Biological responses climate warming in lakes from the northern Urals, Russia

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Abstract

Diatom changes during the last 200 years in ^{210}Pb dated sediment cores from five remote arctic and subarctic lakes in the northern Urals were analysed. The degrees of compositional turnover 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 turnover and stratification periods and habitat availability. 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 the Vankavad Lake situated in northern taiga. The degree of the 20th century diatom changes in Vankavad Lake is greater than in most circum arctic and subarctic lakes from northern Europe and Canada.

Keywords: Polar Urals, lake sediments, 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 1.5ºC being observed in the periods between approximately 1915 and 1940 and from the end of 1960s until 2000. The Arctic is warming at about twice the rate of the rest of the planet [1] 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. Climate warming is now detectable in various terrestrial and aquatic arctic ecosystems including lakes and ponds [2]. 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.

Instrumental records of mean annual air temperature from the northern Urals do not show 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 ice-free season [3]. 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. Recent palaeolimnological changes in Mitrofanovskoe and Vanuk-ty Lakes were analysed by [3]. 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 in the lakes. 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. The region is unique in continental Europe for having an extensive lowland tundra with permafrost, together with an upland area of the Urals. It comprises arctic treeline and the southern limits of discontinuous and continuous permafrost. Spruce and larch dominated boreal forest and tundra are the major vegetation zones in the study area. The area is underlain by Permian rocks and Quaternary deposits [4]. 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 0ºC). The coldest month is February with minimum temperatures of about -55ºC; the warmest month is July with maximum temperatures reaching 31ºC Annual precipitation varies between 370 and 395 mm with 60% falling during the summer months, and a maximum in August.

Summary characteristics of the study lakes are shown in Table 1. Two lakes had no names and they were named informally from the nearby rivers: Malyi Patok Lake and Moreju Lake (in the SPICE project, these lakes were named F6-4 and F8-4 respectively). 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 [5] and within the TUNDRA and SPICE projects (pers. comm.). All lakes are relatively dilute and circumneutral (Table 1) typical of the northern Ural region.

Shrub-lichen tundra in the catchments of Mitrofanovskoe, Vanuk-ty and Moreju Lakes is dominated by *Betula nana*, with some *Empetrum nigrum*, and *Vaccinium vitis-idaea*. *Vaccinium myrtillus* prevails on drier patches and hills. 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 Malyi Patok Lake is mixed spruce-fir forest comprising *Picea odovata* (up to 70%) with *Larix sibirica* (up to 30%). Deciduous trees include mainly young stands of *Betula pubescens* (SPICE final report). The ice-free period at Mitrofanovskoe, Vankavad and Malyi Patok lakes lasts approximately three months, from June to September and planktonic diatoms have normally two peaks of abundance, in June and September. At Moreju and Vanuk-ty Lakes 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.

3. Methods

Sediment cores were collected using a Glew corer 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 [3].

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 [6]. ^{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 [7] 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.

Slide preparation of spheroidal carbonaceous particles (SCPs) from lake sediment followed Rose [8, 9]. 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}).

Diatom slide preparation followed standard methods [10] using the water-bath technique. Slides were mounted using Naphrax®. The diatom accumulation rate was estimated using microsphere markers. Between 300 and 400 valves were counted where possible at 1000 times magnification. Diatom nomenclature followed Krammer and Lange-Bertalot [11] (1986-1991) and AL:PE guidelines.

The AL:PE diatom-pH model was used for pH inferences [12]. Detrended canonical correspondence analysis (DCCA) was used to estimate the overall species turnover measured in SD units and to generate sample scores, which provide an estimate of compositional change along a temporal gradient [13]. 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 nonlinear rescaling and detrending by segments were used. All DCCAs were carried out using CANOCO 4.5 [14]. Rate-of-change analysis [15] was used to quantify the total amount of biostratigraphical change in diatom assemblages per unit time. Rates of change were estimated as chord distances 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.

4. Results and interpretations

At all sites equilibrium between supported and unsupported ^{210}Pb, corresponding to c.100-120 years of accumulation, was reached at depths of between 7 and 16 cm (Table 2). At Vankavad and Vanuk-ty there were irregularities in the unsupported ^{210}Pb activity versus depth profiles, indicating non-uniform sedimentation rates. ^{210}Pb dates were therefore calculated using the CRS dating model [7]. All ^{210}Pb-based chronologies are in good agreement with the independently determined 1963 date from the ^{137}Cs stratigraphy. Sedimentation rates are low and mostly uniform except for Vankavad and Vanuk-ty Lakes, where they increase within the last 15-20 years (Table 2). More details on ^{210}Pb chronology for Mitrofanovskoe and Vanuk-ty Lake are given in [3].

SCPs first appeared in the sediments of the above lakes in the mid-1950s except for Malyi Patok Lake, where no SCPs were found. 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 [16]. The same pattern was found in many other lakes in the northern Ural region and it implies largely local origin of SCPs in lake sediments [16]. The highest SCP accumulation rate occurred in Vanuk-ty Lake (up to 79 $cm^{-2}\ y^{-1}$) in 1990, and this is also the lake closest to Vorkuta. Figure 2 clearly shows that SCP accumulation rate decreases in Moreju and Mitrofanovskoe Lakes, which are located further to the west from Vorkuta compared to Vanuk-ty. SCPs in the Vankavad Lake sediments occurred at a very low concentration and only in the top two surface layers [16]. The SCP accumulation rate in Vankavad Lake is nearly 80 times as low as it is in Vanuk-ty Lake. Vankavad Lake is located at about 40 km west from small industrial town of Inta, which is a minor source of air pollution compared to Vorkuta [16]. No SCPs were found in the sediments of Malyi Patok Lake, 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 ALPE-inferred pH shows little change, increasing slightly in the top and implying that the lakes are not affected by acidification. 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 [16].

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 [3, 13, 16] and in the Pechora delta and in Siberia [17, 18].

Sedimentary diatom assemblages from all studied lakes show distinct changes in the 20th century. The most striking diatom changes occurred at Vankavad Lake where *Asterionella formosa* increased from about 1-2% abundance between 1880s and 1940s to c. 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 Mitrofanovskoe Lake, *Asterionella formosa* also first occurred in the 1950s, and it reached maximum abundance (20%) in Malyi Patok Lake at around the same period. The rates of change of diatom composition are significant in Vankavad ($p < 0.05$) during the last 100 years.

In Mitrofanovskoe Lake, the first diatom changes occurred at about 1900s, when *Fragilaria robusta* increased and *Aulacoseira islandica*, *Fragilaria pseudoconstruens*, *Cyclotella tripartita* and *Navicula digitulis* decreased. Another set of changes occurred in Mitrofanovskoe Lake between the 1960s and 1970s when planktonic *Tabellaria flocculosa* and *Aulacoseira islandica* increased together with *Fragilaria robusta*. The later diatom changes coincided with the substantial increase in diatom accumulation rate

(DAR). In Mitrofanovskoe Lake, the rates of change of diatom composition are also are significant ($p< 0.05$) between 1971 and 2001.

In Malyi Patok Lake 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 Malyi Patok Lake between 1960 and 2001.

In Vanyk-ty Lake the most pronounced diatom changes occurred after 1971 first with the appearance of planktonic *Tabellaria flocculosa*, 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 Vanyk-ty from the 1980s and the rate of change in diatom composition was statistically significant ($p< 0.05$) between 1910 and 2001.

Major diatom changes occurred in Moreju Lake 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 *Tabellaira 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. The rate of change in the diatom composition was statistically significant ($p<0.05$) between 1901 and 2001.

The overall diatom compositional changes are reflected by the gradual changes in the profiles of DCCA sample scores and by the length of gradient of DCCA axis 1 shown in Table 3. The highest diatom species turnover occurred in Vankavad Lake (gradient length 1.52 SD), and the lowest in Malyi Patok Lake (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 Mitrofanovskoe Lake, in the 1950s in Vankavad Lake, in the 1970s in Mitrofanovskoe, Malyi Patok and Vanuk-ty Lakes and in the 1990s in Moreju Lake.

5. Discussion

As all the lakes are remote with no permanent settlements in the catchments, there are no sources of local pollution. There is also no evidence for acidification or eutrophication from diatom changes [3, 16, 19]. In all lakes, except for 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 Moreju, the SCP accumulation rate is relatively low, so it is unlikely that atmospheric contamination could have affected the diatom flora in this lake. In Vanuk-ty, which is the most contaminated of all the studied lakes, the peak SCP accumulation rate is still lower than in many European and northern Ural lakes [16] (Solovieva et al., 2002) and is comparable to the SCP accumulation rates in lakes from Svalbard [20] and subarctic Finland [21]. Analysis of stable lead isotopes in the sediments of Mitrofanovskoe Lake [3] shows a low degree of global lead contamination, which is comparable with the remote lakes in West Greenland [22].

Being the largest among the studied lakes, Vanuk-ty is the only lake with some degree of commercial fishing, which, however, has no direct influence on diatom assemblages [3]. By this means, global and local pollution and atmospheric contamination has none or very low influence on diatom flora in the studied lakes

In all study lakes compositional changes in diatom assemblages occurred for different periods in the 20th century with all five lakes exhibiting 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. 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 habitat availability. 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 turnover and stratification periods, which are essential to establishing planktonic populations. Previously we have established by regression modelling that June and August/September temperatures have statistically significant effect on both planktonic and benthic sediment diatom assemblages in Mitrofanovskoe and Vanuk-ty Lakes [3].

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 1.5ºC has been observed in the periods 1920-40 and 1970-present [23] and the last two decades (from c. 1980s) have been especially warm [24] (Comiso, 2003). The tree-ring measurements from Salekhard (66º 50'N, 65º 15'E) in the eastern part of the northern Urals also indicate an increase in summer temperature between 1901 and 1990 [25] and there is also c. 1º C increase in chironomid-inferred summer temperature in Mitrofanovskoe Lake during the 20th century [3].

Although the lakes exhibit different degrees of diatom turnover (Table 3), there is no north-south gradient with northernmost lakes showing greater change, which has been suggested by [2]. The greatest species turnover occurred in a subarctic forest lake Vankavad, and the northernmost lake, Vanuk-ty, showed the second highest species turnover values. The diatom assemblages from upland the southernmost Malyi Patok Lake appeared to have the lowest degree of change. Most temperature records show very similar trends, with the greater temperature increase occurring the Khorei Ver weather station, which is located in tundra in the middle of the study area.

The 20th century diatom compositional changes in subarctic Vankavad lake are greater than in most arctic lakes from Canada and northern Europe recently described by [2]. The only lakes, showing greater degree of changes are deep high-arctic Sawtooth Lake and shallow ponds from Ellesmere islands in Canada [26]. However, all the above lakes are located much more to the north in high-arctic desert whereas Vankavad Lake 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 study lakes appear to show no effect from local and global 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 turnover and stratification periods and habitat availability. 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 subarctic forest Vankavad Lake.

The degree of the 20th century diatom changes in Vankavad Lake is greater than in most circum arctic and subarctic lakes from northern Europe and Canada.

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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 tundra	Shrub lichen tundra		Northern taiga	Northern taiga
	April 2001		April 2001	July 2001		
pH	6.88	6.71	6.8;	7.06	7.08	6.79
Alk, μeq l^{-1}	622.9	229	588.9;	365	70.90	186
Cond, μS cm^{-1}	70.9	30	67.2;	44.6	4.40	27
K^{+}, mg l^{-1}	0.91	0.23	0.95;	0.48	0.01	0.19
Na^{+}, mg l^{-1}	2.3	1.11	2.75;	1.09	2.80	0.69
$Ca^{2+,}$ mg l^{-1}	8.6	3.67	8.4;	5.3	2.70	3.73
Mg^{2+}, mg l^{-1}	1.92	0.93	1.72;	1.12	0.74	0.37
Cl^{-}, mg l^{-1}	2.0	1.64	4.4;	1.23	1.79	0.24
$SO4^{2-}$, mg l^{-1}	1.0	0.68	1.24;		0.96	3.47
P_{tot}, μg l^{-1}	14	-	19;	58	-	-
N_{tot}, μg l^{-1}	1600		250;	105	-	-

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

Sites	Mean sedimentation rates, g cm^{-2} y-1	Equilibrium depth, cm	Dating models used
Vanuk-ty Lake	0.033 until c. 1985 0.064 from c. 1985	11	CRS
Moreju Lake	0.013 ± 0.002	10	CRS, CIC
Mitrofanovskoe Lake	0.027 ± 0.002 g	16	CRS, CIC
Vankavad Lake	0.022 until c.1980 0.045 from 1980	5-6 cm	CRS
Malyi Patok Lake	0.020 ± 0.002	7.5 – 8.5	CRS, CIC

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

Study lakes	Length of gradient (SD)	Eigevalue (λ_1)
Vanyk-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