Links between biota and climate-related variables in the Baltic region using Lake Onega as an example*

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Abstract

This paper aims to reveal current changes (recent decades) in regional climatic variables like water temperature (WT), the duration of the ice-free period (ICE-FREE) and the precipitation rate (P), as exemplified by Petrozavodsk Bay (Lake

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Onega, European Russia), and to analyse their relationships with the global climatic indices NAO, AO and structural characteristics of biota (chlorophyll a concentration (Chl a), phytoplankton and zoobenthos abundance/biomass) in the lake ecosystem, which lies within the Baltic Sea catchment area. Spearman's rank correlations yielded significant ($p < 0.05$) relationships between the NAO and planktonic Cyanobacteria abundance, and also between NAO, AO, WT, P and the abundance and biomass of zoobenthos. Chl a correlates positively ($R = 0.66$; $p = 0.03$) with WT and negatively with ICE-FREE ($R = -0.53$; $p = 0.05$). At the same time, multiple regression analysis confirmed that the global climate governs primarily the regional climatic variables and productivity level in the lake's ecosystem, whereas most of the biotic characteristics respond to variability in the regional climate.

1. Introduction

In recent decades one of the main priorities for scientific research worldwide has been the study of climate variability on the planet and its possible consequences for aquatic ecosystems. It was found that the climatic index NAO determines the river flow, water temperature, ice conditions and the rate of convective mixing in European waters (Smirnov et al. 1998, Dokulil et al. 2006, Pociask-Karteczka 2006, Blenckner et al. 2007). Such changes in environmental conditions can affect the biota of both marine and fresh waters, affecting directly or indirectly the population dynamics of aquatic organisms and their geographical distributions (Ottersen et al. 2001, Stenseth et al. 2002, Drinkwater et al. 2003). In spite of a number of publications testifying to current changes in climate variables for different European aquatic ecosystems (Nõges 2004, Weyhenmeyer 2004, Markensten 2006, Filatov et al. 2012), little is known about the responses of biota to climate change.

The aim of this paper was to find possible changes in biota as a response to climate variability in the Lake Onega[1] ecosystem, the second-largest lake in Europe. Our previous studies of large lakes in European Russia (Ladoga, Onega) showed that the phytoplankton and zoobenthos of shallow-water areas were the most sensitive communities among the biota to climate change and pollution (Moiseenko & Sharov 2011, Sharov et al. 2012). Based on long-term monitoring data from Petrozavodsk Bay, in the western part of Lake Onega, we analyse relationships between climatic global indices and

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[1] Some experts have recently recommended using the transliterated old Russian name for this lake, namely, Lake Onego (Filatov & Rukhovets 2013). So far, however, there has been no general acceptance of this recommendation. Therefore, in this paper we use the well-known, most commonly used name for this lake – Onega – in accordance with the English-Russian geographical dictionary (2014).

regional variables on the one hand, and the structural characteristics of the phytoplankton and benthos on the other.

2. Material and methods

Situated in the eastern part of the Baltic Sea basin, Lake Onega is 9720 km^2 in area, and has a water volume of 285 km^3, a mean depth of 30 m and a maximum depth of 120 m. Petrozavodsk Bay is 72.6 km^2 in area and has a mean depth of 15 m (Figure 1). This area is used for transport, industrial and recreational activities by the population of the city of Petrozavodsk. Water from this area is collected for drinking and other human needs.

In our attempt to understand current climate variability, we used both global indices (North Atlantic Oscillation – NAO, Arctic Oscillation – AO)

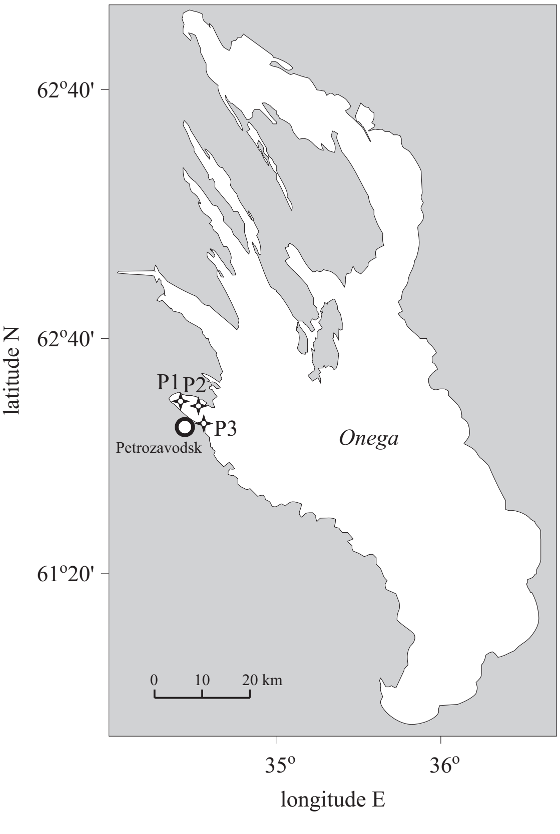

Figure 1. Map of Lake Onega showing the study sites (P1–P3) in Petrozavodsk Bay

and regional characteristics, such as the duration of the ice-free period (ICE-FREE), air (AT) and water temperatures (WT), and the precipitation rate (P). The average annual climate indices like NAO and AO were obtained from the Internet site http://www.cgd.ucar.edu. Regional values of AT, ICE-FREE and P for the study area were obtained from observational data collected at the meteorological stations located in the Lake Onega catchment area. Surface and bottom temperatures were measured and biological material was sampled during each field campaign.

Biological data such as the chlorophyll *a* concentration in water (Chl *a*), the abundance (N) and biomass (B) of phytoplankton and zoobenthos (and their separate taxa) were taken from the Database of the Northern Water Problems Institute of the Karelian Scientific Centre, Russian Academy of Sciences (NWPI) (registration number 2012620882). The material used in this study was collected at three sites in Petrozavodsk Bay (N 61°47′, E 34°26′, Figure 1), a shallow-water area of Lake Onega, by staff from NWPI during cruises of r/v 'Ecolog' in summer (July, August) from 1999 to 2010. Samples were processed in the Laboratory of Hydrobiology using standardised methodology.

Chl *a* was determined using a standard spectrophotometric method by measuring the absorbance (optical density) of the extract at various wavelengths. Algal cells were concentrated by passing water through a membrane filter (1 μm pore size). The pigments were extracted from the concentrated algal sample in an aqueous solution of acetone. The resulting absorbance measurements were then applied to a standard equation (SCOR-UNESCO 1966).

To estimate N and B of phytoplankton, 1 L (dm^3) samples of water were taken using a Ruthner bathometer from the lake surface (0.5 m) and subsequently preserved with a few drops of 40% formaldehyde up to a 2% concentration in the sample. After a 3-day sedimentation, the phytoplankton samples were processed using a Nageotte chamber (0.02 cm^3) under an optical microscope at 420× and 600× magnifications. N of basic taxa (individual cells and colonies of algae size > 4 μm) were re-calculated as the total number of algae per 1 dm^3. All the organisms identified belonged to a number of taxonomic groups: Cyanobacteria, Euglenophyceae, Dinophyceae, Cryptophyceae, Chrysophyceae, Bacillariophyceae and Chlorophyceae.

The benthos was sampled with an Ekman grab (two grabs per site) with a 0.025 m^2 sampling area. The samples were sieved (mesh net size 0.33 mm) and rinsed with pure water and preserved with 4% formaldehyde. In the laboratory, invertebrates with body sizes > 2 mm were hand-picked from the sample. Three taxa – Oligochaeta, Amphipoda and Chironomidae – were found to be the predominant ones in all the samples. The animals were counted and weighed on an electro-balance to the nearest 0.001 g. Prior to weighing the animals were blotted with filter paper to remove water. N and B were re-calculated as the total number of organisms per 1 m^2.

The relationships between the climatic variables and the biological characteristics were analysed using Spearman's rank correlation and multiple regression analysis (Statistica 6.0).

3. Results

3.1. Regional climatic variables

The annual AT over the catchment area of Lake Onega for the long-term period of 1951–2010 was calculated as 2.4°C (Figure 2). This value exceeded the current climatic norm (2.1°C), obtained for the period of 1961–1990. The annual AT over the past 15 years made the most important contribution to this increase. Analysis of changes in annual AT using a linear trend showed a 0.2°C per ten years increase in average temperature in the study area. This temperature increase was accompanied by a reduction in the ice cover of Lake Onega. ICE-FREE in Petrozavodsk Bay during the study period averaged 233 days (Figure 3), exceeding the average value for 1960–2010 by 6 days.

During June–October (ice-free period) of 1950–2010, WT in the study area averaged 12.1°C with a July maximum (Figure 4). July WT averaged 15.0°C for 1950–2010 and 17.8 for 2000–2011. The trend of the increase in summer WT was notable especially in recent years, when maximum July

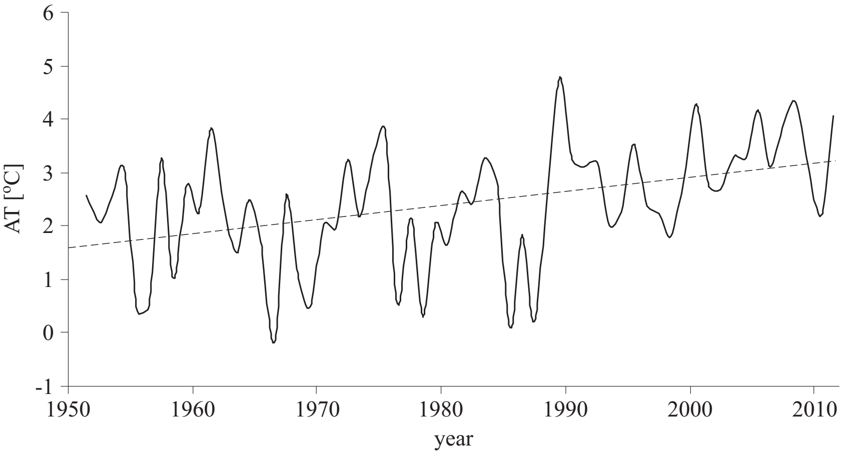

Figure 2. Annual air temperature over the Lake Onega catchment area for 1951–2010

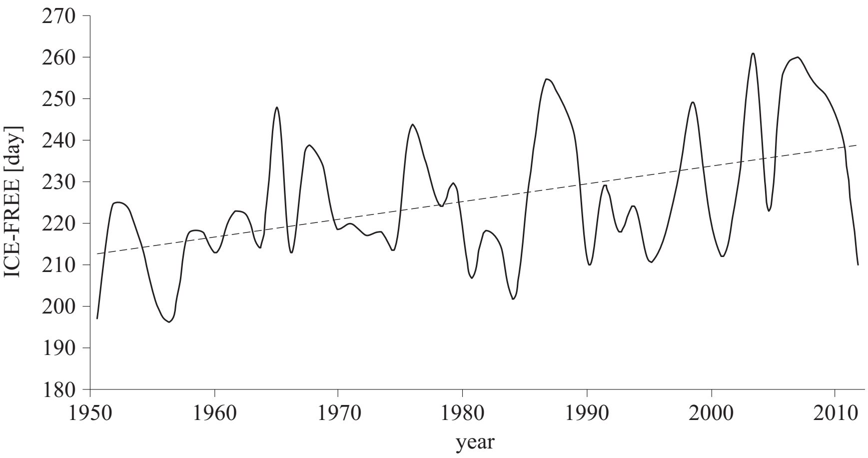

Figure 3. Trend of changes in the ice-free period (in days) on Lake Onega (based on data for 1960–2011)

WTs were recorded (20.1°C in 2010 and 21.4°C in 2011). For 1999–2010 WT averaged from 14.6 to 19.7°C at the water surface and from 5.6 to 14°C at 15 m depth (Figure 4).

Annual P over the Lake Onega catchment ranged between 550 and 750 mm in different years of 1951–2010, reaching a maximum during summer. Summer P for Petrozavodsk Bay in 1999–2010 varied significantly between years (38–233 mm per month) with a tendency to increase in the late 2000s (Figure 5).

3.2. Biotic variables

The Chl *a* concentration recorded in the water of Petrozavodsk Bay was high in the summers of 2005 (6.4 μg dm^{-3}) and 2007 (7.2 μg dm^{-3}), but was generally much lower in recent years compared with the beginning of the 2000s (Figure 6).

The dominant phytoplankton complex consisted of diatoms, a common taxon in every season throughout the period studied. Summer phytoplankton abundances in Petrozavodsk Bay varied from 0.35 to 1.2 in 1991–1993 and from 0.15 to 1.2×10^6 indiv. dm^{-3} during 1999–2008, with a tendency to decrease in the latter period (Figure 7). A characteristic feature of the summer phytoplankton in the study area, which was observed every year in 1990–2010, was the growth of Cyanobacteria and the presence of species from Chlorophyceae and Cryptophyceae.

The zoobenthos of Petrozavodsk Bay consisted of glacial relict crustaceans (*Monoporeia affinis* and *Palasea quadrispinosa*), oligochaetes and chironomids with low species richness (14 taxa). Recent years have seen an

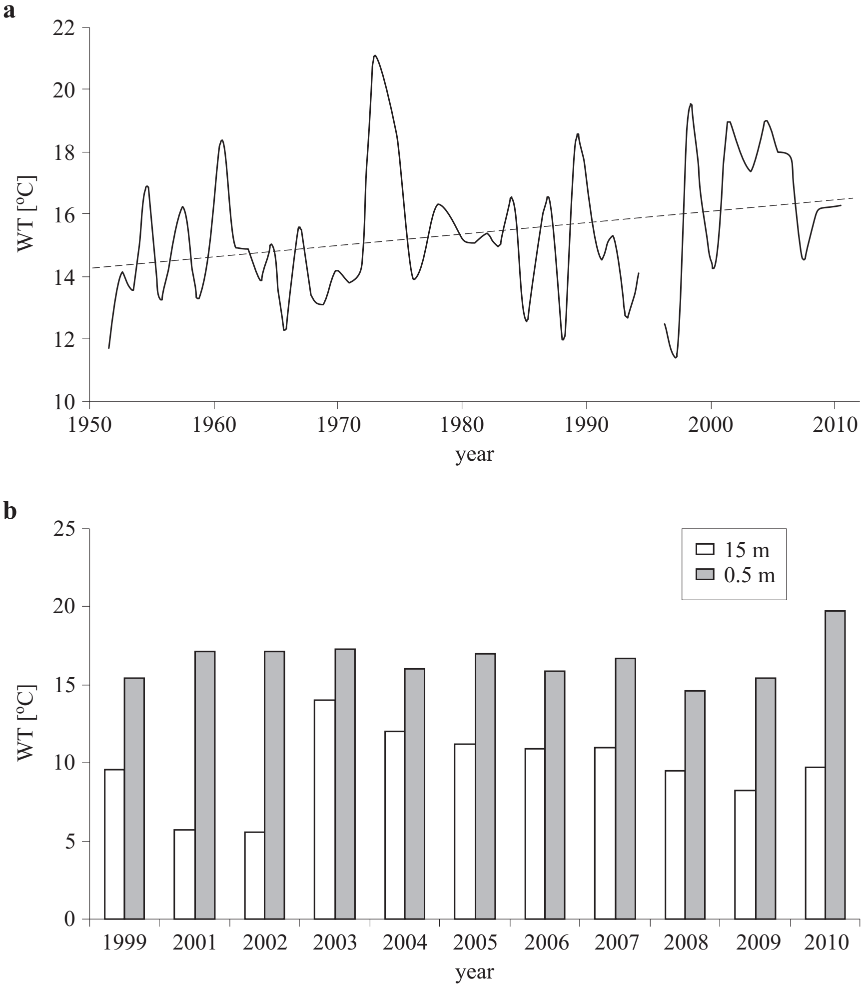

Figure 4. Summer water temperature in Petrozavodsk Bay (Lake Onega); a) long-term (1951–2009) water surface temperature for July, b) water surface and bottom temperature during the study period (1999–2010)

increasing trend in the zoobenthos biomass, however. The average current abundance and biomass reached 0.4– 5.4×10^3 indiv. m^{-2} and 1.1– 5.7 g m^{-2} respectively (Figure 8). A high abundance and biomass were recorded in 2010 (up to 17×10^3 indiv. m^{-2} and 19 g m^{-2} respectively), the maximum value in the last 40 years.

3.3. Correlation of biological and climatic parameters

Spearman's rank correlations yielded significant ($p < 0.05$) relationships between the climatic and biotic variables (Table 1). Chl *a* correlated

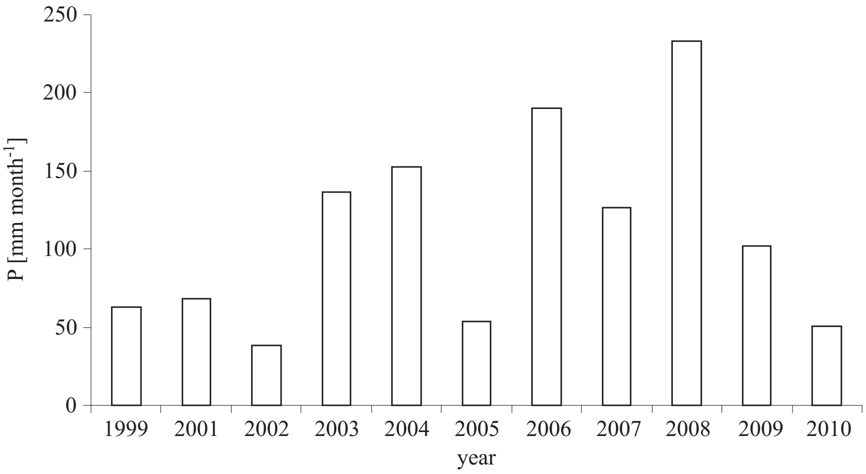

Figure 5. Current changes (1999–2010) in average summer precipitation for the Petrozavodsk Bay area (Lake Onega)

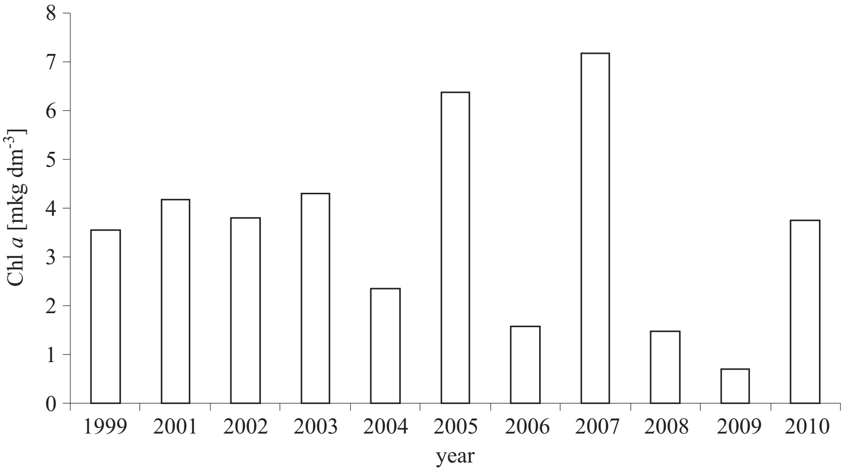

Figure 6. Current changes (1999–2010) in summer chlorophyll *a* in Petrozavodsk Bay (Lake Onega)

positively ($R = 0.66$; $p = 0.03$) with WT and negatively with ICE-FREE ($R = -0.53$; $p = 0.05$).

The phytoplankton abundance depended on the duration of the ice free period ($R = -0.89$; $p = 0.006$); higher values were recorded in summers following longer periods of ice cover. The abundance of planktonic Cyanobacteria increased significantly ($R = 0.89$; $p = 0.006$) in years with a high NAO index.

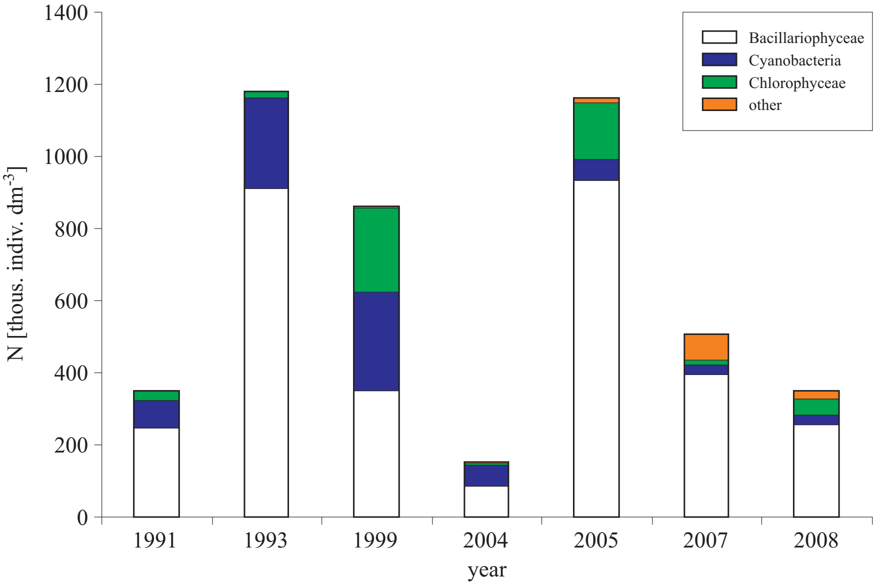

Figure 7. Structure and abundance of phytoplankton in different periods in Petrozavodsk Bay (Lake Onega)

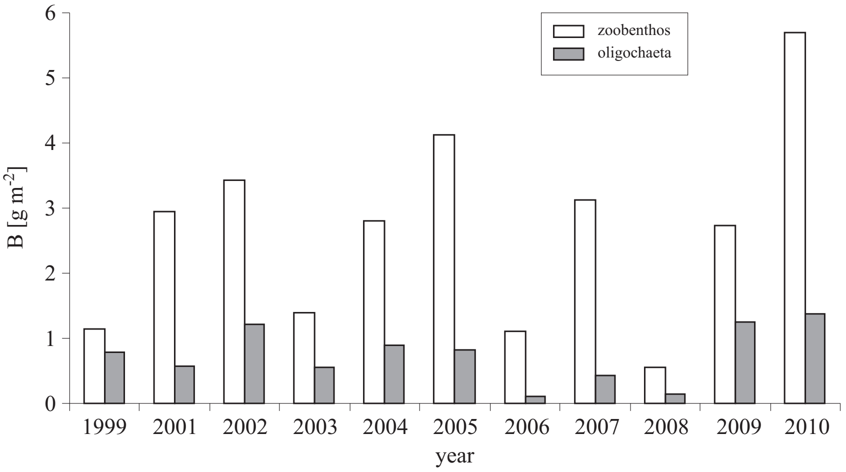

Figure 8. Current changes (1999–2010) in the summer zoobenthos biomass in Petrozavodsk Bay (Lake Onega)

Negative correlations were obtained between the global indices and the N and B of the zoobenthos (Table 1); the same tendency was observed for the several benthic groups (Oligochaeta). At the same time the B of zoobenthos correlated positively at a high level of significance with WT ($R = 0.72$; $p = 0.01$) and negatively with P ($R = -0.77$; $p = 0.005$).

Table 1. Spearman Rank Order Correlations. N – abundance, B – biomass, cyan – Cyanobacteria, zoob – zoobenthos, olig – Oligochaeta, Chl *a* – chlorophyll *a*

Climatic index	Biotic index	Spearman	t(N − 2)	*p*-level
NAO	Chl *a*	NS		$p > 0.5$
	N phyto	NS		$p > 0.5$
	N cyan	0.89	4.43	**0.006**
	N_zoob	−0.69	−2.85	**0.02**
	B_zoob	NS		$p > 0.5$
	N olig	−0.60	−2.28	**0.05**
	B olig	NS		$p > 0.5$
AO	Chl *a*	NS		$p > 0.5$
	N phyto	NS		$p > 0.5$
	N cyan	NS		$p > 0.5$
	N_zoob	−0.73	−3.19	**0.01**
	B_zoob	−0.60	−2.25	**0.05**
	N olig	−0.82	−4.27	**0.002**
	B olig	−0.83	−4.42	**0.002**
T	**Chl *a***	0.66	2.61	**0.03**
	N phyto	NS		$p > 0.5$
	N cyan	NS		$p > 0.5$
	N_zoob	NS		$p > 0.5$
	B_zoob	0.72	3.11	**0.01**
	N olig	NS		$p > 0.5$
	B olig	NS		$p > 0.5$
P	**Chl *a***	NS		$p > 0.5$
	N phyto	NS		$p > 0.5$
	N cyan	NS		$p > 0.5$
	N_zoob	NS		$p > 0.5$
	B_zoob	−0.77	−3.65	**0.005**
	N olig	−0.54	−1.95	**0.05**
	B olig	−0.71	−3.02	**0.01**
ICE-FREE	**Chl *a***	−0.53	−1.86	**0.05**
	N phyto	−0.89	−4.43	**0.006**
	N cyan	NS		$p > 0.5$
	N_zoob	NS		$p > 0.5$
	B_zoob	NS		$p > 0.5$
	N olig	NS		$p > 0.5$
	B olig	NS		$p > 0.5$

Multiple regression analysis confirmed close relationships between NAO and regional climate variables (WT, P, ICE-FREE) at $p < 0.01$ (Table 2) and also between AO and these climatic variables at $p < 0.02$ (Table 3). Chl *a* was governed mainly by WT at $p < 0.05$ (Table 4). Similar WT-dependent correlations were recorded for other zoobenthos variables (Table 5). Also, zoobenthic B and N depended on ICE-FREE ($p < 0.05$).

Table 2. Multiple Regression analysis: NAO and dependent variables (T, P, ICE-FREE). $R = 0.70$, $F(1.9) = 8.78$, $p < 0.016$, Std. error: 1.01

	Beta	Std. err.	B	Std. err.	t(9)	*p*-level
intercept			16.281	0.322	50.579	**0.000**
NAO	−0.703	0.237	−0.810	0.273	−2.964	**0.016**

Table 3. Multiple Regression analysis: AO and dependent variables (T, P, ICE-FREE). $R = 0.66$, $F(1.9) = 7.1$, $p < 0.026$, Std. error: 1.07

	Beta	Std. err.	B	Std. err.	t(9)	*p*-level
intercept			16.32	0.336	48.56	**0.000**
NAO	−0.664	0.249	−2.38	0.891	−2.67	**0.026**

Table 4. Multiple Regression analysis: NAO, AO, regional factors and dependent variable (Chl *a*). $R = 0.86$, $F(5.5) = 2.95$, $p < 0.13$, Std. error: 1.42

	Beta	Std. err.	B	Std. err.	t(9)	*p*-level
intercept			−34.2	13.83	−2.48	**0.056**
NAO	0.571	0.846	1.0	1.43	0.68	0.529
AO	0.294	0.806	1.5	4.25	0.36	0.730
T	1.138	0.425	1.7	0.63	2.67	**0.044**
P	−0.216	0.354	−0.0	0.01	−0.61	0.569
ICE-FREE	0.498	0.250	0.0	0.02	1.99	0.103

Table 5. Multiple Regression analysis: regional factors and dependent variables (N zoob., B zoob., N olig.). $R = 0.83$, $F(3.7) = 5.47$, $p < 0.03$, Std. error: 1.07

	Beta	Std. err.	B	Std. err.	t(9)	*p*-level
intercept			−20.3	8.326	−2.43	**0.045**
T	0.648	0.275	0.8	0.332	2.36	**0.051**
P	−0.296	0.258	−0.0	0.007	−1.15	0.289
ICE-FREE	0.585	0.226	0.0	0.018	2.59	**0.036**

4. Discussion

Evidence from the analysis of long-term data sets shows that many of the effects of changing climate are already occurring in different lakes. These changes include an increase in the surface water temperature of lakes and a reduction in lake ice-cover (Blenckner et al. 2007); often, there are also diverse changes in water levels, habitat structures and water residence times (Jones & Elliot 2007).

The trend of increasing water temperatures and longer ice-free periods in recent decades, confirmed in Lake Onega, was also found to apply to various small lakes in north-western Russia, Finland, Sweden, Norway (Weyhenmeyer et al. 1999, Adrian et al. 2009, Finland's Fifth National Communication 2010, Efremova et al. 2010) and other regions (Austin & Colman 2008). For example, it was found in Lake Superior, the largest and coldest of the North American Great Lakes, that the summer water temperature had increased by 3.5°C over the previous 100 years (Austin & Colman 2008): this is the greatest warming of any lacustrine ecosystem in the last three decades.

Significant correlations between physical parameters (ice-free period, water temperature, precipitation) and different characteristics of biota (Chl *a*, zoobenthos), revealed by the present study of the Petrozavodsk Bay ecosystem, were also found for other shallow and relatively unpolluted small lakes in northern Russia (Maksimov et al. 2012).

The expected impacts on biota, however, can differ strongly between ecosystems depending on the climatic region. One of the first studies of the impact of climate on biota was done by Adrian et al. (1995, 1999) and showed that the composition, timing and maximum abundance of the phytoplankton and zooplankton communities that start to develop in the spring were strongly dependent on the duration of the winter ice-cover.

In different lakes climate warming leads to greater primary productivity with intense algal blooms (Blenckner et al. 2007, Jeppesen et al. 2009). As far as Lake Onega is concerned, we also found a close correlation between the abundance of phytoplankton and, in particular, between the abundance of Cyanobacteria and climatic variables (especially NAO).

The positive correlations between NAO and summer Cyanobacteria abundance found for the study area may be mediated by the precipitation rate. This rate increases significantly in years with a high positive NAO, resulting in an increase of nutrient loading from the catchment area. The Cyanobacteria bloom, a common summer phenomenon, has been observed in Petrozavodsk Bay since the 1980s (Sharov 2008). Results from Swedish lakes (Weyhenmeyer 2004) and Lake Pääjärvi, Finland (Järvinen et al. 2006) suggest, moreover, that temperature-sensitive phytoplankton groups such as Cyanobacteria and Chlorophyta would benefit from the earlier warming-up of the lake water and the earlier onset of temperature stratification.

Water temperature was distinguished as the most important factor reflecting climatic variability in different studies (Adrian et al. 2009). In the case of Lake Onega it is the factor determining the quantitative development of phytoplankton and zoobenthos as well as the trophic level of the lake (Chl *a*). Although many researchers assume the temperature regime to be a sensitive marker for the testing of climate changes, other characteristics such as the duration of the 'biological summer' (the period with temperatures $>10°C$, Efremova & Palshin 2012) can be used as an important marker of climate change, because it determines the initial biomass growth rate and the reproduction rate (abundance) of aquatic organisms. The example of six lakes in Karelia from 1953 to 2009 shows that the duration of the 'biological summer' has increased by 12–23 days and that the trend of the prolongation of the 'biological summer' is positive ($p < 0.05$) (Efremova & Palshin 2012).

The majority of the lakes in East Fennoscandia are characterised by an increase in the ice-free period (Filatov et al. 2012). Earlier ice-melting in Lake Onega can result in a shift of the spring bloom period of diatoms. The negative correlation between the ice-free period and plankton characteristics (Chl *a* and N phytoplankton) may be explained by the predominance of large-sized diatoms (*Tabellaria fenestrata* and *Aulacoseira islandica*) in the summer phytoplankton. Chl *a* in these species is lower than in other algae (diatoms).

The negative correlations between NAO, AO, precipitation and zoobenthos abundance and biomass testify that nutrient and organic matter loads from the catchment area can increase together with the increase of precipitation in years with a positive NAO. In turn, eutrophication phenomena (hypoxia, H_2S production etc.) can reduce the numbers of sensitive species (relict amphipods) and, conversely, favour eurybiotic taxa (oligochaetes). Oxygen depletion and higher temperatures accelerate nutrient release processes at the sediment-water interface (Søndergaard et al. 2003) and increase the stress on aquatic organisms (Weider & Lampert 1985, Saeger et al. 2000, Wilhelm & Adrian 2007), resulting in a decrease in their abundance.

5. Conclusion

Significant correlations between climate indices, physical parameters in Petrozavodsk Bay, Lake Onega, and some characteristics of its biota (phytoplankton, zoobenthos) were found in this research. We conclude that global climate primarily determines the regional hydrological variables of a lacustrine ecosystem and its productivity level, whereas biotic characteristics are a reflection principally of the variability in the water temperature and the ice-free period, both of which determine the duration of the 'biological summer' (WT $>10°C$). At the same time, the responses of biological communities and whole ecosystems to climate variability are complex and often difficult to recognise, especially in the case of large ecosystems with a long period of water exchange.

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