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# Palaeolimnological evidence for recent climatic change in lakes from the northern Urals, arctic Russia

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## Abstract

The recent sediments from two deep arctic lakes, Mitrofanovskoe and Vanuk-ty, situated in the permafrost belt within the Bol'shezemel'skaya Tundra in the northern Ural region, were studied for diatoms, chironomids, spheroidal carbonaceous particles and stable lead isotopes. The magnitudes and rates-of-change in diatom and chironomid assemblages were numerically estimated. Instrumental climate records were used to assess statistically the amount of variance in diatom and chironomid data explained by temperature. August and September air temperatures have a statistically significant effect on diatom composition at both lakes. At Mitrofanovskoe Lake, major compositional changes in diatom and chironomid assemblages occurred at the turn of the 20th century and might be related to the regional increase in temperature. Chironomid-inferred air temperature also increased by approximately 1 °C since the early 1900s. At both lakes diatom compositional changes, coincident with the increase in June and September temperatures, also occurred in the late 1960s. These compositional changes are correlated with the increase in diatom production, sediment organic content and diatom species richness, and are likely to be a diatom response to the lengthening of the growing season. These changes are also correlated with the circum-Arctic temperature increase from the 1960s. A chironomid response to the late 1960s temperature increase was less pronounced at both lakes. Pollution levels are relatively low and pollution history is unrelated to ecological changes. Both lead isotopes and spheroidal carbonaceous particles show a clear atmospheric pollution signal, peaking in the 1980s.

## Introduction

The last 100 years have been marked by rising global pollution levels and associated global climate change (e.g., UNEP 1999; IPCC 2001). There is mounting evidence that many parts of the globe, including the most remote Arctic areas, are affected by global pollution, including the increased deposition of heavy metals, spheroidal carbonaceous particles and nitrogen (e.g., Weller 1995; Bindler et al. 2001; Simoes and Zagorodnov 2001; Solovieva et al. 2002; Rose et al. 2004). It is also well established that global warming is especially pronounced in the Arctic through amplified feedbacks (Overpeck et al. 1997) and that arctic ecosystems are particularly vulnerable to environmental changes (ACIA 2004). There is substantial evidence that lake ecosystems in the Canadian Arctic and Fennoscandia are undergoing changes which have been linked to human-induced climate warming during the last 150–100 years (Douglas et al. 1994; Overpeck et al. 1997; Hughen et al. 2000; Sorvari et al. 2002; Perren et al. 2003; Wolfe 2003; Smith et al. 2004; Brooks et al. 2005;). However, it is still unclear how other arctic regions respond to global environmental change and whether the cause of the recent changes in lakes can be solely explained by global warming.

In this work, we used lacustrine sediment records to study the effects of global changes on two lakes from the arctic Urals in European Russia. The two lakes, Mitrofanovskoe and Vanuk-ty, were chosen for their relative remoteness from possible local sources of pollution. Both lake ecosystems have been extensively studied in the past, and this makes the current work quite different from many other palaeolimnological arctic studies, which often lack modern limnological and ecological data. A recent comprehensive survey of Mitrofanovskoe Lake edited by Drabkova and Trifonova (1994) includes research on the hydrology, water chemistry, phyto- and zooplankton, zoobenthos and fish populations. Vanuk-ty Lake has also been studied in detail (e.g., Belyaev et al. 1966). However, both studies provide mostly qualitative data over 1 or 2 years, as there was no continuous monitoring of the lakes. In our work, we attempted to use these ecological, limnological and hydrological data in order to explain palaeolimnological changes in Mitrofanovskoe and Vanuk-ty lakes.

This work is the first attempt to provide a dated, high-resolution record of environmental changes over the last ca. 150 years in a geographically remote and poorly studied region of arctic Russia. We used high-resolution $^{210}$ Pb-dated sedimentary records of diatoms, chironomids and spheroidal carbonaceous particles (SCPs) to infer past ecosystem change during the last 100–150 years in two lakes from the arctic Ural region. We also used sediment lead concentrations and the $^{206}$Pb/$^{207}$Pb ratio to reconstruct the history of atmospheric pollution (Renberg et al. 2002).

## Study area and study sites

The lakes are situated to the west of the Ural Mountains on a large lowland plain, the Bol'shezemel'skaya Tundra, within the zone of continuous permafrost (Figure 1). The area is underlain by Permian rocks and Quaternary deposits (Vlasova 1976). Relief is hilly, with maximum altitudes reaching 226 m a.s.l. Climate is severe with an eight-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). Shrub-lichen tundra is dominated by *Betula nana*, with some *Empetrum nigrum*, and *Vaccinium vitis-idaea*. *Vaccinium myrtillus* prevails on drier patches and hills.

Both lakes were formed during the last glaciation, and are deep, dimictic lakes, which are stratified during the winter and summer seasons (Zvereva et al. 1966; Davydova et al. 1994). 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).

Both lakes are dilute and circumneutral (Table 1) typical of the northern Ural region (Zvereva et al. 1966; Solovieva et al. 2002). They are both oligo-mesotrophic although $N_{tot}$ values are much higher at Vanuk-ty Lake.

The ice-free period at Mitrofanovskoe Lake lasts approximately from the third week in June to mid-September. Planktonic diatoms have two peaks of abundance: the first in mid-June to the beginning of July and the second at the end of July to the beginning of August (Trifonova and Petrova 1994). The spring peak starts from under the ice and *Aulacoseira islandica* dominates phytoplankton

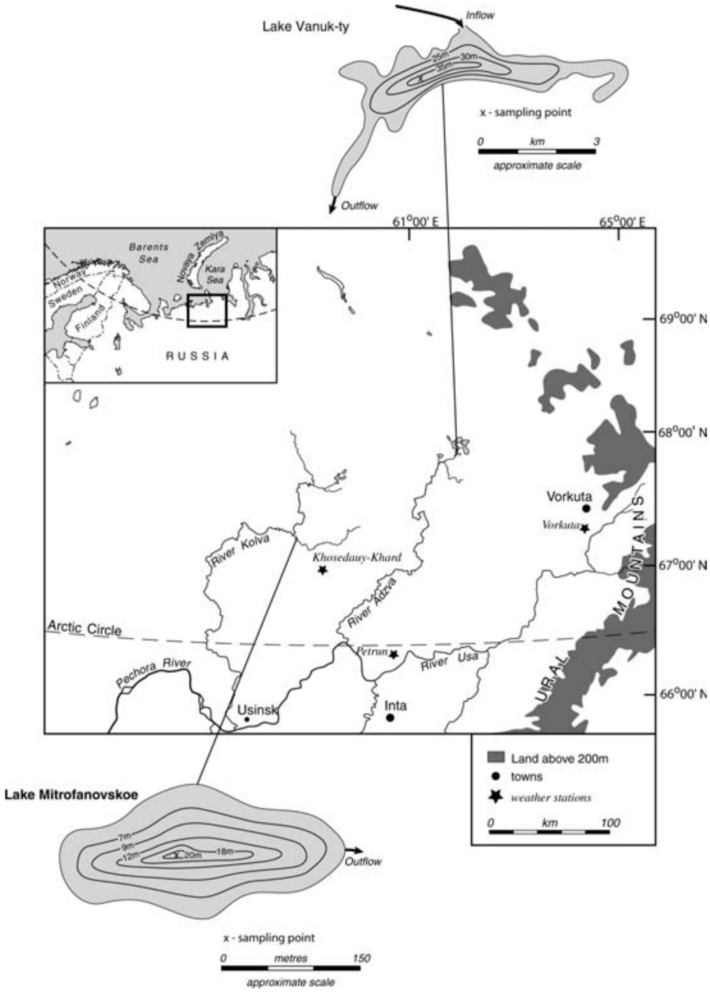

*Figure 1.* Study area and morphometry of the study lakes. Main industrial centres and weather stations are also shown.

during both peaks. In July, when the lake is stratified, *Asterionella formosa* and *Rhizosolenia longiseta* become dominant in the phytoplankton together with some dinoflagellates, chrysophytes and chlorophytes (Trifonova and Petrova 1994).

Vanuk-ty Lake is a part of the Vashutkiny lake system, which comprises nine interconnected lakes (Figure 1). Vanuk-ty Lake has a large littoral zone with depths between 1 and 1.5 m and abundant macrophytes, e.g., *Carex aquatilis*, *Arctophila fulva* and *Equisetum heleocharis* (Zvereva et al. 1966). The ice-free period, slightly shorter than at Mitrofanovskoe Lake, lasts between the first week in July and the first week in September. In Vanuk-ty, *Aulacoseira* spp. (mainly *A. islandica*, *A. subarctica* and *A. italica*) dominate the plankton during the single peak of abundance, which occurs at the beginning of July and coincides with the period of water mixing (Getsen 1966). In August, when the lake becomes stratified, the phytoplankton is dominated by *Asterionella formosa* together with several *Anabaena* (Cyanobacteria) and several chysophyte taxa. In September, more benthic and meroplanktonic diatom taxa (e.g., *Cymbella*, *Fragilaria*, *Navicula*) occur in plankton which might be due to strong wind-induced mixing.

Vanuk-ty Lake has been used for small-scale commercial fishing since the late 1940s (Solovkina and Sidorov 1966). Fishermen (recently up to 80 people) arrive during the ice-free period, and stay for 20–30 days. Catches mainly comprise peled (*Coregonus peled*), whitefish (*Coregonus lavaretus pidschian*), grayling (*Thymallus thymallus*) and pike (*Esox lucius*). During the 1960s the fish catches in the whole Vashutkiny lake complex were more than two times higher than in the 1980s,

*Table 1.* Summary characteristics of the study lakes.

| | Mitrofanovskoe Lake | | Vanuk-ty Lake |
|---|---|---|---|
| Latitude | 67°51′ N | | 68°00′ N |
| Longitude | 58°59′ E | | 62°45′ E |
| Altitude, m a.s.l. | 123.9 | | 132 |
| Average depth, m | 6.1 | | 1.73 |
| Max depth, m | 20 | | 35 |
| Area, km$^2$ | 0.309 | | 8.3 |
| Catchment vegetation | Shrub lichen tundra | | Shrub lichen tundra |
| | April 2001; | July 2001 | April 2001 |
| pH | 6.8; | 7.06 | 6.88 |
| Alkalinity, $\mu$eq l$^{-1}$ | 588.96; | 365 | 622.9 |
| Conductivity, $\mu$S cm$^{-1}$ | 67.2; | 44.6 | 70.9 |
| $K^+$, mg l$^{-1}$ | 0.95; | 0.48 | 0.91 |
| $Na^+$, mg l$^{-1}$ | 2.75; | 1.09 | 2.3 |
| $Ca^{2+}$, mg l$^{-1}$ | 8.4; | 5.3 | 8.6 |
| $Mg^{2+}$, mg l$^{-1}$ | 1.72; | 1.12 | 1.92 |
| $Cl^-$, mg l$^{-1}$ | 4.4; | 1.23 | 2.0 |
| $SO_4{}^{2-}$, mg l$^{-1}$ | 1.24 | | 1.0 |
| $P_{tot}$, $\mu$g l$^{-1}$ | 19; | 58 | 14 |
| $N_{tot}$, $\mu$g l$^{-1}$ | 250; | 105 | 1600 |

decreasing further by nearly 10 times by 2002 (Table 2). Decreasing fish catches and increasing fishing pressure since the 1960s suggests that fish populations in Vanuk-ty Lake may have declined substantially in recent decades.

## Material and methods

### *Field and laboratory methods*

Sediment cores were collected in April 2001 using a Glew corer (Glew 1989) from the deepest point of the lake and were extruded at 0.25 cm intervals.

*Table 2.* Total fish catches for Vashutkiny Lakes (this includes Vanuk-ty Lake) (data compiled from Annual Fishery reports – unpublished).

| Years | Total catch, kg | Number of fishers |
|---|---|---|
| 1959 | 44,000 | No data |
| 1960 | 48,900 | No data |
| 1961 | 53,400 | No data |
| 1980 | 20,269 | 6 |
| 1985 | 26,885 | 10 |
| 1986 | 22,769 | 20 |
| 1990 | 3906 | 15 |
| 2002 | 2300 | 78 |

Water samples were collected in acid-washed, polyethylene, 1 l bottles in April (both lakes) and July (Mitrofanovskoe only) 2001. In summer, pH was measured in the field using a portable Beckman meter. Specific conductivity was measured using a Jenway meter. Alkalinity was measured by potentiometric titration. Major cations ($Na^+$ and $K^+$) were determined by flame emission, and $Mg^{2+}$ and $Ca^{2+}$ were analysed using atomic adsorption spectroscopy. Chloride ($Cl^-$) was determined by potentiometric titration and sulphate ($SO_4{}^{2-}$) was analysed photometrically. Total nitrogen ($N_{tot}$) was analysed using ion chromatography. Analysis of total phosphorus ($P_{tot}$) in unfiltered water followed Murphy and Riley (1962).

Sediment samples 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 and 352 keV $\gamma$-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 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.

Total lead concentrations and stable lead isotopes, $^{206}$Pb and $^{207}$Pb, were analysed in the core from Mitrofanovskoe Lake using a strong acid digestion and ICP-MS (Renberg et al. 2002).

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

Percentage organic content of the sediments was measured by loss on ignition (% LOI) at 550 °C (Dean 1974).

Diatom slide preparation followed standard methods (Battarbee et al. 2001a) using the water-bath technique (Renberg 1990). Slides were mounted using Naphrax®. Diatom concentration was estimated using microsphere markers

*Table 3.* Performance statistics and model summaries for the models used in the study.

| | AL:PE pH (Cameron et al. 1999) | Total phosphorus (TP) (Kauppila et al. 2002) | Mean July air temperature (Brooks and Birks 2001) |
|---|---|---|---|
| Origin of lakes | Kola Peninsula, Alps, Norway, Spain, Svalbard etc. | Finland | Norway, northern Urals (Bol'shezemel'skaya Tundra |
| Number of samples | 118 | 68 | 178 |
| Number of taxa | 530 | 500 | 148 |
| Mean percentage of fossil taxa present in the modern samples | Mitr, 75%; Vanuk-ty, 72% | Mitr, 68%; Vanuk-ty, 65% | Mitr, 100%; Vanuk-ty, 100% |
| RMSEP (based on leave-one-out cross validation) | 0.326 | 0.16log $\mu$g TP $l^{-1}$ | 1.09 °C |
| Maximum bias | 0.742 | 0.28log $\mu$g TP $l^{-1}$ | 0.59 °C |

(Battarbee and Kneen 1982). Between 300 and 400 valves were counted where possible at 1000× magnification. Diatom nomenclature followed Krammer and Lange-Bertalot (1986–1991) and AL:PE guidelines (Cameron et al. 1999).

Chironomid sample preparation and slide mounting followed standard techniques described in Brooks and Birks (2000). Slides were mounted in Euparal®. Between 50 and 200 head capsules were counted at 200–400× magnification. Chironomids were identified with reference to Wiederholm (1983), Oliver and Roussel (1983), Schmid (1993), Makarchenko and Makarchenko (1999), Rieradevall and Brooks (2001) and the national Chironomidae collection at The Natural History Museum, London, UK.

### *Numerical analysis*

All ordinations were performed using the program CANOCO 4.0 for Windows (ter Braak and Šmilauer 1998). Detrended correspondence analysis (DCA) was used to assess the overall changes in species composition throughout the sediment core for both diatoms and chironomids.

The AL:PE diatom–pH model was used for pH inferences (Cameron et al. 1999). Total phosphorus (TP) reconstructions using weighted averaging are based on a diatom–TP data set from Finland (Kauppila et al. 2002). Mean July air temperature was inferred using a Norwegian chironomid–temperature inference model (Brooks and Birks 2001; unpublished data) and supplemented with an additional 26 lakes from Bol'shezemel'skaya Tundra. Table 3 presents more details on all the models used in this study.

Diatom and chironomid species richness $E(S)$ at a constant sample count (see Figures 4–6 for the base sample count of diatom and chironomid data) was estimated by rarefaction analysis using the program RAREPOLL version 1.0 Birks and Line 1992). The effective number of occurrences of diatom and chironomid species were estimated by the index $N2$ (Hill 1973).

The program ZONE version 1.2 (Juggins 1991, unpubl. program) was used to divide the diatom data into stratigraphic zones. Within ZONE we used the following procedures: constrained single-link analysis (Gordon and Birks 1972); constrained incremental sum-of-squares cluster analysis (Grimm 1987); binary division using least squares (Gordon and Birks 1972); binary division using information content (Gordon and Birks 1972); and optimal division using least squares (Birks and Gordon 1985). Zone boundaries were identified where there was a consensus between methods. For the chironomids, the optimal division using least squares (Birks and Gordon 1985) was used and the number of statistically significant zones was determined by comparison with the broken stick model (Bennett 1996).

Ordinary least square regression was used to find any potential statistically significant relationships between diatom and chironomid species composition and the instrumentally reconstructed climatic variables, i.e., predictor variables. The species composition data were summarised as principal component axes before being used as response variables. Due to the relatively short time span relative to the resolution of the samples, a linear response was assumed for the species compositions along the major underlying gradient. Therefore, a default analysis for principal component analysis (PCA) in CANOWIN 4.0 (ter Braak and Šmilauer 1998) was used, with the exception that a square root transformation of the species abundance data expressed as percentages was used prior to the PCA. All four PCA axes are used as response variables.

The monthly average temperatures for each year from 1946 to 1998 were based on the data from the Vorkuta weather station (64°01′ E; 67°17′ N), which was the closest weather station to both lakes (Annual Reports on Meteorology, 1920–2001). These were subsequently used to obtain the following climatic parameters on a yearly basis: summer, June, July, August and September temperatures. Similar methods to those described in Battarbee et al. (2002) were used to harmonise the climatic predictors and the response variables prior to least square regression. A LOESS regression (Cleveland et al. 1993) was used to smooth the climatic variables along a time axis. Three different spans were applied to the climatic predictors (spans chosen are 0.5, 0.2, and 0.1). The interpolated climatic values for the corresponding year of the mid-point of each sample were used as predictor variables. A linear regression was performed, and a F-test was applied to provide an approximate *p*-value for each regression model.

Rate-of-change analysis (Grimm and Jacobson 1992; Birks et al. 2000) was used in attempt to quantify the total amount of biostratigraphical change in both the diatom and chironomid 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 4.0 for time series (ter Braak and Šmilauer 1998).

## Results

### *Core chronologies and pollution history*

At Mitrofanovskoe Lake the two $^{210}$Pb models both suggest a relatively uniform sedimentation rate since the mid-19th century, with a mean value of $0.027 \pm 0.002$ g cm$^{-2}$ y$^{-1}$. These results place 1963 between $8.5 \pm 0.25$ cm, a little deeper than suggested by the $^{137}$Cs record. The discrepancy could be due to a small loss of sediment from the top of the core before or during sampling, or to a small change in the pattern of sediment focusing in recent decades. Figure 2(a) presents a corrected chronology based on the latter of these two possibilities.

At Vanuk-ty Lake the $^{210}$Pb dating places 1963 at a depth of 8 cm, which is in good agreement with the depth indicated by the $^{137}$Cs/$^{241}$Am stratigraphy (Figure 2(b)). The $^{210}$Pb results suggest that up to ca. 1985 there was a relatively uniform sedimentation rate of about 0.033 g cm$^{-2}$ y$^{-1}$, apart from a brief episode of very rapid accumulation in the mid-1930s and a smaller such event in the 1960s. During the past ca. 15 years sedimentation rates have been significantly higher, with a mean value of 0.064 g cm$^{-2}$ y$^{-1}$.

Loss on ignition (LOI) gradually increases from 7.2% at the bottom of the Mitrofanovskoe sediment core to 28.8% at the surface layer (Figure 4). The Vanuk-ty core is less organic with LOI varying from 5.6% at the bottom levels to 13.2% at the surface (Figure 6).

Figure 3 compares the $^{206}$Pb/$^{207}$Pb isotope ratios with the Pb profile in the core from Mitrofanovskoe Lake. The lead concentration increases from ca. 1860 reflecting the increase in industrial activity in the mid-19th century. A clear pollution signal is reflected by the decreasing isotope ratio. The bottom level of 19.5 cm does not reach unpolluted (background) conditions, since the isotope ratio is declining through the whole core (no stable background values). This early airborne pollution might be both regional and long-distance in nature given the long history of global lead pollution dating back to the Greek–Roman times (e.g., Renberg et al. 1994).

There are many similarities between SCP profiles from Mitrofanovskoe and Vanuk-ty lakes (Figures 4 and 6). At both lakes SCPs first appear in the sediments about 50 years ago, peaking

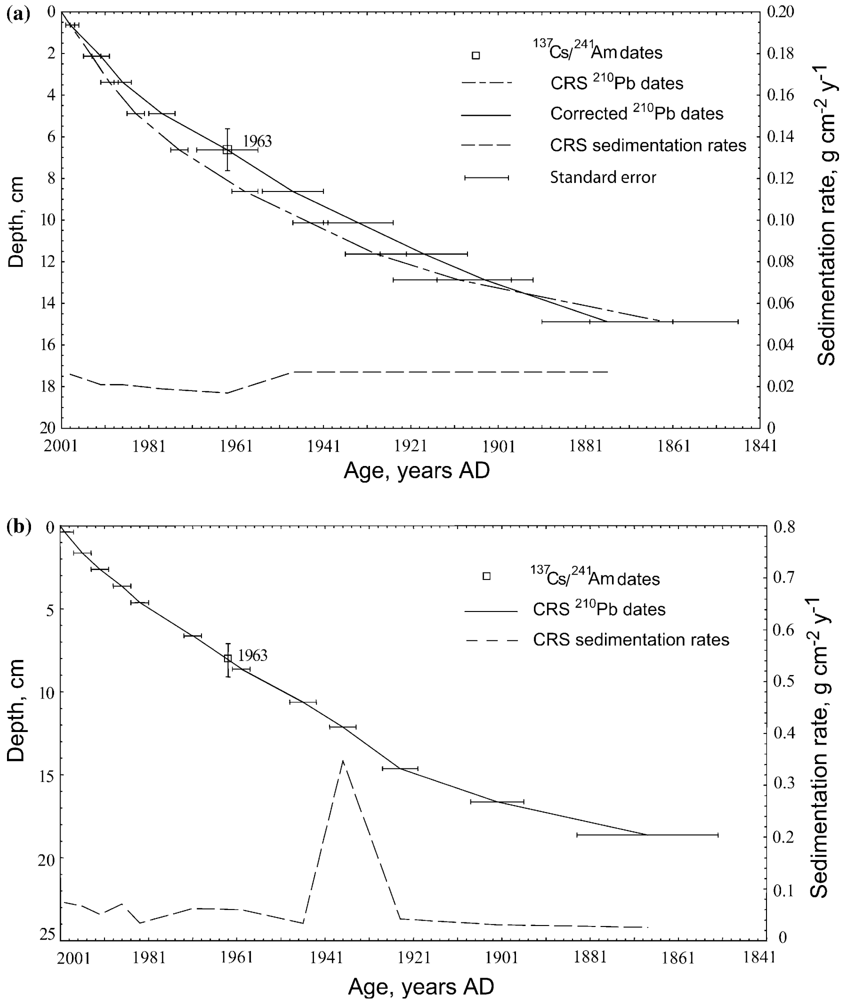

*Figure 2.* Radiometric chronologies of Mitrofanovskoe (a) and Vanuk-ty (b) cores, showing the CRS model dates and sedimentation rates, together with the 1963 depth determined from the $^{137}$Cs/$^{241}$Am stratigraphy.

between ~1981 and ~1991. Similar to many other northern Ural lakes, the SCP concentration peaks in Vanuk-ty and Mitrofanovskoe cores coincide with the period of most intensive coal production in the regional industrial centre of Vorkuta (Solovieva et al. 2002). The SCP concentrations in the Vanuk-ty sediments are more than twice as high as in Mitrofanovskoe between ~1981 and ~1991 and Vanuk-ty Lake is also much closer to Vorkuta than Mitrofanovskoe Lake (Figure 1). These suggest that the SCPs in the sediments have a largely local rather than long-distance origin although SCPs also show a marked increase from the 1950s in many western European sites (Wik and Renberg 1996; Rose et al. 1999). However, in most western European lakes SCPs first appear in the 1880s (e.g., Wik and Renberg 1996; Rose et al. 1999; Korhola et al. 2002) whereas no SCPs were found in the sediments of Mitrofanovskoe and Vanuk-ty lakes before the 1950s.

### *Biological indicators: Mitrofanovskoe Lake*

In total, 126 diatom taxa were identified in the sediment core from Mitrofanovskoe Lake. *Fragilaria pinnata* dominates throughout the core, and *Fragilaria brevistriata*, *F. elliptica*, *F construens* v. *binodis*, *F. pseudoconstruens*, and *F. robusta* are also abundant (Figure 4). These small benthic taxa are widespread in the circumneutral to slightly alkaline waters in the Arctic (e.g., Douglas et al.

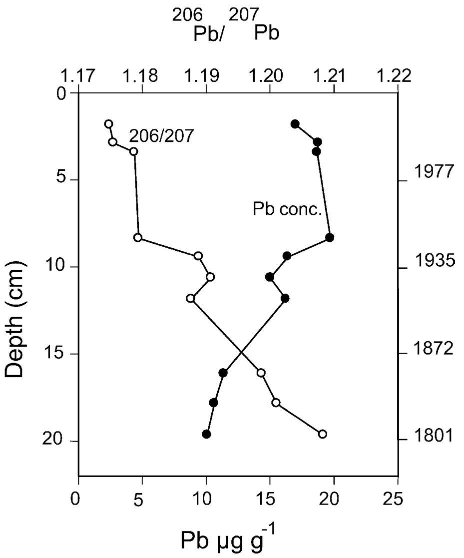

*Figure 3.* Pb concentrations and $^{206}$Pb/$^{207}$Pb isotope ratios in the sediment core from Mitrofanovskoe Lake.

1994; Rühland et al. 2003; Jones and Birks 2004), and they occur at high abundance in many Ural lakes and ponds (e.g., Stenin 1972; Getsen et al. 1994; Solovieva et al. 2002); in the Pechora delta and in Siberia (Laing et al. 1999; Laing and Smol 2000, 2003). Planktonic *Aulacoseira islandica* and *A. subarctica* also occur at high abundance. These diatoms are the most common planktonic diatoms in deep lakes from the northern Urals (e.g., Getsen 1966; Stenin 1972; Solovieva et al. 2002) and are found in the modern phytoplankton samples from Mitrofanovskoe Lake (Trifonova and Petrova 1994).

The diatom stratigraphy from Mitrofanovskoe Lake was split into two assemblage zones, M-Dt1 and M-Dt2 (Figure 4). Within M-Dt1 (19.5–12.5 cm, 1811–1907) *Aulacoseira islandica* together with *Fragilaria pinnata* dominate the diatom assemblage comprising up to 40% of the total relative abundance. *Aulacoseira subarctica* increases from ca. 5 to 15% towards the end of the zone. *Fragilaria brevistriata* and *F. pseudoconstruens* are also common occurring at 5–10% of the total abundance.

*Asterionella formosa* and *Nitzschia perminuta* first appear in the sediments within M-Dt2 (12.5–0 cm, ~1907–2001), with *Asterionella formosa* reaching 5% abundance within the top 1 cm of the core. In M-Dt2, *Fragilaria pinnata* increases together with *Fragilaria robusta* and *Tabellaria flocculosa*. In contrast, *Aulacoseira islandica* and *A. subartcia* decrease and *Cyclotella tripartita* together with *Navicula digitulis* almost disappear in M-Dt2.

Total diatom accumulation rate (TDAR) is rather stable between 19.5 and 12.5 cm (~1811–1906). It decreases slightly between 12.0 and 6.0 cm (~1906–1968) and starts to increase again from ca. 4.5 cm (~1981) reaching maximum values for the whole core between 4.5 and 0 cm. DCA axis 1 scores steadily decrease throughout the sediment core reflecting an overall monotonic compositional change during the last 200 years. Diatom species richness $E(S)_{260}$ shows no major trend throughout the core. From having its maximum values between 19.5 and 17 cm (~1811–1844), $N2$ decreases and shows no major changes for the most part of the core increasing slightly from ca. 3.5 towards the surface. Inferred pH shows no major change, ranging between 7.2 at the base of the core and 7.0 at the surface.

The diatom-inferred total phosphorus (TP) increases gradually from the base of the core to 10.5 cm (~1928). From 1928, TP starts to decrease and reaches a minimum at 1.75 cm (~1994) after which it increases slightly in the surface layer. The decrease in inferred TP during the most of the 20th century is mainly driven by the decrease in *Fragilaria pinnata* together with *F. brevistriata* and *F. pseudoconstruens*. The wide TP-tolerance range of these taxa reduces their utility as indicator species of TP. Sayer (2001) found that these taxa were more sensitive to habitat availability than to phosphorus in shallow lakes. It is more likely, therefore, that the decrease in *Fragilaria* taxa in Mitrofanovskoe Lake is caused by habitat changes (e.g., change in water level) or interspecific competition. In Mitrofanovskoe Lake, the rates of change of diatom composition are significant ($p < 0.05$) during the last ~30 years (Figure 4). The species composition data were summarised as principal component axes before being used as response variables.

The results of the regression between the temperature data from the Vorkuta weather station and species composition data summarised as PCA axes 1–3 scores during the ice-free period (June, July, August and September) show that both August and September temperature have a statistically significant relationship ($p < 0.01$) with the diatom composition at Mitrofanovskoe. However, the correlation is stronger in September ($r^2 = 0.71$,

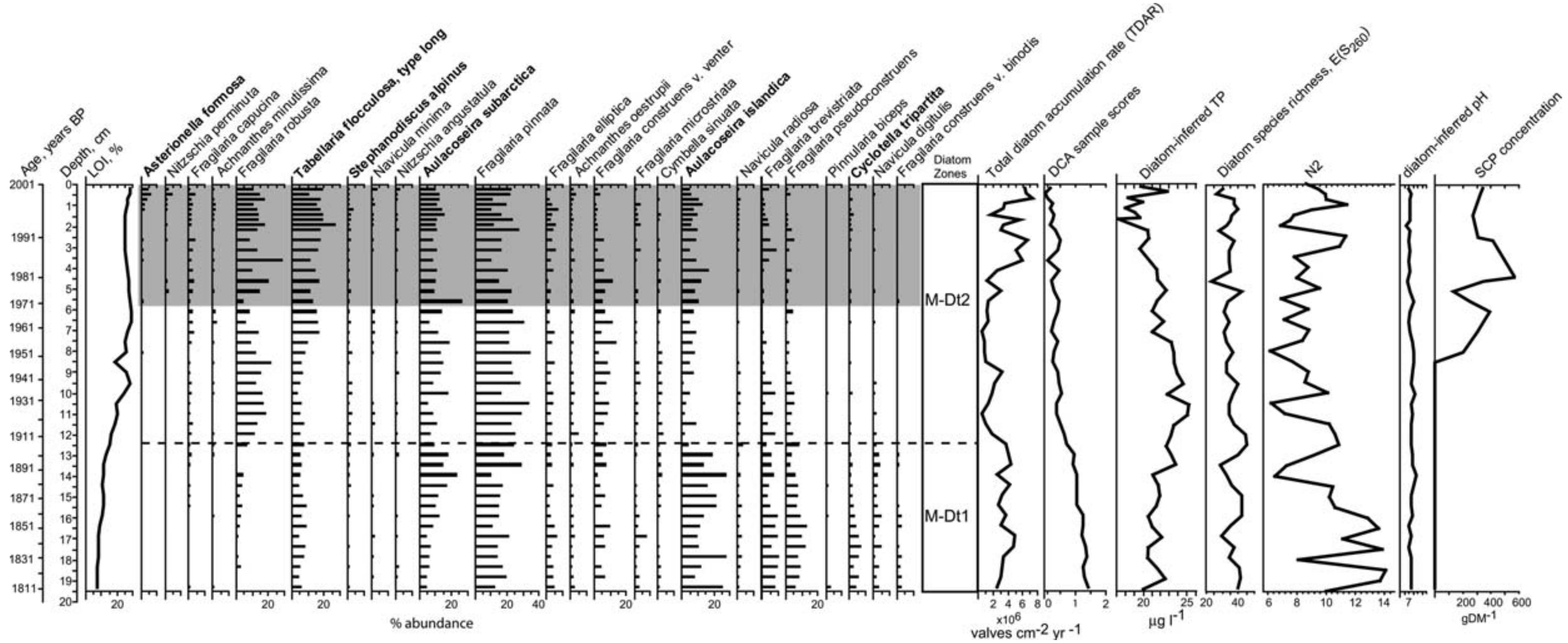

*Figure 4*. Sediment organic content (LOI%), SCP profile and diatom stratigraphy from Mitrofanovskoe Lake. All diatom taxa with an abundance ≥3% are shown. The period of statistically significant ( $p < 0.05$) rates of changes in the diatom assemblages is highlighted in grey. The taxa are sorted by their weighted averaging scores from upper left to bottom right to highlight the major stratigraphic changes. Planktonic taxa are shown in bold.

span = 0.2, $r^2 = 0.66$, span = 0.5, PCA axis 3) than in August ($r^2 = 0.48$, span = 0.1, PCA axis 1). Apparently, both PCA axes 1 ($\lambda = 0.26$) and 3 ($\lambda = 0.06$) are partially related to climate as planktonic taxa with the abundance peaks in the spring and autumn (e.g., *Aulacoseira islandica*, *A. subarctica*) have high loadings on these axes. Planktonic taxa with the highest abundance in summer (e.g., *Asterionella formosa*, *Tabellaria flocculosa*) have high loadings on PCA axis 2. Most benthic *Fragilaria* have higher loadings on PCA axis 1 although *Fragilaria construens* v. *venter* has a high loading on PCA axis 3.

A total of 60 chironomid taxa was recovered from the Mitrofanovskoe core. In the lower part of the core, below 14.5 cm (~1880), the chironomid fauna is dominated by *Micropsectra insignilobus*-type and *Zalutschia zalutschicola*-type (Figure 5). Both taxa are typical of oligotrophic lakes with *Micropsectra insignilobus*-type favouring cool lakes and *Zalutschia zalutschicola*-type being typical of dystrophic lakes. Since ~1909 the chironomid fauna has been dominated by *Paratanytarsus penicillatus*-type and *Psectrocladius sordidellus*-type. Both taxa are typical of more productive, warmer lakes than *Micropsectra insignilobus*-type and *Zalutschia zalutschicola*-type. Two significantly different chironomid assemblages were identified with the zone boundary at 12.25 cm (~1910). In zone M-Ch1 the fauna is dominated by *Zalutschia zalutschicola*-type, but *Micropsectra insignilobus*-type, *Paratanytarsus penicillatus*-type and *Constempellina* are also important elements. The peak diversity of the fauna is in the bottom two samples, which have the highest *N*2 values.

Above 12.25 cm (M-Ch2), a cold stenotherm *Abiskomyia* disappears from the fauna. In addition, there are declines in other cold stenotherms, in particular *Sergentia*, *Micropsectra insignilobus*-type, *Heterotrissocladius brundini*-type and the dystrophic taxon *Zalutschia zalutschicola*-type. Within M-Ch2, *Paratanytarsus penicillatus*-type and *Psectrocladius sordidellus*-type, both warm stenotherms, increase their abundance together with *Limnophyes*, a taxon associated with the extreme littoral margins of lakes, and *Tanytarsus lugens*-type, a cold stenothermous taxon associated with the profundal zone of deep lakes. Towards the top of the core, above 4.0 cm (~1984), several taxa associated with relatively productive temperate lakes appear in the assemblage for the first time or have their highest abundance, such as *Dicrotendipes*, *Tanytarsus pallidicornis*-type and *Cricotopus* type B.

DCA axis 1 sample scores show a slow overall decline from the base of the core to the present. There is a sharp decline in DCA scores above 1.3 cm (after ~1996) and a slight increase between 14.0 and 10.0 cm (~1886–1935).

*N*2 and $E(S)_{64}$ values show no major change throughout the core, declining slightly within the top 2 cm (~1992). Chironomid accumulation rate declines sharply above 8.5 cm (~1949) after which the rate gradually increases towards the present day. There is an overall rise in chironomid-inferred mean July air temperatures of about 0.7 °C from the core base to the present day. From the mid-19th century to ~1991, chironomid-inferred temperatures show a gradually increasing trend from ca. 10.5–11 °C but during the last decade rise more quickly by a further 0.5 °C. The estimate for modern July air temperatures of 11.5 °C is close to the present average of 12.0 °C.

The rate of change in chironomid data becomes significant ($p < 0.05$) between 12.5 cm and the surface (Figure 5). As the chironomids were analysed at lower resolution than diatoms, the results of the regressions between chironomid data and the temperature did not yield statistically significant results, and they are not discussed further.

### *Biological indicators: Vanuk-ty Lake*

The sediment diatom assemblages from Vanuk-ty Lake comprise 167 taxa and are similar to those in Mitrofanovskoe Lake. *Fragilaria pinnata* is also the dominant species reaching a maximum relative abundance of 47% (Figure 6), which is almost twice as high as its abundance in Mitrofanovskoe. Other common *Fragilaria* species (i.e., *Fragilaria brevistriata*, *F. construens* v. *venter*, *F. microstriata* and *F. pseudoconstruens* are also slightly more abundant in Vanuk-ty Lake, whereas planktonic *Aulacoseira islandica* and *A. subarctica* are present in lower abundances compared to Mitrofanovskoe Lake. Overall, the proportion of planktonic taxa in Vanuk-ty Lake averages 9% whereas in Mitrofanovskoe Lake it reaches 24% of the total. This might be due to the extensive shallow (< 1.5 m) littoral zone in Vanuk-ty Lake, which provides an optimal habitat for periphytic *Fragilaria* taxa.

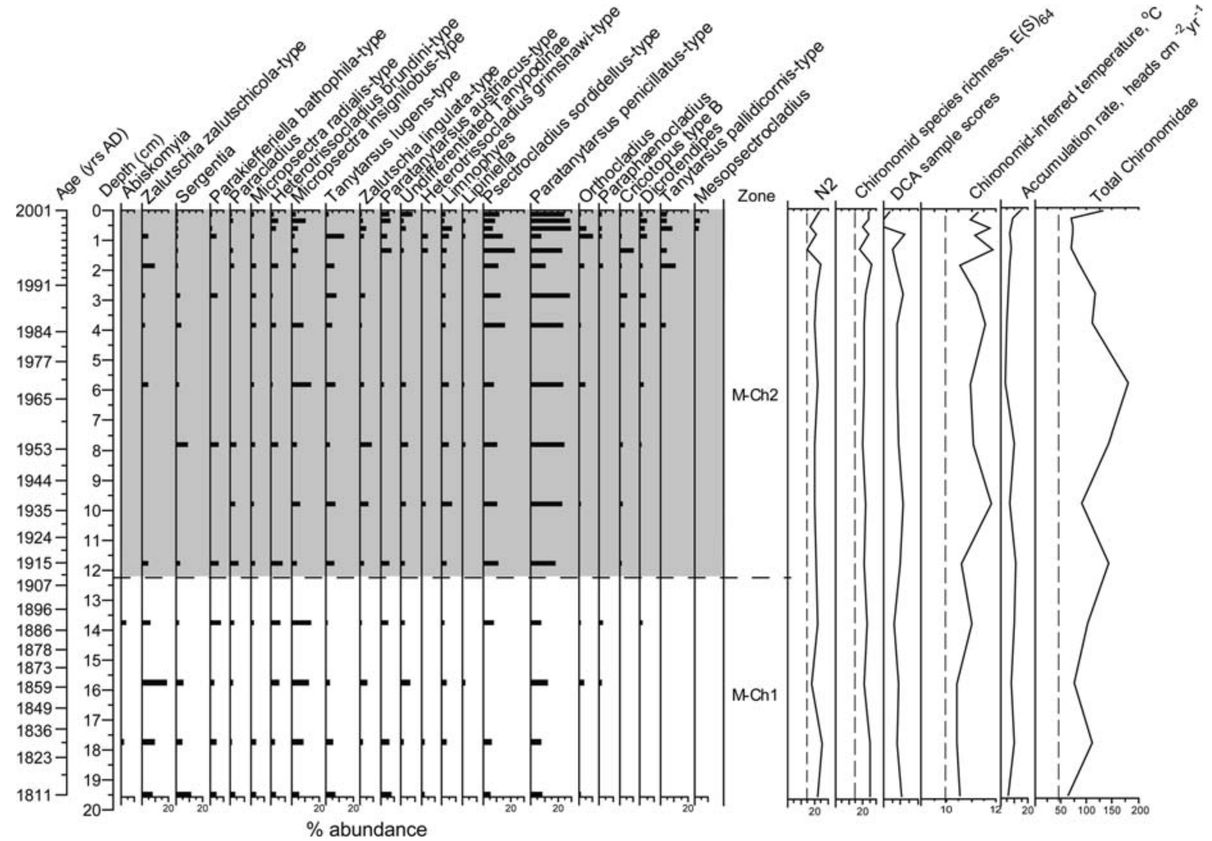

*Figure 5*. Chironomid stratigraphy from Mitrofanovskoe Lake. All chironomid taxa with abundance ≥3% are shown. The period of statistically significant rates of change ($p < 0.05$) in the chironomid assemblages is highlighted in grey. The taxa are sorted by their weighted averaging scores from bottom left to upper right to highlight the stratigraphic changes.

The diatom stratigraphy of Vanuk-ty Lake was also divided into two V-DT assemblage zones. *Fragilaria pinnata* together with *F. construens* v. *venter* comprise up to 50% of total abundance in V-Dt1 (19.0–6.0 cm, ~1870–1975). The relative abundance of *Aulacoseira islandica* varies from 0 to 5.68% within V-Dt1, but shows no apparent trend. *Aulacoseira subarctica* is less abundant, ranging between 0.64 and 3.65%.

*Fragilaria capucina* v. *mesolepta* first appears within V-Dt2 (6–0 cm, ~1985–2001). Planktonic *Asterionella formosa* and *Aulacoseira islandica* and benthic *Navicula minima*, *Cymbella minuta*, *Fragilaria microstriata*, *F. brevistriata*, *F. pseudoconstruens* all increase in relative abundance within V-Dt2. In contrast, *Fragilaria pinnata*, *F. construens* v. *venter*, *Caloneis bacillum*, *Cymbella sinuata* and *Navicula jaernefeltii* decrease within V-Dt2.

The TDAR values show little variation within V-Dt1. In V-Dt2, beginning at 4.3 cm, TDAR values increase. TDRA peaks at 3 cm (~1990) and at 0.5 cm (~1999). The maximum TDAR values at the Vanuk-ty core are about five times higher than those at the Mitrofanovskoe core.

Similarly to the Mitrofanovskoe record, DCA axis 1 sample scores slowly decrease throughout the core. The monotonic decrease in DCA sample scores is slightly less pronounced at Vanuk-ty compared to Mitrofanovskoe, reflecting less compositional change at this site. Diatom species richness $E(S)_{190}$ and $N2$ show similar trends, both decreasing from the base of the core to about 10.5 cm (~1946) and then increasing again within the top 6 cm of the core. Similar to Mitrofanovskoe Lake, Vanuk-ty diatom-inferred pH largely remains the same throughout the core and shows no major trend. The inferred value for the surface layer (7.4) is slightly higher than the measured pH (6.88). Inferred TP shows little change between the bottom of the core and

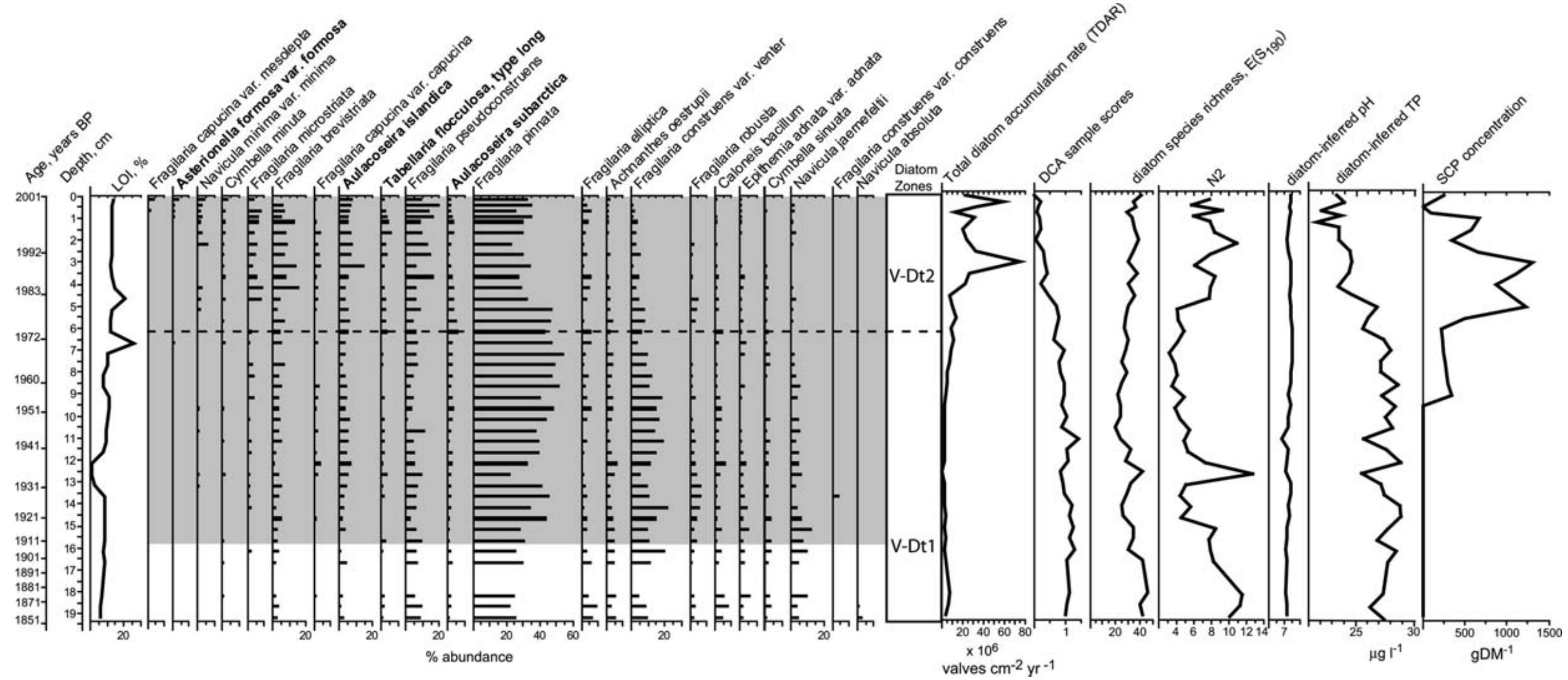

*Figure 6.* Sediment organic content (LOI%), SCP profile and diatom stratigraphy from Vanuk-ty Lake. All diatom taxa with an abundance ≥3% are shown. The period of statistically significant ($p < 0.05$) rates of changes in the diatom assemblages is highlighted in grey. The taxa are sorted by their weighted averaging scores from upper left to bottom right to highlight the major stratigraphic changes. Planktonic taxa are shown in bold.

7.5 cm (~1966). It decreases between 7.5 and 1 cm (~1966–1998) and remains stable within the top 1 cm. As at Mitrofanovskoe Lake, the apparent decrease in TP at Vanuk-ty Lake is driven by the changes in *Fragilaria pinnata* abundance and may reflect possible changes in habitat (i.e. extensive littoral zone) rather than a decrease in trophic status.

Regression analyses show that both June and August temperatures have a significant relationship ($p < 0.01$) with the diatom composition (summarised as PCA axes 1–3 scores) at Vanuk-ty Lake. However, only the correlation in August is relatively strong ($r^2 = 0.65$, span = 0.5, PCA axis 1, $\lambda = 0.20$). In contrast to Mitrofanovskoe Lake, at Vanuk-ty Lake all planktonic diatoms (including 'summer' blooming species such as *Asterionella formosa*) have high scores on PCA axis 1. As the summer season is shorter at Vanuk-ty Lake, the spring–autumn diatom peak and summer stratification peak are probably only 2–3 weeks apart with all diatom blooms taking place between July and August. Most of the *Fragilaria* taxa, including planktonic *Fragilaria capucina* agg. and many periphytic taxa (e.g., *Achnanthes minutissima*, *A. laterostrata*, *Cymbella minuta*, *Navicula jaernefeltii*, *N. minima*, *Nitzschia perminuta*), also have high scores on PCA axis 1, which implies that the changes in their relative abundances are also partially correlated with the August temperature. During the last ~90 years the rates of change in the diatom composition from the Vanuk-ty core are significant ($p < 0.05$).

A total of 59 chironomid taxa was recovered from Vanuk-ty Lake. The fauna is dominated by species of *Zalutschia* (Figure 7). Two stratigraphic zones have been identified. Zone V-Ch1

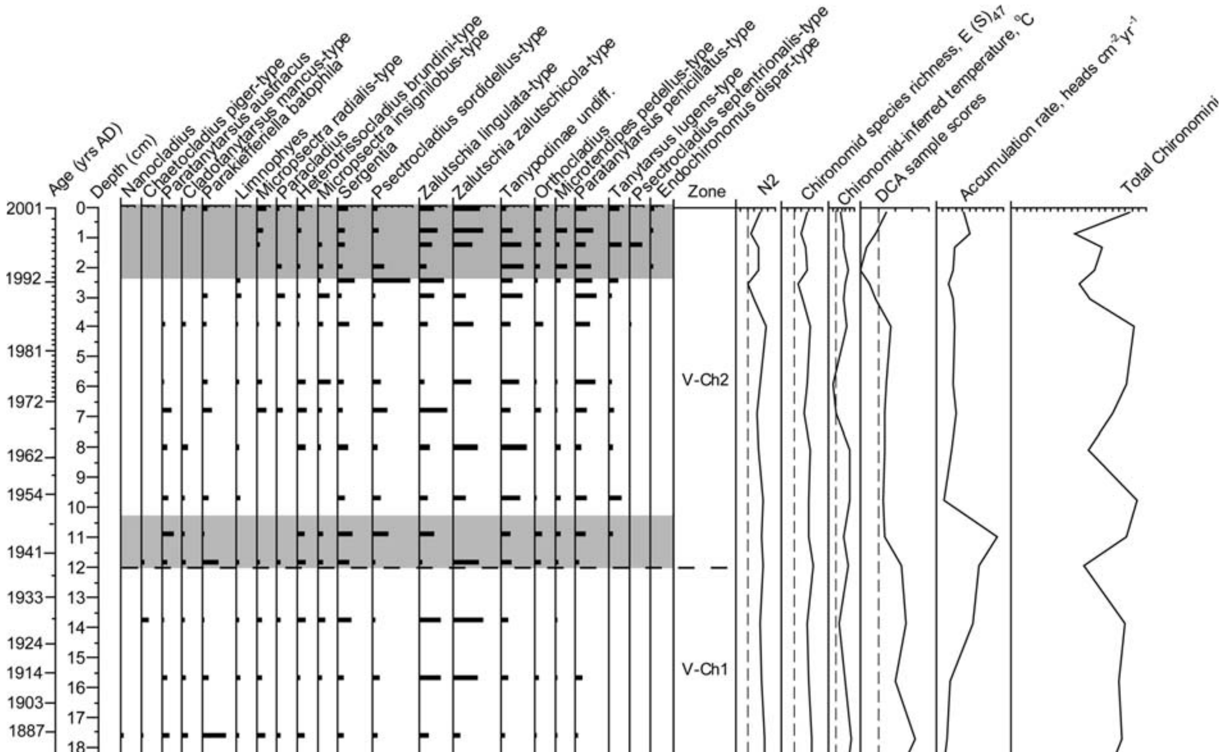

*Figure 7*. Chironomid stratigraphy from Vanuk-ty Lake. All chironomid taxa with abundance ≥3% are shown. The periods of statistically significant rates of change ($p < 0.05$) in the chironomid assemblages are highlighted in grey. The taxa are sorted by their weighted averaging scores from bottom left to upper right to highlight the stratigraphic changes.

covers the period from the core bottom to ca. 12 cm (~1938). *Zalutschia* spp. is an important element in the fauna at this time in addition to *Parakiefferiella bathophila*-type and *Endochironomus albipennis*-type. Above 12 cm (zone V-Ch2) there are marked increases in several taxa, in particular *Tanytarsus lugens*-type, *Paratanytarsus penicillatus*-type, Tanypodinae and *Psectrocladius sordidellus*-type. At this time there are declines in *Phaenopsectra* and *Parakiefferiella bathophila*-type. Above 2.5 cm (~1990) *Psectrocladius sordidellus*-type declines but several other taxa increase or appear in the fauna for the first time, notably *Microtendipes pedellus*-type and *Endochironomus dispar*-type.

DCA axis 1 sample scores show an overall decline from the base of the core to the present day with a sharp decline at 4 cm (~1986). $N2$ and $E(S)_{47}$ values remain fairly constant throughout the core, although highest values are attained at 4 cm (~1986) after which there is a marked decline to the present day. Accumulation rate has an increasing trend from the base of the core to the present with a sharp peak between 14.0 and 11.0 cm (~1926–1944). There is no overall trend in the chironomid-inferred temperatures, which generally show minor oscillations around throughout most of the sequence. A marked decline of about 1 °C occurred in the early 1970s, which reflects a similar trend in the instrumental data (Figure 8). However, too much emphasis should not be placed on this since there is only one data point.

In the Vanuk-ty sediment record, there are two periods with significant rates of change ($p < 0.05$) of chironomid composition: between 11.5 and 10 cm (~1941–1950) and between 2.5 cm and the surface (~1992–2001).

## Discussion

### *Mitrofanovskoe Lake*

There is substantial evidence for compositional changes in both the diatom and chironomid assemblages during the last 90–100 years in Mitrofanovskoe Lake.

What drives these compositional changes? As the lake is very remote and any local disturbance is unlikely, there are three major reasons for these changes: first, climate change; second, the effect of regional and global pollution; and, third a combination of both.

At Mitrofanovskoe Lake, there is a strong correlation between September temperature and diatom relative abundances as established by regression modelling. Planktonic taxa (e.g., *Aulacoseira islandica*) have an autumn abundance peak, which occurs in August–September with the exact timing being temperature dependent. Figure 8 shows that September temperature recorded at the Vorkuta weather station increased slightly (by 0.4 °C on average) since the late 1960s. This coincides with the increase in abundance of *Asterionella formosa*, *Nitzschia perminuta*, *Tabellaria flocculosa* and *Aulacoseira islandica* (from 4.6 to 8.1% on average) (Figure 4). Interestingly, June temperatures also show a steady rise from the 1960s (Figure 8). A similar increase in June temperature from the ~1960s also occurs at the Petrun and Khosedauy-Khard weather stations (Figure 8) although there is no similar rise in September temperature at these sites. The increase in June temperature in the northern Ural region might be a reflection of a circum-Arctic (north of 60° N) annual air temperature increase from the 1960s (McBean et al. 2004) At the same time, there is no marked increase in the annual or July–August temperatures in the region. However, 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 habitat availability (e.g., Smol 1988; Sorvari and Korhola 1998; Lotter and Bigler 2000; Korhola et al. 2002; Sorvari et al. 2002, Rühland et al. 2003). Planktonic taxa (e.g. *Asterionella formosa*, *Tabellaria flocculosa*) are dependent on changes in ice-cover because it affects the length and timing of the water turnover and stratification periods, which are essential to establishing planktonic populations. The slight increase in the $N2$ values during the last 15–16 years might also reflect the changes in diatom succession as the increased growing seasons would allow for more diverse and complex diatom assemblages (Douglas and Smol 1999). However, there is no corresponding changes in diatom species richness $E(S)$. One of the major planktonic species, *Aulacoseira subarctica*, shows no response to the temperature

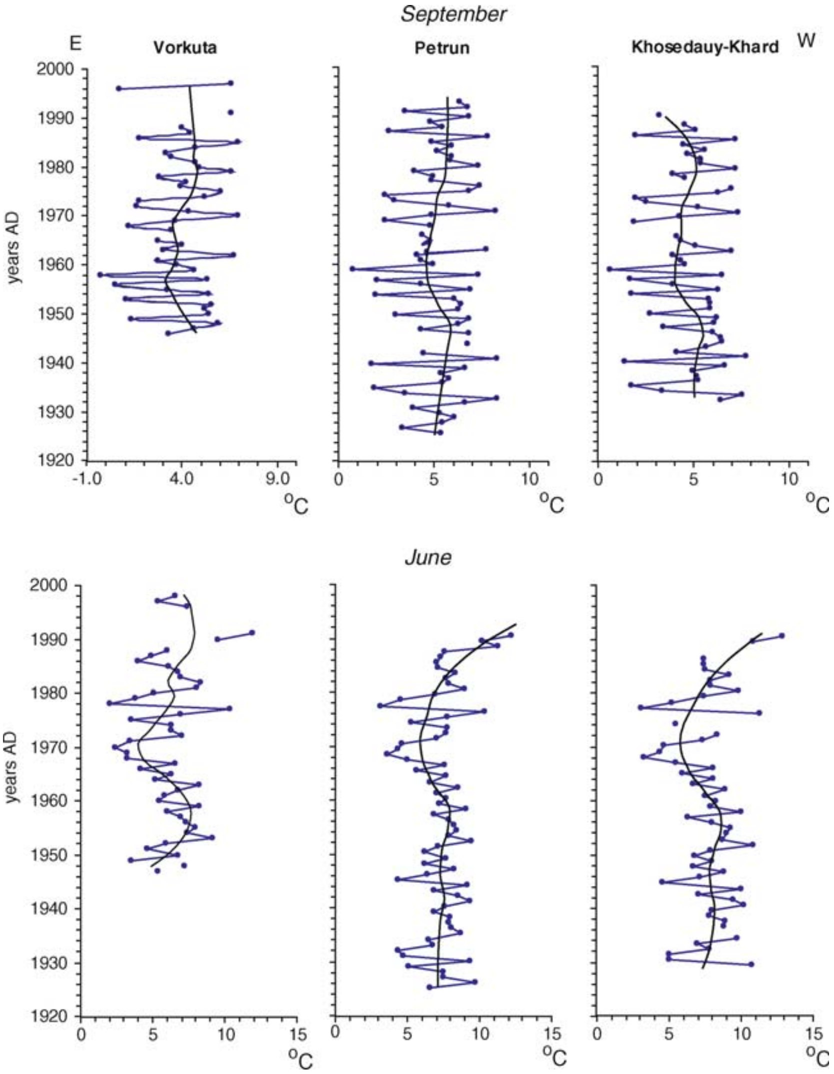

*Figure 8*. September and June average temperatures from Vorkuta, Petrun, and Khosedauy-Khard weather stations (Annual reports on meteorology, 1920–2001). The trend lines are fitted by LOESS smoothing with a span of 0.5. Graphs are arranged in east–west direction.

increases in June and September. Apparently, the timing of its spring and autumn blooms was not affected by the temperature changes. It is also unclear when exactly *A. subarctica* peaks in the plankton as this taxon was not mentioned in the phytoplankton survey by Trifonova and Petrova (1994).

During this temperature rise from the end of the 1960s the rate of change of the diatom assemblages is significant ($p < 0.05$) compared to the earlier period (Figure 4). Total diatom accumulation rate (TDAR) also increases to its highest values during the last ca. 20 years and this increase almost coincides with the period of statistically significant rate of change. Anderson et al. (1996) showed that temperature changes were positively correlated with the diatom accumulation rate in a Swedish boreal lake. Wolfe (2003) also found that diatom productivity was influenced by late Holocene temperature changes in the Canadian Arctic. Loss-on-ignition (LOI) values, which in Mitrofanovskoe Lake probably reflect overall lake productivity, also increase from about ~1907. The link between LOI and temperature has been suggested in many palaeolimnological studies, including Greenland (Willemse and Törnquist

1999), Scotland (Battarbee et al. 2001b) and subarctic Finland (Korhola et al. 2002).

Unlike diatoms, there is no apparent change in the chironomid stratigraphy in the 1960s, but changes are apparent from the early 1980s when several taxa associated with warm productive lakes appear for the first time and other thermophilic taxa increase in abundance (notably *Dicrotendipes*, *Tanytarsus pallidicornis*-type, *Cricotopus* type B and *Mesopsectrocladius*). This result is consistent with a rise in summer temperatures in the region.

Major changes occurred at the turn of the 20th century in the abundance of planktonic diatoms *Aulacoseira islandica*, *A. subarctica* and *Cyclotella tripartita*, which all decreased, whereas benthic *Fragilaria robusta* and *F. pinnata* increased. These changes are more pronounced than the later changes during the 1960s. At this time there was also a decline in cold-stenothermous chironomid taxa and increases in thermophilic taxa. The increase in the profundal taxon *Tanytarsus lugens*-type may reflect an improvement in oxygen concentrations in the hypolimnion as a result of a reduction in the period of winter ice-cover. Although the available regional temperature records only cover the period from the 1930s to present time, it is likely there was an annual temperature increase at the turn of the 20th century. The circum-Arctic annual air temperature increased between ~1900 and 1940s (McBean et al. 2004) and 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). We therefore suggest that the diatom changes observed at the turn of the 20th century were climatically induced. However, interestingly, the expression of this in terms of changing planktonic to benthic ratio is different to that seen in the 1960s. This may be related to a different seasonal expression of climate warming but we are unable to test this.

Results of Pb isotope analysis suggest that Mitrofanovskoe Lake has been influenced by global Pb pollution for the entire period represented by the core. However, the lead concentrations in the sediments are relatively low, and are comparable with the lead concentrations from lake sediments in West Greenland (e.g., Bindler et al. 2001). Lead concentrations are 2–3 times higher downstream of the Pechora River (Lukin et al. 2000) and 1.5–2 times higher in the lakes located closer to the regional pollution sources (e.g., towns of Inta and Vorkuta, Dr. V. Dauvalter, pers. comm.). SCPs are also present at relatively low concentrations compared to the sites located nearer to the regional industrial centres (Solovieva et al. 2002). The major diatom and chironomid assemblage changes at ca. 1907 actually predate the first appearance of SCP in the sediments thus implying that the atmospheric contamination had no influence on the biota. The SCPs in the sediments, which occurred before the diatom changes in the 1960s and the chironomid changes in the 1980s, have no obvious correlation with any chironomid and diatom changes. It is therefore unlikely that global and regional pollution have a marked effect on the diatom and chironomid assemblages of the lake.

We therefore suggest that the main reason behind the diatom and chironomid compositional changes at ~1900s and 1960s at Mitrofanovskoe Lake are changes in temperature although the expression of these changes is different. The general increase in thermophilic chironomid taxa since 1907 is consistent with increasing air temperature. The overall increase in chironomid-inferred temperature by 0.7 °C during the 20th century, which increases most dramatically in the last ten years, supports this conclusion.

### *Vanuk-ty Lake*

At Vanuk-ty Lake the results of regression analysis also imply that temperature affects the diatom assemblages as the correlation between August temperature and diatom composition is significant. It appears that August temperature influences not only planktonic taxa, which have an abundance peak in August (e.g., *Aulacoseira islandica*, *A. subarctica* and *Asterionella formosa*), but also many benthic *Achnanthes*, *Fragilaria*, *Navicula* and *Nitzschia* taxa. There is also a marked increase in TDAR beginning at ca. 1970 and this coincides with the changes in diatom composition. Both indices of diatom species richness $E(S)$ and $N2$ also show an increase from ca. 1970. In contrast, both indices of chironomid species richness show a sudden decline from late 1980s to early 1990s followed by an increase in the most recent samples.

At Vanuk-ty, fishing as well as global and regional pollution could also have had an effect on the diatom and chironomid assemblages. The overall SCP concentration in the Vanuk-ty sediments is relatively low compared to many European (Rose et al. 1999) and northern Ural lakes (Solovieva et al. 2002) and is comparable to the SCP concentrations in lakes from Svalbard (Rose et al. 2004) and subarctic Finland (Korhola et al. 2002). It is, however, higher than at Mitrofanovskoe Lake and the first appearance of SCP in the sediments predates the major diatom changes (Figure 6). Similar to Mitrofanovskoe Lake, there is no evidence for acidification or eutrophication which can be correlated with the SCP record.

Effects of over-fishing on the lake ecosystem could be, potentially, more substantial than atmospheric contamination. A reduction in the number of fish might be expected to lead to an increase in the accumulation rate of chironomid larval head capsules, since chironomid larvae are an important component in the diet of bottom-feeding fish, and rising pupae and emerging adults are taken by surface-feeding fish (Solovkina 1966). However, fishing seemed to have had little direct impact on chironomids as no such post-1960s increase is evident in the data. Fish catches actually peaked in the 1960s just before the diatom changes. At Vanuk-ty Lake, the major change in the chironomid fauna is centred around 1940, and so is not synchronous with the changes recorded in the diatom flora or with the changes in diatoms or chironomids at Mitrofanovskoe Lake. In any case the Vanuk-ty chironomid changes are difficult to interpret in terms of climate change since some of the taxa that increase are thermophilic, such as *Paratanytarsus penicillatus*-type, Tanypodinae and *Psectrocladius sordidellus*-type, whereas others that increase, including *Tanytarsus lugens*-type and *Heterotrissocladius grimshawi*-type, prefer cool conditions. These latter taxa occur in deeper water and their increase might indicate an increase in dissolved oxygen, which may be related to a decrease in the length of ice cover. One of the reasons behind the ambiguous chironomid evidence at Vanuk-ty Lake might be its complex morphometry. Unlike Mitrofanovskoe Lake, Vanuk-ty Lake has an extensive shallow littoral zone, which may have a different chironomid fauna from the profundal area. Changes in the ice-cover duration would affect littoral and profundal parts of the lake in different ways.

## Conclusions

There is evidence that recent diatom and chironomid changes at both Mitrofanovskoe and Vanuk-ty lakes have been driven, largely, by temperature. At Mitrofanovskoe Lake the evidence is clearer: the major compositional changes in diatom and chironomid communities are synchronous, and they are supported by increases in total diatom accumulation rate and loss-on-ignition. The chironomid-inferred summer temperature seems to show an increase by ~1 °C during the last 100 years. The rate of change in diatom assemblages from the end of the 1960s is statistically significant at Mitrofanovskoe Lake, and the diatom changes are correlated with September air temperature changes during this period. We suggest that the mechanism behind the changes in the diatom community in the 1960s is related to an increase in the length of the ice-free season. The increase in deep-water chironomid taxa may also be in response to reduction in ice-cover and the consequent reduction in oxygen stress. At Mitrofanovskoe Lake the levels of global and regional pollution are relatively low, and the pollution signals are not correlated with the changes in diatoms and chironomids. We can, therefore, conclude that at Mitrofanovskoe Lake the major driving force behind the diatom and chironomid changes since ca. 1907 are temperature changes.

At Vanuk-ty Lake, diatom changes show a clearer response to temperature changes during the last 30 years whereas chironomid evidence is more ambiguous. The compositional changes in many planktonic and benthic diatom taxa are strongly correlated with August temperature and are coincident with the increase in diatom species richness and diatom production. Although these changes are predated by the rise in SCPs, it is unlikely that global and regional atmospheric contamination have had a pronounced effect on diatom composition as the overall pollution level is low and there is no evidence of acidification or eutrophication. We therefore suggest that the mechanism behind the changes in diatom assemblages at Vanuk-ty Lake is similar to Mitrofanovskoe Lake and is dependent on temperature. However, there is no strong evidence for warming from changes in the chironomid fauna. One of the reasons behind the ambiguous chironomid evidence from Vanuk-ty Lake might lie in its complex morphometry with extensive shallow littoral and profundal zones, which allows for a coexistence of ecologically different chironomid groups.

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## 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, 139 pp. [in Russian].

Anderson N.J., Odgaard B.V., Segeström U. and Renberg I. 1996. Climate-lake interactions recorded in varied sediments from a Swedish boreal forest lake. Global Change Biol. 2: 399–405.

Appleby P.G. 2001. Chronostratigraphic techniques in recent sediments. In: Last W.M. and Smol J.P. (eds), Tracking Environmental Change Using Lake Sediments, Vol. 1: Basin Analysis, Coring, and Chronological Techniques. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 171–205.

Appleby P.G., Nolan P., Gifford D.W., Godfrey M.J., Oldfield F., Anderson N.J. and Battarbee R.W. 1986. $^{210}$Pb dating by low background gamma counting. Hydrobiologia 141: 21–27.

Battarbee R.W., Jones V.J., Flower R.J., Cameron N.G., Bennion, H., Carvalho L. and Juggins S. 2001a. Diatom analysis. In: Last W.M. and Smol J.P. (eds), Tracking Environmental Change Using Lake Sediments, Vol. 3: Terrestrial, Algal and Siliceous Indicators. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 171–205.

Battarbee R.W., Cameron N.G., Golding P., Brooks S.J., Switsur R., Harkness D., Appleby P., Oldfield F., Thompson R., Monteith D.T. and McGovern A. 2001b. Evidence for Holocene climate variability from the sediments of a Scottish remote mountain lake. J. Quat. Sci. 16: 339–346.

Battarbee R.W., Grytnes J.A., Thompson R., Appleby P.G., Catalan J., Korhola A., Birks H.J.B., Heegaard E. and Lami A. 2002. Comparing palaeolimnological and instrumental evidence of climate change for remote mountain lakes over the last 200 years. J. Paleolimnol. 28: 161–179.

Battarbee R.W. and Kneen M. 1982. The use of electronically counted microspheres in absolute diatom analysis. Limnol. Oceanogr. 27: 182–188.

Belyaev G.M., Vinberg G.G., Gaevskaya N.S., Zhadin V.I., Zenkevich L.A., Reznichenko O.G. and Scherbakov A.P. (eds) 1966. Hydrobiological Studies and Fish Resources of Lakes from Extreme North of the USSR. Nauka, Moscow, 168 pp. [in Russian].

Bennett K.G. 1996. Determination of the number of zones in a biostratigraphical sequence. New Phytol. 132: 155–170.

Birks H.H., Battarbee R.W. and Birks H.J.B. 2000. The development of the aquatic ecosystem at Kråkenes Lake, western Norway, during the late-glacial and early Holocene – a synthesis. J. Paleolimnol. 23: 91–114.

Birks H.J.B. and Gordon A.D. 1985. Numerical Methods in Quaternary Pollen Analysis. Academic Press, London, 317 pp.

Birks H.J.B. and Line J.M. 1992. The use of rarefaction analysis for estimating palynological richness from Quaternary pollen-analytical data. The Holocene 2: 1–10.

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

Briffa K.R., Jones P.D., Schweingruber F.H., Shiyatov S.G. and Cook E.R. 1995. Unusual twentieth-century summer warmth in a 1,000 year temperature record from Siberia. Nature 376: 156–159.

Brooks S.J. and Birks H.J.B. 2000. Chironomid-inferred Late-glacial-early Holocene mean July air temperatures for Kråkenes Lake, western Norway. J. Paleolimnol. 23: 77–89.

Brooks S.J. and Birks H.J.B. 2001. Chironomid-inferred air temperatures from late-glacial and Holocene sites in north-west Europe: progress and problems. Quat. Sci. Rev. 20: 1723–1741.

Brooks S.J., Udachin V. and Williamson B.J. 2005. Impact of copper smelting on lakes in the southern Ural mountains, Russia, inferred from chironomids. J. Paleolimnol. 33: 229–241.

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., Sánchez-Castillo P., Schmidt R., Šiško M., Solovieva N., Štefková E. and Toro M. 1999. Surface- sediment and epilithic diatom calibration set for remote European mountain lakes (AL:PE Project) and their comparison with the Surface Waters Acidification Programme (SWAP) calibration set. J. Paleolimnol. 22: 291–317.

Cleveland W.S., Grosse E. and Shyu W.M. 1993. Local regression models. In: Chambers J.M. and Hastie T.J. (eds), Statistical Models S. Chapman & Hall, London, pp. 309–376.

Davydova N.N., Kuznetsov V.K, Delusina I.V. and Subetto D.A. 1994. Environment and history of Bol'shezemel'skaya Tundra. Geography of the study area and the history of lake development. In: Drabkova V.G. and Trifonova I.S. (eds), Lake Ecosystems of the Extreme North. Nauka, St. Petersburg, pp. 6–17 [in Russian].

Dean W.E. 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss-on-ignition: comparison with other methods. J. Sed. Petrol. 44: 242–248.

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

Douglas M.S.V. and Smol J.P. 1999. Freshwater diatoms as indicators of environmental change in the High Arctic. In: Stoermer E.F. and Smol J.P. (eds), The Diatoms: Applications for the Environmental and Earth Sciences. Cambridge University Press, Cambridge, pp. 227–245.

Drabkova V.G. and Bystrov S. 1994. Hydrochemistry of lakes. In: Drabkova V.G. and Trifonova I.S. (eds), Lake Ecosystems in the Extreme North. Nauka, St. Petersburgh, pp. 48–65 [in Russian].

Drabkova V.G. and Trifonova I.S. (eds) 1994. Lake Ecosystems in the Extreme North. Nauka, St. Petersburgh, 247 pp. [in Russian].

Getsen M.V. 1966. Algoflora of the tundra lakes. In: Belyaev G.M., Vinberg G.G., Gaevskaya N.S., Zhadin V.I., Zenkevich L.A., Reznichenko O.G. and Scherbakov A.P. (eds), Hydrobiological Studies and Fish Resources of Lakes from the Extreme North of the USSR. Nauka, Moscow, pp. 22–50 [in Russian].

Getsen M.V., Stenina A.S. and Patova E.N. 1994. Algal Flora of the Bol'shezemel'skaya Tundra under Anthropogenic Influence. Ekaterinburg, Nauka, 183 pp. [in Russian].

Glew J.R. 1989. A new trigger mechanism for sediment samples. J. Paleolimnol. 2: 241–243.

Gordon A.D. and Birks H.J.B. 1972. Numerical methods in Quaternary palaeoecology. I. Zonation of pollen diagrams. New Phytol. 71: 961–979.

Grimm E.C. 1987. A Fortran 77 program for incremental sum of squares. Comp. Geosci. 13: 13–35.

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

Hill M.O. 1973. Diversity and evenness: a unifying notation and its consequences. Ecology 54: 427–432.

Hughen K.A., Overpeck J.T. and Anderson R.F. 2000. Recent warming in a 500-year palaeotemperature record from varied sediments, Upper Soper Lake, Baffin Island, Canada. The Holocene 10: 9–19.

Intergovernmental Panel on Climate Change (IPCC) 2001. Climate Change 2001: The Scientific Basis. In Houghton J.T., Ding Y., Griggs M.C., Noguer M., der Linden P.J., Dai X., Maskell K. and Johnson C.A. (eds), A Special Report of IPCC working Group I.

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

Kauppila T., Moisio T. and Salonen V.-P. 2002. A diatom-based inference model for autumn epilimnetic total phosphorus concentration and its application to a presently eutrophic boreal lake. J. Paleolimnol. 27: 261–273.

Kitchell J.A., Estabrook G. and 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. and Cameron N. G. 2002. A multi-proxy analysis of climate impacts on recent developments of subarctic lake Saanajärvi in Finnish Lapland. J. Paleolimnol. 28: 59–77.

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

Laing T.E., Rühland K.M. and Smol J.P. 1999. Past environmental and climatic changes related to tree-line shifts inferred from fossil diatoms from a lake near the Lena River Delta, Siberia. The Holocene 9: 547–557.

Laing T.E. and Smol J.P. 2000. Factors influencing diatom distributions in circumpolar treeline lakes of northern Russia. J. Phycol. 36: 1035–1048.

Laing T. and Smol J.P. 2003. Late Holocene environmental changes inferred from diatoms in a lake near the Taimyr Peninsula, Northern Russia. J. Paleolimnol. 30: 231–247.

Lotter A.F. and Bigler C. 2000. Do diatoms in Swiss Alps reflect the length of ice-cover? Aquat. Sci. 62: 125–141.

Lukin A.A., Dauvalter V.A. and Novoselov A.P. 2000. Ecosystem of Pechora River. Kola Science Centre, Russian Academy of Sciences, Apatity, 192 pp. [in Russian].

Makarchenko E.A. and Makarchenko M.A. 1999. Chironomidae. Non-biting midges. In: Tsalolikhin S.J. (ed.), Key to Freshwater Invertebrates of Russia and Adjacent lands, Vol. 4. Higher Insects, Diptera. St. Petersburgh, pp. 210–295 and 670–857 [in Russian].

McBean G.A., Alekseev G., Chen D., Forland E., Fyfe J., Groisman P.Y., King R., Melling H., Vose R. and Whitfield P.H. 2004. Arctic Climate Impact Assessment, Chapter 2. The Arctic Climate – Past and Present. Cambridge University Press, 67 pp.

Mukhin N.I., Petrakova V.M. and Shevchenko A.I. 1964. Climatic characteristics of the Pechora basin. In: Geocrinological Conditions of Pechora Coal Basin. Moscow, pp. 20–28. [in Russian].

Murphy J. and Riley J. 1962. A modified single solution for the determination of phosphate in natural waters. Analyt. Chim. Acta 27: 31–39.

Oliver D.R. and Roussel M.E. 1983. The Genera of Larval Midges of Canada. Diptera: Chironomidae. Biosystematics Research Institute, Ottawa, Ontario.

Overpeck J., Hughen K., Hardy D. Bradley R., Case R., Douglas M., Finney B., Gaewski K., Jacoby G., Jennings A., Lamoureux S., Lasca A., MacDonald G., Moore J., Retelle M., Smith S., Wolfe A. and Zielinski G. 1997. Arctic environmental change of the last four centuries. Science 278: 1251–1256.

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

Prentice I.C. 1980. Multidimensional scaling as a research tool in Quaternary palynology: a review of theory and methods. Rev. Palaeob. Palynol. 31: 71–104.

Renberg I. 1990. A procedure for preparing large sets of diatom slides from sediment cores. J. Paleolimnol. 4: 87–90.

Renberg I., Brännvall M.-L., Bindler R. and Emteryd O. 2002. Stable lead isotopes and lake sediments – a useful combination of atmospheric lead pollution history. Sci. Tot. Environ. 292: 45–54.

Renberg I., Wik-Persson M. and Emteryd O. 1994. Pre-industrial atmospheric lead contamination detected in Swedish Lake sediments. Nature 368: 323–326.

Rieradevall M. and Brooks S.J. 2001. An identification guide to subfossil Tanypodinae larvae (Insecta: Diptera: Chironomidae) based on cephalic setation. J. Paleolimnol. 25: 81–99.

Rose N.L. 1990. A method for the extraction of carbonaceous particles from lake sediment. J. Paleolimnol. 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. J. Paleolimnol. 11: 201–204.

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

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

Rühland K., Priesnitz A. and Smol J.P. 2003. Paleolimnological evidence from diatoms for recent environmental changes in 50 lakes across Canadian Arctic treeline. Arc. Ant. Alpine Res. 35: 110–123.

Sayer C.D. 2001. Problems with the application of diatom–total phosphorus transfer functions: examples from a shallow English lake. Freshwater Biol. 46: 743–757.

Schmid P.E. 1993. A Key to the Larval Chironomidae and their Instars from Austrian Danube Region Streams and Rivers. Part 1. Diamesinae, Prodiamesinae and Orthocladiinae. Federal Institute for Water Quality, Vienna.

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

Simoes J.C and Zagorodnov V.S. 2001. The record of anthropogenic pollution in snow and ice in Svalbard, Norway. Atmos. Environ. 35: 403–413.

Smol J.P. 1988. Palaeoclimate proxy data from freshwater diatoms. Verh. Int. Ver. Limnol. 23: 837–844.

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

Solovkina L.N. 1966. Growth and feeding of the fishes from Vashutkiny Lakes. In: Belyaev G.M., Vinberg G.G., Gaevskaya N.S., Zhadin V.I., Zenkevich L.A., Reznichenko O.G. and Scherbakov A.P. (eds), Hydrobiological Studies and Fish Resources of Lakes from Extreme North of the USSR. Nauka, Moscow, pp. 137–164 [in Russian].

Solovkina L.N. and Sidorov G.P. 1966. Fish resources of lakes and rivers in Bol'shezemel'skaya Tundra. In: Belyaev G.M., Vinberg G.G., Gaevskaya N.S., Zhadin V.I., Zenkevich L.A., Reznichenko O.G. and Scherbakov A.P. (eds), Hydrobiological Studies and Fish Resources of Lakes from Extreme North of the USSR. Nauka, Moscow, pp. 164–169 [in Russian].

Sorvari S. and Korhola A. 1998. Recent diatom assemblage changes in subarctic Lake Saanajärvi, NW Finnish Lapland, and their paleoenvironmental implications. J. Paleolim. 20: 205–215.

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

Smith S.V., Bradley R.S. and Abbot M.B. 2004. A 300 year record of environmental change from Lake Tuborg, Ellesmere Island, Nunavut, Canada. J. Paleolimnol. 32: 137–148.

Stenin V.N. 1972. Diatom flora in the modern glacial lakes from the Polar Urals. Scientific Reports of Higher School. Biol. Sci. 5: 66–73 [in Russian].

Trifonova I.S. and Petrova A.L. 1994. Structure and dynamics of phytoplankton. In: Drabkova V.G. and Trifonova I.S. (eds), Lake Ecosystem in the Extreme North. Nauka, St. Petersburg, pp. 80–109 [in Russian].

ter Braak C.F.J. and Šmilauer P. 1998. CANOCO. Reference manual and user's guide to Canoco for Windows: Software for Canonical Community Ordination (version 4). Microcomputer Power, Ithaca, NY.

United Nations Environment Programme (UNEP) 1999. Global Environment Outlook-2000. UNEP's Millennium Report on the Environment. Earthscan Publications Ltd, 398 pp.

Vlasova T.A. 1976. Hydrology and hydrochemistry of Kharbei Lakes. Physical geography of the study area. In: Vinberg G.G. and Vlasova T.A. (eds), Productivity of Lakes in the East of Bol'shezemel'skaya Tundra. Nauka, Leningrad, pp. 5–26 [in Russian].

Weller G. 1995. Global pollution and its effect on the climate of the Arctic. Sci. Tot. Environ. 160(161): 19–24.

Wiederholm T. (ed.) 1983. Chironomidae of the Holarctic region. Keys and diagnoses. Part 1. Larvae. Entomol. Scand. Suppl. No. 19.

Wik M. and Renberg I. 1996. Environmental records of carbonaceous fly-ash particles from fossil fuel combustion. A summary. J. Paleolimnol. 15: 193–206.

Willemse N.W. and Törnquist T.E. 1999. Holocene century-scale temperature variability from West Greenland lake records. Geology 27: 580–584.

Wolfe A.P. 2003. Diatom community responses to late-Holocene climatic variability, Baffin Island, Canada: a comparison of numerical approaches. The Holocene 13: 29–37.

Zvereva O.S., Vlasova T.A. and Goldina L.P. 1966. History of Vashutkiny Lakes. In: Belyaev G.M., Vinberg G.G., Gaevskaya N.S., Zhadin V.I., Zenkevich L.A., Reznichenko O.G. and Scherbakov A.P. (eds), Hydrobiological Studies and Fish Resources of Lakes from the Extreme North of the USSR. Nauka, Moscow, pp. 4–21. [in Russian].