ФИЗИКО-МАТЕМАТИЧЕСКИЕ НАУКИ

ТЕРМИЧЕСКИЙ И ЛЕДОВЫЙ РЕЖИМЫ ЛАДОЖСКОГО ОЗЕРА В УСЛОВИЯХ ВОЗМОЖНЫХ КЛИМАТИЧЕСКИХ ИЗМЕНЕНИЙ (ПО РЕЗУЛЬТАТАМ МОДЕЛИРОВАНИЯ)

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THERMAL AND ICE PROCESSES IN LADOGA LAKE AT POSSIBLE CLIMATE CHANGES (ON THE SIMULATION RESULTS)

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Аннотация

Представлены результаты трехмерного математического моделирования термического и ледового режимов Ладожского озера в условиях климатических изменений. Показано, что предполагаемое к концу XXI века потепление климата скажется, в первую очередь, на скорости нарастания и таяния льда. Быстрое таяние льда приведет к раннему очищению озера от ледового покрова. При этом сроки начала ледовых явлений в озере не изменятся. Раннее исчезновение ледового покрова приведет к временному сдвигу в термических процессах в озере, что скажется на химико-биологическом режиме озера.

Abstract

Results of 3D mathematical modeling of the thermal and ice conditions in Ladoga Lake at possible climatic changes are presented. It is shown that the expected climate warming by the end of the XXI century will affect, first of all, the rate of growth and melting of ice. The fast melting of the ice will lead to the early disappearance of the ice cover that, in turn, will cause a temporal shift in the thermal processes in the lake. This will affect the temperature dependent chemical and biological processes in the lake.

Ключевые слова: Ладожское озеро, температурный и ледовый режимы, изменение климата, трехмерное моделирование

Key words: Ladoga Lake, thermal and ice processes, climate change, 3D modeling

Introduction

Among the numerous factors that determine the status and functioning of the aquatic ecosystems in natural and artificial reservoirs and the quality of water resources, the thermal regime of the water body, mixing conditions and ice phenomena are of paramount importance. Therefore, practically all chemical and biological processes in reservoir, such as formation and decay of organic matter, dissolution of atmospheric gases (primarily of oxygen and carbon dioxide), red – ox reactions, vital activity of almost all aquatic organisms are temperature dependent [3, 6, 11].

In turn, thermohydrodynamic (THD) processes that occur in the water bodies arise as a result of atmospheric effects on them and therefore are subject to fluctuations in the regional climate. In order to assess the response of the aquatic ecosystem to possible changes in the regional climate, it is necessary, first of all, to understand what changes can occur in THD processes under the impact of climate change.

In the present study on the basis of 3D model simulations the effect of possible changes of regional climate on THD processes in the Ladoga Lake is assessed.

Materials and methods

A three-dimensional (3D) mathematical model of the inland sea hydrodynamics (MISH) developed at the Institute of numerical mathematics RAS was used to perform the calculations [2]. To describe the water mass circulation in a water object of any configuration the 3D THD equations are incorporated in the model. The interaction between the atmosphere and the water body is described through the fluxes of momentum, heat and moisture. The ice module of MISH is activated when the temperature at the water surface reaches the freezing point. The module calculates the ice temperature and thickness as well as the dynamics of ice fields within the water object. Herewith, over the water area where the ice cover is present the fluxes of momentum, heat and moisture at the air-water interface are replaced by similar fluxes across the air-ice and ice-water boundaries. The water exchange through the lateral and air - water boundaries are explicitly prescribed taking into account the properties of water (heat content and mineralization). Also the model explicitly assigns precipitation and evaporation at the air-water interface. The model has been successfully tested through calculation of the THD of the Caspian Sea, which is a typical representative of the inland seas.

Taking into account the spatial scale of Ladoga Lake, up to 230 km in length and 125 km in width with a depth difference of several meters in the southern part to 250 meters in the North-the lake can be considered rather as a freshwater inland sea than as a lake. Therefore, MISH was chosen to perform the calculations for Ladoga Lake. Before the calculations, MISH was adapted for use in the fresh water conditions [1]. In particular, taking into account the fact that the mineralization of water in Ladoga Lake and its tributaries differs from each other and its values are much less than the typical salinity in the ocean, the equation of state for salty water was replaced by the equation of state of slightly mineralized water [5]. Parameters of the computational grid were 600x600 meters horizontally and 30 levels in vertical direction. The time step of calculations was 6 minutes.

The data of the reanalysis, a joint project of the National Centers for Environmental Prediction (NCEP) and Atmospheric Research (NCAR) [7] were used to assign initial meteorological conditions for calculation of the current "medium-climatic" state of the THD processes. As a scenario of possible climate change the scenario MPI B2 developed at the Max Planck Institute (Hamburg, Germany) was chosen [8]. This scenario is characterized by the following main parameters: 1) moderate emission of greenhouse gases into the atmosphere; 2) it is assumed that the main climate warming will occur in winter, which corresponds to the data of long-term field observations made over the last 40-50 years; 3) the General trends of emissions are also close to those observed over the past 40 years; 4) the air temperature on the planet at the end of the century can increase by up to 3–5 °C. According to its main parameters the MPI B2 scenario can be considered as a scenario of maintaining the current warming trend [8, 9, 10].

Initial conditions at the MISH calculations were set for the conditions of early October. The fact is that in October the thermal structure of the lake is homogeneous over the entire area [4]. This is the only month in the year when the initial conditions can be set up correctly. The inflow from the main tributaries of the lake, the rivers Volkhov, Svir' and Vuoksa, as well as the runoff of the Neva River, were taken into account during the calculations. The results of numerical experiments and their brief discussion are presented below. The data of calculations obtained using the NCEP/NCAR meteorological reanalysis are shown at the left (a) panels of the figures. The results of simulations corresponding to the climate scenario MPI B2 are presented at the right panels (b). Color scale stands for water temperature (°C), the white-grey-black one for ice thickness (m).

Results and discussion

The initial distributions of the lake surface temperature on October, 1 of the middle climatic year and at the end of the XXI century are shown in Fig. 1a, b respectively.

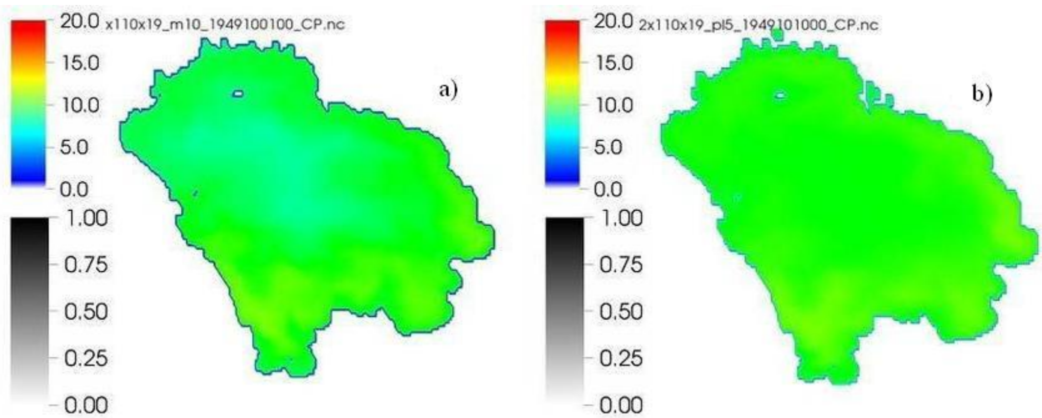

Figure 1. Initial spatial distribution of the water temperature in the Ladoga Lake

As follows from the data in figure 1 a, b, the lake at this time is thermally homogeneous; the water temperature throughout the entire area is close to 7-8 °C [4]. October is the time of year when density convection prevails over all dynamic processes in the lake. Due to intensive vertical mixing caused by the convection, the water column becomes thermally homogeneous.

Further cooling leads to the formation of spatial temperature heterogeneity. At this time the most cooled are the shallow areas of the lake, localized mainly in the South-Eastern, Southern and South-Western regions. At the end of October – early November the fall thermal frontal zone (thermal bar) starts to develop. In the case of "medium-climatic" year the thermal bar is formed earlier and the rate of its moving towards deeper sites is higher (Fig.2). That takes place due to lower values of the air temperatures, and hence, the larger heat losses through the free surface of the lake.

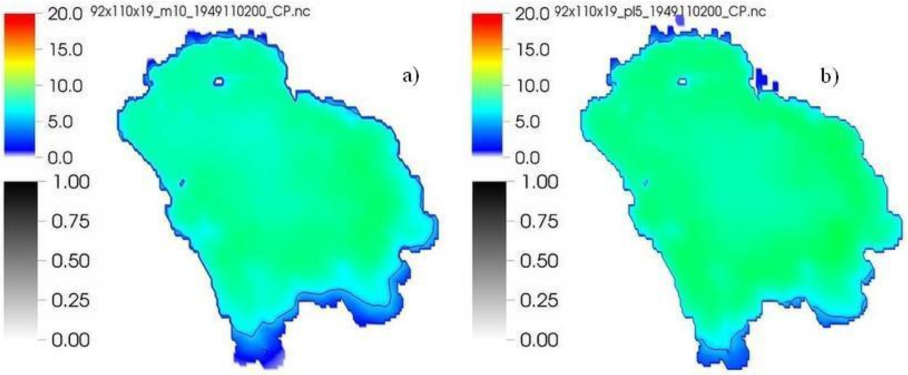

Figure 2. The thermal bar localization (blue line) by November 2 corresponding to "medium-climatic" (a) and scenario-based (b) atmospheric impact

At the end of November, the localization of the thermal bar in both versions of the calculations is almost the same. The main differences are observed in the thickness of the ice and the area of the lake covered by ice: both parameters are greater at the "average climatic" atmospheric exposures (Fig. 3 a, b).

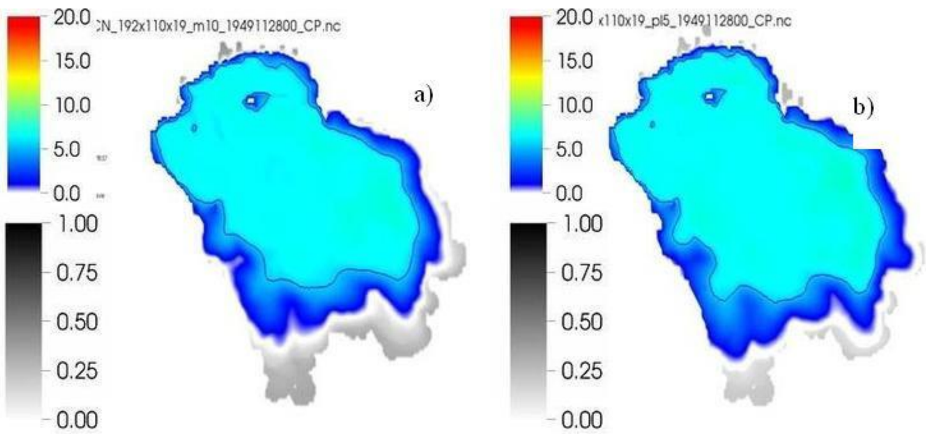

Figure 3. The thermal bar localization and the ice cover by the end of November

At the end of December, the thermal bar ceases to exist in both versions of the calculations (Fig. 4 a, b). At the same time, it should be noted that in the case of "scenario" atmospheric effect, the ice-free surface of the lake cools faster, compared with the "medium-climatic" conditions. The fact is that corresponding to scenario B2, the temperature of air boundary layer is higher during this period, which leads to more intensive evaporation at the water surface and, accordingly, to accelerated surface cooling. Due to the higher air temperature, the rate of ice growth in the "scenario" version is lower, and the ice thickness is less than in the case of "medium-climatic" impact.

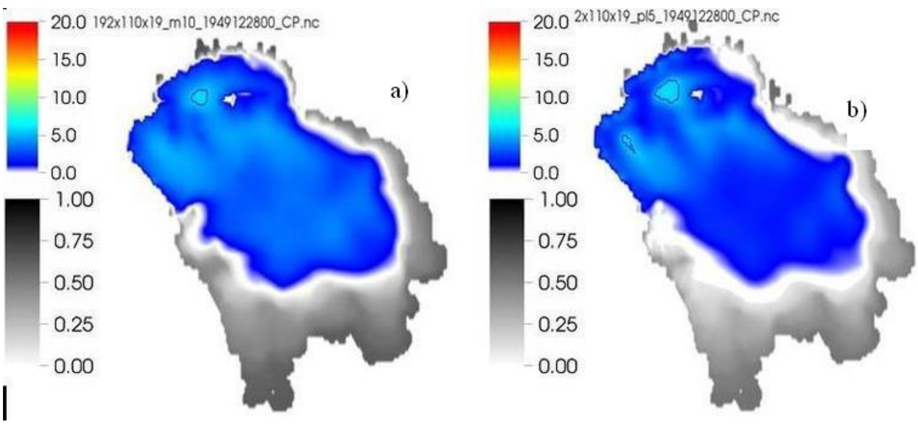

Figure 4. The thermal bar disappearance and ice cover by the end of December

In both versions of atmospheric impact the lake is completely frozen by the middle of February. Intense evaporation in the case of scenario impact has one more additional effect. The earlier formation of the ice cover on the entire surface of the lake leads to the fact that in the central part the ice thickness becomes even greater compared to "average climatic" case (Fig. 5 a, b). At the same time, the maximum ice thickness for the "average climatic" year can reach 1 meter in the southern regions of the lake. In the same areas, if calculated according to the climate scenario, the ice thickness will be less by about 25%. In the North-Western part of the lake the ice is practically absent in both versions of calculations.

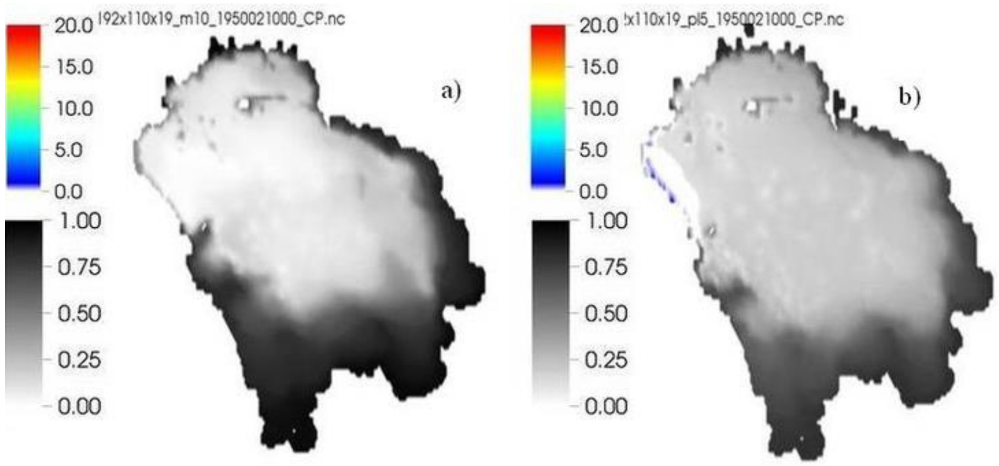

Figure 5. The ice cover in the lake by the mid February

In mid-March, the differences in the state of the ice cover become much more significant. In case of "average climatic" atmospheric impact, the lake remains completely covered by ice, although its thickness in the North-Western deep-water area is about 10 – 15 cm. In the case of climate scenario calculation, a significant part of the North-Western water area is ice-free. Moreover, ice becomes thin in most of the central areas of the lake, reaching only 10 – 15 cm (Fig. 6 a, b).

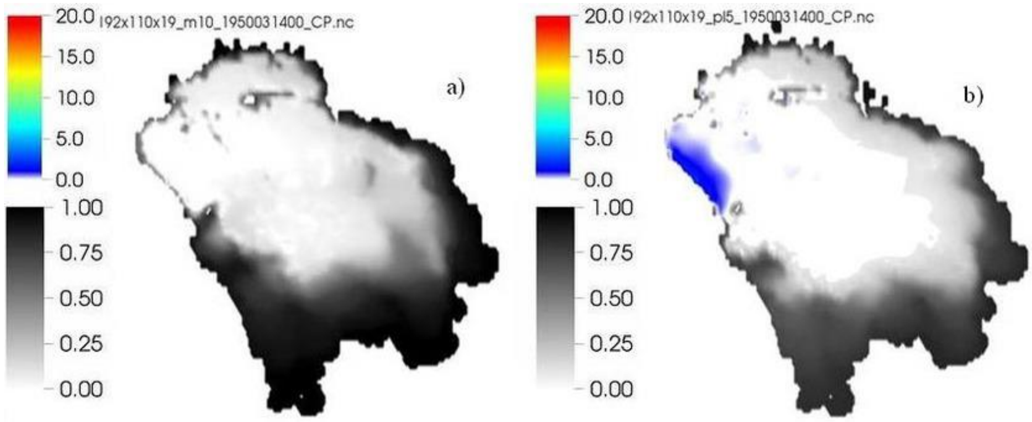

Figure 6. The ice cover in the lake by the mid March

By the end- April and in the first days of May (Fig. 7 a, b) in the case of "average" year the lake becomes completely ice-free. At the same time, in the case of the climate scenario the thermal bar has been already formed in the Bay of Petrokrepost', partly in the Volkhov Bay, in the area of Priozersk and it started to spread towards the central parts of the lake (Fig. 7b). This means that in these areas the water masses have already warmed up to the temperature of the maximum density of slightly mineralized water.

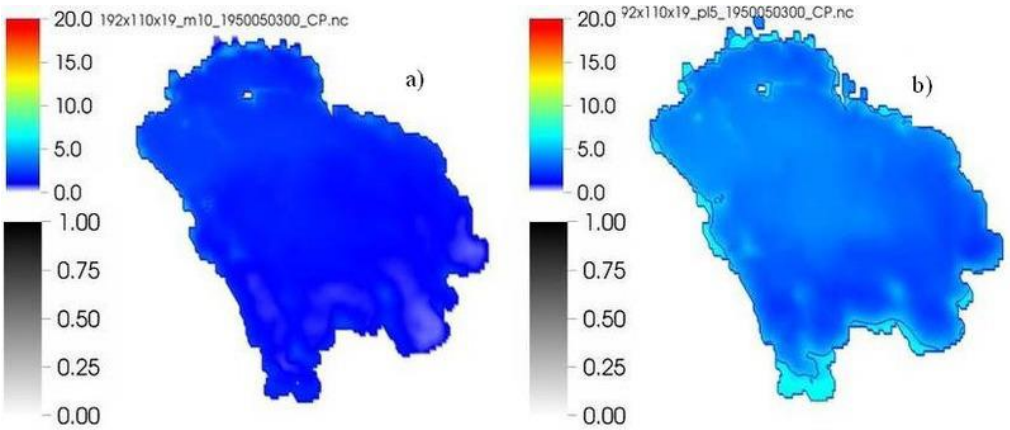

Figure 7. Distribution of the temperature in Ladoga Lake by May 3 for mean-climatic (a) and scenario (b) atmospheric impacts. Blue line marks the location of 4°C isotherm characterizing the position of the thermal bar

By mid-June (Fig. 8 a, b), the THD processes in Ladoga Lake, determined by the "average climatic" atmospheric effects, lag behind the "scenario" ones by one month on the average. The thermal frontal zone is only approaching the central areas of the lake from the Southern side. From the Eastern direction the thermal bar slightly moved to the center of the lake. In the North and North–West thermal bar is still close to the coastline. The water temperature is close to 20 °C only in the Bay of Petrokrepost' and partly in the Volkhov's Bay. The pattern is quite different in the case of THD processes defined by the climate scenario. Thermal bar ceased to exist, and an intense warming up of the whole lake is started. The water temperature in the Bay of Petrokrepost', in the Volkhov's and in the Svir's Bays has already exceeded 20 °C, or is close to this value. The same temperature is observed in the skerries. Over the rest of the lake the water temperature varies from 7-8 to 15°C.

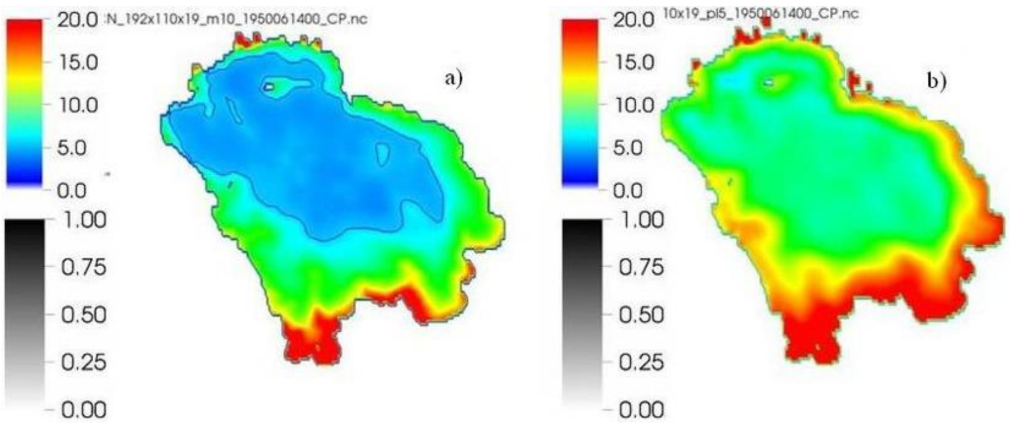

Figure 8. The same as in Fig. 7 by the mid-June

By mid-July (Fig.9 a, b) the thermal bar ceases to exist in the case of mean-climatic year and the lake starts to warm up. The temperature field approximately corresponds to the "scenario" one month earlier. The central, Northern and North-Western parts of the lake are exceptions. Around these regions the water temperature is in the range of 7-8 °C. In the case of a climatic scenario, the intense warming up of the lake continues. The water temperature in almost all coastal areas has either reached 20 degrees or approaching it. The entire central part is warmed up to 15-16 °C, and only in a small area in the North–West of the lake the water temperature is about 10 – 12 °C.

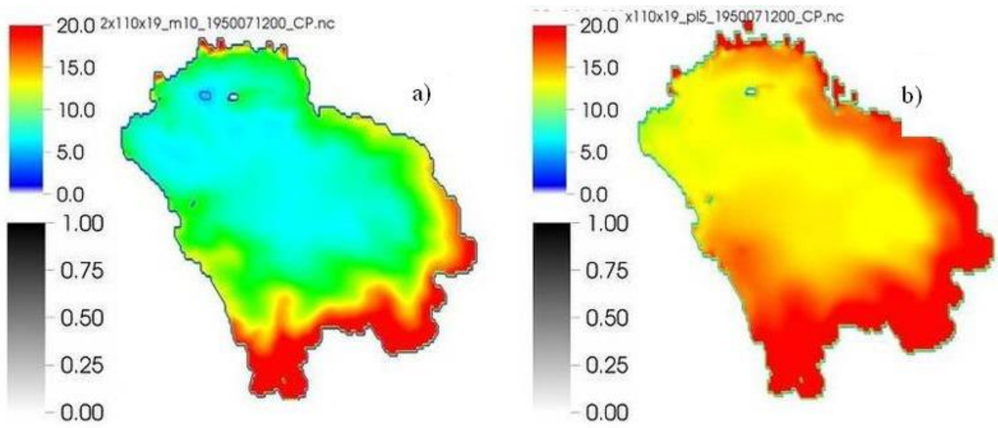

Figure 9. Distribution of water temperature in Ladoga Lake by mid-July

August (Fig. 10 a, b) is characterized by the fact that in the case of the "average climatic" year, the warming of the lake is almost completed. Calculations according to the climate scenario show that by mid-August, almost the entire water area of the lake warms up to 20°C and more.

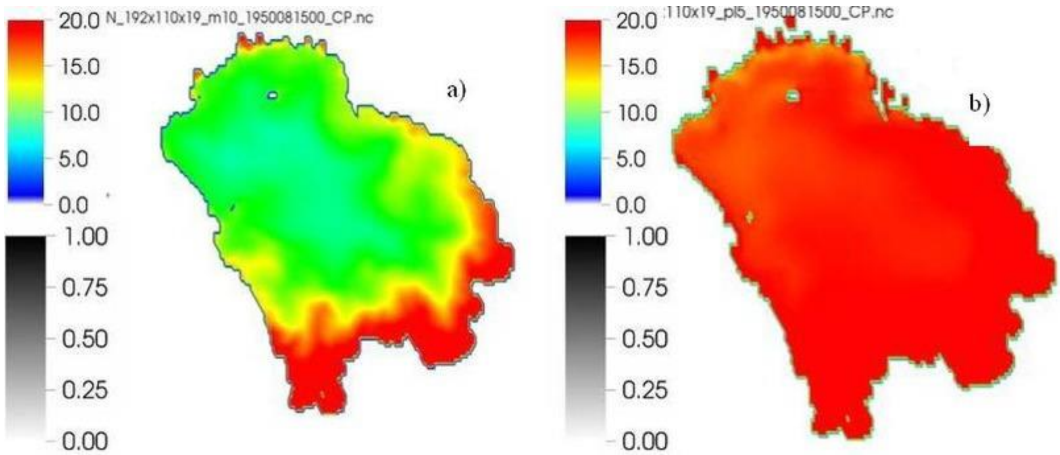

Figure 10. Distribution of water temperature in Ladoga Lake by mid-August

In the second half of August and in the beginning of September the rapid cooling of the lake begins. Herewith, in the case of calculations according to the climate scenario, it occurs much faster compared to the "average climate" year. By the mid-September only in the Bay of Petrokrepost' the temperature is about 20 °C (Fig. 11 a, b).

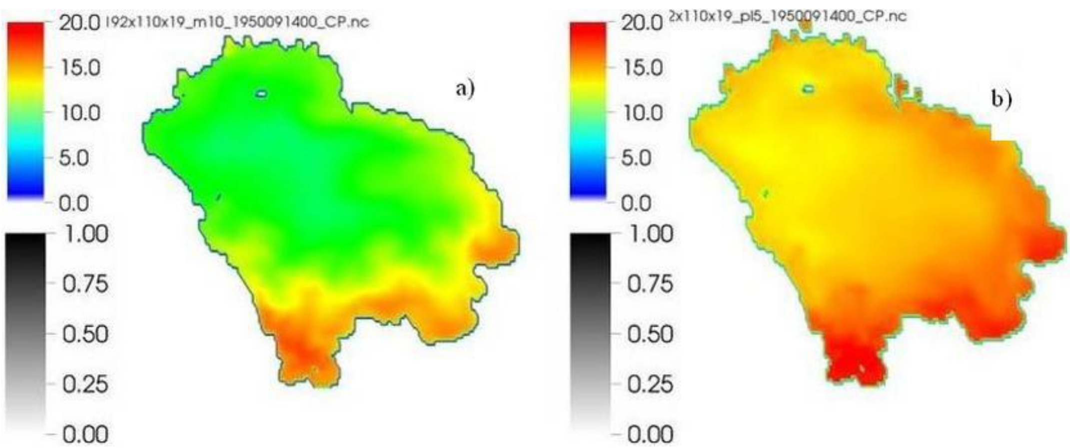

Figure 11. Distribution of water temperature in Ladoga Lake by mid-September Finally, as noted above, in October the lake in both cases cools to 7 – 8 °C (see Figure 1 a, b).

Conclusions

Preliminary conclusions about the impact of possible climate change on THD processes in Ladoga Lake are the following. The expected climate warming will affect both the thermal and ice conditions in the lake. Herewith the terms of formation of the ice cover will not change. Onset of freezing, both in the case of the "average climatic" year and under the climate scenario, occurs in early November in the southern areas of the lake. The main influence of warming can have on the rate of ice growth and melting. In the "scenario" case, the lake is completely covered by ice. However, small ice thickness predetermines early melting. On the average, it should be noted that the complete ice melting may occur on 2-3 weeks prior to the conditions of the "average" atmospheric impact. Early disappearance of the ice cover may lead to a temporary shift in the processes that determine the thermal regime of the lake in spring and summer. So, the formation of the thermal frontal zone (thermal bar) will start earlier on the same 2-3 weeks and the speed of its propagation offshore will be higher. As a result, the spring–summer thermal bar will terminate in mid-June, instead of the average climatic mid-July [4]. As a result, the summer warming of the main water mass will start almost 1 month earlier that inevitably will affect the temperature regime of the whole lake. Under the conditions of the climate scenario, almost the entire area of the lake will warm up over 20 °C, which does not happen under the conditions of the "average" climate scenario. If the predicted B2 scenario fulfills, it should be expected that climatic changes will lead to drastic changes in THD processes in the lake and, as a consequence, in the functioning of the aquatic ecosystem. Among the latter we can expect changes in the gas regime of the lake (see introduction), in the species composition of aquatic organisms, the emergence of new organisms at all trophic levels and decrease/increase in biodiversity.

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