Arctic tree-line region of the Kola Peninsula, north-western Russia (Fig. 1). This region was deglaciated about 13,000 cal yr BP (Snyder et al., 1997, 2000). Both lakes are of 3–5 ha in size. Lake KP-2 (68°48’N, 35°19’E) is a sub-Arctic lake located in the sparse mountain-birch zone about 25 km north of the limit of pine (*Pinus sylvestris*). Mountain birch (*Betula pubescens* ssp. *tortuosa*) is the only tree species around the lake, interspersed with patches of *Juniperus communis* (Gervais et al., 2002). Dwarf shrubs such as *Vaccinium myrtillus* and *Empetrum nigrum* dominate the field layer on dry sites and willows (*Salix* spp.) are common on moister sites. Lake Yarnyshnoe (69°04’N, 36°04’E) is a tundra lake on the central Murman coast. The surrounding vegetation is dominated by ericoids and sedges, with diverse tundra herbs and mosses on moister sites. Scattered stands of mountain birch occur on lower ground and in sheltered sites. The distance to the northern limit of pine forest is about 50 km (Snyder et al., 2000).

Figure 1. The location of the study region and the two lakes on the Kola Peninsula (A = Lake KP-2, B = Lake Yarnyshnoe). Other key sites referred to in Figure 5 are also shown (C = Lake Ifjord, D = Lake Isohattu, E = Lake Tsuolbmajavri, F = Lake Toskaljavri, G = Lyngen Peninsula, H = Abisko).

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Table 1
Summary performance statistics of the pollen-climate calibration model used for the quantitative T_{jul} reconstructions

Number of sites	304
Temperature gradient	7.7–17.1°C
Temperature range	9.4°C
Number of taxa	156
R^2 between predicted and modern T_{jul}	0.722
RMSEP	0.995°C
Maximum bias	3.939°C
RMSEP as % of the gradient length	10.6%

The root-mean square error of prediction (RMSEP), R^2 and maximum bias are based on leave-one-out cross-validation for 2-component WA-PLS model.

The sediment cores obtained from the lakes were dated by ^{14}C dating. Eight dates were obtained from Lake KP-2 and 12 from Lake Yarnyshnoe. The dates were calibrated with the CALIB 4.3 program (Stuiver and Reimer 1993), using the bidecadal tree-ring data set (set A) of the INTCAL98 calibration curve (Stuiver et al., 1998). A ten-sample smoothing of the calibration curve was applied in order to avoid multiple intersections. The age-depth models were developed by applying a third-order polynomial curve to the calibrated dates. More detailed information about the dates is given in Snyder et al. (2000) and Gervais et al. (2002).

A minimum of 500 terrestrial pollen and spore were identified from most of the samples. However, for some samples with a low pollen concentration, mostly from the late-glacial or early Holocene periods, this sum was not reached. The pollen percentage values were calculated on the basis of the total sum of terrestrial pollen grains and spores.

The pollen-based July mean temperature (T_{jul}) reconstructions were carried out using a transfer function technique. The transfer functions are based on a combined Norwegian–Finnish–Swedish pollen-climate calibration set. This set contains 304 modern pollen surface samples (the top 1 cm) collected from small to medium-sized lakes (Seppä and Birks, 2001). The modern T_{jul} values were estimated for each surface sample site from the 1961–1990 Climate Normals data. The transfer functions were developed using weighted-averaging partial least squares (WA-PLS) regression (ter Braak and Juggins, 1993; Birks, 1995), implemented by the program CALIBRATE (S. Juggins and C.J.F. ter Braak, unpublished program). The square-root transformed values of all 156 pollen and spore types were used in the transfer function. The numerical performance of the WA-PLS calibration model was tested by leave-one-out cross-validation, where the modern T_{jul} is reconstructed n times using a calibration set of the size $n-1$, omitting the sample from the site for which the modern T_{jul} is reconstructed or "predicted" (ter Braak and Juggins, 1993; Birks, 1995). The cross-validated root-mean square error of prediction is 0.995°C and the R^2 between the predicted and observed T_{jul} is 0.72, both based on a two-component WA-PLS model (Table 1). Sample-specific errors of the reconstructed values were generated by Monte-Carlo simulation (100 simulations), using the WA-PLS program (ter Braak and Juggins, 1993). For more detailed information, see Seppä and Birks (2001) and Birks and Seppä (2004).

For evaluating the reliability of the quantitative reconstructions, a canonical correspondence analysis (CCA) (ter Braak, 1986) of the fossil and modern pollen samples were carried out with T_{jul} as the only constraining variable to assess the lack of fit of the fossil samples to T_{jul} (Birks et al., 1990; Birks, 1995; Bigler et al., 2002). The squared residual distance of the modern samples was used as a criterion of lack of fit. Fossil samples were deemed to have a 'poor fit' to T_{jul} if their residual distances lie outside the extreme 5% of the modern residual distances and a 'very poor fit' if their residual distances lie outside the extreme 1% of the modern residual distances. This evaluation procedure indicates how well the composition of the fossil samples fits into the modern pollen-climate calibration set but it does not evaluate how accurate the reconstructions are (Birks, 1995). Fossil samples with a 'poor' fit may provide reliable estimates of T_{jul}, whereas samples with 'good' fit may not always provide accurate estimates (Bigler et al., 2002). Some fossil samples may have a poor fit to T_{jul} because the fossil pollen assemblage is dominated by taxa poorly represented in the modern data (e.g. *Artemisia*) or by taxa that have a weak relationship to climate today (e.g. *Betula*). In addition, to assess how well the fossil pollen assemblages are represented in the modern pollen-climate

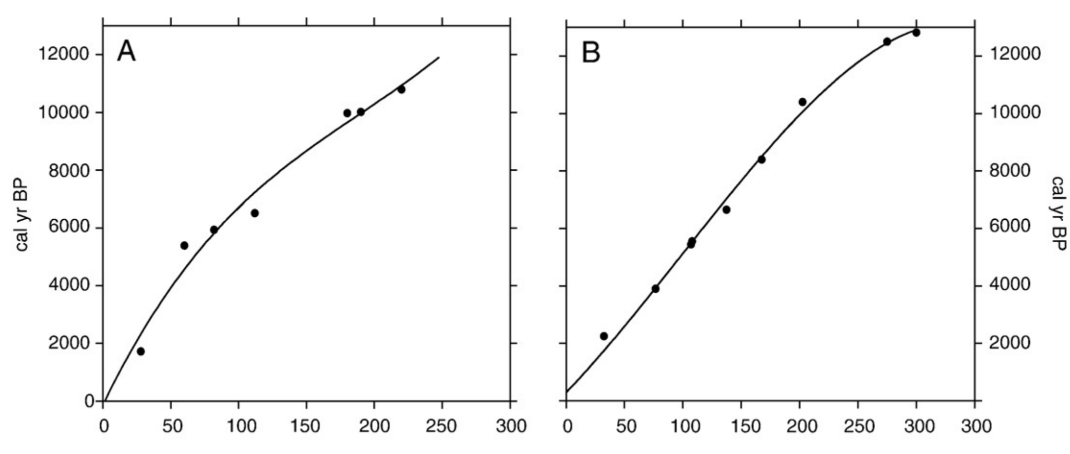

Figure 2. The age-depth models for the KP-2 (2A) and Yarnyshnoe (2B) records. A third-order polynomial curve was fitted to the calibrated ^{14}C dates. All dates were included in the models.

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calibration set, the percentages of the individual fossil samples consisting of taxa not represented in the calibration set were calculated (Birks, 1998; Bigler et al., 2002).

Results

Chronology

All radiocarbon dates were included in the age-depth modelling for Lake KP-2. The model suggests a basal age of about 11,900 cal yr BP for the core, and thus that the basal part of the core dates from the later part of the Younger Dryas (YD) stadial period (Fig. 2A). This agrees with pollen-stratigraphical features of the basal pollen samples, reflecting features typical of the end of the YD in northern Europe, notably high (~ 10%) but decreasing *Artemisia* values and high *Salix* (20–30%) values (Hyvärinen, 1975; Seppä et al., 2002a). The model suggests a relatively steady sedimentation rate during the early to mid-Holocene, with a marked slowing during the last 4000 yr.

The age-depth model for Lake Yarnyshnoe suggests a stable long-term sedimentation rate (Fig. 2B). The basal age of 12,500 cal yr BP dates to the early YD. This is supported by the pollen stratigraphy, characterized by *Artemisia* values that reach over 50% in the lowermost pollen assemblage zone, comparable with *Artemisia* values during the YD in northern Norway (Hyvärinen, 1975; Fimreite et al., 2001; Seppä et al., 2002a). The date 1200 cal yr BP for the core top (depth 1.5 cm) is due to the fact that the top section of unconsolidated watery sediment was lost during the coring (Snyder et al., 2000).

Reconstruction evaluation

The results of the CCA lack-of-fit analysis between the fossil samples and the samples in the Nordic calibration set show that the lack of fit becomes greater towards the basal parts of the stratigraphies. Lake KP-2 has a generally better fit, although the eight basal pollen samples, dating prior to 11,300 cal yr BP, have a very poor fit (Fig. 3A). Lake Yarnyshnoe has almost all samples older than 9500 cal yr BP with a poor or very poor fit and all samples before 11,000 cal yr BP with a very poor fit (Fig. 3B). Thus, samples dating to the YD and to the YD–Holocene transition have very poor fits in our data, which must be borne in mind when evaluating the T_{jul} estimates. After about 9500 cal yr BP, all samples in the records have good fits with the calibration set. Moreover, only 0%–1.0% of the fossil assemblages consist of taxa not included in the modern calibration set. Thus, in terms of pollen composition, the fossil assemblages are well covered by the calibration set.

Reconstruction results

The KP-2 record starts at 11,900 cal yr BP. T_{jul} varies markedly during the late YD, ranging from 8.5 to 11.5°C (Fig. 3A). The long-term average rises to over 10.0°C at the YD–Holocene

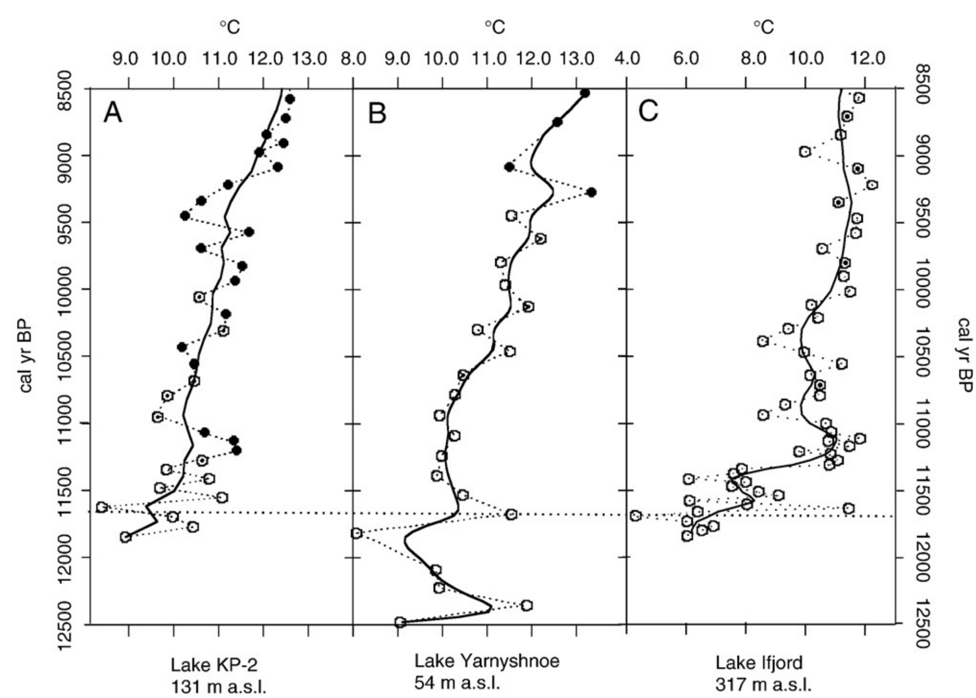

Figure 3. The T_{jul} trends during the YD–early Holocene transition at 3A) Lake KP-2, 3B) Lake Yarnyshnoe, and 3C) Lake Ifjord, located on the Norwegian North coast (Seppä et al., 2002a). All records are shown with a LOESS smoother with a span of 0.10. The filled circles indicate fossil samples with good or very good fit, the open circles with filled centres indicate samples with poor fit, and open circles samples with very poor fit with the samples of the modern calibration set, as assessed by the squared residual distances to T_{jul} in a canonical correspondence analysis. The chronology for the Lake Ifjord curve was modified from that used by Seppä et al. (2002a) by assigning an updated age for the YD–Holocene transition, 11,700 cal yr BP, in the NGRIP ice core (Rasmussen et al., 2006) with the pollen-stratigraphically detected YD–Holocene transition. The YD-Holocene boundary is shown by the dashed line. The sample-specific errors of the reconstructed values of the KP-2 and Yarnyshnoe records in Figures 3 and 4 range from 1.02 to 2.40°C.

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transition at 11,700 cal yr BP, and continues to rise steadily during the early Holocene. The maximum value, 13.5°C, is reached at about 7500 cal yr BP (Fig. 4B). After 7500 cal yr BP there is a slight decrease of about 1.0°C, but in general the values stay above the Holocene average values until 4000 cal yr BP. At that point there is a marked cooling which is followed by a steady fall towards the present.

The Yarnyshnoe record has a coarser time resolution than KP-2 and the sediment core ends at about 1600 cal yr BP. The record is valuable, however, because it extends further back in time that the KP-2 core (Fig. 3B). The T_{jul} values during the YD vary between 8.0 and 12.0°C, but are generally consistent with the KP-2 record, suggesting that average T_{jul} during the YD in the Kola Peninsula tree-line region varied between 8.0–10.0°C. There was a rapid rise to over 10°C at the transition to the early Holocene at 11,700 cal yr BP. Consistent with the KP-2 record, this was followed by a steady rise during the early Holocene. Maximum values, over 13.0°C, are recorded at 7500–6500 cal yr BP (Fig. 4A). In general, the Yarnyshnoe record is consistent in terms of the absolute values and the general trends with the KP-2 record. More precise correlations are, however, hampered by the poor temporal resolution of the Yarnyshnoe record.

Discussion

Late-glacial to Holocene transition

The KP-2 and Yarnyshnoe records provide the first quantified late-glacial and early Holocene temperature reconstructions from the Kola Peninsula, and add to previous attempts (Seppä et al., 2002a; Birks et al., 2005) to quantify late-glacial climatic conditions along the Norwegian north coast that was ice-free before the halt of deglaciation during the YD at 12,900–11,700 cal yr BP, adopting the revised Greenland ice-core chronology for the late-glacial (Rasmussen et al., 2006). The new records agree with previous ones in showing markedly lower temperature during the YD and a clear shift towards a rising trend at the YD–Holocene transition. However, the previous two pollen-based records from

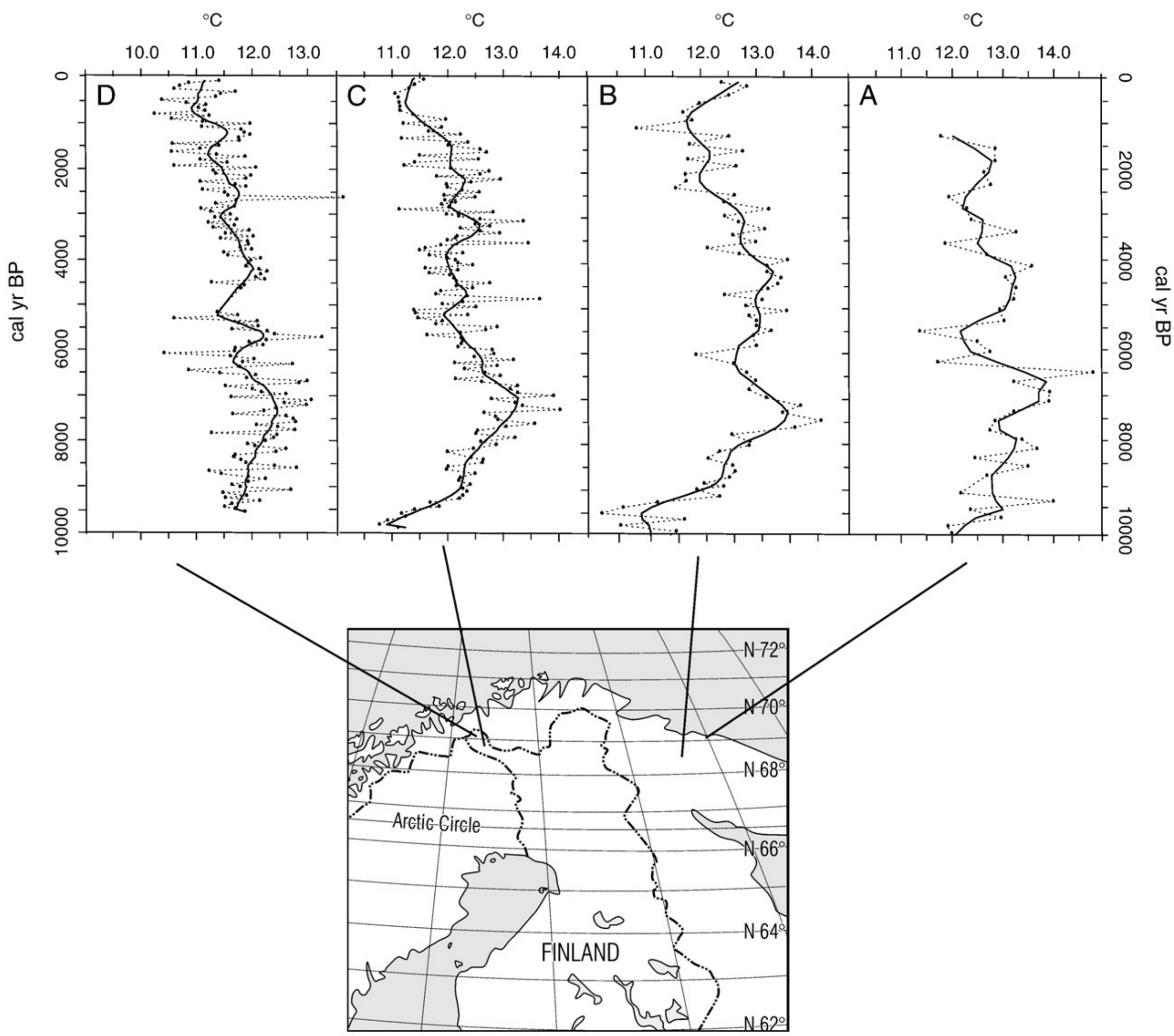

Figure 4. The Holocene T_{jul} records from (4A) Lake Yarnyshnoe and (4B) Lake KP-2, compared with the (4C) Lake Tsuolbmajavri (Seppä and Birks, 2001) and (4D) Lake Toskaljavri (Seppä and Birks, 2002) T_{jul} records. LOESS smoothers with span 0.10 are also shown.

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northernmost Norway both suggest an average T_{jul} of about 6.0°C during the YD (Seppä et al., 2002a; Birks et al., 2005). The lower reconstructed temperature may be partly due to the higher altitude of the Norwegian lakes, but, compared with the average value of 8.0–10.0°C in the KP-2 and Yarnyshnoe records, the summer temperatures during the YD seem to have been a few degrees higher on the Kola Peninsula than in northern Norway.

Due to the higher YD values, the magnitude of the T_{jul} change during the YD–Holocene transition is lower on the Kola Peninsula (1.0–2.0°C) than in northern Norway (4.0–5.0°C) and western Norway (4.0–5.0°C) (Birks et al., 2005). Although present evidence of late-glacial summer temperatures is too scarce for detailed comparisons, the Kola records suggest that summer temperatures during the YD were higher towards the east in northern Europe. This supports evidence obtained from the Timan Ridge and Pechora basin in northern Russia, about 500–800 km east of the Kola Peninsula, where a number of paleoecological and paleoeclimatological records, notably the presence of *Picea* and *Typha* macrofossils, suggest that temperature during the YD may have been only a few degrees below modern values (Paus et al., 2003; Väliranta et al., 2006). The emerging picture of the YD is that the stadial period was characterized by major expansion of winter ice cover in the North Atlantic, leading to a pronounced winter cooling, whereas the summer temperature may have fallen only a few degrees (Denton et al., 2005, Broecker, 2006; Lie and Paasche, 2006). This corroborates the inferred higher YD summer temperatures in the eastern sector of the European tree-line area, where the changes of the Atlantic ice cover and SST influence the climate less than in Scandinavia and elsewhere on the eastern Atlantic seaboard.

Holocene changes

A comparison of the KP-2 and Yarnyshnoe records with two pollen-based high-resolution T_{jul} reconstructions from the Finnish tree-line region, about 500 km west of the Kola Peninsula sites, shows generally consistent features (Fig. 4). All three records reaching back to 10,000 cal yr BP suggest that T_{jul} at 10,000 cal yr BP was below the modern value, but started to rise steadily until a T_{jul} peak at 8000–6500 cal yr BP. This was followed by a minor decline and a stable period between 6000–4000 cal yr BP, followed by a decrease towards the present. The reconstructed T_{jul} values are mostly consistent in relation to the location and modern T_{jul} values of sites. Thus, KP-2 and Tsuolbmajavri, the two sites that have the same modern T_{jul} and are located about 25 km north of the limit of the pine forest, both show a T_{jul} of 11.0 at 10,000 cal yr BP and a T_{jul} of 13.0–13.5°C during the peak at 7500 cal yr BP, while the values obtained form Lake Toskaljavri, located in the Arctic-Alpine zone, are about 1.0°C lower throughout the record. The values of Lake Yarnyshnoe, another lake located in the Arctic zone, are comparable to those from Lake KP-2 and Tsuolbmajavri, and are therefore slightly higher than expected on the basis of location of the lake. The quantitative T_{jul} record obtained from pollen stratigraphy of Lake Chuna, an altitudinal tree-line lake in the central Kola Peninsula, also shows an early- to mid-Holocene T_{jul} of about 13.0°C, followed by marked cooling during the last 4000 yr (Solovieva et al., 2005).

In addition to the main trends, all records show substantial small-scale variability but, as pointed out by Seppä and Birks (2002), the small-scale features in the quantitative temperature reconstructions from the Fennoscandian tree-line region are generally inconsistent and therefore may mostly represent noise. A consistent feature in the records is the rise of T_{jul} to peak values at 7500–6500 cal yr BP (Fig. 4) when summers were, on average, 1.5°C warmer than at present (roughly the average 20th century reconstructed T_{jul}). This agrees with the quantitative reconstructions of the peak summer temperature from a comparable latitude and environmental setting in northern Iceland (Caseldine et al., 2006) but is lower than the estimated corresponding values farther east in the Eurasian tree-line region. MacDonald et al. (2000b), for example, estimated that T_{jul} during the HTM along the North Russian tree-line area was from 2.5°C up to 7.0°C warmer that at present. The pattern of increasingly high HTM temperature from the Atlantic towards the east and more continental regions corroborates the picture obtained in climate model simulations (Ganopolski et al., 1998).

Some records from northern Europe suggest that the summer temperature maximum may have occurred in the early Holocene. Especially chironomid-based reconstructions from the Northern Swedish mountains and the Kola Peninsula indicate highest summer temperatures roughly at 10,000–9000 cal yr BP, followed by a cooling trend towards the present (Larocque and Hall, 2004; Ilyashuk et al., 2005). A comparison of various independent summer temperature or summer temperature-related records from northern Europe does not support such an early-Holocene temperature maximum (Fig. 5). The chironomid-based T_{jul} record from Lake Toskaljavri, northern Finland, shows highest summer temperatures at 8000 to 4000 cal yr BP (Fig. 5A), although there is no evidence for a peak at 7500–6500 cal yr BP and the magnitude of temperature variability is lower than in the pollen-based reconstructions (Fig. 5B). A similar general trend but with a higher temperature magnitude is shown by a diatom-based T_{jul} record from the Swedish mountains (Fig. 5C). The lake-level records from northern Finland suggest a marked dry period at 8000–4000 cal yr BP, apparently due to high summer temperature and associated increased evapotranspiration (Fig. 5D). The glacier record from the Lyngen Peninsula in north-western Norway suggests that modern ice cap did not exist at about 8500–4000 cal yr BP, probably due to the high summer temperature and/or low winter precipitation (Fig. 5E). Thus, many independent bodies of evidence demonstrate that highest summer temperature were reached no earlier than about 8000 cal yr BP and that the inferred early-Holocene maximum temperatures in some of the chironomid-based reconstructions are probably more related to the unusual early post-glacial limnological conditions than to the regional summer temperatures in northern Europe (Velle et al., 2005; Brooks, 2006).

The pine megafossil and stomata records obtained from the Kola Peninsula and the tree-line region of north-western Finnish Lapland (Fig. 5F) are of special interest because in northern Europe pine is the northernmost conifer species and its distribution and growth are generally regarded as highly dependent on summer temperature. The earliest macrofossil evidence confirms its presence already at 9700 cal yr BP in north-western Norway

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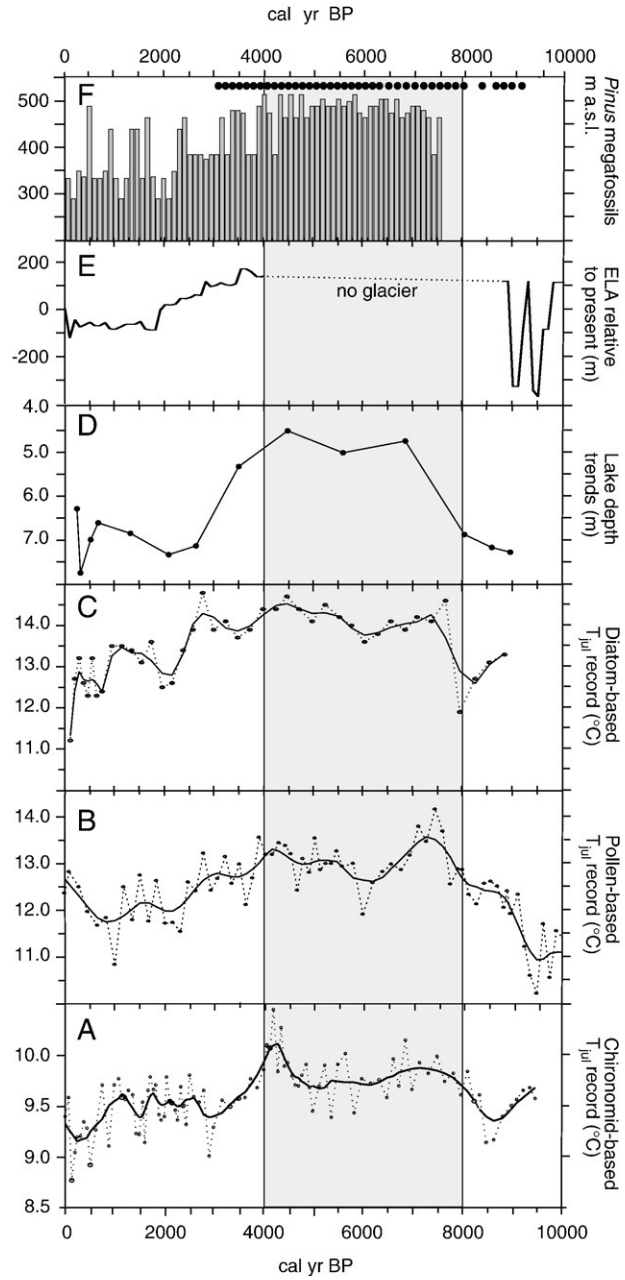

Figure 5. Records reflecting summer temperature trends in the northern-European tree-line region during the last 10,000 yr. 5A) A chironomid-based T_{jul} record from Lake Toskaljavri, an Arctic-Alpine lake in northern Finland (Seppä et al., 2002b), 5B) The pollen-based T_{jul} record from Lake KP-2 (this paper), 5C) a diatom-based T_{jul} reconstruction from Abisko in northern Sweden (Bigler et al., 2006), 5D) A lake-level record generated from a cladoceran-based transfer function model from Lake Isohattu, a closed basin in northern Finland, showing lake-level in relation to modern lake-level (Korhola et al., 2005). The record has been inverted to show low lake levels at 8000 to 4000 cal yr BP, 5E) A glacier equilibrium altitude record from the Lyngen Peninsula, northern Norway (Bakke et al., 2005), 5F) A pine megafossil record indicating the altitude of the highest pine megafossil in 200-yr periods in Finnish Lapland (Eronen et al., 1999; Helama et al., 2004), 5F) A pine stomata record from Lake KP-2 is shown above the megafossil record. Each dot represents a pollen sample containing one or more stomata (Gervais et al., 2002). Curves in Figures 5A, B, and C are shown with a LOESS smoother fitted with a span of 0.10. The gray column indicates the period of highest summer temperature (Holocene thermal maximum, HTM) in the region.

(Jensen et al., 2002). The stomata record from Lake KP-2 shows its presence at 9100 cal yr BP on the Kola Peninsula, when T_{jul} was rapidly rising but still lower than at present (Fig. 5F). This suggests that pine spread to the region as scattered individuals, probably concentrated in sheltered sites such as lake shores. At about 8000 cal yr BP, when T_{jul} rose markedly, the stomata record at the Lake KP-2 became continuous, suggesting an expansion of the pine population at the beginning of the HTM (Gervais et al., 2002). Interestingly, records from Finland and the Kola Peninsula show the appearance of pine megafossils no sooner than at 7600 cal yr BP and 7300 cal yr BP, respectively (Eronen et al., 1999; Gervais et al., 2002; Helama et al., 2004; Kultti et al., 2006). Pine megafossils do not therefore reflect the timing of the regional pine colonization, and the delayed start of the pine megafossil record does not imply a delayed immigration in relation to the rise of summer temperature at about 8000 cal yr BP. The lack of pine megafossils older than 7600 cal yr BP may be due to the scattered nature of the early-Holocene pine population and possibly poorer megafossil preservation. Apart from the delayed beginning, the period of abundant pine megafossils at 7500–5000 cal yr BP agrees with the reconstructed HTM and represents the highest altitudinal location of pine in northern Fennoscandia, consistently with high summer temperatures and predominantly dry, snow-poor soil conditions (Barnekow, 1999; Seppä et al., 2002b).

Conclusions

Quantitative reconstructions of the late-glacial climate in northern Europe are potentially unreliable because of the low number of records and poor fit between fossil samples and modern samples in the calibration data sets. Nevertheless, the main feature in the existing few records is that the inferred T_{jul} during the YD in the Kola Peninsula was 3.0–4.0°C higher than in the far north of Fennoscandia and thus only 3.0–4.0°C below the Holocene maximum level. In contrast, Holocene T_{jul} records from the Kola Peninsula are consistent with records from northern Fennoscandia and other Arctic and sub-Arctic regions in north-western Europe, including northern Iceland (Caseldine et al., 2006) and Greenland (Dahl-Jensen et al., 1998; Johnsen et al., 2001), and show that the summer temperature in the Fennoscandian and the Kola Peninsula tree-line regions rose slowly and gradually from the YD–Holocene transition until the HTM values were reached no sooner than 8500–8000 cal yr BP. The HTM lasted to about 4000 cal yr BP and was followed by a gradually falling summer temperature until present. As the records from northernmost European Russia show that the HTM began already at about 10,000 cal yr BP, there appears to have been a major early-Holocene west-to-east summer temperature gradient along the tree line. In the European Russian Arctic the summer temperature may have more directly responded to insolation variations, while the delayed warming in northern Fennoscandia may have resulted from the stronger proximal influence of North Atlantic circulation and high SSTs, including winter ice-free conditions, and possibly enhanced westerly or northerly airflow from the Atlantic (Seppä and Birks, 2001; Shemesh et al., 2001; Hammarlund et al., 2002; Wolfe et al., 2003). The high early-Holocene SST may have influenced the air pressure contrast

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between the continent and the Atlantic, thus weakening the preconditions for the development of anticyclonic atmospheric circulation pattern that is at present associated with highest summer temperatures in Fennoscandia (Busuioc et al., 2001; Aschberger et al., 2007). The region with delayed beginning of the HTM is roughly comparable with the modern extent of the warm Norwegian coastal current and associated winter ice-free conditions (Kvingedal, 2005), reaching from the North Atlantic to the eastern tip of the Kola Peninsula, possibly up to the Kanin Peninsula. Thus, the hypothesis stressing the link between the delayed rise of the summer temperature to the HTM level and the Atlantic can be tested in the future by obtaining continental paleotemperature records from the large coastal tree-line region east of the Kola Peninsula.

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