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REPRODUCTION OF THE CURRENT CLIMATIC STATE OF THE LAKE LADOGA ECOSYSTEM

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Abstract

A three-dimensional ecohydrodynamic model of Lake Ladoga based on the St. Petersburg Baltic Eutrophication Model (SPBEM) is proposed. Unlike existing models of the Lake Ladoga ecosystem, the proposed model is implemented on a high-resolution spherical grid (horizontal grid size ≈1 km), contains a benthic layer module and describes the cycles of nitrogen and phosphorus in the water column and bottom sediments. A run of the seasonal and interannual variability of the state of Lake Ladoga in the period 1979–2018 was carried out when setting as forcing the atmospheric influence and runoff of rivers flowing into Lake Ladoga for the hydrothermodynamic module and the supply of nutrients from the atmosphere and from land for the biogeochemical module. A comparison of the results of calculating the current climatic state of Lake Ladoga with the available satellite and expeditionary observation data showed that the model correctly reproduces the climatic seasonal variation of the surface temperature field, its vertical distribution, average values and range of changes in the main characteristics of the lake's ecosystem. The proposed model can be used to study the influence of external natural and anthropogenic factors on biogeochemical processes and the functioning of the Lake Ladoga ecosystem.

Keywords: lake ecosystem, circulation, climate, seasonal and interannual fluctuations, modeling, Lake Ladoga

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ВОСПРОИЗВЕДЕНИЕ СОВРЕМЕННОГО КЛИМАТИЧЕСКОГО СОСТОЯНИЯ ЭКОСИСТЕМЫ ЛАДОЖСКОГО ОЗЕРА

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Аннотация

Предлагается трехмерная экогидродинамическая модель Ладожского озера, основанная на Санкт-Петербургской модели эвтрофикации Балтийского моря (SPBEM). В отличие от существующих моделей экосистемы Ладожского озера, предлагаемая модель реализована на сферической сетке высокого разрешения (шаг сетки по горизонтали ≈1 км), содержит модуль бентосного слоя и описывает циклы азота и фосфора в водной толще и донных отложениях. Выполнен расчет сезонной и межгодовой изменчивости состояния Ладожского озера в период 1979–2018 гг. при задании в качестве форсинга атмосферного воздействия и стока рек, впадающих в Ладожское озеро, для гидротермодинамического модуля и поступления биогенных элементов из атмосферы и с суши для биогеохимического модуля. Сравнение результатов расчета современного климатического состояния Ладожского озера с имеющимися данными спутниковых и экспедиционных наблюдений показало, что модель правильно воспроизводит климатический сезонный ход поля поверхностной температуры, её вертикальное распределение, средние значения и диапазон изменений основных характеристик экосистемы озера. Предложенная модель может быть использована для исследования влияния внешних естественных и антропогенных факторов на биогеохимические процессы и функционирование экосистемы Ладожского озера.

Ключевые слова: озерная экосистема, циркуляция, климат, сезонные и межгодовые колебания, моделирование, Ладожское озеро

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1. Introduction

Currently, despite the significant amount of field research performed, the observational data obtained are not enough to quantitatively describe complex multifactor interactions in a lake ecosystem. The lack of a quantitative description of such interactions does not allow us to predict possible changes in the state of the Lake Ladoga ecosystem, even with an indication of the forecast uncertainty degree. When we don't have enough observational data, the most reliable tool for solving the problem of a quantitative description of the aquatic ecosystem functioning, suitable for applied use, is mathematical modeling of aquatic ecosystems on the appropriate spatiotemporal scales.

Globally, mathematical models of large lake ecosystems have been developed over the past few decades [1–6]. However, today the general level of lake models is still lower than that of marine ones [6, 7], which, in particular, is reflected in the fact that until now models for lake systems have been normally used for one-time calculations when solving certain limited tasks.

Since the 1980s, several models of the Lake Ladoga ecosystem have been developed [8–12]. The use of these models allowed to assess the response of the Lake Ladoga ecosystem to an increase in phosphorus load and to identify maximum permissible loads. However, these models were implemented on a coarse computational grid, and also poorly described (or did not describe at all) the exchange processes at the boundary between water and bottom sediments, since they did not contain a submodel of the benthic layer. Calculations on the discussed models were mainly performed for detection with fixed external influences, which did not allow to reproduce long-term variability of ecosystem characteristics [13]. The influence of various sources of nutrient load (river, atmospheric, industrial, including aquaculture) on the lake ecosystem functioning has also not been studied yet.

This article proposes a three-dimensional eco-hydrodynamic model of Lake Ladoga based on the St. Petersburg Baltic Eutrophication Model (SPBEM) [14, 15]. The SPBEM model has proven itself well in assessing climate changes in the ecosystem, both for the Baltic Sea in modern and future climates [16–18], and in reproducing the current state of the Lake Onega ecosystem [19, 20]. The model is based on a description of the nitrogen and phosphorus cycles in the water column and bottom sediments, which allows to use it both in marine nitrogen-limited systems and in freshwater phosphorus-limited systems. A good confirmation of the model's performance in waters with different limiting nutrients can be a reliable reproduction of the boundaries of changing limit zones using the example of the Gulf of Finland mouth area in the Baltic Sea [15].

Unlike the above-mentioned models of the Lake Ladoga ecosystem, the proposed model is implemented on a high-resolution grid, contains a benthic layer module and, most importantly, describes the cycles of nitrogen and phosphorus in the water column and bottom sediments. The main goal of this article is to demonstrate the stable operation of the model on a climatic time scale (several decades) and assess the quality of reproduction of the lake ecosystem functioning for 1979–2018 period.

2. Materials and methods

2.1. Model description

The biogeochemical module of the model describes the interaction of nitrogen and phosphorus cycles in water and bottom sediments of the lake. State variables in the pelagic subsystem are represented by the biomass of zooplankton, two functional groups of phytoplankton (diatoms and non-diatoms), concentrations of detrital nitrogen and phosphorus, dissolved organic (labile and persistent) compounds of nitrogen and phosphorus, dissolved inorganic nitrogen compounds (ammonium and oxidized nitrogen, including nitrites plus nitrates) and dissolved mineral phosphorus (phosphates), as well as the 'recorder' of the production-destructive process balance – oxygen dissolved in water. The sediment subsystem describes the dynamics of benthic nitrogen and phosphorus. Biogeochemical interactions between these variables describe a set of processes that are crucial for the ecosystem functioning: the primary production of phytoplankton consuming dissolved mineral compounds of nitrogen and phosphorus; grazing of phytoplankton by zooplankton; the death of phytoplankton and zooplankton, replenishing the reserves of detritus that settles down to the bottom; regeneration of mineral compounds due to the excretion of zooplankton metabolic products and in the process of detritus mineralization, as well as labile and persistent components of dissolved organic compounds of nitrogen and phosphorus; mineralization of bottom sediments with the entry of its products into the water column; denitrification in water and bottom sediments. The absence of silicon, which is an important biogenic element used by diatom phytoplankton, in the model cycle is explained by the fact that this element is not limiting for the Lake Ladoga conditions [21]. Taking into account the characteristics of diatom phytoplankton, which has a greater cell mass compared to other types of phytoplankton due to the presence of a siliceous shell, consists in setting a higher rate of gravitational settling of diatom phytoplankton and detritus, in accordance with the parameterizations used in the model. Parameterization of the above interactions follows the general practice developed over decades in modeling ecosystems of seas and lakes [2, 6, 22–25]. All equations, parameterizations, coefficients and constants of the biogeochemical module are presented in detail in [15], and adaptation for the conditions of freshwater phosphorus-limited ecosystems is presented in [19, 20].

Hydrothermodynamic module. The University of Massachusetts MITgcm model was used as a basis for reproducing the lake hydrothermodynamics and solving the tracer advection-diffusion equation [26, 27]. The use of this model for hydrodynamic conditions of large stratified lakes is justified by its successful application to modeling lakes Michigan and Superior [28–30], as well as, together with the proposed model of biogeochemical cycles, to assessing the current state of hydrophysical and biogeochemical characteristics of Lake Onega [19, 20]. To reproduce hydrophysical conditions, this model was adjusted to the bathymetry of Lake Ladoga, specified according to the data of the Institute of Limnology, RAS (Fig. 1). The TKE turbulent closure scheme (GGL90 package) [31] was used to parameterize subgrid vertical mixing processes. The horizontal turbulent

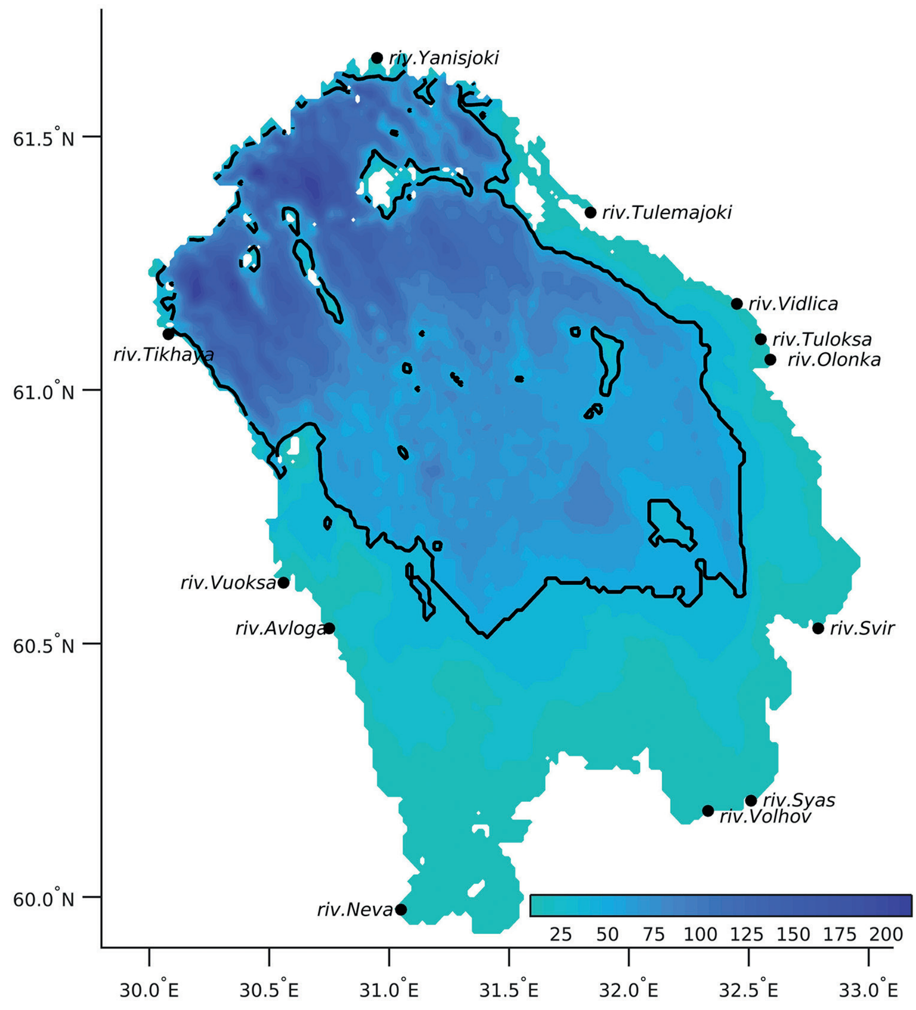

Fig. 1. Rivers of the basin and model bathymetry (meters) of Lake Ladoga (black line is the 40 m isobath)

viscosity coefficient was calculated based on the Smagorinsky parameterization [32], and the horizontal turbulent diffusion coefficient was constant and equal to 2 m^2/s. Modeling of seasonal ice cover was performed using the SeaIce package, included in the MITgcm model complex and adapted for a freshwater body. The PTtracer package was used to solve the tracer advection-diffusion equations required to implement the biogeochemical cycle model.

The solution of the combined model was carried out on a spherical grid with a horizontal step of 0.54' in latitude and 1.08' in longitude, which at the lake latitude constitutes approximately 1 km for each of the horizontal coordinates. The vertical z-coordinate was used with a uniform step of 2 m from the surface to the 40 m horizon and 5 m from the 40 m horizon to the bottom.

2.2. Boundary conditions

When modeling Lake Ladoga, it is required to specify as boundary conditions the atmospheric forcing and runoff of rivers flowing into Lake Ladoga (Fig. 1) for the hydrothermodynamic module and the supply of nutrients from the atmosphere and from land for the biogeochemical module.

To set the atmospheric forcing fields, an archive was prepared based on ERA-5 reanalysis data (https://www.ecmwf.int), including hourly fields of atmospheric pressure, wind speed components, temperature, humidity, precipitation, incoming short-wave and long-wave radiation.

External nutrient load enters a water body with river runoff, atmospheric precipitation, from point sources, as well as with direct diffuse runoff, i.e. the entry of nutrients with rain and melt waters, which enter the water body, bypassing the rivers.

Inputs from river runoff. Detailed studies of the supply of nutrients to Lake Ladoga for various time periods were performed in [33–35]. According to these works, the main contribution to the formation of external nutrient load comes from river runoff, which accounts for 96.3% of the incoming total phosphorus and 87.1% of the total nitrogen. Atmospheric precipitation accounts for 0.7% of incoming phosphorus and 10.9% of nitrogen. The contribution of point sources is 1.6% and 0.7%, and the contribution of direct diffuse input is 1.4% and 1.3% of the total external load for phosphorus and nitrogen, respectively. Thus, the main source of nutrients entering Lake Ladoga is river runoff.

As a result of long-term studies of the nitrogen and phosphorus supply to Lake Ladoga with river runoff, estimates reflecting interannual variability were obtained. They were published in a monograph summarizing existing observational data and model estimates [21]. It presents series of interannual variability in the volume transport of river water entering Lake Ladoga for the period from 1979 to 2018, as well as phosphorus and nitrogen supplied with river water, respectively, for the period from 1976 to 2011 and from 1981 to 2003 (Fig. 2). The indicated series of data on the phosphorus and nitrogen supply to Lake Ladoga were reconstructed for the period from 1979 to 2018. The choice of this period was determined by the availability of actual data on river transport into Lake Ladoga only for the specified period (see Fig. 2, top fragment). As you can see (Fig. 2, bottom fragment), the temporal variations in the annual phosphorus supply into the lake can be divided into 2 periods: the period from 1976 to 1991 with relatively high input values and the period from 1996 to 2011 with relatively low values. Reconstruction of phosphorus load for the period from 2012 to 2018 assumes that average phosphorus concentrations in rivers remain unchanged during this period and are equal to their averages for the period from 1996 to 2011. The average phosphorus concentration in rivers for the period from 1996 to 2011 was calculated as the ratio of the average annual phosphorus supply to the river transport for the period. Based on the calculated concentration, phosphorus loads were reconstructed for the period from 2012 to 2018 as the product of the indicated average concentration and the average annual transport. A similar procedure was used to reconstruct the nitrogen load, but unlike phosphorus, the average concentration was sought over the entire available series (from 1981 to 2003) since the temporal variability of nitrogen supply is not characterized by any trends or strong differences between the periods.

Inputs from atmospheric precipitation. The most comprehensive coverage of assessing the Lake Ladoga phosphorus load is provided in works [33, 36]. The estimates given in these studies are based on the data from the Voeikov Main Geophysical Observatory on the concentration of chemicals in the snow cover in the winter-spring period of 1994 at eight points in the water area and at four points in the coastal zone on the east coast near the cities of Olonets and Pitkyaranta, on the north-west coast, between the coastline and the border with Finland,

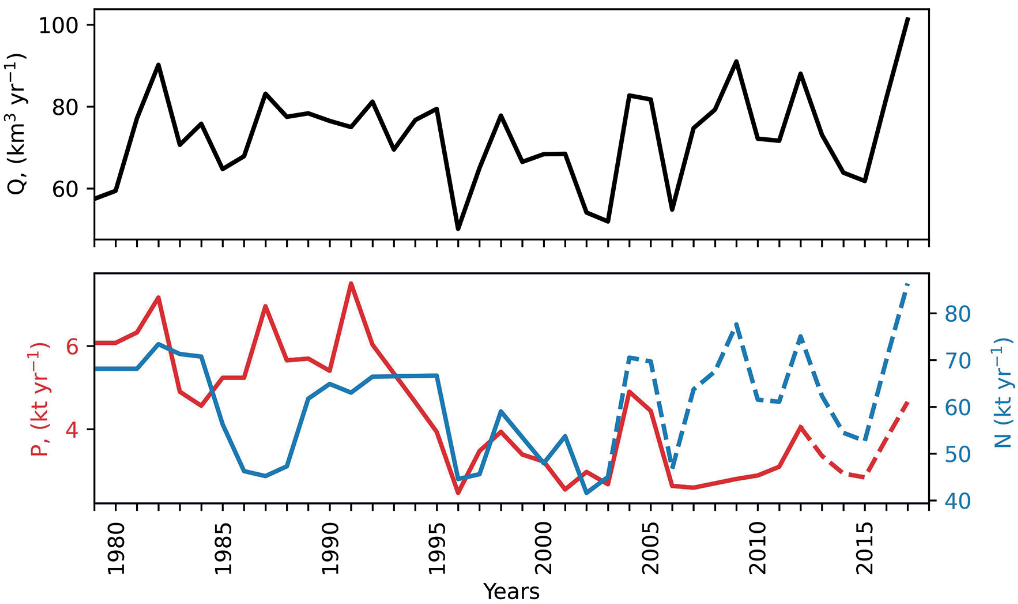

Fig. 2. Interannual variability of the annual river volume transport entering Lake Ladoga (*a*), and the annual input of phosphorus and nitrogen with river waters (*b*). Solid line — published data [21], dotted line — reconstruction

as well as on the south-west coast of Lake Ladoga. The values of the admixture mass accumulated per 1 m^2 of area during the freeze-up period, the average monthly intensity of dry fallout, and the average concentration of admixture in 1 mm of solid precipitation were determined. The average concentration of the substance in liquid precipitation was calculated by comparing average monthly data on the chemical composition of atmospheric precipitation at the 'St. Petersburg' and 'Voeikovo' stations for 1959–1961 and 1967–1980 periods. According to the assessment, the phosphorus load for the waters of Lake Ladoga is 34.5 tons P_{total} per year. Since there are no more recent published estimates, this value is used in current research. To set the nitrogen falling from the atmosphere onto the lake water surface, we used data from the Norwegian Meteorological Institute obtained using mathematical modeling (https://emep.int/mscw/mscw_moddata.html). Modeling results provide estimates of nitrogen deposition in oxidized and reduced forms at monthly resolution for the period from 1990 to 2020. The average long-term supply of nitrogen compounds is 6500 tons per year, while the standard deviation is 1200 tons per year.

Inputs from point sources and direct diffuse runoff. Due to the lack of published data on the interannual variability of loads from point sources and direct diffuse runoff, and allowing for the small contribution of these sources to the total load, phosphorus and nitrogen inputs from these sources throughout the period considered are assumed to be fixed parts of the load coming with river runoff. In accordance with the above estimates, they are equal to $0.963\times(0.016+0.014) \approx 0.029$ (2.9%) for phosphorus and $0.871\times(0.007+0.013) \approx 0.017$ (1.7%) for nitrogen.

2.3. Initial conditions

Since field observation data are insufficient to form consistent fields of biogeochemical variables, to obtain the initial distribution of model variables, a calculation was performed with repeated boundary conditions (atmospheric forcing, river runoff and nutrient load), corresponding to the conditions of 1979, until a quasi-steady state of the lake seasonal variability was obtained. The values of the required physical and biogeochemical characteristics on January 1, 1979 in this quasi-steady state were used as initial conditions for calculating the seasonal and interannual variability of the state of Lake Ladoga for 1979–2018 period.

2.4. Observational data

To verify the model, contact and remote measurements of temperature were used, as well as observations of the concentrations of these mineral and total phosphorus forms and phytoplankton biomass. Remote sensing data from Aqua-Modis and Aqua-Terra satellites were taken from the website https://oceandata.sci.gsfc.nasa.gov/directdataaccess/Level-2/ (date of access: 29.10.2024). The website provided daily temperature measurements in the IR range with L2 processing level, performed with MODIS and VIIRS spectroradiometers from the Aqua, Terra and Suomi NPP satellites from January 2000 to December 2020. The spatial resolution of the data was about 1 km. L2 processing level refers to second-level data, which include measurement time, georeferencing, and processing to account for atmospheric correction.

Contact measurement data were obtained by employees of the Institute of Limnology, RAS from 1991 to 2017. These data include the results of measuring temperature, concentrations of phosphorus mineral and total forms, and phytoplankton biomass. Note that the maximum number of measurements of various parameters occurs during the warm period of the year (May—September), while for some winter and spring months there are no measurements at all.

3. Model verification

3.1. Temperature

Quality assessment of the model's reproduction of the surface temperature seasonal variation was obtained as follows. Instant images were selected from the archive of satellite images, where more than 60% of the lake's water area had measurements with a quality flag of 0 or 1, meaning that these measurements are, most likely, close to the true temperature values. Then, the satellite measurement data on the selected images were interpolated onto the computational grid in the areas covered by the measurement data, and the average daily surface temperature fields corresponding to the measurement date were selected from the modeling results for the same coverage areas. As a result, for each image a series was obtained, which represents paired values of the calculated and measured temperature in each grid cell. Using these series, long-term monthly averages of the measured and calculated area-average surface temperature of the lake and monthly averages of the spatial standard deviation of these characteristics were obtained. The indicated climatic monthly averages of area-average temperature and its spatial standard deviation are given in Table 1 for the data obtained by MODIS spectroradiometers from the Aqua and Terra satellites from January 1, 2000 to December 31, 2020.

Table 1

Comparative characteristics of surface water temperature according to satellite measurements of MODIS-Aqua and MODIS-Terra and modeling results

Month	MODIS-Aqua					MODIS-Terra				
	Number of images	Average temperature, °C		Standard deviation, °C		Number of images	Average temperature, °C		Standard deviation, °C	
		Satellite	Model	Satellite	Model		Satellite	Model	Satellite	Model
1	7	2.8	2.3	0.7	0.9	10	2.0	1.5	0.8	0.8
2	4	1.2	0.4	0.5	0.3	3	0.8	0.3	0.5	0.4
3	16	0.7	0.1	0.3	0.1	13	0.9	0.1	0.4	0.1
4	64	1.6	0.9	0.5	0.2	83	1.7	1.2	0.5	0.2
5	118	3.7	2.7	1.5	0.8	143	3.7	2.8	1.6	0.9
6	70	10.4	10.0	2.8	2.9	77	10.0	9.4	2.9	2.8
7	158	18.8	17.0	1.3	2.0	188	18.8	17.3	1.3	2.0
8	130	18.8	18.4	0.8	1.0	147	18.5	18.2	0.8	1.0

Fin table 1

Month	MODIS-Aqua					MODIS-Terra				
	Number of images	Average temperature, °C		Standard deviation, °C		Number of images	Average temperature, °C		Standard deviation, °C	
		Satellite	Model	Satellite	Model		Satellite	Model	Satellite	Model
9	82	13.8	13.9	0.8	0.7	91	13.6	13.4	0.8	0.7
10	47	9.4	9.4	0.7	0.6	45	9.5	9.5	0.7	0.6
11	11	6.2	6.4	0.8	0.9	18	6.1	6.3	0.8	0.9
12	15	3.8	3.7	0.7	0.9	12	3.7	3.5	0.8	1.0

Analysis of the table shows that, in general, the model reproduces the seasonal variation of surface temperature quite well. The underestimation of surface temperature in July, which is 1.8 °C for the MODIS-Aqua data and 1.5 °C for the MODIS-Terra data, is apparently due to the fact that satellite measurements characterize the temperature of the surface itself, while the model data represent an average value for the top 2-meter layer. Therefore, considering that in July the weakest winds and vertical mixing are observed, which contribute to the formation of a vertical temperature gradient almost at the surface of the lake, we can say that the indicated model underestimation of the surface temperature is quite acceptable. In August, the underestimation of surface temperature is much smaller – only 0.4 °C. With the onset of autumn and the beginning of intense wind-wave and convective mixing, the surface temperature values according to measurement data and modeling results almost coincide.

A clear idea of the reproduction quality of the surface temperature spatial distribution is given in Fig. 3, which shows the average long-term distributions of the surface temperature of Lake Ladoga for May and June,

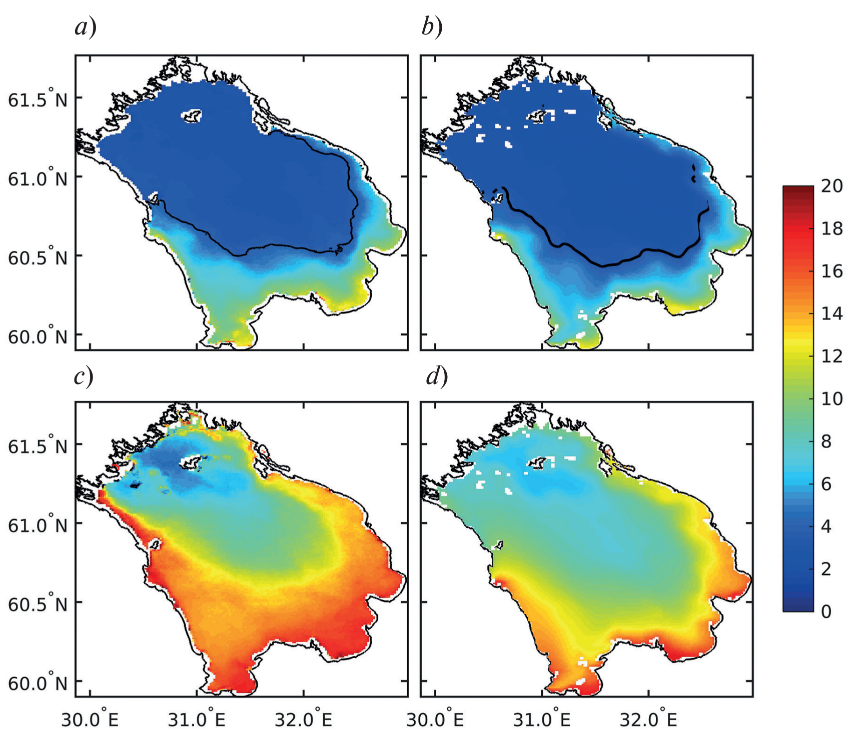

Fig. 3. Average long-term (for 2000–2020 period) distributions of Lake Ladoga surface temperature for May (*a*, *b*) and June (*c*, *d*) according to satellite data (*a*, *c*) and modeling results (*b*, *d*) (the black line shows the position of the isotherm of 4 °C).

reconstructed from satellite data and modeling results. As you can see, the model reproduces the main spatial features of the surface temperature distribution in the indicated months quite well. One of the important features of the seasonal dynamics of the freshwater body temperature is a thermal bar, which ensures vertical mixing of water from the surface to the bottom when the temperature of the highest density is reached (for fresh water it is 4 °C). As you can see from Fig. 3, the modeling results reproduce the climatic position of the spring thermal bar quite well when compared with remote sensing data, which is expressed in a good agreement with the spatial position of the 4 °C isoline. In addition, the model temperature distribution in the southern part of Lake Ladoga is in good agreement with satellite data, where after the passage of the thermal bar a rapid increase in surface temperature and the formation of seasonal stratification with a surface layer temperature of more than 4 °C begin. The June surface temperature distributions (both satellite and model) are also in good qualitative agreement with each other and are characterized by a strong decrease in temperature from the southeast to the northwest and its increased values in coastal shallow areas. Temperature values throughout the region in June turned out to exceed 4 °C, which indicates the absence of a thermal bar at that time. Note that we are talking about average long-term temperature distributions.

Changes in water temperature with depth are illustrated in Fig. 4, which shows the average vertical temperature distributions in the central deep-water part of Lake Ladoga in May, June, July, August and September for

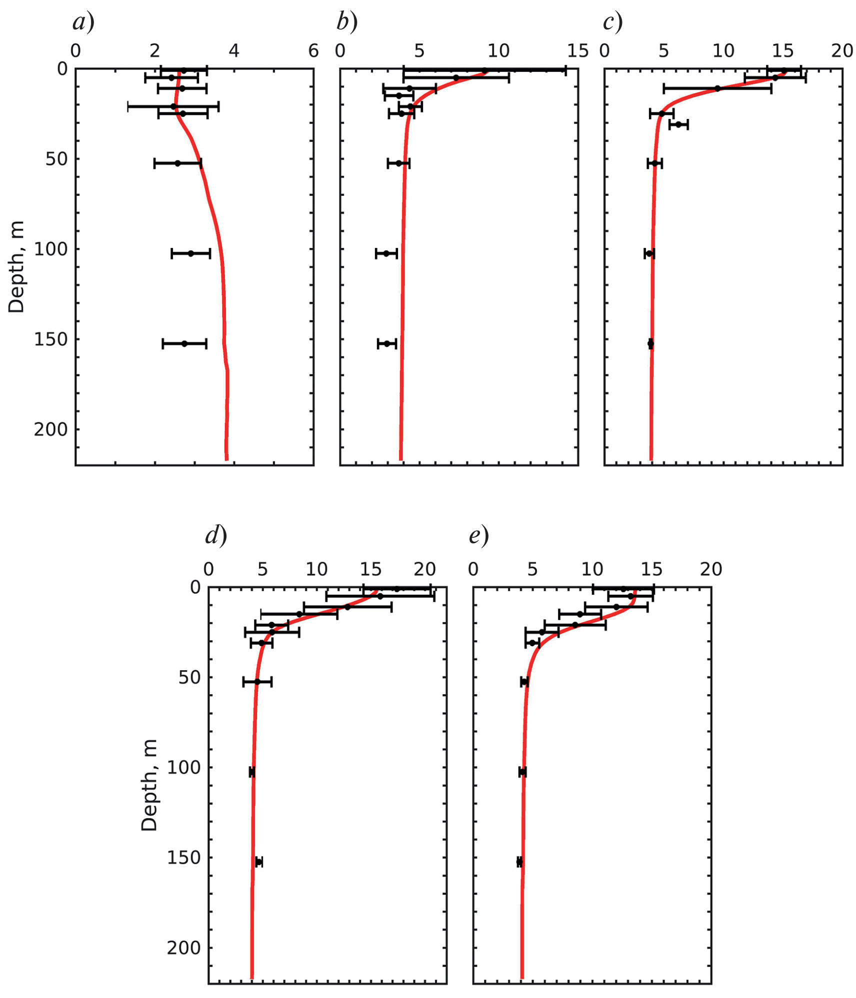

Fig. 4. Average for 1991–2017 period vertical distribution of temperature (°C) in the central deep-water part of Lake Ladoga in May (*a*), June (*b*), July (*c*), August (*d*) and September (*e*) according to expeditionary measurements (points are average values, black horizontal lines are the standard deviation) and modeling results (red curves). The deep-water part of the lake is identified by the position of the 40-meter isobath (see Fig. 1)

1991–2017 period, constructed based on expeditionary measurements and calculation results. As can be seen, in May (the period of spring convective mixing) homothermy is observed, i.e. the vertical temperature distribution is close to uniform with values of 2.5–3 °C, while the model distribution shows slightly elevated temperatures (about 4 °C) in the deep layers of the lake. In the summer months (the period of lake heating), a distinctive stable stratification in the upper 25–30-meter layer with an increase in surface temperature from May to August and almost constant temperature in the underlying layers are observed. In September (the beginning of the autumn cooling and convective mixing period), a slight decrease in surface temperature is accompanied by the appearance of an upper mixed layer of 8–10 m and a slight deepening of the thermocline lower boundary. All these features are correctly reproduced by the model.

3.2. Biogeochemical characteristics

The model of Lake Ladoga biogeochemical cycles was verified using in-situ measurement data obtained by the Institute of Limnology, RAS as part of expeditionary research and including the following biogeochemical characteristics: mineral and total phosphorus, oxidized forms of nitrogen and total nitrogen content in the aquatic environment, and phytoplankton biomass for the period from 1991 to 2020. Verification of the model was based on the following scheme of comparing the reproduced and measured characteristics. For each measurement, which is characterized by location (latitude and longitude of the station) and sampling date, the values of the reproduced characteristics were selected from the grid cell where the coordinates of the measurement point landed. The paired values of the main parameters characterizing the ecosystem state, collected in this way, were analyzed using box plots and the dimensionless cost function (CF) [37]. The CF function represents the absolute value of the difference between the average values of the characteristic calculated from the observational data (D) and model data (M), related to the standard deviation of the observational data (Sd), i.e. $CF = |D - M|/Sd$. It is generally accepted that the CF function shows how large the systematic differences between model results and observational data are. Traditionally, a modeling result is considered good if CF is less than 1, acceptable if CF is between 1 and 2, and bad if CF is greater than 2.

Since Lake Ladoga is a phosphorus-limited water body, phosphorus compounds are of the greatest importance among the biogenic elements in model verification. Fig. 5a shows the box plots for mineral phosphorus, built using 664 values. As you can see, the median value of model phosphates is 2.3 μg/m^3, and the median of field observation data is 2.8 μg/m^3. In this case, the difference in the 75% quartile between the reproduced and measured values is 0.1 μg/m^3. The calculated quality function for phosphates is 0.1. Note that the limit of phosphate detection in natural waters in accordance with current methods ranges from 2.5 to 5 μg/m^3. Therefore, we can confidently say that the model reproduces the concentration of mineral phosphorus quite well. A comparison of model and observed values of total phosphorus content (Fig. 5b) shows that the model underestimates the median value by 1.8 μg/m^3 and has a larger range between the 25 % and 75 % quartiles. However, the CF function for total phosphorus is 0.15.

A similar comparison of modeling results with observational data for nitrates and total nitrogen (Fig. 5d, e) shows that the model reproduces the observed concentration levels of these characteristics quite well. Thus, the comparison of 356 nitrate measurements with the model results made it clear that the model underestimates the median value by 10 μg/m^3, which is approximately 5 % of the observed value. However, although the underestimation of the 75 % quartile is approximately 40 μg/m^3, the CF function is only 0.35. For total nitrogen, having compared 440 pairs of measured and modeled values, we also noticed a general underestimation of the average total nitrogen level in the model compared to observations. The model also greatly underestimates the range of fluctuations in total nitrogen content. However, CF for total nitrogen is 1.5, i.e. meets an acceptable level.

Note that the mentioned discrepancies between the modeling results of nutrients and observational data are most likely associated with inaccuracies in setting the supply from external sources.

Comparison of 584 phytoplankton biomass measurements with model results (Fig. 5c) showed that the model generally underestimates phytoplankton biomass. The underestimation of the median value is 0.34 gww/m^3 (30 %), of the 25 % quartile is 45–50 % and of the 75 % quartile is 10 %. The quality function value is 0.39. Underestimated values of reproduced phytoplankton biomass are associated with underestimation of phosphorus content.

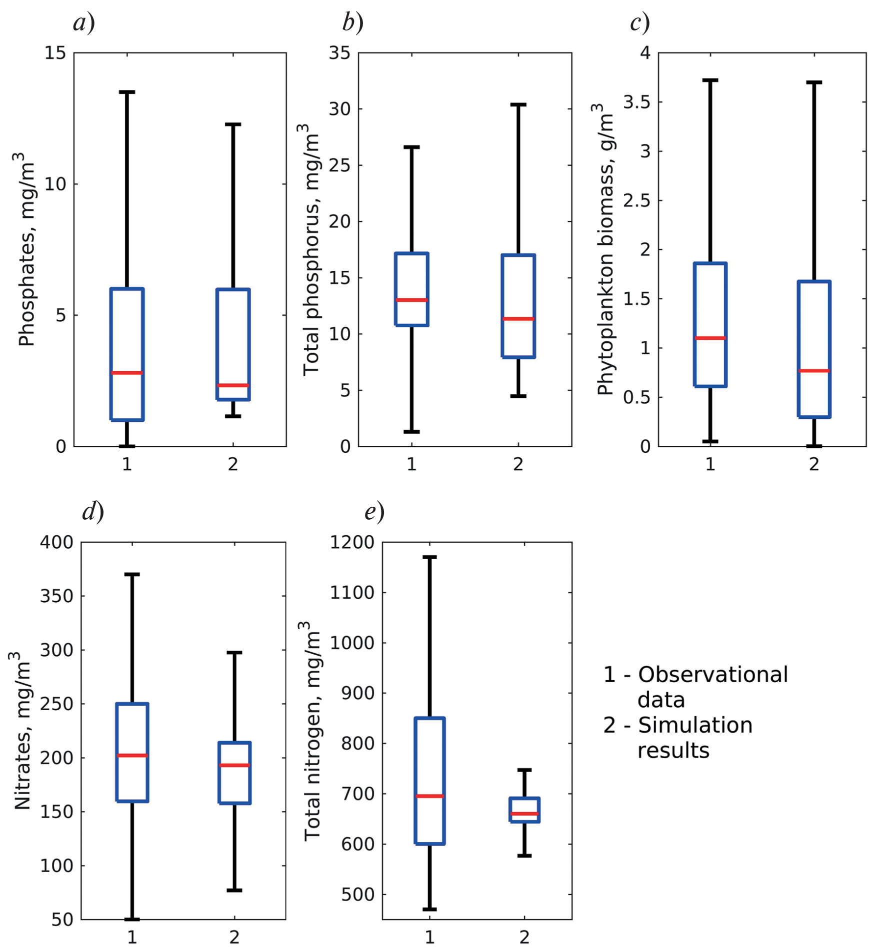

Fig. 5. Comparison of modeling results with field observation data for phosphates (*a*), total phosphorus (*b*), phytoplankton biomass (*c*), nitrates (*d*) and total nitrogen (*e*) (red line – the median value, blue line – 25 and 75 % quartiles, black line – minimum and maximum).

4. Spatial and temporal variability

In contrast to the sparse data from expeditionary measurements, which are characterized by spatial and temporal gaps, the obtained model results allow to present a much more complete spatiotemporal picture of the lake ecosystem seasonal variability and assess its compliance with common ideas about its functioning.

The main indicators of the state of the Lake Ladoga ecosystem include phytoplankton and the biogenic element limiting its development – phosphorus (in the form of phosphates). The model average long-term distribution of phosphates on the lake surface at the end of winter (Fig. 6a) is heterogeneous, which indicates the unevenness of their accumulation in the upper layer during this period. The highest concentrations of mineral phosphorus (up to 25–30 mg/m^3), due to its supply with river waters, are observed in the Volkhov and Svir Bays, as well as near the mouth of the Vuoksi River. In open areas of the lake, winter phosphate concentrations range from 10 to 15 mg/m^3. The lowest concentrations of phosphates are observed in the northern part of the lake, where they range from 5 to 10 mg/m^3. In summer, photosynthesis of organic matter by phytoplankton leads to a decrease in the concentration of phosphates in the upper layer of the lake to (0.5–5.0) mg/m^3 (Fig. 6b). The exceptions are the Volkhov and Svir Bays, as well as the eastern coast, where phosphate concentrations in summer can reach 10–12 mg/m^3 due to the supply of phosphates with river runoff.

According to Fig. 6c, the maximum values of diatom phytoplankton biomass in May-June (8–10 g/m^3) are observed in the areas of maximum accumulation of phosphates in winter. In open areas of the lake, the biomass of diatom phytoplankton ranges from 1 to 4 g/m^3, the lowest values (<1 g/m^3) are observed in the northern part of the water body. In general, the distribution of diatom phytoplankton biomass follows the distribution of phosphates in the period before the spring bloom, which is explained by the fact that in spring, phytoplankton growth is provided mainly by nutrients accumulated over the winter and is not controlled by zooplankton that has not had time to develop yet. Non-diatom phytoplankton is not developed in spring, its biomass is insignificant (Fig. 6e). In summer (Fig. 6d, f), the situation changes to the opposite: throughout the entire water area of the lake, the biomass of diatom phytoplankton is small and we observe the predominance of non-diatom

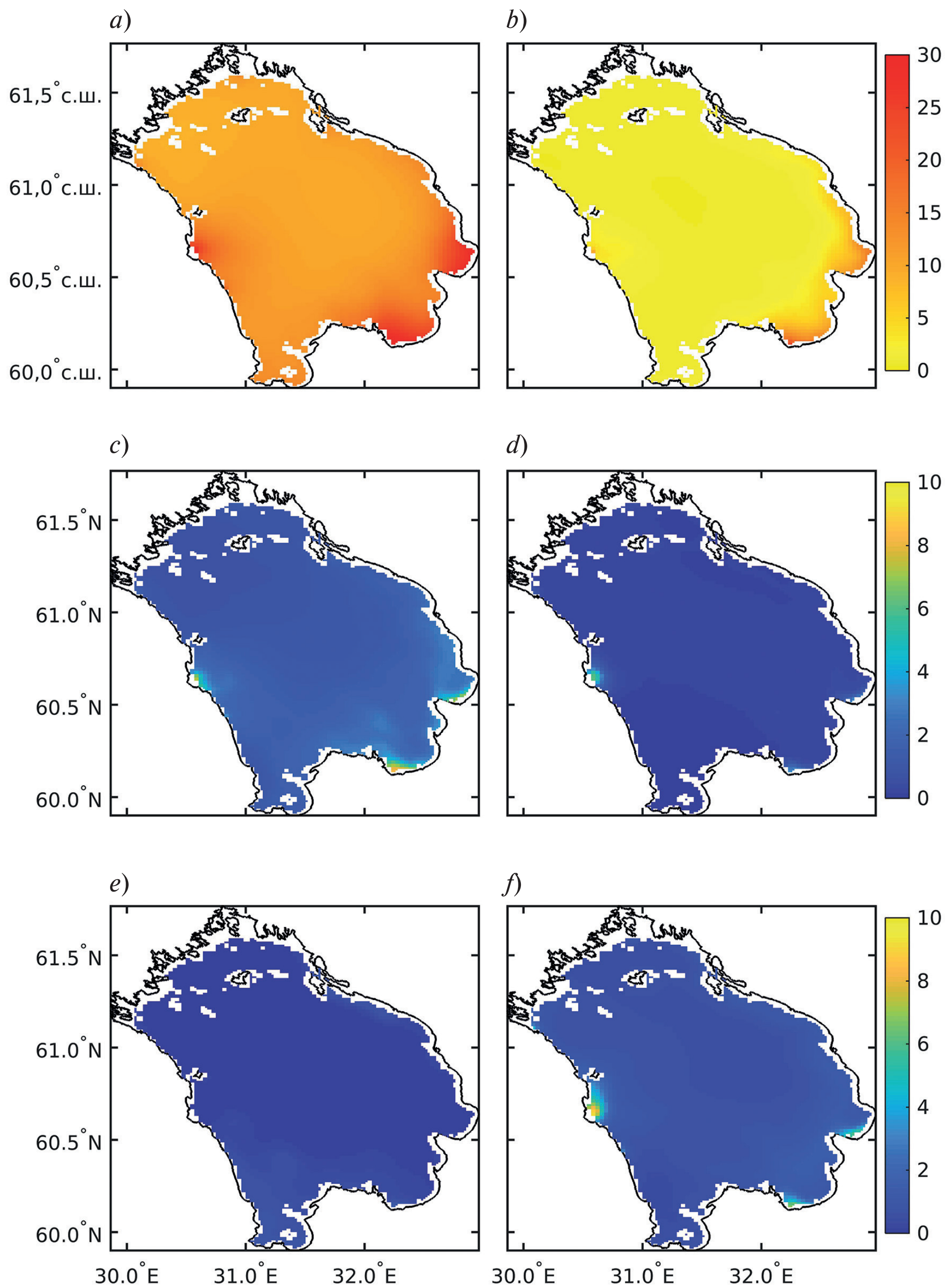

Fig. 6. Average long-term (for 1979–2018) surface distributions of phosphates (mg/m^3) in the last ten days of April (*a*) and July–September (*b*), diatoms (gww/m^3) in May–June (*c*) and July–September (*d*), non-diatoms (gww/m^3) in May–June (*e*) and July–September (*f*) in Lake Ladoga according to modeling results

phytoplankton, the concentration of which in the surface layer ranges from 1.5 to 3 g/m^3, excepting the mouth areas of the confluence of the main Lake Ladoga tributaries – Svir, Volkhov and Vuoksi. In these areas, the phytoplankton biomass content reaches 7–8 g/m^3. The noted feature of the model solution – the predominance of diatom phytoplankton in spring and non-diatom phytoplankton in summer – is fully consistent with the existing ideas about the functioning of the Lake Ladoga ecosystem, formed according to field studies [21].

In accordance with Fig. 7, which shows average long-term seasonal changes (by time and depth) in temperature and ecosystem characteristics in the central deep-water part of Lake Ladoga, the seasonal dynamics of phosphates in the water column has 4 distinct periods (Fig. 7d). These are periods of winter and summer accumulation of phosphates in the hypolimnion, when due to stable thermal stratification (Fig. 7a), the exchange of heat and admixtures between the epilimnion and hypolimnion is difficult, as well as periods of the spring and autumn thermal bar development, when, as a result of vertical mixing, phosphates accumulated in the hypolimnion enter the photic layer. This feature of phosphate seasonal dynamics explains the mechanism of phytoplankton seasonal variations (Fig. 7b). Namely, phosphates accumulated in the hypolimnion in summer

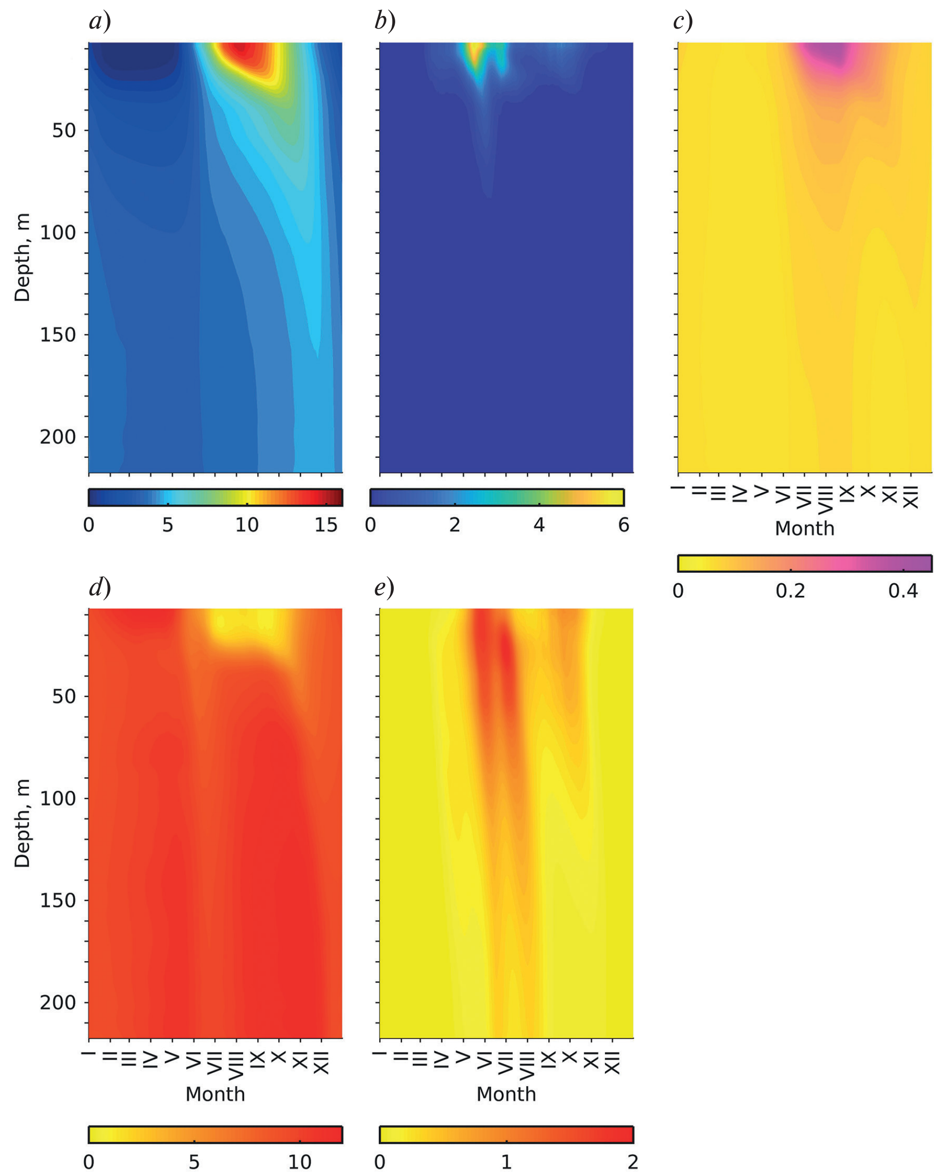

Fig. 7. Calculated average long-term (for 1979–2018) time-depth seasonal dynamics of temperature, °C (*a*), phytoplankton, gww/m^3 (diatoms + non-diatoms) (*b*), zooplankton, gww/m^3 (*c*), phosphates, mg/m^3 (*g*) and phosphorus in detritus, mg/m^3 (*d*) in Lake Ladoga

as a result of the autumn thermal bar (mid-November) enter the upper photic layer, but cannot be used there for the production of organic matter during photosynthesis due to the lack of light. In the subsequent winter period, the phosphates that entered the photic layer during the autumn thermal bar are replenished due to the supply of phosphates with river runoff. At the same time, there is a process of phosphate accumulation in the hypolimnion due to the mineralization of settling detritus (Fig. 7e), which is facilitated by the winter phase of stable stratification of the lake's water column. Melting ice and increased light levels in spring lead to a strong diatom bloom in mid-May. This increase in phytoplankton biomass occurs due to winter phosphate reserves. By the time these reserves are consumed, the spring heating of the lake upper layer leads to the development of a spring thermal bar, which ensures the entry of phosphates accumulated in the hypolimnion into the photic layer, thereby supporting the spring bloom of diatoms. After the end of the diatom spring bloom, caused by the depletion of mineral nutrition and the consumption of phytoplankton by zooplankton, the summer phase of organic matter production by non-diatoms begins. It is supported by the flow of phosphates into the upper layer mainly due to the excretion of zooplankton, as well as the mineralization of detritus produced by phyto- and zooplankton, which actively develops in July-August (Fig. 7c). At the beginning of the autumn-winter convection period (late September – early October), a small autumn outbreak of diatoms is observed (Fig. 7b), which is ensured by the supply of phosphates from the deep layers of the lake and light conditions still sufficient for the process of photosynthesis.

5. Conclusion

Comparison of the results of calculating the current climatic state of Lake Ladoga for 1979–2018 period using a three-dimensional eco-hydrodynamic model with available satellite and expeditionary observation data showed that the model correctly reproduces the climatic seasonal variation of the surface temperature field and its vertical distribution. According to the estimates of the quality function, the model also reproduces quite well the average values and the range of changes in the main characteristics of the Lake Ladoga ecosystem, and the identified features of the climatic seasonal cycle do not contradict common ideas about the functioning of freshwater lake ecosystems in the boreal zone. All this indicates that the proposed model can be used to study the influence of external natural and anthropogenic factors on biogeochemical processes and the functioning of the Lake Ladoga ecosystem.

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