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Holocene climate variability on the Kola Peninsula, Russian Subarctic, based on aquatic invertebrate records from lake sediments

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ABSTRACT

Sedimentary records of invertebrate assemblages were obtained from a small lake in the Khibiny Mountains, Kola Peninsula. Together with a quantitative chironomid-based reconstruction of mean July air temperature, these data provide evidence of Holocene climate variability in the western sector of the Russian Subarctic. The results suggest that the amplitude of climate change was more pronounced in the interior mountain area than near the White Sea coast. A chironomid-based temperature reconstruction reflects a warming trend in the early Holocene, interrupted by a transient cooling at ca. 8500–8000 cal yr BP with a maximum drop in temperature (ca. 1°C) around 8200 cal yr BP. The regional Holocene Thermal Maximum, characterized by maximum warmth and dryness occurred at ca. 7900–5400 cal yr BP. During this period, July temperatures were at least 1°C higher than at present. The relatively warm and dry climate persisted until ca. 4000 cal yr BP, when a pronounced neoglacial cooling was initiated. Minimum temperatures, ca. 1–2°C lower than at present, were inferred at ca. 3200–3000 cal yr BP. Faunal shifts in the stratigraphic profile imply also that the late-Holocene cooling was followed by a general increase in effective moisture.

Introduction

The Kola Peninsula constitutes the eastern part of northern Fennoscandia and lies almost entirely above the Arctic Circle. In a European Arctic perspective, this land mass, located between the Scandinavian seaboard with its relatively mild climate and the Russian Arctic coastline characterized by increasingly continental climatic conditions, is of great interest for studies of long-term climate dynamics. The climate of the Kola Peninsula is subject to the moderating influence of the surrounding seas and especially the northern extension of the North Atlantic Current (Filatov et al., 2005), thus differing from areas further east in Russia, which are influenced largely by the Arctic Ocean. The most typical features of the regional climate are cool and rainy summers, relatively mild winters, and unstable and suddenly changing weather caused by frequent changes in air masses related to frontal passages (Elshin and Kupriyanov, 1970).

In spite of a generally increased attention to past climates of Fennoscandia over the last decades, palaeoclimatic data from the Kola Peninsula are still fragmentary. The main focus of many palaeoecological studies in this region has been on vegetation changes, particularly tree-line migration. Evidence from pollen and plant macrofossil sequences (Vaschalova, 1986; Kremenetski et al., 1997, 1999; Gervias et al., 2002; Kremenetski et al., 2004) and radiocarbon-dated tree megafossils (MacDonald et al., 2000a; Hiller et al., 2001; Boettger et al., 2003) indicates a relatively warm climate on the Kola Peninsula during the early Holocene and a cooling after 6000–4000 cal yr BP. In contrast to the vegetation dynamics, little attention has been paid to the long-term changes in aquatic communities in the region. Inferences based on diatoms (Lebedeva et al., 1987; Snyder et al., 2000; Grönlund and Kauppila, 2002; Solovieva and Jones, 2002) and midges (Ilyashuk and Ilyashuk, 2001; Ilyashuk et al., 2005) are available only from a few lakes. Stable-isotope records from lacustrine sediments (Wolfe et al., 2003; Jones et al., 2004) have been used as independent qualitative evidence of Holocene humidity changes. With respect to quantitative palaeotemperature records, few well-dated sequences are available in the region. Two quantitative 400-year-long temperature reconstructions have been based on tree-ring records, one from a latitudinal tree-line site (Gervais and MacDonald, 2000) and another from the altitudinal tree-line in the Khibiny Mountains (Kononov et al., 2009). As regards the Holocene, quantitative temperature reconstructions are also still sparse in the region compared to other parts of northern Fennoscandia. There are chironomid-based inferences from the southern coastline (Ilyashuk et al., 2005), and pollen-based from the northern coastline (Seppä et al., 2008) and the central part of the peninsula (Solovieva et al., 2005), providing evidence of some differences in

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spatial and temporal patterns of Holocene climate changes across the Kola Peninsula. For example, the Holocene Thermal Maximum (HTM) dates to 8000–6500 cal yr BP in the north-western coastal areas, 9000–5000 cal yr BP in the central mountain area, and 10,000–8600 cal yr BP at the southern coast. The differences are attributed primarily to regional variations in atmospheric circulation patterns and also depend on the proxies used. Thus, new well-dated Holocene palaeoclimatic records and the incorporation of other proxies are required to clarify regional aspects of Holocene climate dynamics on the Kola Peninsula.

Lake ecosystems situated at ecotonal boundaries, such as arctic or alpine tree-line, where the major controlling factor is often climate, are highly responsive to even minor changes in climatic and environmental conditions (MacDonald et al., 1993; Smol and Cumming, 2000; Lotter and Psenner, 2004; Thompson et al., 2009). The relationship between biotic assemblages and climate in such extreme ecosystems is usually straightforward, and therefore, fossil remains of various organisms preserved in lake sediments may provide valuable proxy climate records (Korhola et al., 2002; Heegaard et al., 2006). Although aquatic organisms may also respond indirectly to climatic changes through numerous environmental drivers, factors other than climate often appear to be much less important in affecting species composition in lakes at the subarctic alpine tree-line.

In this study, a small mountain lake in the forest–alpine tundra ecotone was selected to investigate the freshwater ecosystem development and to reconstruct long-term climate changes during the Holocene based on chitinous aquatic invertebrate remains from its sediment succession. The principal aim of the study was to provide a chironomid-inferred temperature record for the central part of the Kola Peninsula and to determine the main features of the Holocene environmental and climatic development based on associated invertebrate data. Our new temperature inferences for the continental area of the Kola Peninsula were compared to a chironomid-based temperature reconstruction for the boreal coastal area in the southern part of the peninsula (Ilyashuk et al., 2005), as well as to various other proxy climate records from the region and then to other records from northern Fennoscandia.

Study area

Lake Kupal'noe (67°39.55′N; 33°37.56′E) is a small lake located in the Khibiny Mountains at 352 m asl in the west-central part of the Kola Peninsula, ca. 130 km north of the Arctic Circle (Fig. 1). The Khibiny is a low-elevation crystalline mountain system formed by alkaline Caledonian intrusions connected with a regional tectonic fracture within the Precambrian Baltic Shield. The highest peaks reach about 1200 m asl. The bedrock underlying the lake is composed mainly of late Devonian nepheline syenites. Quaternary strata are composed of tills and glaciofluvial sediments (Atlas Murmanskoy oblasti, 1971). During the last glaciation, the Kola Peninsula was covered by the north-eastern sector of the Fennoscandian ice sheet. Deglaciation of the Khibiny area began at ca. 16,000 cal yr BP, and was completed at 9500–8500 cal yr BP (Miagkov, 1986).

Lake Kupal'noe (ca. 230 m × 120 m) is located in a depression dominated by two larger lakes, Malyi Vudjavr (1.5 km^2) and Bolshoi Vudjavr (3.6 km^2). Its maximum depth is 4.5 m. The lake has no permanent inflows and outflows. The lake is clear, dilute, oligotrophic and slightly acidic (Table 1). The aquatic moss *Warnstorfia exannulata* (B.S.G.) Loeske is abundant at depths of 3.0–4.5 m. The depression experiences strong cold winds from the Kukisjok River valley and is characterized by temperature inversions and relatively dry and poor soils. Therefore, although forests grow in the valleys and the mountain slopes of the Khibiny Mountains up to 350–400 m asl, typical alpine tundra communities dominated the catchment area of the lake in 1970–1980s (Miagkov, 1986). According to a recent tree-ring based summer temperature reconstruction (Kononov et al., 2009), a temperature increase occurred in the Khibiny Mountains during the past decades. Consequently, birch trees have established in the area, and dwarf birch forest–tundra is the modern vegetation surrounding the lake (Fig. 2). Small conifer trees (Norway spruce) also occur occasionally. The limit between the subarctic tundra zone and the forest tundra zone usually follows closely the July isotherm of 10°C (Alexandrova, 1970).

At an elevation of 360 m asl, ca. 4 km northeast of the lake, the weather station Apatitovaya Gora was operated from 1930 to 1960. According to meteorological data from this period, the mean annual air temperature was -1.1°C (Terziev, 1965) and the mean annual precipitation was 540 mm (Kobysheva, 1988). The mean air temperature of the coldest month (February) and the warmest month (July) was -11.6°C and $+12.5$°C, respectively (Terziev, 1965). In the Lake Kupal'noe area, it can be 1–2°C colder than at the weather station because of cold air masses from the Kukisjok River valley affecting the local microclimate.

Materials and methods

Sediment sampling, chronology, and elemental analysis

In August 1999, over-lapping sediment cores were obtained using a Russian peat sampler (Jowsey, 1966), 7.5 cm in diameter and 1 m long, from a floating platform in the central part of the lake at a water depth of 4.5 m. The uppermost unconsolidated sediments were sampled with a HTH-teknik gravity corer (Renberg and Hansson, 2008) with an inner diameter of 63 mm and subsampled in the field. Sediment depths below the water surface were used for the sediment description. For analyses of biological proxies (aquatic invertebrate remains) and elemental geochemistry, the 131 cm-thick sediment sequence was sectioned contiguously into 62 subsamples, taking into account lithostratigraphical boundaries: at 1–2 cm resolution within short lithostratigraphic units and 3–4 cm resolution within relatively long units.

Chronological control for the sediment sequence was provided by five accelerator mass spectrometry (AMS) radiocarbon dates derived from plant macrofossils (Table 2). The age–depth model was developed with the aid of the Bayesian statistical method of the OxCal 4.1 program (Bronk Ramsey, 2012), in which calendar ages for a sequence of ^{14}C ages are calculated using the INTCAL 09 dataset of Reimer et al. (2009). The P sequence ($k = 100$) deposition model (Bronk Ramsey, 2008) was used as the most appropriate. A third-order polynomial fit was then performed to establish the best age–depth model (Fig. 3). The ages are expressed in years before present (cal yr BP), where “present” is defined as AD 1950.

Total carbon content (TC) and total nitrogen content (TN) were determined on freeze-dried and homogenized samples following acid-washing (10% HCl at 60°C during 2 h) and repeated rinsing in deionised water to remove trace amounts of inorganic carbon, using a CE Instruments NC2500 elemental analyzer. The TC and TN data are expressed as percentages of dry weight of the sediment (DW), and carbon/nitrogen ratios (C/N) are expressed as atomic ratios. The potential presence of inorganic nitrogen in the sediments was tested through linear regression based on a TN–TC cross plot (Talbot, 2001) but only negligible amounts of inorganic nitrogen were detected.

Analysis of biological proxies

All 62 sediment samples were analysed for head capsules of chironomids (non-biting midges), ceratopogonids (biting midges), and exoskeletons of aquatic oribatids (moss mites). Processing and sorting of chironomid remains followed standard procedures outlined in Walker (2001) and Brooks et al. (2007). As recommended by Heiri and Lotter (2001), at least 50 chironomid head capsules (HC) were counted and identified in each sample in order to provide a basis for reliable temperature reconstructions. Concentrations of invertebrate remains were calculated as numbers of remains per gram of dry sediment (remains g^{-1} DW). During the sorting of invertebrate remains, aquatic

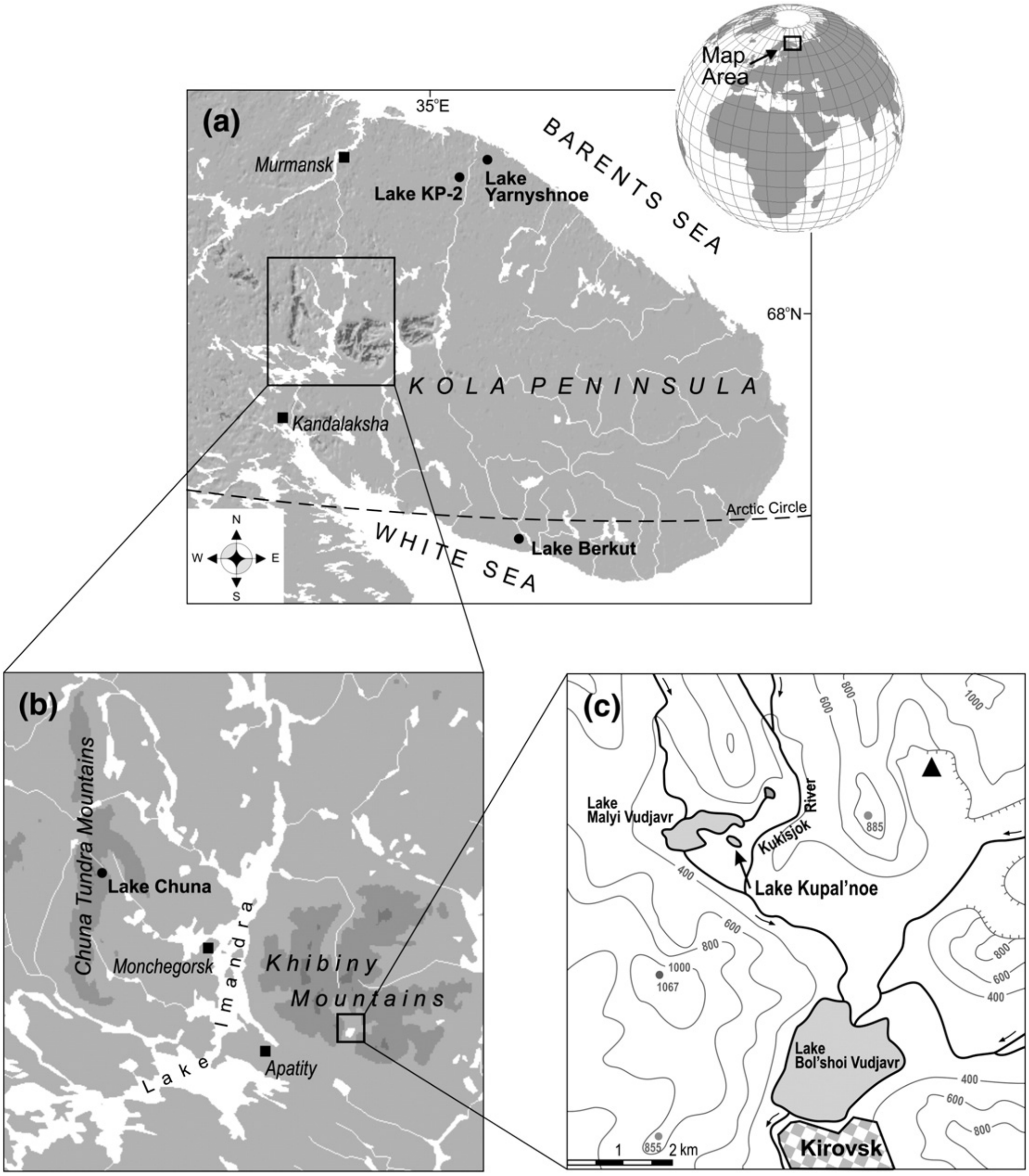

Figure 1. Map of: (a) the Kola Peninsula and (b) the west-central part of the Kola Peninsula showing the location of (c) the study area. The triangle indicates the position of the meteorological station Apatitovaya Gora. Sites used for comparisons, Lake Berkut (Ilyashuk et al., 2005), Lake Chuna (Solovieva et al., 2005), and Lake KP-2 and Lake Yarnyshnoe (Seppä et al., 2008) are also shown.

plant macrofossils were picked out and identified using the key by van de Weyer et al. (2007).

Chironomid identifications were mainly based on Wiederholm (1983), Brooks et al. (2007) and other taxonomic guides (Pankratova, 1970; Makarchenko and Makarchenko, 1999). The morphotypes of ceratopogonids were identified following Walker (2001). The taxonomic keys by Narchuk et al. (1997) and Weigmann (2006) were used for the identification of oribatid exoskeletons.

Numerical analyses

The relative abundances of individual invertebrate taxa were calculated as percentages of the total number of specimens in each sample. The TGView 2.0.2 software (Grimm, 2004) was used for the calculation of percentages and for drawing of stratigraphic diagrams. Only chironomid taxa occurring in at least two sediment samples with a relative abundance of more than 2% in at least one sample were included in further numerical analyses. Zonation was carried out by optimal partitioning using sum-of-squares criteria (Birks and Gordon, 1985) in the program Psimpoll 4.27 (Bennett, 2002), and the number of statistically significant zones was determined with the broken stick model (Bennett, 1996).

Mean July air temperature (T_{July}) at the Lake Kupal'noe area was reconstructed using a chironomid–temperature transfer function based on a modern chironomid calibration dataset of 100 lakes from the Abisko Mountains, northern Sweden, and a two-component weighted averaging partial least-squares regression (WA-PLS) model (Larocque et al., 2001). We used this model for the reconstruction because it was developed in the nearest subarctic mountain area (600 km southwest of the lake) and the chironomid fauna represented in the calibration set is quite similar to that found in the Khibiny Mountains. The relative explanatory strength of T_{July} as a predictor of chironomid assemblage composition in the training set was tested using redundancy analysis (RDA) with T_{July} as a single explanatory variable by calculating the ratio of the eigenvalue of the first constrained RDA axis (λ_1) with the first unconstrained axis (λ_2) (Juggins, 2013). T_{July} accounts for a total of 9.1% of the total variance in the chironomid data, and this component is highly significant

($p = 0.001$, 999 permutations). The ratio λ_1/λ_2 of 0.93 suggests, however, that not only T_{July} is the main determinant of chironomid distribution but also co-varying secondary variables can affect the chironomid–temperature relationship. The taxonomy of the down-core assemblages was harmonized with that of the modern calibration set before the T_{July} reconstruction. Sample-specific prediction errors (SSPE) were estimated by Monte Carlo simulations (500 runs) following Birks (1995). Palaeotemperatures were modelled with the computer program C^2 1.7.2 (Juggins, 2003). A locally weighted regression smoothing (LOESS; Cleveland et al., 1993) with a span of 0.2 (order = 1) was used to identify the main long-term trends in the quantitative reconstruction.

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). Furthermore, chironomid taxa in the down-core record with a Hill's N2 (Hill, 1973) below 5 in the calibration data were considered to be rare in the modern dataset (Brooks and Birks, 2001; Heiri et al., 2003). The modern analogue technique with chi-square distance as the dissimilarity coefficient was used to identify the similarity between each analyzed subfossil assemblage and the most similar subfossil assemblage within the modern calibration dataset (Birks et al., 1990). A cut level of the 5th percentile of all chi-square distances within the modern data was assumed to define down-core samples with no 'good' modern analogues. Canonical correspondence analysis (CCA) of the modern calibration data and the down-core passive samples with T_{July} as the sole constraining variable was carried out to assess the fit of the analyzed individual down-core assemblages to temperature (Birks et al., 1990; Birks, 1995, 1998). The residual distance of the modern samples from the environmental variable axis was used as a criterion of fit. Any down-core sample with a residual distance to the first CCA axis equal to or larger than the 95th percentile of the residual distances of all the modern samples was considered to have a 'poor fit' to T_{July} (Birks et al., 1990). Hill's N2 value calculations and analogue matching were carried out using the program C^2 1.7.2 (Juggins, 2003), and CCA was accomplished with the program CANOCO 4.5 (ter Braak and Šmilauer, 2002). In addition, the reconstruction was assessed by performing the significance test developed by Telford and Birks (2011). For the test we use RDA and generated 999 transfer functions trained on random data. The statistical software R version 2.15.2 (R Development Core Team, 2012) with the package palaeoSig 1.1-1 (Telford, 2012) was used for the calculation.

Results and interpretations

Sediment characteristics

The sediment sequence begins with 10 cm of greyish brown, slightly silty gyttja with macroscopic plant remains followed by a uniform 121-cm sequence of brown detritus gyttja with abundant macroscopic remains of the aquatic moss *W. exannulata*. The records of TC and TN contents and the resulting C/N ratio are illustrated in Figure 4. The basal sediments (ca. 10,400–10,100 cal yr BP) are characterized by the lowest organic matter content. During the next ca. 500 yr the TC values rise rapidly from 13% to 32%, and the sediments contain numerous *Chara*/*Nitella* oospores encrusted with calcium carbonate. The increase in C/N ratio from 23 to 31 within this sediment section may be interpreted as an increase in the proportion of terrestrial organic matter (cf. Kaushal and Binford, 1999) due to subalpine vegetation and soil development in the recently deglaciated lake catchment. The following part of the sequence (ca. 9600–8500 cal yr BP) exhibits relatively high TC contents (33–36%), followed by a decrease to 28% at ca. 8200 cal yr BP and a generally increasing trend to 44% in the interval of 8200–5800 cal yr BP. Throughout the rest of the sequence (ca. 5800–0 cal yr BP) the TC content remains high, varying between 39% and 46%. The C/N ratio ranges from 27 to 32 within the period of ca. 9600–4000 cal yr BP, then decreases gradually during ca. 200 yr, and persists at a nearly constant level (25–26) after ca. 3200 cal yr BP. The lower C/N ratios in the later part of the record may reflect an increase in the proportion of autochthonous organic matter, possibly due to a more extensive development of the aquatic moss, whose remains occur in the sediment record from ca. 9700 cal yr BP until present time, in response to the relatively low temperatures during this period, a weakening of plankton community production and an increase in water transparency. Most likely, the relative stable TC values and increased TN values indicate a decrease in the decomposition of moss remains in the sediments under cold conditions and, as a consequence, the accumulation of coarse organic matter in the lake.

Table 1
Selected geographic, morphometric, hydrophysical and hydrochemical (0.5 m water depth) characteristics of Lake Kupal'noe, September 2000.

Parameter	
Latitude, N	67°39.55′
Longitude, E	33°37.56′
Altitude, m asl	352
Lake area, km^2	0.02
Max depth, m	4.8
Mean depth, m	2.0
Secchi depth, m	2.5
pH	6.02
Conductivity, μS cm^{-1} at 20°C	10.0
Alkalinity, μeq l^{-1}	11.0
Total N, μg l^{-1}	192.0
Total P, μg l^{-1}	16.0
Ca, mg l^{-1}	0.16
Na, mg l^{-1}	1.30
Al, μg l^{-1}	57.0
Fe, μg l^{-1}	38.7

Invertebrate records

No aquatic invertebrate remains were found in the bottom-most section (581–574 cm, before ca. 10,100 cal yr BP) of the Lake Kupal'noe sediment sequence. Subsequent count sums of identifiable chironomid HC varied from 53 to 154 (mean = 71) per sample, except in one bottom sample (571–574 cm), which contained only 35 chironomid HCs. Concentrations of invertebrate remains, especially chironomids and oribatids, varied significantly throughout the sequence (Fig. 4). Among the chironomids, 22 taxa have relative abundances >2% in at least one sample. Two taxa, *Trimalaconothrus maior* and *Limnozetes ciliatus*, dominate the oribatid mite assemblages, making up over 95% of the total oribatids. Ceratopogonids were represented by both morphotypes, *Bezzia*-type and *Dasyhelea*-type. Six statistically significant zones (Ai-1 to Ai-6) were established in the invertebrate stratigraphy (Fig. 5).

Zone Ai-1 (574–566 cm; ca. 10,100–9900 cal yr BP) reflects colonization of the lake by aquatic invertebrates. Only chironomids were found and their concentration increased rapidly from 28 to 5524 remains g^{-1} DW within this zone. Assemblages were dominated mainly by *Corynocera ambigua* (31–51%), which is often found in newly deglaciated lakes (e.g., Ilyashuk et al., 2005; Sarmaja-Korjonen et al., 2006; Larocque-Tobler et al., 2010). This shallow-water taxon is well represented in the Swedish calibration dataset, where it occurs in 59 of the 100 training lakes at abundances from 0.4% to 41%, and has a rather broad distribution in terms of temperature; its T_{July} optimum in the dataset is ca. 10°C (Larocque et al., 2001). However, temperature is not the main factor influencing its occurrence in lakes (Brodersen and Lindegaard, 1999; Larocque-Tobler, 2010; Larocque-Tobler et al., 2010). Many observations suggest a co-occurrence of *C. ambigua* and charophyte algae (Brodersen and Lindegaard, 1999 and references therein), but an obligate relationship between them does not exist (Brodersen and Lindegaard, 1999). Charophyte algae (including *Chara* and *Nitella* genera) prefer

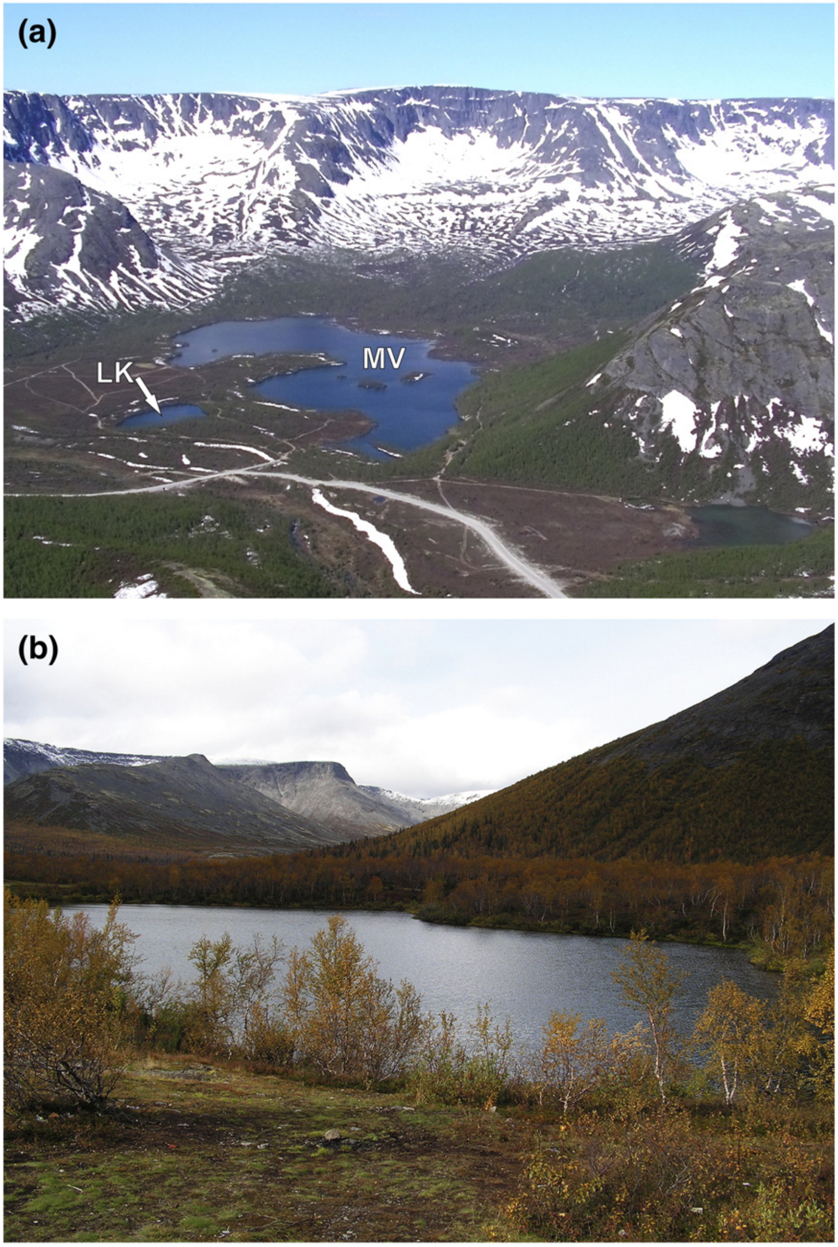

Figure 2. (a) Lake Kupal'noe (LK) and Malyi Vudjavr (MV) and their catchments, and (b) the modern vegetation. (Photographs by D. Denisov).

oligo- to mesotrophic calcareous clear-water lakes where they often cover large bottom surfaces (Bornette et al., 1996; Kufel and Kufel, 2002; Lambert-Servien et al., 2006). It is possible that calcareous clear-water conditions, which were favourable for charophyte algae as well as for *C. ambigua*, occurred in the lake during this period. Co-dominant chironomids in this zone were *Psectrocladius* (*P.*) *sordidellus*-type (4–19%) and *Microtendipes pedellus*-type (11–24%), taxa that are commonly associated with littoral habitats and indicative of moderate to warm temperatures (e.g., Wiederholm, 1983; Larocque et al., 2001). The deep-water inhabitant *Tanytarsus lugens*-type also occurred at the beginning of the period but at very low abundances (3%). Thus, the chironomids of this zone represent the first colonisers, whose appearance was prompted by warming following the deglaciation. The productivity in the littoral of the lake was steadily rising during these 200 yr, as reflected by a distinct increase in the sediment TC content.

Zone Ai-2 (566–558 cm; ca. 9900–9500 cal yr BP) is characterized by the disappearance of *P.* (*P.*) *sordidellus*-type, a marked decline in *C. ambigua* and *M. pedellus*-type and a major increase in *Zalutschia* type A (21–35%). The latter taxon is well adapted to temperate summers with T_{July} of 8–12°C (Larocque et al., 2001) and commonly found in humified lakes (Pankratova, 1970; Sæther, 1976). The temperate *Psectrocladius* taxa, *Psectrocladius* (*M.*) *septentrionalis*-type (11–21%) and *Allopsectrocladius*/*Mesopsectrocladius* (6–20%), show well-defined occurrences in this zone. The thermophilous *Chironomus anthracinus*-type, a taxon associated with elevated organic content of lake sediments, appears for the first time in the record at abundances of 2–8%. This shift in chironomid assemblages is accompanied by an increase in the true aquatic oribatid mites *L. ciliatus* and *T. maior* (11–28%), which are shallow-water dwellers usually found in association with submerged mosses (Solhøy and Solhøy, 2000; Larsen et al., 2006; Seniczak et al., 2010). All these invertebrate changes were apparently related to soil development in the catchment area under a continued period of warming and influx of dissolved humic compounds into the lake, resulting in slightly acidic water favourable for an extensive development of aquatic mosses on the bottom of the lake. The

Table 2
Radiocarbon dates of samples from the Lake Kupal'noe sediment sequence.

Sample depth, cm	Sample no.	Material dated and [weight, mg]	δ^{13}C, ‰ VPDB[a]	Reported age, ±1σ, ^{14}C yr BP	Calibrated age, cal yr BP	Calibrated age, 2σ range, cal yr BP
489.0–492.0	LuS-5858	Aquatic moss *Warnstorfia exannulata* [4.9]	−25.0[b]	4010 ± 50	4505	4630–4380
504.0–506.5	Ua-16765	Aquatic moss *Warnstorfia exannulata* [ca. 10]	−28.1	4865 ± 75	5605	5750–5460
531.0–532.5	LuS-5857	Catkin scales, fruits and leaf fragments of *Betula pubescens* [8.6]	−25.0[b]	7205 ± 60	8055	8170–7940
552.4–554.0	Ua-16766	Catkin scales and leaf fragments of *Betula pubescens* and *Populus tremula* [6.0]	−27.7	8255 ± 90	9235	9450–9020
567.5–569.0	Ua-16767	Catkin scales, fruits and small twigs of *Betula pubescens*, needles of *Pinus sylvestris* [4.2]	−25.0[b]	8790 ± 95	9765	9970–9560

[a] VPDB, Vienna Pee-Dee Belemnite.
[b] Assumed values (δ^{13}C not determined).

rising C/N ratio also implies an increase in the supply of terrestrial organic matter to the lake.

Zone Ai-3 (558–531 cm; ca. 9500–7900 cal yr BP). The beginning of this zone is marked by the final shift from charophyte algae to aquatic mosses among the submerged macrophytes. The zone displays a dominance of the temperate chironomids *Zalutschia* type A (18–38%) and *P.* (*M.*) *septentrionalis*-type (16–33%), together with oribatid mites (up to 31%). Several other taxa indicative of relatively warm conditions of mesotrophic waters were abundant, including the shallow-water inhabitants *Allopsectrocladius*/*Mesopsectrocladius* (2–12%), *Tanytarsus glabrescens*-type (up to 20%), *Tanytarsus mendax*-type (up to 11%), *Pagastiella orophila* (up to 7%), *Dicrotendipes* (up to 7%) and Pentaneurini (up to 6%). Most probably, aquatic mosses formed dense mats on the lake bottom. The presence of the detritivore *C. anthracinus*-type (3–11%) and the facultative predator *Procladius* (1–11%), deep-water taxa indicative of productive conditions (Brodersen and Quinlan, 2006) and tolerant of low oxygen levels (Brodersen et al., 2004; Luoto and Salonen, 2010), may suggest an increase in organic matter decomposition at the lake bottom resulting in decreased hypolimnetic oxygen conditions. Clear changes in the invertebrate assemblages occurred between ca. 8500 and ca. 8000 cal yr BP, with a decrease in the oribatid mites to 3–7% and an increase in the chironomid *Zalutschia* type A to 33–38%. The sediment TC content (Fig. 4) exhibits a distinct decrease, which probably reflects a decrease in aquatic productivity in response to cooler summers. The C/N ratio decreased as well, indicating a decrease in the supply of terrestrial organic matter from the catchment.

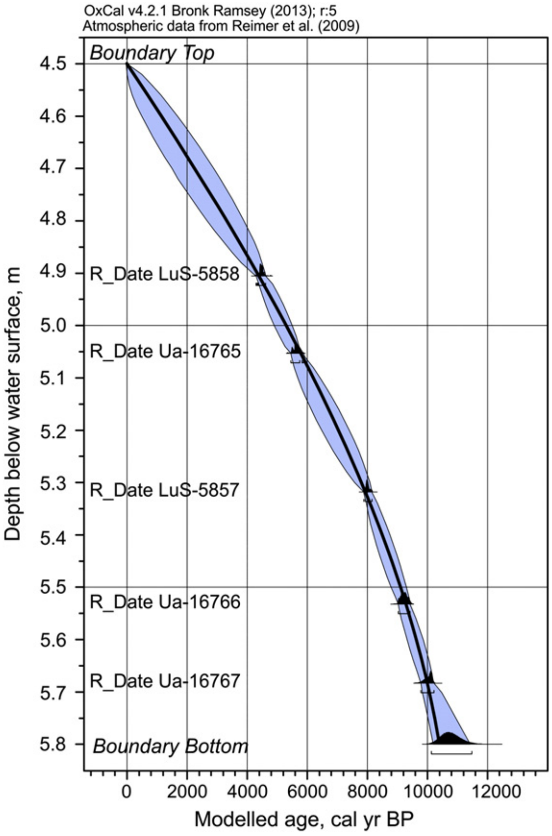

Figure 3. Age–depth relationship for the Lake Kupal'noe sediment profile based on Bayesian modelling, showing 2-sigma ranges of probability distributions for each calibrated radiocarbon age, the 95.4% confidence limits for the fitted model (color shaded envelope), and the third-order polynomial curve (black solid line).

Zone Ai-4 (531–526 cm; ca. 7900–7500 cal yr BP) is distinguished by maximum abundances of oribatid mites (43–56%) and the appearance of the biting midge larvae (Ceratopogonidae; 1–4%), many species of which are also associated with macrophyte habitats (Szadziewski et al., 1997; Glukhova and Brodskaya, 1999). *Zalutschia* type A, which inhabits relatively cool waters diminished to 5–6%. The relative abundances of *C. anthracinus*-type and *Procladius*, which prefer sublittoral and profundal habitats, do not exceed 3%, but the abundance of another thermophilous, littoral chironomid, *Polypedilum*, increased to 8%. These major changes in the invertebrate assemblages suggest a pronounced warming. The dominance of taxa commonly preferring relatively warm and shallow habitats implies an increase in productivity of the lake, which was apparently related to warm summers during this period. Most likely, the summers were relatively dry, leading to a lake-level lowering, as inferred from an expansion of shallow-water habitats with aquatic mosses preferred by Oribatida and Ceratopogonidae.

Zone Ai-5 (526–501 cm; ca. 7500–5400 cal yr BP) is marked by generally high frequencies of aquatic oribatids (up to 40%) and relatively low abundances of the chironomid *Zalutschia* type A (3–19%). *P.* (*M.*) *septentrionalis*-type (13–34%), a chironomid with a broad range of thermal tolerance (e.g., Larocque et al., 2001), was continuously present at high frequencies throughout the zone. Ceratopogonids were also recorded, reaching abundances of 5%. These invertebrate characteristics are indicative of relatively warm climatic conditions, a generally low lake level and coverage of large parts of the lake bottom with submerged vegetation. The chironomid *C. anthracinus*-type became more common (4–24%) and *Sergentia coracina*-type appeared for the first time in the record at abundances of 1–12%. Both taxa are able to thrive in low-oxygen environments (e.g., Quinlan and Smol, 2001), and their presence suggests a stable thermal stratification of the lake, accompanied by decreased hypolimnetic oxygen concentrations during this period. The productivity of the lake was rising throughout the zone as reflected by increasing sediment TC contents from 31% to 44% (Fig. 4).

Zone Ai-6 (501–450 cm; ca. 5400–0 cal yr BP) reveals conspicuous changes in the invertebrate record. Ceratopogonids, indicative of relatively warm and productive shallow waters, disappeared in the beginning of the zone. It is noticeable that the oribatid mites, which prefer relatively shallow waters, declined to very low abundances (1–4% in most samples of the zone) at ca. 4000 cal yr BP, whereas the deep-water inhabitant *Chironomus plumosus*-type (e.g., Nagell, 1978; Sæther, 1979) made up a great part of the assemblage (up to 13%) from about this time. These

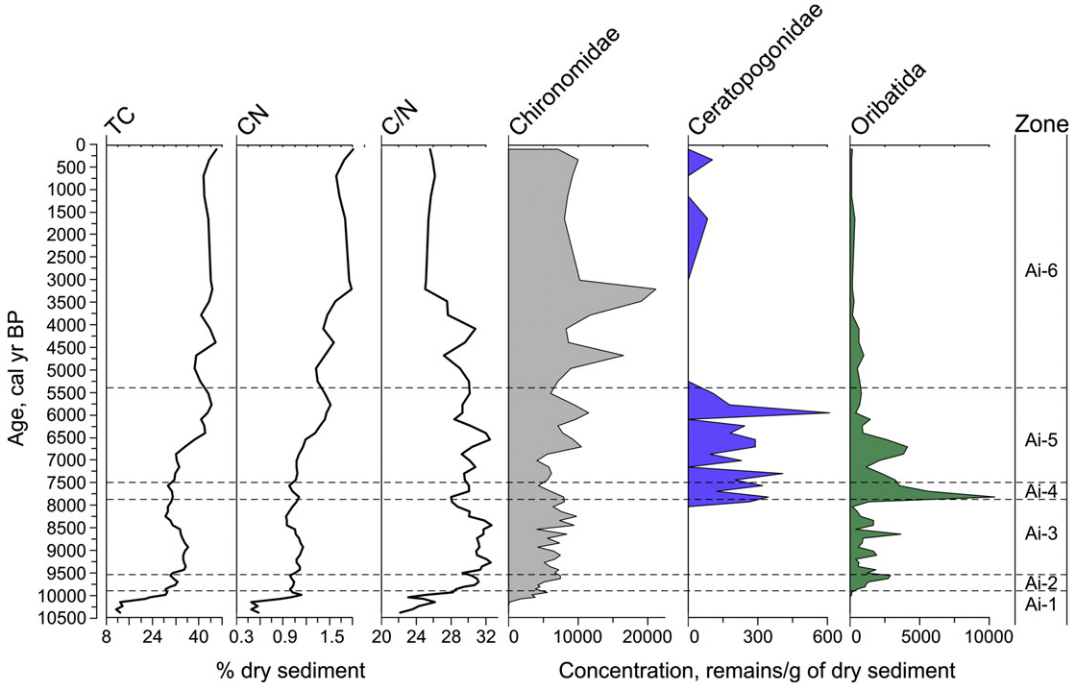

Figure 4. Diagram showing the stratigraphic records of total carbon content (TC), total nitrogen content (TN), atomic carbon to nitrogen (C/N) ratio, and concentrations of fossil remains of aquatic midges (Chironomidae and Ceratopogonidae) and oribatid mites in the Lake Kupal'noe sediment profile.

changes in the invertebrate assemblages indicate that a lake-level lowering associated with relatively dry climatic conditions may have persisted until ca. 4000 cal yr BP. The temperate chironomids *Zalutschia* type A (20–52%) and *P.* (*M.*) *septentrionalis*-type (14–30%) show high abundances throughout the zone. *P.* (*P.*) *sordidellus*-type, a taxon tolerant of relatively cool conditions (e.g., Bedford et al., 2004), became more important (4–14%). The chironomids *C. anthracinus*-type and *S. coracina*-type, which are able to tolerate oxygen depletion, persisted in the zone. All these shifts in the assemblages point towards an overall cooling trend. The sediment TC content ranges between 39% and 46%, and the C/N ratio decreased from 31 to 25 between ca. 4000 and ca. 3200 cal yr BP, likely in response to decreased terrestrial organic matter input, followed by stable values.

Chironomid-based temperature inferences

Of the 30 chironomid taxa found in the Lake Kupal'noe sediment sequence, 24 taxa had abundance of more than 2% in at least one sample. Of these, 23 taxa occur in the training set lakes compiled by Larocque et al. (2001). Only *Pseudochironomus prasinatus*, comprising 3.5–7.5% in two samples, is not presented in the calibration set. Of these taxa, no taxon has been identified as rare in the modern data; the values for Hill's N2 diversity index range between 9 and 80. These numerical evaluations provide supportive evidence that the chironomid-based temperature inferences may be considered as robust (Birks, 1998; Brooks and Birks, 2001). As revealed by goodness-of-fit statistics, 81% of the down-core samples had a good fit to T_{July}, which suggests that the assemblages are not dominantly influenced by secondary (non T_{July}) gradients. 54% of the samples analysed in this study had no good modern analogues within the training-set samples, indicating the presence of time intervals with chironomid assemblages having no close modern counterparts. Nevertheless, WA-PLS performs relatively well in no-analogue situations (Birks, 1998) and, consequently, the temperature reconstructions can be considered as generally reliable. The reconstruction, however, fails the significance test ($p = 0.267$) recommended by Telford and Birks (2011). The amount of variance explained by the reconstruction is less than that explained by 95% of the random reconstructions. This is not unexpected as the amplitude of reconstructed Holocene T_{July} changes is not large compared with the root mean square error of prediction (RMSEP), and factors other than temperature may be important. The non-significance of the reconstruction may be also related to a relatively low number of effective taxonomic units in the record, 9.2 as estimated by Hill's N2 diversity index (Hill, 1973). We used the LOESS regression as a data smoothing technique to provide a clearer view of the true underlying behaviour of the data and to highlight temporal trends. Our interpretations of the inferred temperature changes are thus based on a combination of sample-to-sample inferences (for short-term changes) and of the LOESS-smoothed curve (for long-term changes).

The chironomid-inferred T_{July} reconstruction is presented in Figure 6 together with the LOESS smoothing and the six zones derived from the invertebrate analysis. The inferred temperature estimates varied over the Holocene between 8.7°C and 13.2°C around a mean value of 11.0°C. Within zones Ai-1 and Ai-2, soon after the local deglaciation and the onset of sedimentation (ca. 10,100–9500 cal yr BP), the inferred T_{July} curve shows an increasing trend with values in the range of 9.5–11.4°C. In zone Ai-3 (ca. 9500–7900 cal yr BP), the inferred temperature initially rises to ca. 12.0°C, then falls sharply to 10.8–10.2°C at ca. 8500–8000 cal yr BP, followed by a steep rise. For the samples in zone Ai-4 (ca. 7900–7500 cal yr BP), the model reconstructs the highest temperatures (ca. 13.2°C) of the entire record, i.e. 2.0–2.5°C above the modern value. In zone Ai-5 (ca. 7500–5400 cal yr BP), the inferred temperature is relatively high but fluctuating in the range of 10.4–12.5°C. In zone Ai-6 (ca. 5400–0 cal yr BP), the inferred T_{July} rapidly decreases and reaches the lowest values (8.7–9.8°C) of the record at ca. 3400–3000 cal yr BP. Subsequently, the inferred temperature increases, with T_{July} in the surface sample (10.5°C) being close to the assumed modern mean July air temperature at the study site. Overall, the last three millennia are represented by low-resolution chironomid data and, therefore, we consider any temperature trends over this period as tentative.

Discussion

The changes in aquatic invertebrate assemblages of the Lake Kupal'noe sediment record and the chironomid-based T_{July} reconstruction

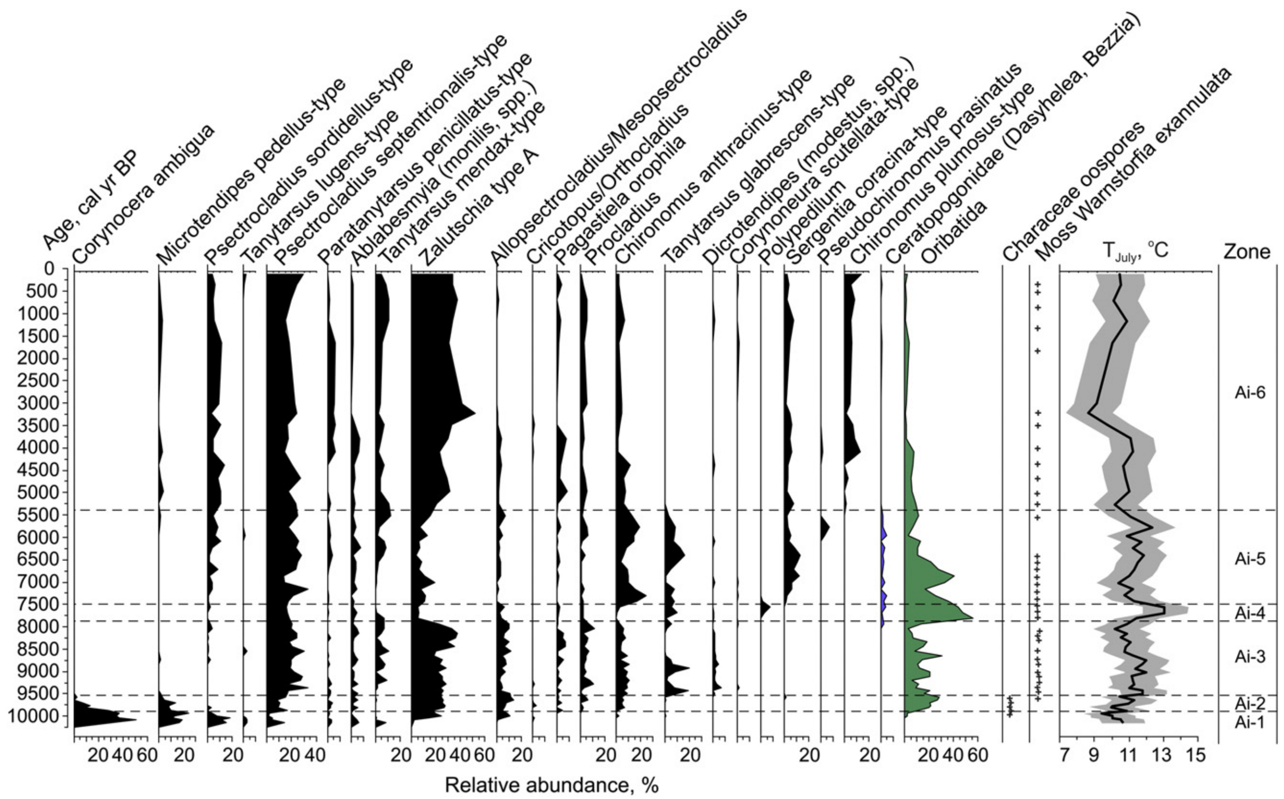

Figure 5. Summary aquatic invertebrate diagram and chironomid-inferred mean July air temperature (T_{July}) with sample-specific prediction errors (grey envelope) from Lake Kupal'noe. Dashed lines represent statistically significant changes in the invertebrate assemblages as determined by sum-of-squares optimal partitioning. The stratigraphic distribution (+) of aquatic plant macrofossils is also shown.

indicate a distinct sequence of climatic events. Figure 6 compares the inferred T_{July} record from Lake Kupal'noe (K-T_{July}) in the central mountain area of the Kola Peninsula with the record from Lake Berkut (B-T_{July}, Ilyashuk et al., 2005), located at lower altitude in the boreal forest zone near the White Sea coast in the southern part of the peninsula, and therefore showing consistently higher reconstructed T_{July} values. Because smoothing commonly reduces irregularities in time-series data, hence demonstrating long-term fluctuations more clearly, the following discussion is mainly based on comparison of the smoothed curves for these two reconstructions.

The K-T_{July} record indicates that July mean temperatures rose rapidly until ca. 9000 cal yr BP and reached values ca. 1°C higher than at present, whereas the B-T_{July} record shows rather stable values similar to the present-day temperature. As continental climates are controlled directly by variations in insolation (Colman et al., 1995), the steady early Holocene warming in the interior part of the peninsula was probably associated with the orbitally forced summer insolation maximum in the Northern Hemisphere. However, this trend may have been reinforced by the recession of the Scandinavian ice sheet, which led to complete deglaciation of the Khibiny Mountains at 9500–8500 cal yr BP (Miagkov, 1986).

The K-T_{July} record reveals that the early-Holocene warming in the central Kola Peninsula was interrupted by a transient cooling at ca. 8500–8000 cal yr BP, centred at about 8200 cal yr BP when T_{July} fell by ca. 1°C as evident from the smoothed values (Fig. 6). The climatic deterioration was initiated at ca. 8500 cal yr BP, well before the sharp meltwater-induced 8200 cal yr BP cold event as recognized in Greenland ice-cores, and probably reflects a longer-term climate anomaly at ca. 8500–8000 cal yr BP, which is recognized in many climate proxy archives around the North Atlantic (Alley et al., 1997; Magny et al., 2003; Rohling and Pälike, 2005). The prolonged period of cooling may be related to reduced solar output and is especially evident in summer-dominated proxies, while the abrupt 8.2 ka cooling event itself is more evident in winter-biased proxies (Rohling and Pälike, 2005). This temporary cooling, however, has not previously been recorded in quantitative temperature reconstructions from the Kola Peninsula. The early-Holocene temperature pattern at Lake Kupal'noe differs from the inferred climatic development on the White Sea coast where the T_{July} lowering after ca. 9200 cal yr BP was more gradual and subdued (Fig. 6). The pollen record from Lake Chuna, which is also located in the centre of the peninsula, in the Chuna Tundra Mountains, only ca. 35 km northwest of Lake Kupal'noe (Fig. 1), does not indicate any cooling around 8200 cal yr BP (Jones et al., 2004; Solovieva et al., 2005). Similarly, this cold period is not reflected clearly in the pollen records from two lakes in the forest–alpine tundra ecotone in the northwestern part of the Kola Peninsula (Seppä et al., 2007, 2008) (Fig. 1).

The lack of a temperature response in many pollen-based reconstructions from northern Europe probably reflects the insensitivity of terrestrial proxy indicators to the cooling and may be explained by the assumption of Seppä et al. (2007) that northern-boreal trees and other plants well-adapted to cold climate responded less sensitively to the transient cooling 8200 years ago than more southerly vegetation communities (e.g., Heikkilä and Seppä, 2003; Seppä et al., 2007, 2009). This is consistent with vegetation-independent abiotic proxy climate records (magnetic susceptibility, total carbon content, loss of ignition), which indicate that lake catchments in central Fennoscandia were more sensitive to the onset of the 8.2 ka cooling event than those north of 64°N (Nesje and Dahl, 2001; Bakke et al., 2005; Bergman et al., 2005; Zillén and Snowball, 2009). Probably, as a consequence, many northern Fennoscandian temperature inferences derived from biological proxy records do not document any cooling around 8200 cal yr BP (Bigler et al., 2002, 2003; Larocque and Hall, 2004). Nevertheless, some climate reconstructions based on chironomids and diatoms do provide evidence of a cold event at about 8200 cal yr BP in northern Sweden (Rosén et al., 2001; Bigler et al., 2006) and northern Finland (Korhola et al., 2000,

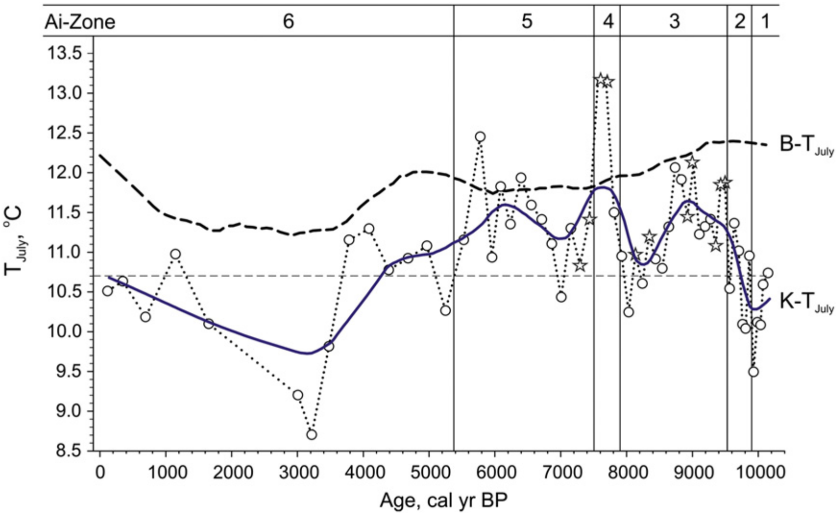

Figure 6. Chironomid-inferred changes in mean July air temperature at Lake Kupal'noe (K-T_{July}), plotted together with the corresponding record from Lake Berkut (B-T_{July}; Ilyashuk et al., 2005) near the Kola White Sea coast (Fig. 1). Open circles and dotted line represent unsmoothed data from Lake Kupal'noe. Samples that had poor fits to T_{July} are marked as white stars. Thick solid and dashed lines represent LOESS–smoothed records (span = 0.20, order = 1). The horizontal thin dashed line indicates the assumed present-day T_{July} value at Lake Kupal'noe. Aquatic invertebrate zones (Ai-1 to Ai-6) follow Fig. 5.

2002), corroborating that arctic and subarctic lake ecosystems respond sensitively to regional climate change (e.g., Pienitz et al., 2004; Smol et al., 2005).

As evident from the K-T_{July} record, the temperatures rose after the cold climate anomaly at ca. 8500–8000 cal yr BP, and the subsequent warm period lasted from ca. 7900 to ca. 5400 cal yr BP. The average chironomid-inferred temperature over this time interval was about 11.6°C, which is ca. 1°C higher than at present. Other aspects of the invertebrate record from Lake Kupal'noe indicate lowered lake levels at ca. 7900–4000 cal yr BP, apparently related to dry conditions due to high summer temperature and associated increases in evapotranspiration. This is supported by pollen data from nearby Lake Chuna, which reflect more continental climatic conditions between ca. 9000 and ca. 5000 cal yr BP, with summer temperatures 1.5–2.0°C higher than at present and lower annual precipitation (Solovieva et al., 2005). These inferences are largely consistent with records of pine megafossils, pollen and stomata from the northern part of the Kola Peninsula, giving evidence of temperatures at least 2°C higher than at present at ca. 8000–4000 cal yr BP (MacDonald et al., 2000a; Gervias et al., 2002; Kremenetski et al., 2004; Seppä et al., 2008). However, it is worth noting that Wolfe et al. (2003) coupled the maximum northward expansion of pine in the treeline zone near the Barents Sea coast at ca. 8000 cal yr BP to increased oceanicity and relatively moist conditions based on oxygen-isotope analysis of lake sediments. This difference, as compared to our study, may indicate that the propagation of moist Atlantic air masses eastward along the northern Eurasian coastline, which probably contributed to forest expansion in low-lying areas during the early- to mid-Holocene (MacDonald et al., 2000b; Wolfe et al., 2003), never reached the interior mountain region of the Kola Peninsula.

As compared to the present study, the B-T_{July} record (Ilyashuk et al., 2005) suggests a more extended Holocene Thermal Maximum (HTM) near the southern coast of the Kola Peninsula, with summer temperatures equivalent to present levels between ca. 10,000 and ca. 4400 cal yr BP (Fig. 6). Lowered lake levels related to decreased effective moisture developed at ca. 7000 cal yr BP, i.e. almost 1000 years later than in the central mountain area of the peninsula (Ilyashuk et al., 2005). Apparently, relatively dry climatic conditions persisted in both areas until ca. 4000 cal yr BP. The differences between the southern coast and the central mountain areas of the peninsula in the timing and magnitude of the HTM and in the effective moisture pattern were probably a result of a more humid, maritime climate near the Kola White Sea coast. There are also numerous independent proxy records of temperature and humidity from other parts of northern Fennoscandia that give evidence of relatively warm and dry conditions during the HTM, at about 8000–4000 cal yr BP, with T_{July} about 1.5–2°C higher than at present (Hammarlund et al., 2002; Bjune et al., 2004; Bakke et al., 2005; Korhola et al., 2005; Bigler et al., 2006; Nesje et al., 2008; Weckström et al., 2010). The warm and dry climate was probably caused by the disappearance of the Scandinavian ice sheet by ca. 8000 cal yr BP, predominantly stable anticyclonic summer conditions over Fennoscandia, and the higher-than-present summer insolation (Seppä and Birks, 2001, 2002; Bakke et al., 2005; St. Amour et al., 2010). It is worth noting that the T_{July} reconstruction from Lake Kupal'noe reveals two second-order temperature minima during the HTM, at ca. 7000 and ca. 5300 cal yr BP, which are also evident in the stacked pollen-based annual temperature record for northern Europe provided by Seppä et al. (2009). This suggests that the colder episodes may represent regionally significant climatic events.

After ca. 5400 cal yr BP, a slightly decreasing trend is evident in the K-T_{July} record and since ca. 4000 cal yr BP the reconstructed average temperatures have remained lower than modern. The temperature reconstruction indicates a distinct minimum (ca. 9°C) at 3000–3200 cal yr BP. Faunal shifts in the Lake Kupal'noe invertebrate record also reflect the prevalence of relatively moist conditions since ca. 4000 cal yr BP. Similar shifts in temperature and humidity have been inferred from other climate proxy records from the Kola Peninsula (MacDonald et al., 2000a; Gervias et al., 2002; Grönlund and Kauppila, 2002; Ilyashuk et al., 2005; Solovieva et al., 2005), in general agreement with an increasing body of evidence documenting the abrupt end of the HTM and the onset of cool and wet conditions in northern Fennoscandia around 5000–4000 cal yr BP (Barnekow, 1999; Rosén et al., 2001; Bigler et al., 2002; Bjune et al., 2004; Hammarlund et al., 2004; Bjune and Birks, 2008). A sudden break-up of the long-standing anticyclonic circulation pattern at this stage (e.g., Seppä and Birks, 2001, 2002; Wanner et al., 2008) was accompanied by the activation of a number of Fennoscandian mountain glaciers (Snowball and Sandgren, 1996; Nesje et al., 2001), forest retreat, and expansion of peatlands (Hammarlund et al., 2004; Weckström et al., 2010; Väliranta et al., 2011). This is supported also by our data from Lake Kupal'noe, in particular through a decrease in organic C/N ratios and changes in chironomid assemblages between ca. 4000 and ca. 3000 cal yr BP, which suggest a gradual decrease in terrestrial vegetation cover and an increase in humic acid input following catchment paludification during this period.

The particularly cold summers inferred for the Kola Peninsula at about 3200–3000 cal yr BP also appear to have a wider geographical significance. This climatic deterioration may be correlated to a short-lasting cooling episode recorded in northern Europe (e.g., van Geel et al., 1996), expressed as a marked drop in sea-surface temperature and an increase in ice-rafted debris in the North Atlantic (Eiríksson et al., 2000; Rohling et al., 2002; Bendle and Rosell-Melé, 2007).

Conclusions

The aquatic invertebrate stratigraphy and the chironomid-based T_{July} reconstruction from Lake Kupal'noe, situated near an ecotone boundary in the Khibiny Mountains, demonstrate that the lake ecosystem has been highly responsive to large-scale climatic forcing during the Holocene. Summer temperatures in the central Kola Peninsula rose rapidly in the early Holocene, followed by a generally warm climate at ca. 9500–5400 cal yr BP. This warm period was temporarily interrupted by a cooling at ca. 8500–8000 cal yr BP which has not previously been recorded on the Kola Peninsula. Summer temperatures in the Khibiny Mountains were at least 1°C colder than prior to and after the cooling centred near 8200 cal yr BP. The warmest and driest conditions occurred at ca. 7900–5400 cal yr BP, with T_{July} ca. 1°C higher than at present. Relatively warm and dry conditions persisted until ca. 4000 cal yr BP. The last four millennia represent the coldest and wettest period during the last 10,000 yr. Particularly cold summers occurred at ca. 3200–3000 cal yr BP with T_{July} ca. 1–2°C lower than at present.

In general, climate changes during the Holocene were more pronounced in the central Kola Peninsula than on the Kola White Sea coast. The range of Holocene T_{July} variations in the inland area was about 4.5°C while it was ca. 3°C in the coastal area. In contrast to the Khibiny Mountains, summer temperatures did not exceed present levels near the White Sea coast, where relatively dry conditions also occurred during a slightly shorter period. The major patterns of Holocene temperature and effective moisture changes on the Kola Peninsula are largely consistent with various other climate records from northern Fennoscandia, which mounts further evidence to the notion that the North Atlantic ocean-atmosphere circulation system is the major driving force of millennial-scale climate changes. Our results contribute to the spatial understanding of Holocene climate dynamics and climate-forcing mechanisms in the region.

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