Acta Biol. Univ. Daugavp. 15 (2) 2015
ISSN 1407 - 8953

PHYTOPLANKTON RESPONSES TO CLIMATE CHANGE IN THE LARGE LAKES OF THE BALTIC SEA BASIN

Andrey N. Sharov, Irina V. Andreeva

Sharov A.N., Andreeva I. V. 2015. Phytoplankton responses to climate change in the large lakes of the Baltic sea basin. *Acta Biol. Univ. Daugavp., 15 (2): 349 – 358.*

This paper aims to reveal current changes (last decades) in regional climatic variables such as water temperature (WT), the duration of ice-free period (ICE-FREE), precipitation rate (PR), annual water level (WL), nutrients (P, N) on example of Lake Onega (Petrozavodsk Bay) and Lake Peipsi; and to analyze their relationships with the global climatic indices of North Atlantic Oscillation (NAO, AO) and structural characteristics of phytoplankton (chlorophyll A concentration (Chl *a*), abundance/biomass) in the lakes ecosystems, the Baltic Sea catchment area. The Spearman rank correlations found the significant ($p < 0.05$) relationships between the NAO and planktonic Cyanobacteria abundance. The diatoms correlated with T ($R = -0.76$; $p = 0.002$) and with water depth ($R = -0.79$; $p = 0.001$) on the sampling station. The phytoplankton abundance depended on the duration of the ICE-FREE ($R = -0.89$; $p = 0.006$). Chl *a* correlates positively ($R = 0.66$; $p = 0.03$) with WT and negatively with ICE-FREE ($R = -0.53$; $p = 0.05$). The total nitrogen content correlates ($R = 0.73$; $p = 0.016$) with WL of the Lake Peipsi. At the same time, the multiple regression analysis confirmed that the global climate determines primarily the regional climatic variables and productivity level in lake ecosystem while a bulk of biotic characteristics responds to variability of the regional climate.

Key words: phytoplankton, Lake Onega, Lake Peipsi, climate variables.

Andrey N. Sharov. St. Petersburg Scientific Research Centre for Ecological Safety, Russian Academy of Sciences, Korpusnaya 18, 197110, St. Petersburg, Russia.
North-West Administration for Hydrometeorology and Environmental Monitoring, 2a, 23th Line, St Petersburg, 199026, Russia; e-mail: sharov_an@mail.ru
Irina V. Andreeva. North-West Administration for Hydrometeorology and Environmental Monitoring, 2a, 23th Line, St Petersburg, 199026, Russia; e-mail: ir-andr@yandex.ru

INTRODUCTION

One of the main research directions around the world is studying of climate variability on the planet and their possible consequences for aquatic ecosystems. The number of studies 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 can affect the biota of both marine and fresh waters, affecting directly or indirectly on the population dynamics of aquatic organisms and their geographical distribution (Ottersen et al. 2001, Stenseth et al. 2002, Drinkwater et al. 2003). In spite of a number of publications testifying current changes in climate variables for different European aquatic ecosystems (Nõges 2004, Weyhenmeyer 2004, Markensten 2006, Filatov et al. 2012), a little is known about responses of phytoplankton to climate change.

Aim of this paper is to study relations between climatic and phytoplankton variables in Lake Onega and Lake Peipsi ecosystems, a large lake in Europe.

Our previous studies of biotic communities responses to climate variability in the large lakes of European Russia showed that the most notable changes in biota can occur in the shallow-water communities of phytoplankton and zoobenthos (Sharov et al. 2014).

In order to highlight the possible changes in biota as a response to climate we analyze relationships between climatic indices and variables (NAO, AO indices, water temperature (WT), water level (WL), duration of ice-cover period (ICE-FREE) and precipitation rate (PR)) and structural characteristics of plankton (Chlorophyll *a* (Chl *a*) concentration in water, abundances/biomass of phytoplankton and separate taxa, nutrients) basing on long-term monitoring data from shallow Petrozavodsk Bay (western part of Lake Onega) and different part of Lake Peipsi.

MATERIAL AND METHODS

Lake Onega (Lake Onezhskoe) area 9720 km^2, water volume 285 km^3, average depth 30 m, maximum depth 120 m. It is the second largest lake in Europe and located in the eastern part of the Baltic Sea basin. Area of Petrozavodsk Bay (Fig. 1) is 72.6 km^2, with mean depths of 15 m. This area is subjected to transport, industrial, recreation uses from Petrozavodsk city. Water from this area collected for drinking and other needs of people.

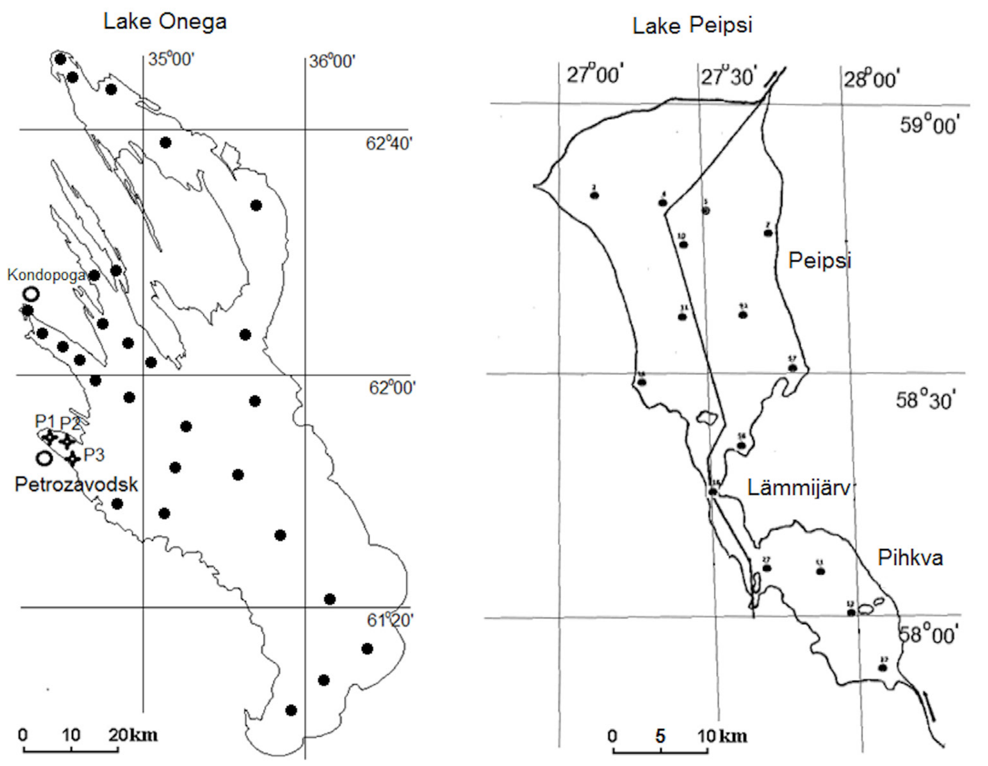

Fig. 1. Map of lakes with indication of sampling sites.

Lake Peipsi (Lake Peipus) surface area 3555 km^2, water volume 85 km^3, average depth 7 m, maximum depth 15 m. It is the biggest transboundary lake and fifth largest lake in Europe on the border between Estonia and Russia. The consists of 3 parts: Lake Peipsi/Chudskoe is the northern part of the lake with the area (73%), Lake Pihkva/Pskovskoe is the southern part of the lake (20%) and Lake Lämmijärv/Teploe is the sound connecting both parts of the lake (7%). The lake is used for fishing and recreation. The main problem of Lake Peipsi is its eutrophication.

In Lake Onega chlorophyll A (Chl *a*) and abundance/biomass of phytoplankton originated from the Database of the Northern Water Problems Institute of the Karelian Scientific Center, Russian Academy of Sciences (NWPI KSC RAS), the registration number 2012620882. The phytoplankton was collected at 30 sites in the different part of Lake Onega (Figure 1) during every year r/v "Ecolog" cruises in summer time (July, August) from 1999 to 2010.

In Lake Peipsi the phytoplankton, Chl *a* and nutrients (P, N) were collected at 15 monitoring sites (Fig. 1) using standardized methodology (Guide on…, 1992).

The North Atlantic Oscillation index (NAO) and Arctic Oscillation index (AO) were collected from Internet site http://climatedataguide.ucar.edu. The regional climate data (AT, WT, WL, ICE-FREE, PR) were obtained from monitoring database in the HYDROMET Meteorological Stations such as Petrozavodsk station in Lake Onega and Raskopel' station in Lake Peipsi.

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

To estimate phytoplankton abundances 1L (dm^3) water samples were takin using Ruthner bathometer from lake surface (0.5 m); and samples were conservated with several drops of 40%-formaldehyde up to 2%-concentration in the sample (Lake Onega). Lake Peipsi phytoplankton was integrated water samples prepared by mixing the same amount of water from every meter from the surface to up to triple Secchi disk transparency deep and samples fixed with neutral Lugol. After 2-weeks sedimentation of samples in laboratory,

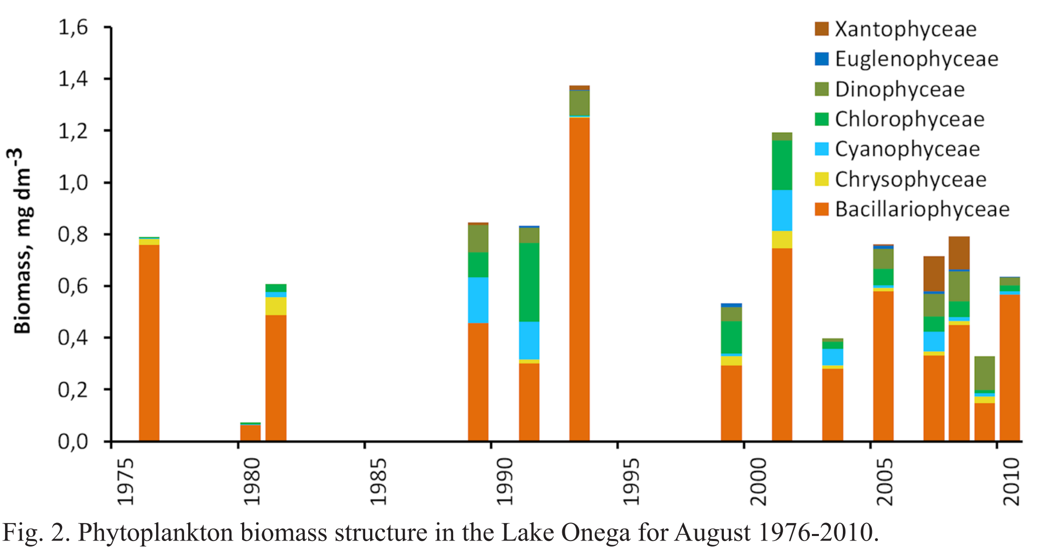

Fig. 2. Phytoplankton biomass structure in the Lake Onega for August 1976-2010.

they were processed using the Nazhotta's camera (0.02 cm^3) under 420x and 600x magnification of optical microscope (Guide on…, 1992).

RESULTS

Planktonic variables

The total list of phytoplankton of Lake Onega includes 780 species: Bacillariophycea 55 %, Chlorophycea 17.5 %, Cyanobacteria 13 %, Chrysophycea 7.5 %, Euglenophycea 2 %, Dinophycea 2 %, Cryptophycea 1.5 %, Xanthophycea 1.5 %. The dominant phytoplankton complex consisted of diatoms a common taxon in every season (mostly *Aulacoseira islandica*) throughout the studied period on the Lake Onega (Fig. 2). A characteristic feature of the species structure of phytoplankton communities of Lake Onega is to increase the species of chlorococcales and Cryptomonad that are indicators of organic pollution (saprobity) of natural waters. This is reflected in parts of the lake by anthropogenic eutrophication (Kondopoga and Petrozavodsk bay).

Phytoplankton abundances in Petrozavodsk Bay summer varied from 0.35–1.2 in 1991–1993 and from 0.15 to 1.2 10^6 ind. dm^{-3} during 1999-2008, with a tendency of decrease in latest period. Characteristic features of the summer phytoplankton in Petrozavodsk Bay and Kondopoga Bay are intensive development of Cyanobacteria, which was observed every year in 1990–2010, and also the presence of algae from classes Chlorophyceae and Cryptophycea. Changes in phytoplankton biomass over the forty-year period related to anthropogenic eutrophication in Petrozavodsk and Kondopoga Bay, indicating that the higher trophic level, compared with other parts of the lake, which retain oligotrophic. The maximum biomass of phytoplankton in Petrozavodsk Bay was 5.9 mg dm^{-3} (1993), in Kondopoga Bay – 4.9 mg dm^{-3} (2001).

243 species of algae was found in the Lake Peipsi phytoplankton in the study period. Green (40%), diatoms (27%) and cyanobacteria (20%) predominated in number of species. Phytoplankton biomass was large amplitude summer values: for Lake Pihkva 4.7–41.3 mg

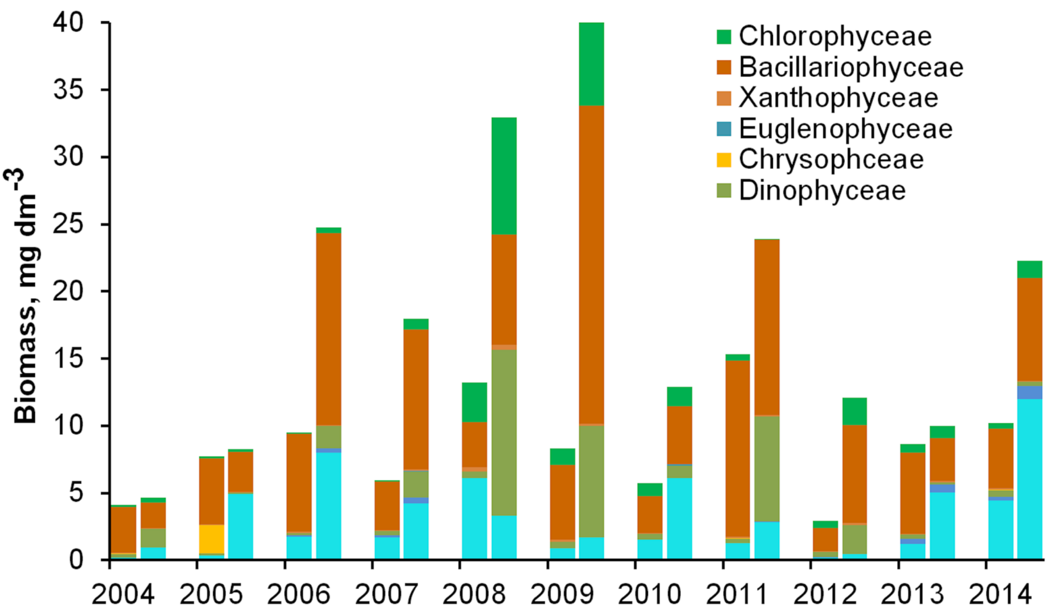

Fig. 3. Phytoplankton biomass structure in the Lake Peipsi (Lake Peipsi - left and Lake Pihkva - right column) for August 2004-2014.

dm^{-3} for Lake Peipsi 2.9–15.3 mg dm^{-3}. The maximum biomass of cyanobacteria in Lake Pihkva was 12 mg dm^{-3} (2014), in Lake Peipsi - 6 mg dm^{-3} (2008). Cyanobacteria ranged from 4 to 60% relative to the total biomass of algae in Lake Pihkva with a maximum in 2005, and in the Lake Peipsi - from 4 to 46% with a peak in 2008 (Figure 3).

The concentration of Chl *a* in water of Petrozavodsk Bay was recorded as high in summer of 2005 (6.4 µg dm^{-3}) and in 2007 (7.2 µg dm^{-3}), generally decreasing notably in last years if to compare with the beginning of 2000s. The summer 2004–2014 Chl *a* varied from 5.12 to 26.91 µg dm^{-3} in the Lake Peipsi. This is less than in Lake Pihkva, where the values ranged from 14.16 to 84.54 µg dm^{-3}, with an average of 34.8 µg dm^{-3}.

Regional climatic variables

The annual air temperature (AT) over the catchment area of Lake Onega for the long-term period of 1951–2014 was calculated as 2.5°C

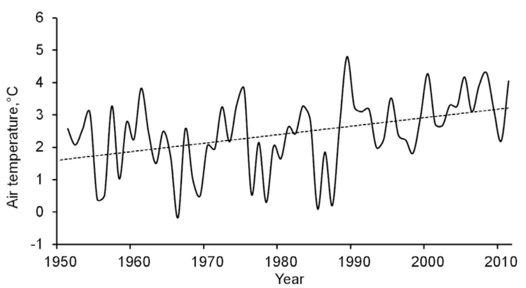

Fig. 4. Annual air temperature over Lake Onega catchment area for 1951–2014.

(Fig. 4). The annual AT over the past 15 years made the most important contribution to this increase. Analysis of changes in AT in the study area using a linear trend produces an estimate of the average annual growth in average AT 0.2°C per ten years. Above the water surface of Petrozavodsk Bay AT reaches its maximum during July and August, 16.6 and 14.1°C, respectively.

The average monthly AT over the catchment area of Lake Peipsi for the period of 1989–2014 during July and August was calculated as 18.8°C and 16.5°C, respectively (Fig. 5). The maximum AT was 24°C in 2010. Analysis of changes in AT over Lake Peipsi using a linear trend produces an estimate of the average annual growth in average July AT 2°C over the last 15 years.

The maximum duration of ICE-FREE in Petrozavodsk Bay reached 260 days and 241 days in the Lake Peipsi during last decades (Figure 4). The average ICE-FREE was 233 and 219 days respectively in 2000–2014. Increasing ICE-FREE trend observed up to 6 days 10 year^{-1} in Lake Onega (data 1960–2011) and up to 4 days 10 year^{-1} in Lake Peipsi (data 1980–2014).

Lake Onega locates in the area of excessive humidification because during most part of year (193–212 days) precipitations above 0.1 mm is registered. The annual precipitation over Lake Onega catchment ranged between 550 and 750 mm in different years of 1951–2010, reaching its maximum during summer. The average summer precipitation for Petrozavodsk Bay in the 1999–2010 varied significantly between

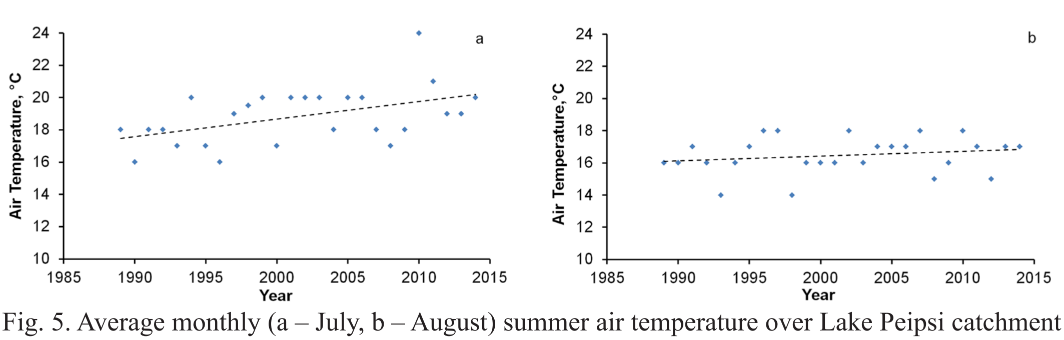

Fig. 5. Average monthly (a – July, b – August) summer air temperature over Lake Peipsi catchment area for 1989–2014.

years (38–233 mm per month) with tendency of increase during late 2000s. The average July–August precipitation for Lake Peipsi in the 1989–2014 was 70±14 mm per month and varied between 4–632 mm per month. The maximum precipitation was in 2003 and 2008–2010.

Correlation of plankton and climatic parameters

The Spearman rank correlations found the significant ($p < 0.05$) relationships between the climate and planktonic variables. Chl *a* correlates positively ($R = 0.66$; $p = 0.03$) with WT and negatively with Lake Onega ICE-FREE ($R = -0.53$; $p = 0.05$). The phytoplankton abundance depends on the duration of ICE-FREE ($R = -0.89$; $R = 0.006$) and was recorded as highest value in summers with longer period of Lake Onega ice cover. The abundance of planktonic Cyanobacteria increase significantly ($R = 0.89$; $p = 0.006$) in years with high NAO index.

We have identified a close correlation between Chl *a*, phytoplankton biomass ($R = 0.63$ $p = 0.001$) and water transparency ($R = -0.83$ $p = 0.000$) in the Lake Peipsi. The biomass of diatoms in August has a negative relationship with water temperature ($R = -0.80$ $p = 0.001$) and the depth of monitoring stations ($R = -0.76$ $p = 0.002$). The annual average N content related to the level of water in the lake. It is obvious that in dry years from catchment receives fewer nutrients to lake than in wet years. However, a significant correlation of P with the water level not detected. There are strong positive correlations ($R = 0.64$-0.83 $p < 0{,}002$) between the concentration of P in the water in August and the summer (June-August) NAO index, and negative with a NAO index in March ($R = -0.82$ $p = 0.001$). The water level in Lake Peipsi related ($R = 0.54$ $p = 0.003$) with an average monthly NAO index in August.

The multiple regression analysis confirms close relation between NAO and regional climate variables (WT, P, ICE-FREE) at $p < 0.01$ and also between AO and these climatic variables at $p < 0.02$. Furthermore, this analysis shows that concentration Chl A in water is determined mainly by global indices dependent WT at $p < 0.05$. In addition, its characteristics depend significantly on the duration of ice-free period ($p < 0.05$).

DISCUSSION

Evidence from the analysis of long-term data sets showed 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), and often also diverse changes in water levels, habitats structure and water residence times (Jones & Elliot 2007). During ice-free period (June–October 1950–2010) water temperatures in Petrozavodsk Bay averaged 12.1°C with maximum in July. Average WT of July reach 15.0°C for the period of 1950–2010 and 17.8°C for the period of 2000–2011. The trend of an increase in summer water temperature is especially notable during years 2010 and 2011, when the maximums of July WT were recorded 20.1°C and 21.4°C, respectively (Sharov et al. 2014).

Trend of increasing water temperatures, duration of the ice-free period during last decades which was confirmed to Lake Onega was also found for different small lakes of north-western Russia, Finland, Sweden, Norway (Weyhenmeyer et al. 1999, Adrian et al. 2009, Finland`s Fifth National Communication 2010, Efremova et al. 2010). Increase in temperatures is accompanied

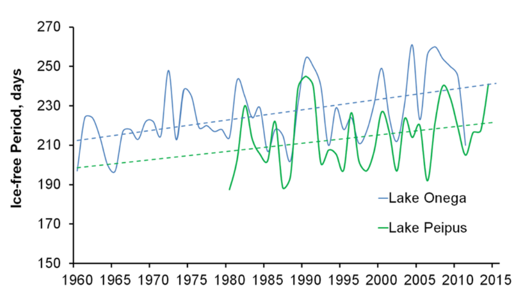

Fig. 6. Trend of changes in ice-free period (in days) on Lake Onega and Lake Peipsi for 1960-2015.

by reduction in the ice cover period on Lake Onega and Lake Peipsi. The average duration of the ice-free period in Petrozavodsk Bay reached 233 days during last decades which on 6 days exceeds the average value for 1960–2010 and testifies about distinct trend to its increase (Filatov et al. 2012, Sharov et al. 2014). There is also a trend of increasing duration ice-free period in the Lake Peipsi (Fig. 6). The Spearman rank correlations found the significant ($R = 0.56$ $p < 0.001$) similarity between ICE-FREE interannual dynamics in the Lake Peipsi and Lake Onega. It confirms the identity of the climatic variations in the area of the two large lakes despite the distance between them is approximately 500 km. The Lake Onega has an ICE-FREE of more than the Lake Peipsi, which is explained with greater depth and the heat storage of Lake Onega.

The majority of lakes of East Fennoscandia are characterized by an increase of ice-free period (Filatov et al. 2012). Negative correlation between ice-free period and plankton characteristics (Chl *a* and phytoplankton) may be explained by peculiarity of summer phytoplankton structure when large-sized diatom species (*Tabellaria fenestrata* and *Aulacoseira islandica*) are predominating taxa. These species contain lower amounts of Chl *a* and lower abundance than other diatoms. Earlier melting results in shifts of period of spring blooms by diatoms.

Significant correlations between physical parameters (ice-free period, water temperature, precipitation) and different characteristics of biota (Chl *a*, zoobenthos) found for some shallow and relatively unpolluted small lakes in northern Russia (Maximov et al. 2012). The expected impacts on biota, however, can differ strongly between ecosystems depending on climate regions. One of the first studies on the impact of climate on biota was done by Adrian et al. (1995, 1999) and showed that composition, timing and maximum abundance of the phytoplankton and zooplankton communities that start to develop in the spring were strongly depend on the duration of winter ice-cover.

For different lakes climate warming leads to the higher primary productivity with intense algal blooms (Blenckner et al. 2007, Jeppesen et al. 2009). As for Lake Onega and Lake Peipsi we also found close correlation between the phytoplankton and climatic variables, especially this NAO.

Positive correlation between average annual NAO and summer Cyanobacteria abundance found for Lake Onega may be mediated by precipitation increasing essentially in years with high positive NAO and leading to increase of nutrient loading from catchment area. Positive NAO index increased precipitation that increases runoff into the lake from the catchment area in the summer. Sunny weather in March (negative NAO index) results in intensive melting of snow and leaching of nutrients. Cyanobacteria bloom as common summer phenomenon is observed in Petrozavodsk Bay from 1980s (Sharov 2008) and Lake Peipsi. The result from Swedish lakes (Weyhenmeyer 2004) and Lake Pääjärvi, Finland (Järvinen et al. 2006) suggest further that the temperature-sensitive phytoplankton groups, cyanobacteria and chlorophytes, would benefit from the earlier warming of the lakes and earlier onset of thermal stratification.

Water temperature was distinguished as the most important factor reflecting climate variability (Adrian et al. 2009). In case study it is the factor determining quantitative development of phytoplankton as well as a trophic level of lake (basing on Chl *a*). The effect of climate change for biota can not be expressed only in the term of temperature. In spite of a lot of researches suppose to use temperature regime as a sensitive marker of climate change, another characteristics such as the duration of the "biological summer" (period with temperatures above 10 ºC, Efremova & Palshin 2012) is probably the most important for biota because it determines the initial potential for growth rate (biomass), reproduction (number of generation, abundance) of aquatic organisms. In six lakes from Karelia (Efremova & Palshin 2012) the positive trend ($p < 0.05$) of increase of this period was recorded. For period from 1953 to 2009 "biological summer" increased on 12-23 days that resulted in increase on 178-427 °C x days. (Efremova & Palshin 2012).

CONCLUSION

Significant correlations between climate indices (NAO, AO), physical parameters in Petrozavodsk Bay of Lake Onega and Lake Peipsi (ice-free period, annual water level, temperature, and precipitation) and different characteristics of its phytoplankton were found in this research. The most significant response of phytoplankton to climate change can be expected in the shallow. Climate change impact on phytoplankton Lake Peipsi mainly mediated through a change in the concentration of nutrients and water temperature. We conclude that global climate determines primarily the regional hydrological variables of a lake ecosystem and its productivity level while biotic characteristics reflect firstly to variability of water temperature and ice-free period that both determine the amount of warm days (WT > 10 ºC) or duration of biological summer. At the same time, responses of phytoplankton to the climate variability are much more complex and difficult to recognize than the responses of physical components, especially in the case of large ecosystem with long period of water exchange.

ACKNOWLEDGMENTS

We thank cordially Dr Nadezhda Berezina for valuable discussion and also staff of the NWPI KSC RAS and North-West Administration Hydrometeorology and Environmental Monitoring of the Russian Federation for sampling and processing of field samples and useful comments.

REFERENCES

Adrian R., Deneke R., Mischke U., Stellmacher R., Lederer P. 1995. A long-term study of the Heiligensee (1975–1992), Evidence for effects of climatic change on the dynamics of eutrophied lake ecosystems, Arch. *Hydrobiol*., 133: 315–337.

Adrian R., O'Reilly C., Zagarese H., Baines S.B., Hessen D. O., Keller W., Livingstone D.M., Sommaruga R., Straile D., Donk E.V., Weyhenmeyer G.A., Winder M. 2009. Lakes as sentinels of climate change. *Limnol. Oceanogr.,* 54 (6, part 2): 283–297.

Adrian R., Walz N., Hintze T., Hoeg S., Rusche R. 1999. Effects of ice duration on the plankton succession during spring in a shallow polymictic lake. *Freshwater Biol.,* 41: 621–623.

Blenckner T., Adrian R., Livingstone D. M., Jennings E., Weyhenmeyer G. A., George D. G., Jankowski T., Jarvinen M., Nic Aonghusa C., Nõges T., Straile D., Teubner K. 2007. Large-scale climatic signatures in lakes across Europe. *A meta-analysis, Global Change Biology,* 13: 1314–1326.

Dokulil M. T., Jagsch A., George G. D., Anneville O., Jankowski T., Wahl B., Lenhart B., Blenckner T., Teubner K. 2006. Twenty years of spatially coherent deepwater warming in lakes across Europe related to the North Atlantic Oscillation. *Limnology and Oceanography,* 51: 2787–2793.

Drinkwater K. F., Belgrano A., Borja A., Conversi A., Edwards M., Greene C. H., Ottersen G., Pershing A. J., Walker H. 2003. The response of marine ecosystems to climate variability associated with the North Atlantic Oscillation. In: Hurrell JW, Kushnir Y, Ottersen G, Visbeck M (eds.) The North Atlantic Oscillation. American Geophysical Union, Washington, DC, 211–234.

Efremova T. V., Palshin N. I. 2012. The reaction of the water temperature in the different types of lakes in Karelia under regional climate change, Ecological problems of the northern regions and their solutions, Apatity, Part 1, 180–184 (in Russian).

Efremova T. V., Zdorovennova G. E., Palshin N. I. 2010. Ice conditions of lakes in Karelia, Water environment: learning for sustainable development. Petrozavodsk: Karelian Research Centre, 31–40 (in Russian).

Filatov N. N., Georgiev A. P., Efremova T. V., Nazarova L. E., Palshin N. I., Rukhovets L. A., Tolstikov A. V., Sharov A. N. 2012. Response of lakes in Eastern Fennoscandia and Eastern Antarctica to climate change, *Doklady Earth of Sciences*, 444(2): 752–755.

Finland`s Fifth National Communication under the United Nations Framework Conventions on climate change. 2010. Helsinki, Pp. 282.

Järvinen M., Lehtinen S., Arvola L. 2006. Variations in phytoplankton assemblage in relation to environmental and climatic variation in a boreal lake. *Verhandlungen der Internationalen Vereinigung der Limnologie*, 29:1841–1844.

Jeppesen E., Kronvang B., Meerhoff M., Søndergaard M., Hansen K. M., Andersen H. E., Lauridsen T. L., Beklioglu M., Ozen A. O., Olesen J. E. 2009. Climate change effects on runoff, catchment phosphorus loading and lake ecological state, and potential adaptations. J*ournal of Environmental Quality*, 38: 1030–1041.

Jones I. D., Elliott J. A. 2007. Modelling the effects of changing retention time on abundance and composition of phytoplankton species in a small lake. *Freshwater Biology*: 52, 988–997.

Maksimov A. A., Berezina N. A., Golubkov S. M., Nikulina V. N. 2012. Long-term climate change productivity of the northern lake ecosystem, In: The dynamics of biological diversity and biological resources of the continental waters, Alimov A. F., Golubkov S. M. (eds.), St. Petersburg, Nauka, 138–144 (in Russian).

Markensten H. 2006. Climate effects on early phytoplankton biomass over three decades modified by the morphometry in connected lake basins, Hydrobiologia, 559, 319–329.

Moiseenko T. I., Sharov A. N. 2011. The Retrospective Analysis of Aquatic Ecosystem Modification of Russian Large Lakes under Anthropogenic Impacts. In: Ecotoxicology around the Globe, Visser J. E. (eds). Nova Science Publishers, 309–324.

Nõges T. 2004. Reflection of the changes of the North Atlantic Oscillation Index and the Gulf Stream Position Index in the hydrology and phytoplankton of Võırtsjärv, a large, shallow lake in Estonia. *Boreal Environ. Res*., 9: 401–407.

Ottersen G., Planque B., Belgrano A., Post E., Reid P. C., Stenseth N. C. 2001. Ecological effects of the North Atlantic Oscillation. *Oecologia*, 128: 1–14

Pociask-Karteczka J. 2006. River Hydrology and the North Atlantic Oscillation: A General Review. *AMBIO*, 35(6): 312–314.

Guide on hydrobiological monitoring of freshwater ecosystems. 1992. Abakumov VA (eds.). - St.Petersburg: Gidrometeoizdat.

SCOR-UNESCO, Working group 17. 1966. Determination of photosynthetic pigments in seawater, Paris, Pp 69.

Sharov A.N., Berezina N.A., Nazarova L.E., Poliakova T.N., Chekryzheva T.A. 2014. Links between biota and climate-related variables in the Baltic region using Lake Onega as an example. *Oceanologia,* 56(2): 291-306.

Sharov A. N. 2008. Phytoplankton as an indicator in estimating long-term changes in the water quality of large lakes. *Water Resources,* 35(6): 668–673.

Smirnov N. P., Vorob'ev V. N., Kochanov S. J. 1998. North Atlantic Oscillation and climate.

Sankt Petersburg, RGGMU, Pp. 121 (in Russian).

Stenseth N. C., Mysterud A., Ottersen G., Hurrell J. W., Chan K.-S., Lima M. 2002. Ecological effects of climate fluctuations. *Science,* 297: 1292–1296.

Weyhenmeyer G. 2004. Synchrony in relationships between the North Atlantic Oscillation and water chemistry among Sweden's largest lakes. *Limnology and Oceanography*, 49(4): 1191–1201.

Weyhenmeyer G., Blenckner T., Pettersson K. 1999. Changes of the plankton spring outburst related to the North Atlantic Oscillation. *Limnol. Oceanogr.,* 44: 1788–1792.

Received: 28.04.2015.
Accepted: 06.07.2015.