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MODERN CHARACTERISTICS OF THE ICE REGIME OF RUSSIAN ARCTIC RIVERS AND THEIR POSSIBLE CHANGES IN THE 21ST CENTURY

ABSTRACT. Changes in rivers ice regime features and the climatic resources of the winter period were examined for the territory of Russia northward from 60° N. Datasets from 220 gauging stations for the period from 1960 to 2014 have been used in the study both with the results of numerical experiments carried out using climate models in the framework of the international project CMIP5. A change in the duration of the ice phenomena period, the ice cover period and the maximum thickness of ice on the rivers for the scenario RCP 8.5 by the end of the 21st century for a spatial grid with a distance between the nodes of 1.75x1.75 degrees in latitude and longitude has been estimated. We elaborated series of the maps. Main features of the ice regime changes are consistent with the expected changes in the duration of the cold season and the accumulated negative air temperatures. The significant changes are expected for the rivers of the Kola Peninsula and the lower reaches of the rivers Northern Dvina and Pechora, whereas the lowest changes - for the center of Eastern Siberia.

KEY WORDS: river ice, climate change

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INTRODUCTION

The study of current trends of the hydrological regime of the Arctic rivers is a relevant scientific and practical task. Ice phenomena can be observed on the Arctic rivers for most of the year. A lot of types of economic activities are related to the terms and duration of ice phenomena (navigation, the construction of ice crossings and the operation of various hydraulic structures). In many cases, ice phenomena cause dangerous hydrological processes, including floods (Agafonova et al. 2017). For the selected region, the population and the economy experience the greatest difficulties due to ice phenomena on the rivers during hanging ice dam or ice jam floods, in the case of a damage to hydraulic structures during a heavy ice run and high water levels, as well as when arranging navigation and ice crossings.

The change in the characteristics of the ice regime from year to year is primarily a function of meteorological characteristics and the characteristics of the river's water regime. There are a lot of studies of trends of the ice regime of rivers to date, including the Arctic zone, the results of which have been summarized in (IPCC 2014; Prowse et al. 2007, Prowse et al. 2011; Vuglinsky 2002; Vuglinsky 2017). There are also estimates of changes in the characteristics of the ice regime of the Russian rivers under various scenarios of climate changes. The studies using a simple model based on the relation between the terms of ice phenomena and the average air temperature of the preceding month, have obtained the probable characteristics of the future ice regime of rivers during the 21st century (Borshch et al. 2001; Ginzburg 2005).

The area under study is located to the north of 60° N and includes the Arctic zone of Russia and the neighboring regions: the Kola Peninsula, Karelia, the basins of the rivers Onega, Northern Dvina and Pechora, the middle and lower reaches of large Siberian rivers (Ob, Yenisei and Lena), the basins of the rivers Yana, Indigirka and Kolyma. The rivers of the area under study are important thruways, first of all, for the Northern Supply Haul. If the main settlements in the Republic of Karelia and the Murmansk region are located along the railway, then within the Arkhangelsk region and the Komi Republic - along the rivers. There are also most of the settlements along the rivers in Siberia. The transport accessibility of such settlements depends on the work of ferry crossings in summer and during ice crossings in winter.

The climate of the area is characterized mainly by a severe long winter and a short cool summer. The water runoff of the studied rivers is formed mainly during the melting of the snow cover with the addition of high mountain snowfields, glaciers and ice coating for a number of rivers. The spring-summer high water lasts, on average, from May to July. The winter low water is stable, its runoff reaches significant values in the north of the European part of Russia and near the rivers of the Kara Sea and decreases to rather low values in the catchment areas of the Laptev Sea, the East Siberian and the Chukchi Seas due to severe environmental conditions. A number of large and medium-sized northern rivers (the rivers Anabar, Olenek, Yana, Alazeya, Palyavaam, Amguema, etc.) are frozen to the bottom in winter (Alekseevsky et al. 2007).

MATERIALS AND METHODS

The observation data obtained at 220 hydrological stations (Fig. 1) for the period from 1960 to 2014 have been used in the study, the most common characteristics of the ice regime of rivers have been considered: the duration of the period with ice phenomena, the duration of ice cover period and the maximum ice thickness. The data omissions were restored by means of hydrological analogy using the information on the sections located on the rivers with similar physical and geographical conditions and characteristics of catchment areas.

To estimate future changes in the characteristics of the ice regime, the indicators of climatic resources for the cold period (October-May) were used: the accumulated negative air temperatures, the accumulated positive air temperatures, the number of days with the air temperature below 0° C and the amount of solid precipitation. The climatic resources were calculated on the basis of the results of numerical experiments carried out using climate models within the framework of the international project CMIP5 (Taylor et al. 2012). Among the main computational experiments of CMIP5 important in estimating the Arctic's further response to climate changes, the experiment historical and the experiment under the scenario RCP8.5 were used (Moss et al. 2008). The choice of the scenario RCP 8.5 is due to the fact that it is the most «severe» among the scenarios estimated in the numerical experiments of CMIP5 in terms of a possible impact of external factors, including anthropogenic ones, on the climate system, taking into account the greenhouse gas emission control policy. Such an intense external impact makes it possible to elicit large and statistically significant response to an increase in the concentration of greenhouse gases.

The climatic resource indicators were calculated based on model data on the daily

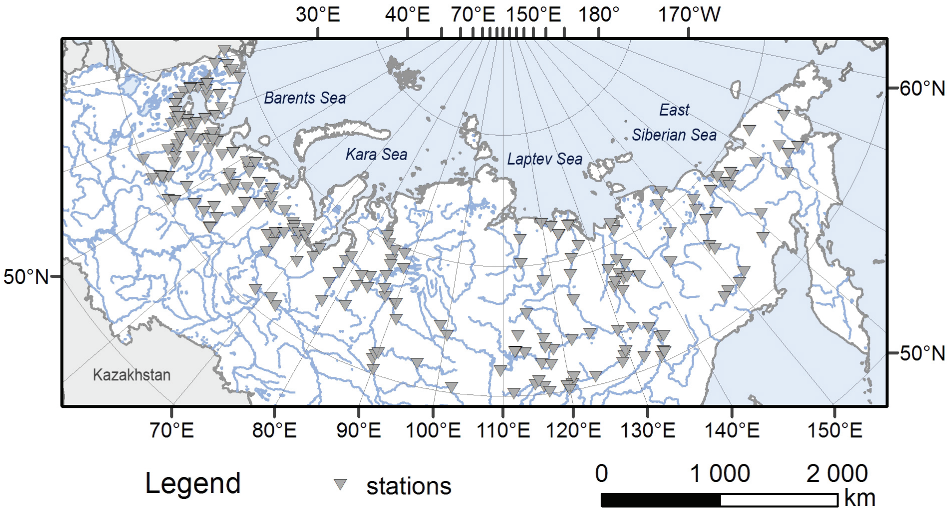

Fig. 1. The study area

values of the average daily temperature of the ground air and the daily precipitation. The results of each model were interpolated onto a single spatial grid with a distance between the nodes of 1.75×1.75 degrees in latitude and longitude, ensemble-averaged models were calculated for the grid nodes.

ICE REGIME OF RIVERS IN MODERN CONDITIONS

The rivers of the area under study are frozen up, on average, in October: in the first days – in the northeast (the rivers Anadyr and Kolyma), by the end of the first decade - within Western Siberia (the rivers Taz, Nadym and the lower reaches of the Ob River), in the middle of the month - the rivers of the European sector (the lower reaches of the rivers Pechora, Mezen and Onega) and by the end of the second decade of October - the rivers of the Kola Peninsula (the rivers Varzuga and Ponoy). Ice cover is on average formed on the rivers of the Asian part - in the middle of October, on the rivers of the European part - in the first days of November. The root-mean-square deviation of the autumnal periods of ice phenomena is 13 to 15 days for Karelia and the southern coast of the White Sea, 10-12 for the lower reaches of the north of the European part, 6-8 for the rivers of Western Siberia, and 3-5 days for the rest of the territory (Agafonova et al. 2016).

The rivers of the area under study are characterized by stable ice cover, the exceptions are rapids and sources of large lakes. There is no stable ice cover in the segments of industrial wastewater discharge, below the dams of hydroelectric power stations, either. The average duration of ice cover period varies from 150 days in the south-west to 240 or more on the rivers of the Taimyr Peninsula (Fig. 2). The isolines are mainly sub-latitudinal, except for the rivers Yana and Indigirka, in the upper reaches of which there is the zone of influence of the Siberian anticyclone. The duration of ice cover period for large rivers (the rivers Pechora, Ob, Yenisei, Lena, etc.) is somewhat lower than on the neighboring middle rivers. Due to the predominant direction of the flow of these rivers from south to north, the duration of ice cover period increases towards the mouth and is 230 days in the gauging sections of the rivers Lena and Yenisei, 210 days for the Ob River and 190 days for the Pechora River (Fig. 3).

For most of the rivers of the area under study, the thickness of the ice cover increases throughout the entire period of ice cover and reaches its maximum values in the last month of ice cover period, the intensity of increase in recent months being minimal. The sharp increases in the thickness of ice in February and March are usually caused by water outflow on the ice, in April – by thaws and the freezing of wet snow with the ice cover. The significant increase in the thickness of ice on small and medium rivers is often due to the freezing of the underlying layers to the bottom and lack of flow in the line of a station.

The wide spread of the values of the maximum ice thickness is characteristic for the northeast of the territory. The average maximum ice thickness for the values of the accumulation negative air temperatures below -5000° C is 0.8 to 2.0 m or more. For individual sections, the ice cover thickness increases due to the freezing of water on river ice, others are characterized

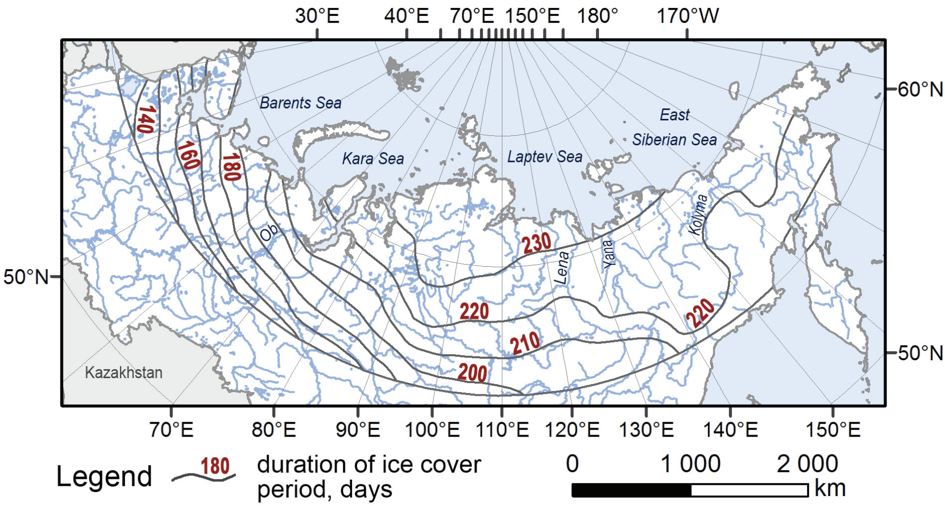

Fig. 2. Duration of ice cover period on middle rivers for the period of 1986-2005

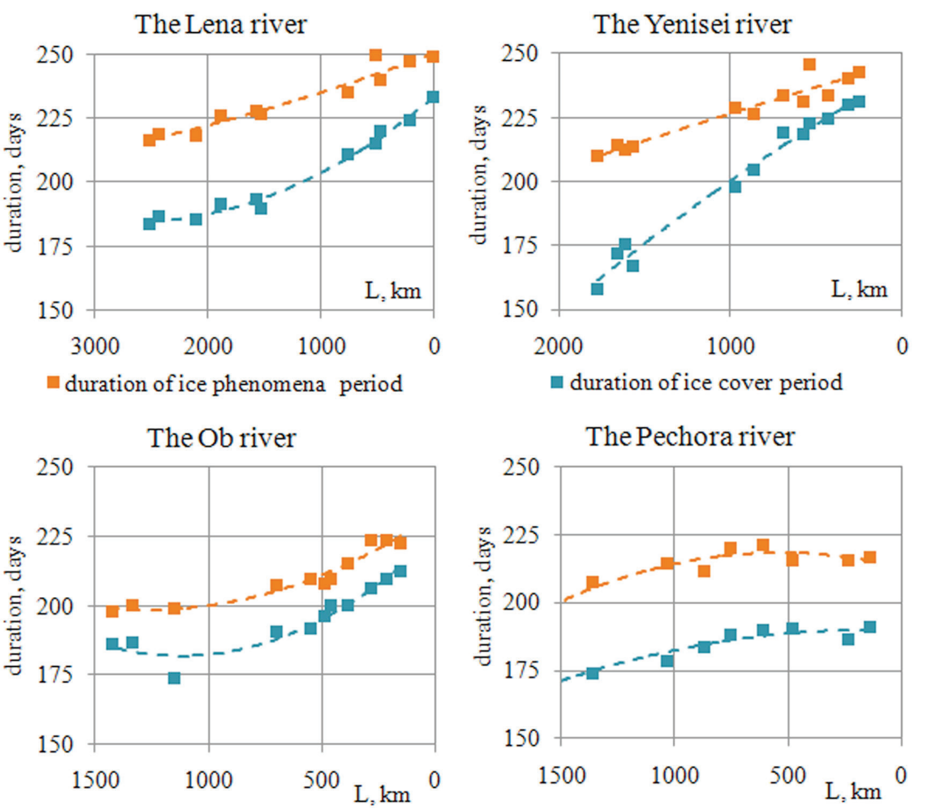

Fig. 3. Duration of ice phenomena and ice cover period by the length of large rivers for the period of 1986-2005 (L – distance from mouth, km).

by special hydrogeological conditions and, as a result, lower ice thickness values, and open leads during the winter period for individual sections of rivers.

For freezing rivers, the thickness of the ice cover ceases to grow long before the end of the winter period. In such cases, the ice thickness in the absence of icing is equal to the depth of the stream before ice cover period. It should be noted that within the European part of Russia, it is mainly small rivers (with a catchment area of up to 5000 km^2) that are frozen, within Siberia, especially in the north-eastern part, the freezing of sections of large rivers with a catchment area up to 200,000 km^2 is possible (Arzhakova 2001).

For the rivers of the Kola Peninsula, the highest values of ice thickness by the end of the ice cover period reach from 0.5 m in warm winters to 1.0 m in severe winters, for the Pechora River - from 0.7 to 1.4 m, respectively, for the rivers of Western Siberia - from 0.8 to 1.5 m, for the Lena River - from 1.3 to 2.0 m and on the rivers of the north-eastern part (the Amguema River and others) - from 1.7 to 2.5 m.

Due to the reduction in runoff in winter, the ice can be formed consisting of several layers separated by an empty, without water, space. Icings are formed on almost all the rivers in the zone of permafrost. River icings are formed when the rivers freeze, when the ice cover subsides under the pressure of snow or transport, when the bed is blocked by ice. In this case, the water flows out onto the surface of the ice cover and freezes. The melting of icing can continue throughout the warm period (Alekseev 1987).

On the rivers of the north-east, the ice cover period ends, on average, in the first decade of June, on the rivers of the Arctic part of Central and Western Siberia - at the end of May, and on the rivers of the Kola Peninsula - in mid-May. The root-mean-square deviation of the spring periods of ice phenomena for the rivers of the European sector of the Arctic zone is 9-11 days, for the rivers of Western Siberia - 6-8 days, for the rest of the territory - 3-5 days.

The average duration of the period with ice phenomena is from 180 days for the rivers of Karelia to 260 days for the rivers of the northeast and the Taimyr Peninsula, for the gauging sections of the Lena river - 250 days, for the Yenisei River - 245 days, for the Ob River - 225 days, and for the Pechora River - 220 days (Fig. 3).

OBSERVED CHANGES IN THE MAIN CHARACTERISTICS OF THE ICE REGIME OF RIVERS

The changes in the terms of ice phenomena are the result of a change in the water and thermal regime of rivers. The ice regime does not immediately react to climatic changes by reducing the duration of ice phenomena, changes in ice characteristics are often not so obvious and remain statistically insignificant for a long time. For the rivers of the area under study, some trends in the characteristics of the ice regime can be seen only after 1990 (Table 1).

In the autumn period, with a decrease in water consumption, the emergence of ice can be observed at a time close to the norm even with a slight increase in the air temperature. The similar situation is, for example, in the north of the European part. After the beginning of stable ice formation (early or near normal), the unstable pattern of the air temperature leads to a return of positive temperatures in November, resulting in floods due to the melting of snow and rainfall. The high levels during this period contribute to later ice formation, an increase in the duration of the autumn ice and sludge run, the formation of ice jams. It should be noted that the shift in the terms of ice formation within the European sector is primarily due to the increasingly frequent cases of extremely late ice cover formation, which significantly effects the duration of the ice cover period.

The greatest shift in the terms of ice emergence is observed on the rivers of Karelia and in the lower reaches of the Onega River (+7-8 days), for the rest of the rivers of the European sector - about +5 days; for Siberian rivers, the changes are statistically insignificant and are up to +2-4 days.

The important factors for the growth of the thickness of the ice cover and a change in its maximum values are the features of weather

Table 1. Change in the characteristics of the ice regime (when comparing 2 periods: 1961-1990 and 1991-2014)

Areas	Change in		
	the duration of		the maximum ice thickness (sm)
	the ice cover period, days	the period with ice phenomena, days	
Kola	–(12–13)	–(10–11)	–(5–10)
Karelia	–(13–14)	–(11–12)	–(10–15)
European North	–(11–12)	–(9–10)	–(5–10)
Western Siberia	–(9–10)	–(8–9)	–(5–10)
Middle Siberia	–(7–8)	–(6–7)	–(5–10)
Eastern Siberia	–(6–7)	–(4–5)	–(0–5)
Northeast	–(3–4)	–(3–4)	–(5–10)

conditions in winter. It is not only about the accumulation of negative air temperatures and snow cover on the ice, but also about the regime of thaws that become deeper and more prolonged in the European part of Russia. While thaws, with rare exceptions, do not lead to the breakup of ice in rivers in winter, snow melting on ice and the formation of snow ice, when negative air temperatures return, can be observed. Some softening of winter conditions does not lead to significant decreases in the average ice thickness values by the end of the winter season. On the rivers of Siberia, the thickness of the ice cover often reaches the values close to the limit ones; in the middle of the ice formation period, the further accumulation of negative air temperatures does not affect the maximum values of ice thickness any longer either. As a result, the change in the thickness of the ice cover on the rivers of Eastern Siberia is not more than -5 cm, on the rest of the rivers of Siberia and on the large rivers of the north of the European part - up to -10 cm, and only on the rivers of Karelia - –10-15 cm.

The ice cover is destroyed under the influence of two forces: 1. the surface and internal melting of ice under the influence of solar radiation, heat exchange with the atmosphere and the water mass; 2. the dynamic effect of the flow with a sufficiently high intensity and velocity of the flood wave. The nature of the spring breakup is determined by the thickness and strength of the ice cover by the time of breakup, the weather and hydrological conditions of the spring period. When the water flow rates are low and the fluctuations in the water level are slight during the breakup period, ice melts in place. On large and medium rivers, along with the weakening of ice strength, when effected by thermal factors, the integrity of the ice cover is disturbed under the influence of fluctuations of the water level and hydrodynamic load. For the rivers under study, most of which flow from south to north, the dynamic effect of the flow in breakup processes is crucial (Donchenko 1987).

The changes in the dates of the breakup of ice in rivers are statistically insignificant for almost all stations, except for the rivers of Karelia and the Kola Peninsula. The shift in the dates of breakup in the rivers of the Kola Peninsula and Karelia is –6-8 days, on the rivers of the north of the European part and Western Siberia - –4-5 days, the shift in the terms of ice clearing is also more pronounced for the rivers of the European sector of the Arctic zone and does not exceed –1-2 days for the rivers of the northeast.

As a result of a shift in the terms of ice phenomena, the change in the duration of ice cover period and the period with ice phenomena is –10-14 days for the European part and only –3-4 for the northeast part.

ESTIMATION OF CHANGES IN THE ICE REGIME

The total global warming predicted by the climate system models according to the scenarios RCP is manifested differently at the regional level. According to the IPCC assessment report (IPCC 2013), in the case of the scenario RCP 8.5, the average global surface temperature is expected to increase by about 2° C by the middle of the 21st century compared to 1986-2005, and by about 4° C by 2100. For the Arctic, according to this scenario, much more intensive climate warming is expected by the end of the 21st century, its value will be 5-10° C depending on the regions. On the larger territory of the Arctic, the anomalies of a lot of indicators of climatic resources are more pronounced during the cold period (Surkova et al. 2017).

To estimate possible future changes, empirical dependencies of indicators of climatic resources for the cold period (October-May), calculated on the basis of the results of numerical experiments carried out using climate models in the framework of the international project CMIP5, and the main characteristics of the ice regime at hydrological stations, were identified. As the initial data, the average (for 10 years) moving values for all stations were used: the accumulated negative air temperatures, the accumulated positive air temperatures, the number of days with the air temperature below 0° C, the amount of solid precipitation, as well as the duration of the period with ice phenomena, the duration of ice cover period and the maximum ice thickness for the period from 1986 to 2005.

For each empirical dependence, optimal combinations of predictors were selected (Table 2). As a result, about 2000 points were used for the dependencies of duration of ice cover period and the period with ice phenomena, and somewhat less for ice thickness. The sections, for which ice thickness increases due to icings or for which the effect of the groundwater outflow is decisive, were excluded. The averaging over the decades and the sharing of data of all stations within one dependence made it possible to smooth the effect of the local conditions of individual sections and the features of weather of individual years. The correlation coefficients of the obtained dependences are statistically significant.

Using the obtained dependences, the values of the ice regime characteristics for a spatial grid with a distance between the nodes 1.75x1.75 degrees in latitude and longitude for the time slices of 1986-2005 and 2081-2100 were calculated. The possible changes in the characteristics of the ice regime were estimated as the difference of the obtained fields. The results are presented in the form of maps (Fig. 4-6).

Table 2. Empirical dependencies of the characteristics of the ice regime

Characteristics of the ice regime of the rivers	Number of points	Predictors	Multiple correlation coefficient
Duration of ice cover period	2060	number of days with a negative air temperature, accumulated negative air temperatures	0.86
Duration of the period with ice phenomena	2050	number of days with a negative air temperature, accumulated positive air temperatures	0.91
Maximum ice thickness	1120	accumulated negative air temperatures, amount of solid precipitation	0.73

The estimates of changes in the main characteristics of the ice regime by the end of the 21st century are consistent with the expected changes in the duration of the cold period and the accumulated negative air temperatures. For Karelia and the Kola Peninsula, in the case of the scenario RCP 8.5, the accumulated negative temperatures is expected to be -700 ... -1000° C, for the north of Western Siberia -1500 ... -2000° C, for Eastern Siberia -3000 ... -3500. According to the estimates, the number of days with a negative air temperature will be reduced to 100-150 days for Karelia, the Kola Peninsula and the basin of the Northern Dvina River, up to 150-200 days for the basin of the Pechora River and the north of Western Siberia and will be 200 days or more for the north of Central and Eastern Siberia and the basins of the rivers Kolyma and Yana and for the north-east.

A significant reduction in the duration of the period with ice phenomena and the period of ice cover (when comparing two periods: 1986-2005 and 2081-2100) are expected for the rivers of the Kola Peninsula and the lower reaches

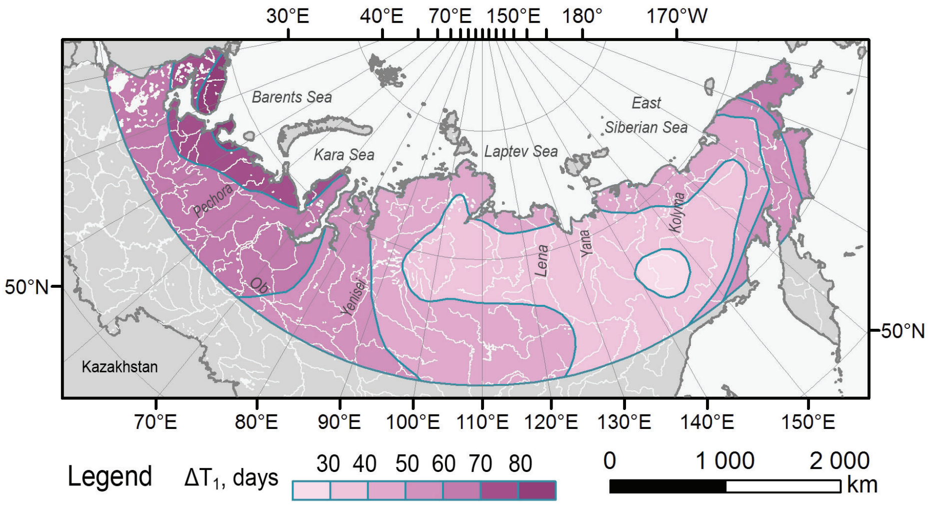

Fig. 4. Estimation of a change in the duration of the ice cover period (ΔT_1, days) by the end of the 21st century.in comparison with the period of 1986-2005

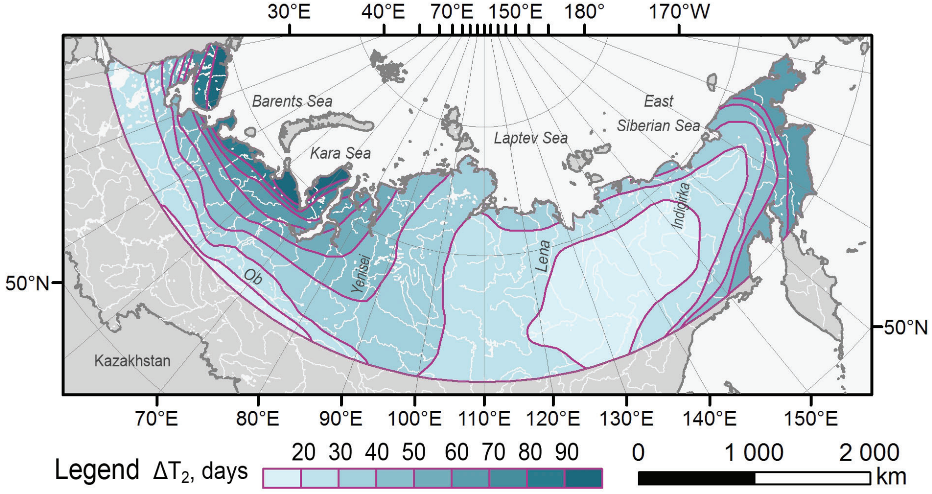

Fig. 5. Estimation of a change in the duration of ice phenomena period (ΔT_2, days) by the end of the 21st century.in comparison with the period of 1986-2005

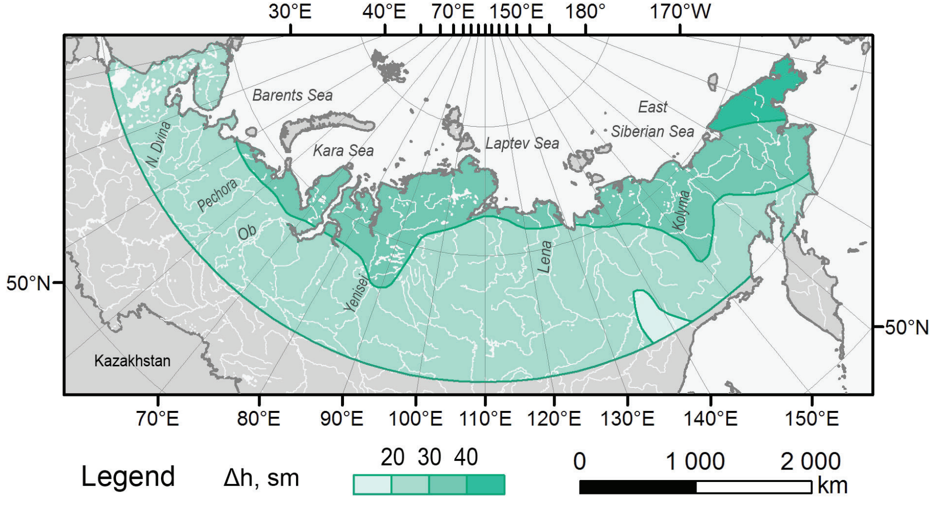

Fig. 6. Estimation of a change in the maximum ice thickness (Δh, sm) by the end of the 21st century.in comparison with the period of 1986-2005

of the rivers Northern Dvina and Pechora (80 days or more, which corresponds to 40-50%). The least changes are expected for the center of Eastern Siberia - about 30 days or 15-20%. For the European part, changes in the duration with ice phenomena are more pronounced, for the Asian part – changes in the period of ice cover are more pronounced (Figure 4, 5).

The reduction of the maximum ice thickness will be up to 30 cm for most of the territory, which is about 30-40% for the rivers of the European sector and Western Siberia (Fig. 6). The most pronounced changes are expected for the rivers of the Chukchi Peninsula (up to 50 cm). It should be noted that it is about a change in the contribution of accumulated negative air temperatures to the values of the maximum ice thickness. This paper does not estimate a change in the contribution of icing processes to the final values of the maximum thickness of the ice cover.

CONCLUSIONS

The analysis of the temporal variability of the main characteristics of the ice regime of Arctic rivers has shown that some trends of these characteristics can be seen only after 1990. As a result of a shift in the periods of ice phenomena and the change in the duration of ice cover period when comparing two periods (1961-1990 and 1991-2014) is 10-14 days for the European part and only 3-4 for the northeast. The duration of the ice cover period on the rivers of the European sector is reduced mainly due to more frequent cases of extremely late ice formation and its extremely early completion.

Some softening of winter conditions does not lead to significant decreases in the average ice thickness values by the end of the winter season. The thickness of the ice cover on the rivers of Siberia often reaches the values close to the limit ones; in the middle of the ice cover period, the further accumulation of negative temperatures does not affect the maximum values of ice thickness any longer either. As a result, the change in the thickness of the ice cover on the rivers of Eastern Siberia is not more than 5 cm, on the rest of the rivers of Siberia and on the large rivers of the north of the European part - up to 10 cm, and only on the rivers of Karelia - 10-15 cm.

According to the analysis of indicators of climate resources by the ensemble of models of the international project CMIP5 (the experiment under the scenario RCP 8.5), intensive warming of the climate is expected for the Arctic by the end of the XXI century. On the larger territory of the Arctic, the anomalies of a lot of indicators of climate resources are more pronounced in the cold period.

The dependences of the most general characteristics of the ice regime of rivers on the indicators of climatic resources for the cold period make it possible to estimate a change in the ice regime for different climatic scenarios and time slices. To elicit significant response, of the scenarios estimated in the numerical experiments of CMIP5 in terms of a possible impact on the climate system, the most «severe» one was chosen.

According to the estimates, by the end of the 21th century, the reduction in the duration of ice cover period and the period with ice phenomena for the rivers of the Kola Peninsula and the lower reaches of the rivers Northern Dvina and Pechora will have been 80 days or more in comparison with the period of 1986-2005, which is consistent with the expected reduction in the period with negative temperatures. The least changes are expected for the center of Eastern Siberia - about 30 days or 15-20%.

By 2081-2100, the reduction of the maximum thickness of the ice cover for the rivers of the European sector will have been about 30 cm or 30-40%. For the rivers of Siberia, the ice thickness provided by the accumulated negative temperatures will be reduced by 20-30%. The most pronounced changes are expected for the rivers of the Chukchi Peninsula (up to 50 cm). For the sections of rivers where the increase in ice thickness is mainly due to the freezing of water on river ice, the changes can be significant.

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