Available online at www.sciencedirect.com
ScienceDirect
PALAEO
Palaeogeography, Palaeoclimatology, Palaeoecology 259 (2008) 96 – 106
www.elsevier.com/locate/palaeo

Diatom responses to 20th century climate warming in lakes from the northern Urals, Russia

Nadia Solovieva [a,*], Vivienne Jones [a], John H.B. Birks [b], Peter Appleby [c], Larisa Nazarova [d,e]

[a] Environmental Change Research Centre, University College London, 26 Bedford Way, London, WC1H 0AP, UK
[b] Botanical Institute, University of Bergen, Allegaten 41, N-5007 Bergen, Norway
[c] Deparment of Mathematical Science, University of Liverpool, PO Box 147, Liverpool L69 3BX, UK
[d] Alfred-Wegener-Institute for Polar and Marine Research, Research Department Potsdam, Telegrafenberg A43, D-14473 Potsdam, Germany
[e] Department of Entomology, Natural History Museum, Cromwell Road, London SW7 5BD, UK

Received 14 October 2005; accepted 25 February 2007

Abstract

Changes in diatom assemblages and spheroidal carbonaceous particle (SCP) profiles during the last 200 years in ^{210}Pb-dated sediment cores from five remote arctic and sub-arctic lakes in the northern Urals were analysed. The study area covers a large territory from arctic tundra in the north to boreal forest on the western slopes of the Ural mountains in the south. pH was reconstructed using a diatom-based model. The degrees of compositional turn-over and rates-of-change were estimated numerically. The 20th century diatom floristic shifts, the rise in diatom accumulation rates and the rates of diatom compositional change in the northern Ural lakes correlate well with June temperature in the region and with the overall circum-arctic temperature increase from the 1970s. The main driving force behind diatom compositional shifts in the study lakes are the changes in the duration of ice-free season, timing of water turn-over and stratification periods and habitat availability. Changes in spheroidal carbonaceous particles show no pronounced effect on diatom assemblages. Pollution is restricted to regional sources originating mainly from the Vorkuta coal industry. Changes in diatom plankton are more pronounced than changes in diatom benthos. There is no clear north–south gradient in degree of compositional changes, with greatest changes occurring in Lake Vankavad situated in northern boreal forest. The degree of the 20th century diatom changes in Lake Vankavad is greater than in most circum-arctic and sub-arctic lakes from northern Europe and Canada.

Keywords: Polar Urals; diatoms; Lake sediments; 20th century climate warming; Spheroidal carbonaceous particles; East-European Russia; Air contamination

1. Introduction

The 20th century global air temperature rise north of 60° N is well documented with warming of the order of 1.5 °C being observed in the periods between approximately 1915 and 1940 and from the end of 1960s until 2000 (Moritz et al., 2002; Jones and Moberg, 2003). The Arctic is warming at about twice the rate of the rest of the planet (ACIA, 2004) and the effects of climate change will be amplified in the north due to positive feedbacks including cryospheric processes such as glacier retreat, ice thinning, permafrost degradation and albedo changes (Giorgi and Mearns, 2002). Climate warming is now

* Corresponding author. Fax: +44 20 76790565.
E-mail address: nsolovie@geog.ucl.ac.uk (N. Solovieva).

0031-0182/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.palaeo.2007.10.001

detectable in various terrestrial and aquatic arctic ecosystems including lakes and ponds (Douglas et al., 1994; Jones and Birks, 2004; Smol et al., 2005; Solovieva et al., 2005). However, spatial and temporal expression of arctic warming is highly variable due to regional differences in continentality, ocean heat transport, glacier and sea ice distribution, topography and vegetation (Smol et al., 2005).

Instrumental records of mean annual air temperature from the northern Urals do not show a distinct temperature increase within the 20th century. However, there is an increase in the summer temperature, notably in June and August–September, leading to an increase in the duration of the ice-free season (Solovieva et al., 2005). In this paper we examine the response of diatom assemblages to the 20th century summer warming in five lakes from the northern Ural region west of the Ural mountains using both limnological and palaeolimnological methods. Some of the lakes have been studied in the past. For instance, a recent comprehensive survey of Lake Mitrofanovskoe, edited by Drabkova and Trifonova (1994), includes research on the hydrology, water chemistry, phyto- and zooplankton, zoobenthos and fish populations. Lake Vanuk-ty has also been studied in detail (Belyaev et al., 1966). However, these studies provide mostly qualitative data over one or two years,

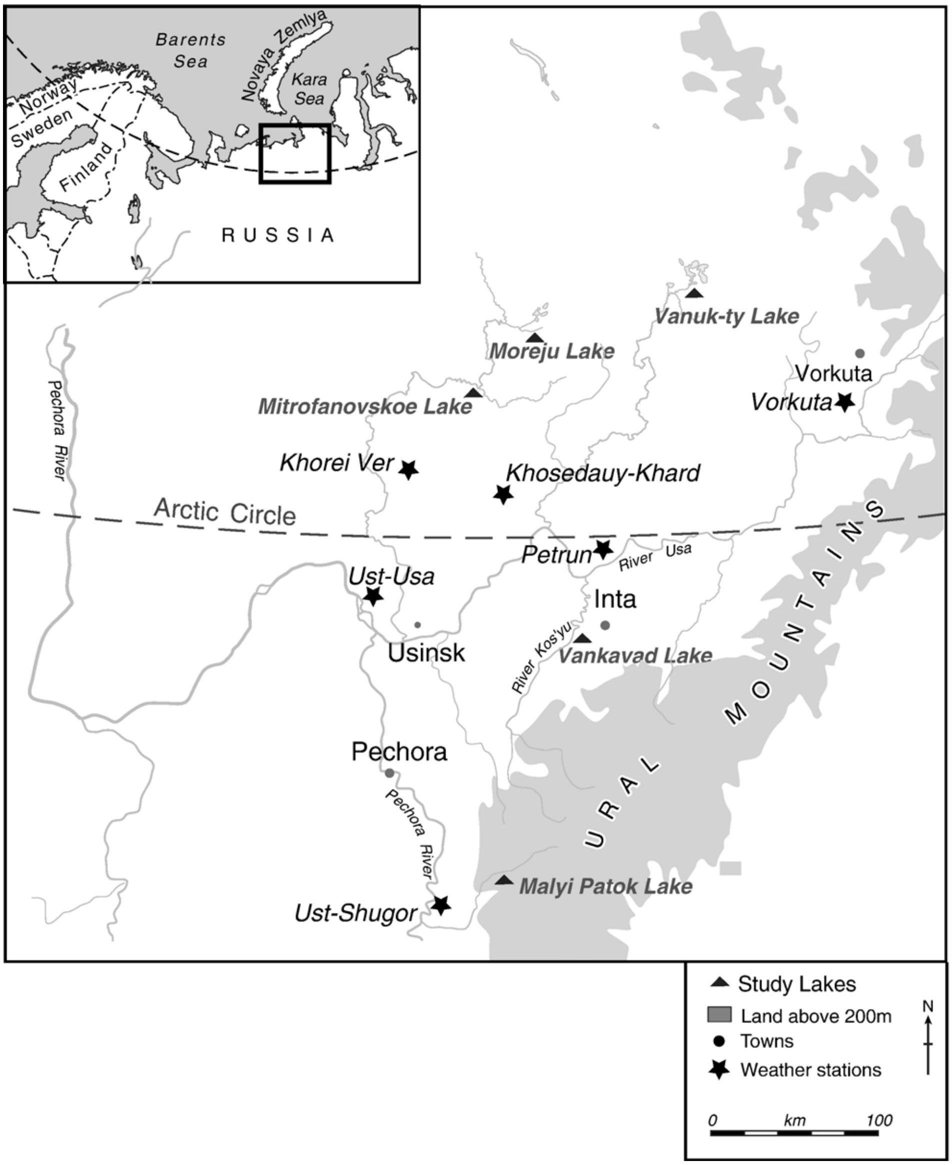

Fig. 1. Locations of studied lakes and weather stations in the northern Ural region.

with no continuous monitoring of the lakes. The Holocene history of Lake Vankavad was examined by Sarmaja-Korjonen et al. (2003) and its pollution history was reconstructed by Solovieva et al. (2002). Recent palaeolimnological changes in Lakes Mitrofanovskoe and Vanuk-ty were analysed by Solovieva et al. (2005).

Here we use the data from the above studies and, with additional data from two other sites, apply further numerical analysis to statistically assess 20th century changes in the diatom flora extending our study to sub-arctic lakes. One of the aims of the study was to test whether sub-arctic forest lakes respond to the 20th century warming in a similar fashion to arctic tundra lakes. As all the lakes are remote with no industry or permanent settlements in the vicinity, the diatom assemblages might be affected either by a long-distance atmospheric contamination or by changes in climate. This paper examined both scenarios. Sedimentary records of spheroidal carbonaceous particles (SCPs) were used as a proxy for atmospheric contamination.

2. Study area and study lakes

The study area covers a large, mostly lowland plain west of the Urals and includes lowland arctic shrub tundra with permafrost in the north and larch- and spruce-dominated northern boreal forest on the western slopes of the Urals in the south (Fig. 1). The area is underlain by Permian rocks and Quaternary deposits (Vlasova, 1976). Relief is hilly, with maximum altitudes reaching 230 m a.s.l. Climate is severe with an eight- to nine-month winter period (mean monthly temperatures below 0 °C). The coldest month is February with minimum temperatures of about −55 °C; the warmest month is July with maximum temperatures reaching 31 °C (Mukhin et al., 1964). Annual precipitation varies between 370 and 395 mm with 60% falling during the summer months, and a maximum in August (Mukhin et al., 1964).

Summary characteristics of the study lakes are shown in Table 1. Two lakes had no names and they were named informally after nearby rivers: Lake Malyi Patok and Lake Moreju (in the SPICE project, these lakes were named 6–4 and 8–4 (Walker et al., in press)). All lakes were formed during the last glaciation, and are deep, dimictic lakes, which are stratified during the winter and summer seasons. The lakes are remote from any industrial sources, and have no roads or permanent settlements in the immediate vicinity. The lakes were classified as ‘undisturbed’ according to comprehensive surveys of their water chemistry, flora and fauna by Zvereva et al. (1966) and Drabkova and Bystrov (1994) and within the TUNDRA and SPICE projects (pers. comm.). All lakes are relatively dilute and circum-neutral (Table 1) typical of the northern Ural region (Zvereva et al., 1966; Solovieva et al., 2002).

Table 1
Summary characteristics of the study lakes

	Vanuk-ty Lake	Moreju Lake	Mitrofanovskoe Lake		Vankavad Lake	Malyi Patok Lake
Lat.	68°00′ N	67°53′ N	67°51′ N		65°59′	64°19′ N
Long.	62°45′ E	59°40′ E	58°59′E		60°01′	59°05′ E
Alt., m a.s.l.	132	15	123.9		59	230
Av. depth, m	1.73	2.5	6.1		–	2.5
Date of sampling	April 2001	June 2001	April 2001		April 1998	July 2001
Max. depth, m	35	6	20		6.6	16
Area, km^2	8.3	–	0.309		0.36	–
Catchment vegetation	Shrub-lichen tundra	Shrub lichen	Shrub-lichen tundra		Northern taiga	Northern taiga
	April 2001		April 2001	July 2001		
pH	6.88	6.71	6.80	7.06	7.08	6.79
Alk, μeq/l	622.9	229	588.96	365	70.90	186
Cond, μS/cm	70.9	30	67.2	44.6	4.40	27
K^+, mg/l	0.91	0.23	0.95	0.48	0.01	0.19
Na^+, mg/l	2.3	1.11	2.75	1.09	2.80	0.69
Ca^{2+}, mg/l	8.6	3.67	8.40	5.30	2.70	3.73
Mg^{2+}, mg/l	1.92	0.93	1.72	1.12	0.74	0.37
Cl^-, mg/l	2.0	1.64	4.40	1.23	1.79	0.24
SO_4^{2-}, mg/l	1.0	0.68	1.24		0.96	3.47
P_{tot}, μg/l	14	–	19	58	–	–
N_{tot}, μg/l	1600		250	105	–	–

Shrub-lichen tundra in the catchments of Lakes Mitrofanovskoe, Vanuk-ty and Moreju is dominated by *Betula nana*, with some *Empetrum nigrum*, and *Vaccinium vitis-idaea*. *Vaccinium myrtillus* prevails on drier patches and hills. Lake Vankavad is surrounded by northern taiga where spruce (*Picea obovata*) prevails together with some birch (*Betula pubescens*), and alder (*Alnus incana*). Scots pine (*Pinus sylvestris*) grows around mires and on sandy patches. Northern taiga around Lake Malyi Patok is mixed spruce–fir forest comprising *Picea odovata* (up to 70%) with *Larix sibirica* (up to 30%). Deciduous trees include mainly young stands of *B. pubescens* (Walker et al., in press).

The ice-free period at Lakes Mitrofanovskoe, Vankavad and Malyi Patok lasts approximately three months, from June to September, and planktonic diatoms have normally two peaks of abundance, in June and September. At Lakes Moreju and Vanuk-ty it is shorter and only continues from the end of June/early July until the end of August. At most times, planktonic diatoms peak only once at those lakes, at around July (Belyaev et al., 1966).

3. Methods

Sediment cores were collected using a Glew corer (Glew, 1989) from the deepest point of the lakes, the dates of sampling are shown in Table 1. The details of sediment extrusion, water sampling and water-chemistry analysis are given in Solovieva et al. (2002), Sarmaja-Korjonen et al. (2003) and Solovieva et al. (2005).

All sediment cores were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay using Ortec HPGe GWL series well-type coaxial low background intrinsic germanium detectors (Appleby et al., 1986). ^{210}Pb was determined via its gamma emissions at 46.5 keV, and ^{226}Ra by the 295 keV and 352 keV γ-rays emitted by its daughter isotope ^{214}Pb following 3 weeks storage in sealed containers to allow radioactive equilibration. ^{137}Cs and ^{241}Am were measured by their emissions at 662 keV and 59.5 keV. Radiometric dates were calculated using the CRS and CIC ^{210}Pb dating models (Appleby, 2001) where appropriate, and the 1963 depths determined from the ^{137}Cs/^{241}Am stratigraphic records. All the dates in the paper are expressed as years AD.

Diatom slide preparation followed standard methods (Battarbee et al., 2001) using the water-bath technique (Renberg, 1990). Slides were mounted using Naphrax®. The diatom accumulation rate (DAR) was estimated using microsphere markers (Battarbee and Kneen, 1982). Between 300 and 400 valves were counted where possible at 1000 times magnification. Diatom nomenclature followed Krammer and Lange-Bertalot (1986–1991) and AL:PE guidelines (Cameron et al., 1999).

Slide preparation of spheroidal carbonaceous particles (SCPs) from lake sediment followed Rose (1990, 1994). Slides were mounted using Naphrax® medium. Particles were counted under light microscope at 400 times magnification and the sediment concentration calculated as number of particles per gram dry mass of sediment (gDM^{-1}).

The AL:PE diatom–pH model was used for pH inferences (Cameron et al., 1999). Detrended canonical correspondence analysis (DCCA) was used to estimate the overall species turn-over measured in SD units and to generate sample scores, which provide an estimate of compositional change along a temporal gradient (ter Braak, 1986). Samples age, based on ^{210}Pb dating, was used as a sole environmental variable in DCCA. In DCCAs, species data were square-root transformed, no rare species down-weighting was applied, and non-linear rescaling and detrending by segments were used. All DCCAs were carried out using CANOCO 4.5 (ter Braak and Šmilauer, 2002). Rate-of-change analysis (Grimm and Jacobson, 1992) was used to quantify the total amount of biostratigraphical change in diatom assemblages per unit time. Rates-of-change were estimated as chord distances (Prentice, 1980) per 50 years. We used simple linear interpolation to produce time series at equally spaced time intervals (10 years). No smoothing was used before or after the interpolation. In an attempt to identify rates-of-change that are greater than one would expect by chance, given the critical sampling density and inherent variance of each data-set, approximate significance values at 95% were obtained by a restricted Monte Carlo permutation test based, in part, on the time-duration or elapsed time test of Kitchell et al. (1987) and, in part, on the restricted Monte Carlo permutation test used in CANOCO 4.5 for time series (ter Braak and Šmilauer, 2002).

4. Results and interpretations

4.1. Core chronologies

At all sites equilibrium between supported and unsupported ^{210}Pb, corresponding to ca. 100–120 years of accumulation, was reached at depths of between 5 and 16 cm (Table 2). At Lakes Vankavad and Vanuk-ty there were irregularities in the unsupported ^{210}Pb activity versus depth profiles, indicating non-uniform sedimentation

Table 2
^{210}Pb dating results: mean sedimentation rates and equilibrium depths

Sites	Mean sediment accumulation rates, g/cm^2yr	Equilibrium depth, cm	Dating models used	Depth of the $^{137}Cs/^{241}Am$ peak, cm
Vanuk-ty Lake	0.033 until ca.1985 0.064 from ca.1985	11	CRS	8.0
Moreju Lake	0.013± 0.002	10	CRS, CIC	4.1
Mitrofanovskoe Lake	0.027± 0.002 g	16	CRS, CIC	7.0
Vankavad Lake	0.022 until c.1980 0.045 from 1980	5–6 cm	CRS	3.0
Malyi Patok Lake	0.020± 0.002	7.5–8.5	CRS, CIC	7.5

rates. ^{210}Pb dates were therefore calculated using the CRS dating model (Appleby, 2001). All ^{210}Pb-based chronologies are in good agreement with the independently determined 1963 date from the ^{137}Cs stratigraphy (Table 2). Sedimentation rates are low and mostly uniform except for Lakes Vankavad and Vanuk-ty, where they increase within the last 15–20 years (Table 2). More details on ^{210}Pb chronology for Lakes Mitrofanovskoe and Vanuk-ty are given in Solovieva et al. (2005).

4.2. Diatom analysis

Diatom assemblages from all five lakes are rather similar, with several small *Fragilaria* (e.g., *F. pinnata*, *F. brevistriata*, *F. pseudoconstruens*) being the dominant benthic taxa and *Aulacoseira subarctica*, *A. islandica*, *Tabellaria flocculosa* (long form) and *Asterionella formosa* prevailing in plankton. This diatom flora is typical for circum-neutral oligo/mesotrophic lakes in the northern Urals region (e.g., Stenin, 1972; Getsen et al., 1994; Solovieva et al., 2002; Cremer et al., 2004; Andreev et al., 2005) and in the Pechora delta and in Siberia (Laing and Smol, 2000, 2003).

Sedimentary diatom assemblages from all studied lakes show distinct changes in the 20th century. The most striking diatom changes occurred at Lake Vankavad (Fig. 3), where *Asterionella formosa* increased from about 1 to 2% abundance between 1880s and 1940s to ca. 25% in the 1950s and up to 55% in 1998. From the 1950s planktonic *Fragilaria capucina* v. *gracilis* also increased, albeit not considerably, and *F. construens* v. *venter* totally disappeared from the sediments. *Tabellaria flocculosa* and *Stauroforma* sp. increased from the 2–3% to 8–9% on average between 1880s and 1960s, whereas *Fragilaria construens* v. *venter* and *F. brevistriata* started to decrease between the 1850s and 1900s. Interestingly, in Lake Mitrofanovskoe, *Asterionella formosa* also first occurred in the 1950s, and it reached maximum abundance (20%) in Lake Malyi Patok at around the same period. The rates-of-change of diatom composition are significant in Lake Vankavad ($p<0.05$) during the last 100 years (Fig. 3).

In Lake Mitrofanovskoe, the first diatom changes occurred at about 1900, when *Fragilaria robusta* increased and *Aulacoseira islandica*, *Fragilaria pseudoconstruens*, *Cyclotella tripartita* and *Navicula digitulis* decreased. Another set of changes occurred in Lake Mitrofanovskoe between the 1960s and 1970s when planktonic *Tabellaria flocculosa* and *A. islandica* increased together with benthic *F. robusta*. The later diatom changes coincided with the substantial increase in DAR. In Lake Mitrofanovskoe, the rates-of-change of diatom composition are also are significant ($p<0.05$) between 1971 and 2001.

In Lake Malyi Patok the major changes also occurred at about 1970s with the increase in planktonic *Aulacoseira subarctica*, *Asterionella formosa* and *Fragilaria capucina* together with small benthic *Fragilaria elliptica* and *Navicula minima*. These changes are consistent with the increase in DAR. The rates-of-change of diatom composition are significant ($p<0.05$) in Lake Malyi Patok between 1960 and 2001.

In Lake Vanuk-ty the most pronounced diatom changes occurred after 1971, first with the appearance of planktonic *Tabellaria flocculosa* and a decrease in benthic *Fragilaria pinnata* and *F. construens* v. *venter* and, later, with the increase in *F. brevistriata* and the decrease in *Aulacoseira islandica*. *Asterionella formosa* and *Navicula minima* occurred at a low abundance in the 1990s. Diatom accumulation rate increased in Lake Vanuk-ty from the 1980s and the rate-of-change in diatom composition was statistically significant ($p<0.05$) between 1910 and 2001 (Fig. 3).

Major diatom changes occurred in Lake Moreju in the 1990s with the more than two-fold increase in planktonic *Aulacoseira subarctica*, and lesser increase in *Asterionella formosa* and *Navicula minima*. At the same time, planktonic *Tabellaria flocculosa* almost disappeared from the sediments between 1990 and 2001, and *Fragilaria pseudoconstruens* remained at around the same abundance. These changes were consistent with the increase in DAR (Fig. 3). The rate-of-change in the diatom composition was statistically significant ($p<0.05$) between 1901 and 2001.

Table 3
Lengths of gradient and eigenvalues of DCCA axis 1. Lakes are arranged in north–south direction

Studied lakes	Length of gradient (SD)	Eigenvalue (λ_1)
Vanuk-ty Lake	1.49	0.17
Moreju Lake	1.18	0.17
Mitrofanovskoe Lake	1.23	0.13
Vankavad Lake	1.52	0.16
Malyi Patok Lake	1.04	0.12

The overall diatom compositional changes are reflected by the gradual changes in the profiles of DCCA sample scores (Fig. 3) and by the length of gradient of DCCA axis 1 shown in Table 3. The highest diatom species turn-over occurred in Lake Vankavad (gradient length 1.52 SD), and the lowest in Lake Malyi Patok (1.04 SD). Thus, all the study lakes exhibit statistically significant changes in the diatom composition and accumulation rate during the last 100 years. The rate-of-change in diatom composition was also statistically significant at all lakes for different periods in the 20th century. However, these changes are not simultaneous, but time-transgressive. Major periods of change occurred at the turn of the century in Lake Mitrofanovskoe, in the 1950s in Lake Vankavad, in the 1970s in Lakes Mitrofanovskoe, Malyi Patok and Vanuk-ty and in the 1990s in Lake Moreju.

4.3. Pollution history

SCPs first appeared in the sediments of the above lakes in the mid-1950s except for Lake Malyi Patok, where no SCPs were found (Fig. 2). The peak in SCP accumulation rate at all sites occurred at around 1990s, and this coincides with the period of most intensive coal production in the regional industrial centre of Vorkuta (Solovieva et al., 2002). The same pattern was found in many other lakes in the northern Ural region and it implies a largely local origin of SCPs in lake sediments (Solovieva et al., 2002). The highest SCP accumulation rate occurred in Lake Vanuk-ty (up to 79 cm^{-2} y^{-1}) in 1990, and this is also the lake closest to Vorkuta (Fig. 2). Fig. 2 clearly shows that SCP accumulation rate decreases in Lakes Moreju and Mitrofanovskoe, which are located further to the west from Vorkuta compared to Vanuk-ty. SCPs in the Lake Vankavad sediments occurred at a very low concentration and only in the top two surface layers (Solovieva et al., 2002). The SCP accumulation rate in Lake Vankavad is nearly 80 times as low as it is in Lake Vanuk-ty (Fig. 2). Lake Vankavad is located at about 40 km west from the small industrial

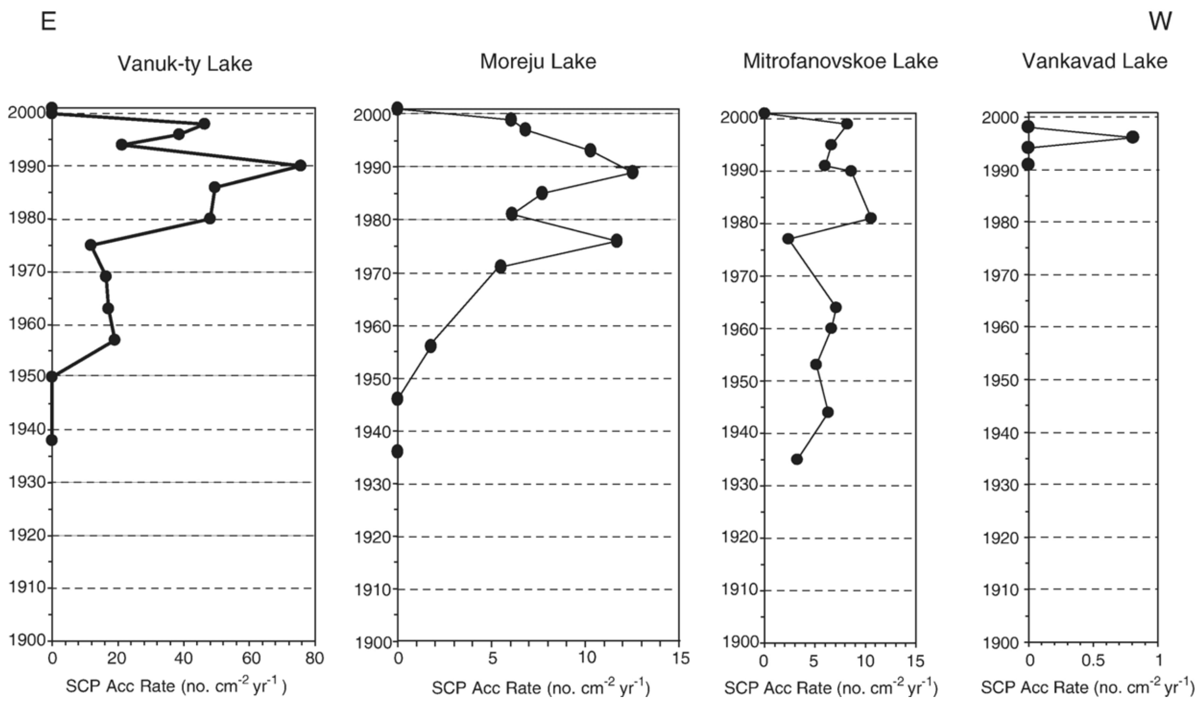

Fig. 2. Profiles of SCP accumulation rate in the studied lakes. No SCPs were found in Lake Malyi Patok. Lakes are arranged in east–west direction to highlight the effect of local pollution.

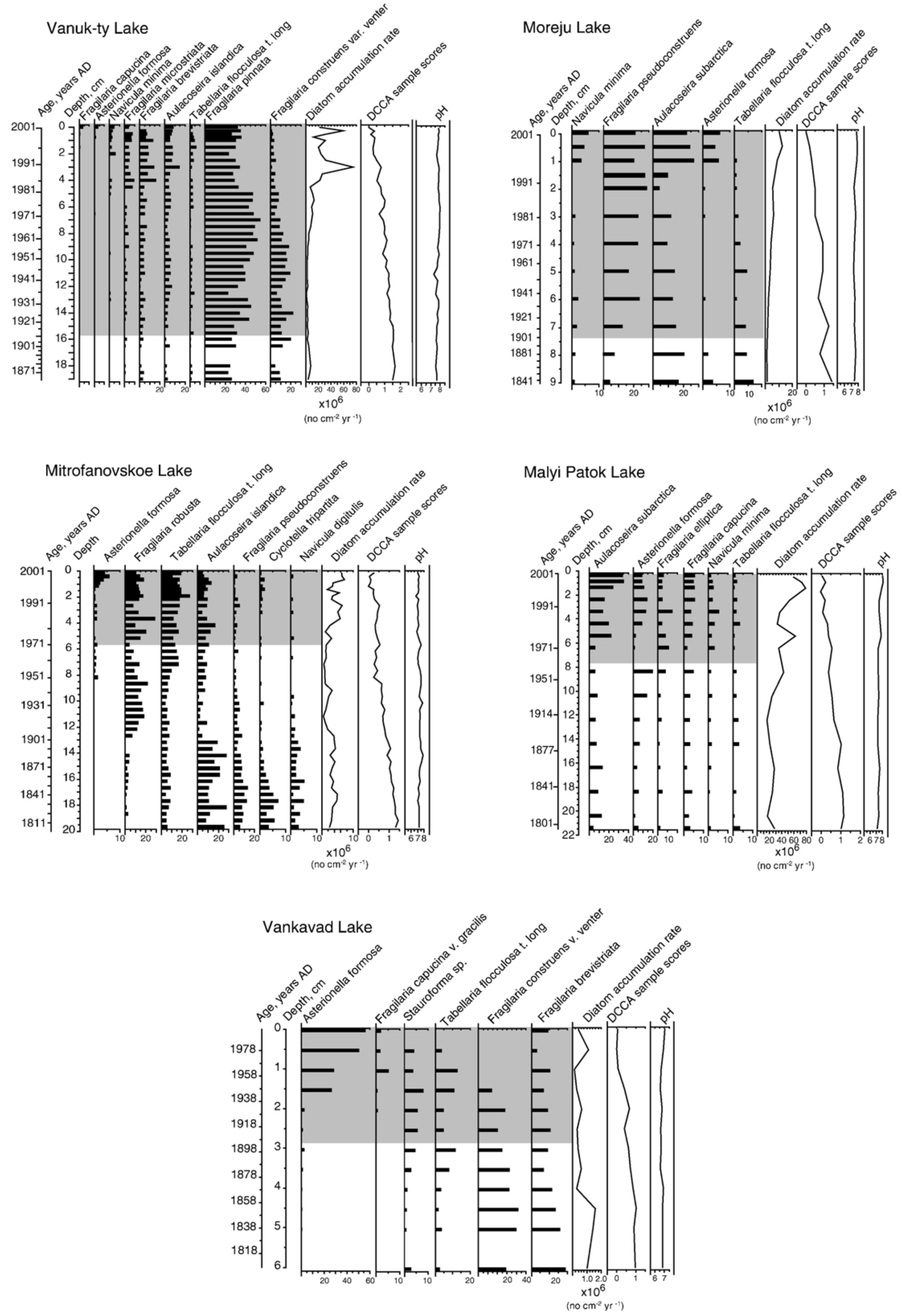

Fig. 3. Stratigraphic changes in selected diatom taxa, diatom accumulation rates, DCCA sample scores and AL:PE-inferred pH from five lakes in the northern Urals. The period of statistically significant ($p<0.05$) rates-of-changes in the diatom assemblages is highlighted in grey. The taxa are sorted by their weighted averaging scores from upper left to bottom right to highlight the major stratigraphic changes.

town of Inta (Fig. 1), which is a minor source of air pollution compared to Vorkuta (Solovieva et al., 2002). No SCPs were found in the sediments of Lake Malyi Patok, which is remote from all sources of local pollution and located in the Nature Reserve Yugyd Va on the slopes of the Ural mountains.

In all lakes AL:PE-inferred pH shows little change, increasing slightly in the top and implying that the lakes are not affected by acidification (Fig. 3). No evidence for acidification was found in most other lakes from this region, which is due both to the high buffering capacity of bedrock and generally low levels of atmospheric pollution (Solovieva et al., 2002).

5. Discussion

As all the lakes are remote with no permanent settlements in the catchments, there are no sources of local pollution, although there is some regional pollution originating from the Varkuta coal industry. There is also no evidence for acidification or eutrophication from diatom changes (Solovieva et al., 2002; Sarmaja-Korjonen et al., 2003; Solovieva et al., 2005). In all lakes, except for Lake Moreju, the major compositional changes predate the peaks in SCPs and the SCP profiles are not coincident with diatom changes in any of the lakes. In Lake Moreju, the SCP accumulation rate is

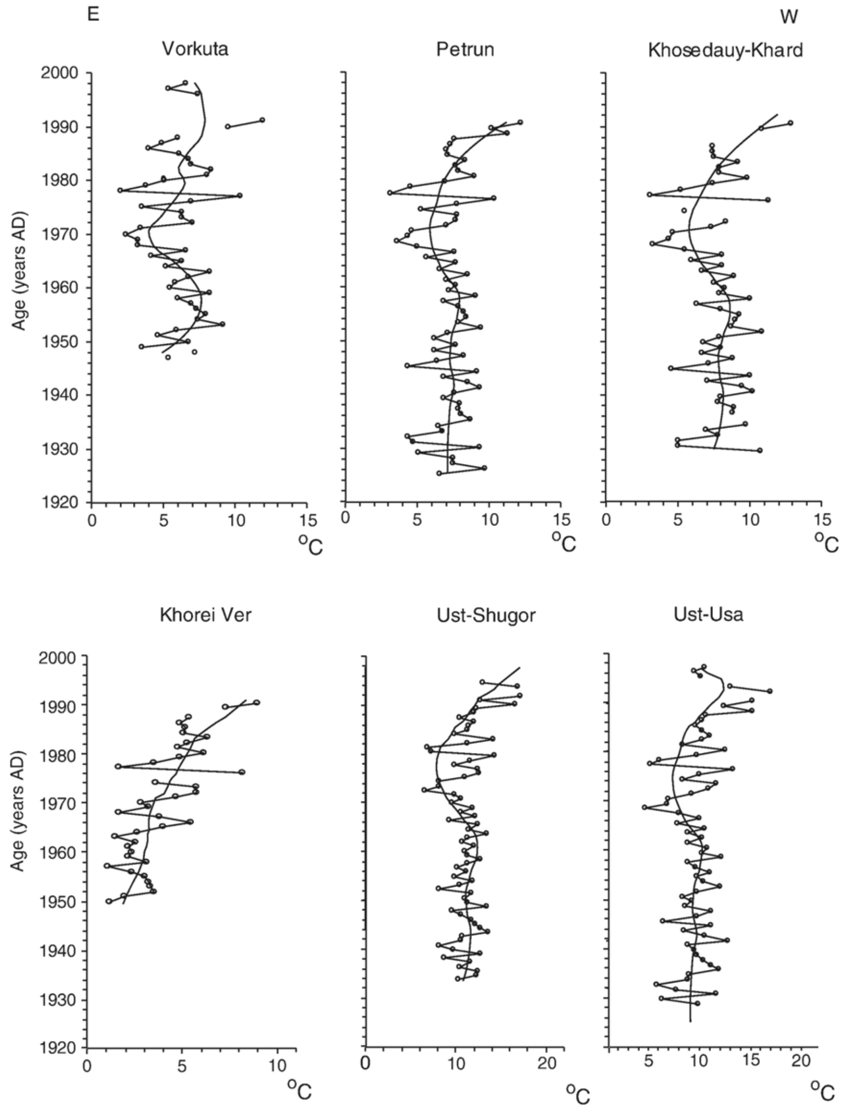

Fig. 4. Average June temperatures from the northern Ural weather stations (Annual Reports on Meteorology, 1920–2001). The trend lines are fitted by LOESS smoothing with a span of 0.5. Graphs are arranged in east–west direction.

relatively low, so it is unlikely that atmospheric contamination could have affected the diatom flora in this lake. In Lake Vanuk-ty, which is the most contaminated of all the studied lakes, the peak SCP accumulation rate is still lower than in many European (Rose et al., 1999) and northern Ural lakes (Solovieva et al., 2002) and is comparable to the SCP accumulation rates in lakes from Svalbard (Rose et al., 2004) and sub-arctic Finland (Korhola et al., 2002). Analysis of stable-lead isotopes in the sediments of Lake Mitrofanovskoe (Solovieva et al., 2005) shows a low degree of global lead contamination, which is comparable with the remote lakes in West Greenland (Bindler et al., 2001).

Being the largest among the studied lakes, Lake Vanuk-ty is the only lake with some degree of commercial fishing, which, however, has no direct influence on diatom assemblages (Solovieva et al., 2005). It can thus be concluded that global and local pollution and atmospheric contamination has none or only a very weak influence on diatom flora in the studied lakes.

In all studied lakes compositional changes in diatom assemblages occurred at different periods in the 20th century with all five lakes exhibiting a different degree of change after 1950. In four out of five lakes the changes are most pronounced after 1970. In all lakes the diatom compositional shifts involve planktonic diatoms, most frequently *Aulacoseira subarctica*, *A. islandica*, *Asterionella formosa* and *Tabellaria flocculosa* (long planktonic form) and several benthic taxa, mostly small epilithic and epipsammic littoral *Fragilaria* and *Navicula*. Mean June temperature also increases after 1970 at six weather stations in the region (Fig. 4). An increase in September temperatures is less pronounced and only occurs at three out of six weather stations (Khorei Ver, Vorkuta and Ust-Shugor), while there is no change in the annual or July–August temperatures.

The temperature increases in June and September are likely to have extended the length of the ice-free season affecting diatom composition and abundance. In ice-covered lakes diatoms are especially sensitive to the changes in growing season, i.e., period of ice-cover and timing of ice break-up (e.g., Livingstone, 1999; Mackay et al., 2003) and habitat availability (e.g., Smol, 1988, Lotter and Bigler, 2000; Sorvari et al., 2002). Planktonic taxa (e.g., *Aulacoseira islandica*, *Asterionella formosa*, *Tabellaria flocculosa*) are dependent on changes in ice-cover because it affects the length and timing of the water turn-over and stratification periods, which are essential for establishing planktonic populations. Previously we have established by regression modelling that June and August/September temperatures have statistically significant effects on both planktonic and benthic sediment diatom assemblages in Lakes Mitrofanovskoe and Vanuk-ty (Solovieva et al., 2005).

Although the study area comprises both arctic and sub-arctic environments (e.g. northern taiga), the June temperature increase in the study area is most likely a reflection of the circum-Arctic temperature increase in the late 20th century as arctic-wide warming of the order of 1.5 °C has been observed in the periods 1920–40 and 1970–present (Jones and Moberg, 2003) and the last two decades (from ca. 1980s) have been especially warm (Serreze et al., 2000; Comiso, 2003). The tree-ring measurements from Salekhard (66°50′ N, 65°15′ E) in the eastern part of the northern Urals also indicate an increase in summer temperature between 1901 and 1990 (Briffa et al., 1995; Shiyatov et al., 2002) and there is also ca. 1 °C increase in chironomid-inferred summer temperature in Lake Mitrofanovskoe during the 20th century (Solovieva et al., 2005).

Although the lakes exhibit different degrees of diatom turn-over (Table 3), there is no north–south gradient with northernmost lakes showing greater change, as has been suggested by Smol et al. (2005). The greatest species turn-over occurred in a sub-arctic forest lake, Lake Vankavad, and the northernmost lake, Lake Vanuk-ty, showed the second highest species turn-over values. The diatom assemblages from upland the southernmost Lake Malyi Patok appeared to have the lowest degree of change. Most temperature records show very similar trends, with the greater temperature increase occurring at the Khorei Ver weather station, which is located in tundra in the middle of the study area.

The 20th century diatom compositional changes in sub-arctic Lake Vankavad are greater than in most arctic lakes from Canada and northern Europe recently described by (Smol et al., 2005). The 20th century changes in diatom assemblages of Lake Vankavad are unique for the last 5000 years of its history (Sarmaja-Korjonen et al., 2003). The only lakes, showing greater degree of changes are deep high-arctic Sawtooth Lake and shallow ponds from Ellesmere islands in Canada (Douglas et al., 1994; Perren et al., 2003). However, all the above lakes are located much more to the north in high-arctic desert, whereas Lake Vankavad is surrounded by northern taiga. It appears, therefore, that the northern Urals might be one of the first northern regions where the global temperature increase has already deeply affected lake ecosystems.

6. Conclusions

The studied lakes appear to show no effect from local and regional pollution and atmospheric contamination.

The 20th diatom floristic shifts, the rise in diatom accumulation rates and the rates of diatom compositional change in the northern Ural lakes correlate well with the 1970s rise in June temperature in the region and with the overall circum-arctic temperature increase from the 1970s.

The main driving force behind diatom compositional changes in the study lakes are the changes in the duration of ice-free season, timing of water turn-over and stratification periods and habitat availability. These changes are connected with the increase in June temperatures from the end of 1960s. Changes in diatom plankton are more pronounced than changes in benthic taxa.

There are no clear geographical patterns in degree of compositional changes, with greatest changes occurring in the sub-arctic forest lake Vankavad.

The degree of the 20th century diatom changes in Lake Vankavad is greater than in most circum-arctic and sub-arctic lakes from northern Europe and Canada. The 20th century changes in diatom assemblages of Lake Vankavad are unique for the last 5000 years.

Acknowledgements

This is a contribution to the NERC project to Dr. V. J. Jones (NER/B/S/2000/00733). L. Nazarova was funded by a Royal Society/NATO travel scholarship. This is also a contribution to EU-funded SPICE (ICA2-CT-2000-10018) and TUNDRA (ENV4-CT97-0522) projects. Water-chemistry data were analysed in the Kola Science Centre, Apatity, Russia. We would like to thank everyone who helped with the fieldwork, namely Vasili Ponomarev, Valeri Illarionov, Kazimir Anet'ko, Leonid Nosov and Alexander Konobratkin.

References

ACIA, 2004. Impacts of a warming Arctic; Arctic Climate Impact Assessment. Cambridge University Press. 139 pp.

Annual Reports on Meteorology. 1920–2001. Center of Hydrometeorology and Environmental Monitoring, Komi Republic. 987 pp. (in Russian).

Andreev, A.A., Tarasov, P.E., Ilyashuk, B.P., Ilyashuk, E.A., Cremer, H., Hermichen, W.D., Wischer, F., Hubberten, H.W., 2005. Holocene environmental history recorded in Lake Lyadhej-To sediments, polar Urals, Russia. Palaeogeography Palaeoclimatology Palaeoecology 223, 181–203.

Appleby, P.G., 2001. Chronostratigraphic techniques in recent sediments. In: Last, W.M., Smol, J.P. (Eds.), Tracking environmental change using lake sediments. . Basin Analysis, Coring, and Chronological Techniques, vol. 1. Kluwer Academic Publishers, the Netherlands, pp. 171–205.

Appleby, P.G., Nolan, P.J., Gifford, D.W., Godfrey, M.J., Oldfield, F., Anderson, N.J., Battarbee, R.W., 1986. Pb-210 dating by low background gamma-counting. Hydrobiologia 143, 21–27.

Battarbee, R.W., Kneen, M.J., 1982. The use of electronically counted microspheres in absolute diatom analysis. Limnology and Oceanography 27, 184–188.

Battarbee, R.W.J.S., Jones, V.J., Flower, R.J., Cameron, N.G., Bennion, H., Carvalho, L., 2001. Diatom analysis. Kluwer Academic Publishers, Dordrecht, pp. 171–205.

Belyaev, G.M., Vinberg, G.G., Gaevskaya, N.S., Zhadin, V.I., Zenkevich, L.A., Reznichenko, O.G., Scherbakov, A.P. (Eds.), 1966. Gidrobiologicheskie issledovaniya I rybnye zapasy ozer krainego severa SSSR (Hydrobiological studies and fish resources of lakes from extreme North of the USSR). Nauka, Moscow. 168 pp, (in Russian).

Bindler, R., Renberg, I., Anderson, N.J., Appleby, P.G., Emteryd, O., Boyle, J., 2001. Pb isotope ratios of lake sediments in West Greenland: inferences on pollution sources. Atmospheric Environment 35, 4675–4685.

Briffa, K.R., Jones, P.D., Schweingruber, F.H., Shiyatov, S.G., Cook, E.R., 1995. Unusual 20th-century summer warmth in a 1000-year temperature record from Siberia. Nature 376, 156–159.

Cameron, N.G., Birks, H.J.B., Jones, V.J., Berge, F., Catalan, J., Flower, R.J., Garcia, J., Kawecka, B., Koinig, K.A., Marchetto, A., Sanchez-Castillo, P., Schmidt, R., Sisko, M., Solovieva, N., Stefkova, E., Toro, M., 1999. Surface-sediment and epilithic diatom pH calibration sets for remote European mountain lakes (AL:PE Project) and their comparison with the Surface Waters Acidification Programme (SWAP) calibration set. Journal of Paleolimnology 22, 291–317.

Comiso, J.C., 2003. Warming trends in the Arctic from clear sky satellite observations. Journal of Climate 16, 3498–3510.

Cremer, H., Andreev, A., Hubberten, H.W., Wischer, F., 2004. Paleolimnological reconstructions of Holocene environments and climate from Lake Lyadhej-To, Ural Mountains, Northern Russia. Arctic, Antarctic and Alpine Research 36, 147–155.

Douglas, M.S.V., Smol, J.P., Blake, W., 1994. Marked post-18th century environmental-change in high-arctic ecosystems. Science 266, 416–419.

Drabkova, V.G., Bystrov, S., 1994. Gidrokhimiya ozer. (Hydrochemistry of lakes). In: Drabkova, V.G., Trifonova, I.S. (Eds.), Ozernye ecosystemy v usloviayx krainego severa. (Lake Ecosystems in the Extreme North). Nauka, St-Petersburg, pp. 48–65 (in Russian).

Drabkova, V.G., Trifonova, I.S. (Eds.), 1994. Ozernye ecosystemy v usloviayx krainego severa. (Lake Ecosystems in the Extreme North). Nauka, St-Petersburg. 247 pp. (in Russian).

Getsen, M.V., Stenina, A.S., Patova, E.N., 1994. Algologicheskaya flora Bol's hezemel's koi tundry v usloviyax antropogennogo vozdeistviya. Bol's hezemel's kaya tundra under anthropogenic influence. Nauka, Ekaterinburg. 183 pp. (in Russian).

Giorgi, F., Mearns, L.O., 2002. Calculation of average, uncertainty range, and reliability of regional climate changes from AOGCM simulations via the "reliability ensemble averaging" (REA) method. Journal of Climate 15, 1141–1158.

Glew, J.R., 1989. A new trigger mechanism for sediment samples. Journal of Paleolimnology 2, 241–243.

Grimm, E.C., Jacobson, G.L., 1992. Fossil-pollen evidence for abrupt climate changes during the last 18,000 years in eastern North America. Climate Dynamics 6, 179–184.

Jones, P.D., Moberg, A., 2003. Hemispheric and large-scale surface air temperature variations: an extensive revision and an update to 2001. Journal of Climate 16, 206–223.

Jones, V.J., Birks, H.J.B., 2004. Lake-sediment records of recent environmental change on Svalbard: results of diatom analysis. Journal of Paleolimnology 31, 445–466.

Kitchell, J.A., Estabrook, G., MacLeod, N., 1987. Testing for equality of rates of evolution. Paleobiology 13, 272–285.

Korhola, A., Sorvari, S., Rautio, M., Appleby, P.G., Dearing, J.A., Hu, Y., Rose, N., Lami, A., Cameron, N.G., 2002. A multi-proxy analysis of climate impacts on recent developments of subarctic lake Saanajärvi in Finnish Lapland. Journal of Paleolimnology 28, 59–77.

Krammer, K., Lange-Bertalot, H., 1986–1991. Bacillariophyceae. Gustav Fisher Verlag, Stuttgart.

Laing, T.E., Smol, J.P., 2000. Factors influencing diatom distributions in circumpolar treeline lakes of northern Russia. Journal of Phycology 36, 1035–1048.

Laing, T.E., Smol, J.P., 2003. Late Holocene environmental changes inferred from diatoms in a lake on the western Taimyr Peninsula, northern Russia. Journal of Paleolimnology 30, 231–247.

Livingstone, D.M., 1999. Ice break-up on southern Lake Baikal and its relationship to local and regional air temperatures in Siberia and to the North Atlantic Oscillation. Limnology and Oceanography 44, 1486–1497.

Lotter, A.F., Bigler, C., 2000. Do diatoms in Swiss Alps reflect the length of ice-cover? Aquatic Science 62, 125–141.

Mackay, A.W., Battarbee, R.W., Flower, R.J., Granin, N.G., Jewson, D.H., Ryves, D.B., Sturm, M., 2003. Assessing potential for developing internal diatom-based transfer functions for Lake Baikal. Limnology and Oceanography 48, 1183–1192.

Moritz, R.E., Bitz, C.M., Steig, E.J., 2002. Dynamics of recent climate change in the Arctic. Science 297, 1497–1502.

Mukhin, N.I., Petrakova, V.M., Shevchenko, A.I., 1964. Klimaticheskie kxarakteristiki Pechorskogo ugol'nogo basseina. (Climatic characteristics of the Pechora basin). In: Geokrinologicheskie usloviya Pechorskogo ugol'nogo basseina. (Geocrinological conditions of the Pechora coal basin), Moscow, pp. 20–28 (in Russian).

Perren, B.B., Bradley, R.S., Francus, P., 2003. Rapid lacustrine response to recent high arctic warming: a diatom record from Sawtooth Lake, Ellesmere Island, Nunavut. Arctic, Antarctic and Alpine Research 35, 271–278.

Prentice, I.C., 1980. Multidimensional scaling as a research tool in Quaternary palynology: a review of theory and methods. Review of Palaeobotany and Palynology 31, 71–104.

Renberg, I., 1990. A procedure for preparing large sets of diatom slides from sediment cores. Journal of Paleolimnology 4, 87–90.

Rose, N.L., 1990. A method for the extraction of carbonaceous particles from lake sediment. Journal of Paleolimnology 3, 45–53.

Rose, N.L., 1994. A note on further refinement to a procedure for the extraction of carbonaceous fly-ash particles from sediments. Journal of Paleolimnology 11, 201–204.

Rose, N.L., Harlock, S., Appleby, P.G., 1999. The spatial and temporal distribution of spheroidal carbonaceous fly-ash particles (SCP) in the sediment records of European mountain lakes. Water, Air and Soil Pollution 113, 1–32.

Rose, N.L., Rose, C.L., Boyle, J.F., Appleby, P.G., 2004. Lake-sediment evidence for local and remote sources of atmospherically deposited pollutants on Svalbard. Journal of Paleolimnology 31, 499–513.

Sarmaja-Korjonen, K., Kultti, S., Solovieva, N., Valiranta, M., 2003. Mid-Holocene palaeoclimatic and palaeohydrological conditions in northeastern European Russia: a multi-proxy study of Lake Vankavad. Journal of Paleolimnology 30, 415–426.

Serreze, M.C., Walsh, J.E., Chapin, F.S., Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W.C., Morison, J., Zhang, T., Barry, R.G., 2000. Observational evidence of recent change in the northern high-latitude environment. Climatic Change 46, 159–207.

Smol, J.P., 1988. Palaeoclimate proxy data from freshwater diatoms. Verdhandlungen Internationale Vereinigung für Limnologie 23, 837–844.

Smol, J.P., Wolfe, A.P., Birks, H.J.B., Douglas, M.S.V., Jones, V.J., Korhola, A., Pienitz, R., Rühland, K., Sorvari, S., Antoniades, D., Brooks, S.J., Fallu, M.A., Hughes, M., Keatley, B.E., Laing, T.E., Michelutti, N., Nazarova, L., Nyman, M., Paterson, A.M., Perren, B., Quinlan, R., Rautio, M., Saulnier-Talbot, E., Siitoneni, S., Solovieva, N., Weckstrom, J., 2005. Climate-driven regime shifts in the biological communities of arctic lakes. Proceedings of the National Academy of Sciences of the United States of America 102, 4397–4402.

Shiyatov, S.G., Hantemirov, R.A., Gorlanova, R.M., 2002. Millenial reconstruction of the summer temperature in the polar Urals: tree-ring data from Siberian juniper and Siberian larch. Archaeology, Ethnology, Anthropology of Eurasia 9, 2–5.

Solovieva, N., Jones, V.J., Appleby, P.G., Kondratenok, B.M., 2002. Extent, environmental impact and long-term trends in atmospheric contamination in the Usa basin of east-European Russian arctic. Water, Air and Soil Pollution 139, 237–260.

Solovieva, N., Jones, V.J., Nazarova, L., Brooks, S.J., Birks, H.J.B., Grytnes, J.A., Appleby, P.G., Kauppila, T., Kondratenok, B., Renberg, I., Ponomarev, V., 2005. Palaeolimnological evidence for recent climatic change in lakes from the northern Urals, arctic Russia. Journal of Paleolimnology 33, 463–482.

Sorvari, S., Korhola, A., Thompson, R., 2002. Lake diatom response to recent Arctic warming in Finnish Lapland. Global Change Biology 8, 171–181.

Stenin, V.N., 1972. Peculiarities of diatom flora in the modern glacial lakes from the Polar Urals. Scientific Reports of Higher School. Biological Sciences 5, 66–73 (in Russian).

ter Braak, C.F.J., 1986. Canonical correspondence analysis: a new eigenvector technique for multivariate direct gradient analysis. Ecology 67, 1167–1179.

ter Braak, C.F.J., Šmilauer, P., 2002. CANOCO Reference manual and CANODRAW for Windows User's guide: Software for Canonical Community Ordination (version 4.5). Ithaca, NY.

Vlasova, T.A., 1976. Gidrologiay I gidrokhimiya Kxarbeiskix ozer. Phyzicheskaya geographiya raiona. (Hydrology and hydrochemistry of Kharbei Lakes. Physical geography of the study area.). In: Vinberg, G.G., Vlasova, T.A. (Eds.), Produktivnost' ozer na vostoke bol's hezemel'skoi tundry. (Productivity of lakes in the east of Bolshezemel'skaya tundra). Nauka, Leningrad, pp. 5–26 (in Russian).

Walker, T., Habeck, O., Karjalainen, T., Virtanen, T., Solovieva, N., Jones, V.J., Kuhry, P., Ponomarev, V., Mikkola, K., Nikula, A., Patova, E., Crittenden, P., Young, S., Ingold, T., 2006. Perceived and measured levels of environmental pollution: interdisciplinary research in the subarctic lowlands of northeast European Russia. Ambio. 35, 220–228.

Zvereva, O.S., Vlasova, T.A., Goldina, L.P., 1966. Istoriay Vashutkinyx ozer. (History of Vashutkiny Lakes). In: Belyaev, G.M., Vinberg, G.G., Gaevskaya, N.S., Zhadin, V.I., Zenkevich, L.A., Reznichenko, O.G., Scherbakov, A.P. (Eds.), Gydrobiologicheskie issledovaniya i rybnye zapasy ozer krainego severa SSSR. (Hydrobiological studies and fish resources of lakes from the extreme North of the USSR). Nauka, Moscow, pp. 4–21 (in Russian).