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MODERN THERMAL REGIME OF RIVERS IN RUSSIAN ARCTIC AND PERMAFROST AREAS

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Thermal regime of rivers plays a great role in rivers ecological state. However, there are a lot of gaps in our knowledge about thermal regime of rivers and about long-term changes of water temperatures and river heat flow due to the scarcity of open-source water temperature data. During the past decade study of thermal regime of rivers has been focused on Arctic Region, primarily on North-East of Russia. Nowadays, we are expanding the spatial coverage of river thermal regime studies to the permafrost areas as regions with the most dynamic climate and landscape changes. Studied area includes territory of Russia North of 60 N, Russian parts of Baikal Lake and Amur River basins, basin of Okhotsk and Japan Seas and Russian part of Caucasus. For all these regions, except the Arctic and Caucasus, our investigations of the thermal regime of rivers are the first ones for the past 5–6 decades. We used monthly average water temperature data from more than 400 gauges on rivers in different landscape conditions for 1961–2022. Annual and monthly heat flux was estimated for data from 200 gauges. Change-point years for all studied characteristics, mean and standard deviations, changes after change-point years and in 1991–2020 in comparison with 1961–1990 were estimated. Moreover, the analysis of air and water temperature relations was carried out. Results are compared for different parts of permafrost zone and compared with Arctic non-permafrost areas. Very low values of the thermal runoff of the North Caucasus are shown. The regions in which local factors play a major role in shaping water temperature compared to climatic ones have been identified, the Baikal basin, for example.

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Introduction. The thermal regime of rivers plays a significant role in the formation and functioning of aquatic ecosystems. Water temperature determines oxygen saturation of water, survival rate, feeding intensity, and geographical distribution of fish, including valuable species [1–6]. The distribution of water temperature in rivers flowing in mountainous conditions is subject to vertical

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zonation [7]. Changes in river water temperature affect the ice regime [8]. The heat flux of rivers largely determines the microclimate of river valleys, influences the ice cover of freezing seas, and in permafrost regions, the heat flux is a factor in intensifying thermal abrasion of riverbanks [9–12].

Intensive climate changes in the Arctic and in permafrost regions, expressed as an increase in air temperature at high latitudes and changes in the characteristics of permafrost, primarily an increase in the seasonally thawed layer, lead to transformations of the thermal regime of rivers. At the same time, the limited amount of open data on water temperature in rivers significantly constrains current understanding of the spatial and temporal characteristics of the thermal regime of rivers.

In Russia, the thermal regime of the Lena River [9, 13, 14], the basins of Northeastern Russia, and the Russian Arctic (North of 60° N) are the most studied. That is, the zone of continuous permafrost is the most studied. In recent years, many long time series with the most recent hydrological data have been used for studies of these regions [15–18].

At the same time, the regions of discontinuous permafrost in Siberia and the Russian Far East, located South of 60° N, are not covered by modern assessments of the spatiotemporal variability of water temperature in rivers. The most recent comprehensive studies for the basins of Lake Baikal, the Amur River (in the Russian part of the basin), Sakhalin Island and the Kamchatka Peninsula, as well as the coasts of the Okhotsk and Japan Seas, were carried out in the 1970s as part of the publications "Surface Water Resources of the USSR", before the onset of intensive climatic changes. Moreover, the level of detail in the study of the thermal regime of rivers in these publications varies significantly.

The permafrost region of the North Caucasus should be mentioned separately. Rivers flowing in the Caucasus are in physiographic conditions that are starkly different from those of the Far East and the Arctic, which provides an opportunity to compare the characteristics of formation and long-term variability of water temperature under different conditions within the permafrost zone of Russia.

The aim of this work is to provide a modern synthesis of data on the thermal regime of rivers in the permafrost zone of Russia.

Materials and Methods. For the analysis, data on mean monthly water temperature in rivers for the period from 1961 to 2020 were used. The choice of mean monthly temperature is justified by its theoretical significant climatic determinacy [19]. The choice of the time period is determined, on the one hand, by the need for two 30-year periods to assess the degree of changes in water temperature characteristics, and on the other hand, by the delay in data processing from hydrological gauges in various departments of Roshydromet, as well as by the fact that before 1957, at most gauges, water temperature observations were carried out once per day (8 a.m. local time), whereas modern observations are carried out twice per day (8 a.m. and 8 p.m. local time). The work analyzed mean monthly temperatures for the period from May to October, which at most gauges corresponds to the open channel period.

It is important to note that water temperature is almost universally measured near the banks. According to a number of studies, water temperature on large rivers may differ between the bank and the midstream by up to 3–5℃. However, there is currently no way to account for these differences, using data from network observations. Rivers are characterized by vertical homothermy, except for sections with intensive groundwater inflow, or with significant warming of surface layers on rivers with relatively slow flow. However, the former cases introduce a systematic error that is leveled out at the regional level, and the latter are leveled out in monthly and, even more so, long-term summaries.

For the analysis, data from 635 hydrological gauges on rivers of various sizes were used. The densest network of hydrological gauges is characteristic of the North of the European territory of Russia and the Southeast of Russia – the Amur River basin and the Sea of Japan basin. Water discharge, necessary for calculating heat flux, is measured at 348 of these gauges. Most of them (237 gauges) are located in the Pacific Ocean basin.

Change-point years in water temperature series were identified using the Buishand test. The presence or absence of a significant trend was determined using the Mann-Kendall test, considering missing data in the series. The magnitude of changes was determined using Sen's slope. All statistical tests were performed at a significance level of 5%.

The magnitudes of changes in water temperature were determined as the difference between the mean values for 1991–2020 and 1961–1990. For convenience, in some cases averaging was performed by river basins and regions of the Russian Federation.

In this work, the current water temperature is considered to be the mean water temperature for the period 1991–2020.

The heat flux of rivers was calculated using the formula

$$W_t = c_p \rho \bar{T} \bar{W},$$

where W_t is heat flux, *J*/month; c_p is specific heat capacity of water, *J*/(*kg*·°C); ρ is water density, kg/m^3; $\bar{T}$ is monthly mean water temperature, °C; $\bar{W}$ is water flow, m^3.

Fluctuations in the density and specific heat capacity of water at different temperatures were not taken into account due to their small magnitude. The heat flux in this work is presented in *EJ*/month ($EJ = J \cdot 10^{18}$). The total heat flux is presented as the sum of monthly heat flux for May-October. For most of the study regions, this value is equivalent to the annual heat flux.

It is important to note that for most rivers flowing into seas, the heat flux is calculated not for the estuarial cross-sections, but for the closing gauges, which may be located 500–700 *km* away from the estuarial cross-section. Therefore, these values should be considered as corresponding to those at the estuarial cross-sections with caution.

The boundaries of the permafrost zone and the boundaries of territories with different permafrost extent were obtained from [20].

Results and Discusion. The analysis showed that change-point years in water temperature at most gauges occur in the 1990s and 2000s (Fig. 1), indicating a lag in significant water temperature changes relative to the onset of climatic changes, which occurred in the 1970s. Extremely early and extremely late change-point years are observed only in cases of significant gaps in the data series. Change-point years may differ from river to river within the same regions, due both to characteristics of the time series and to local factors.

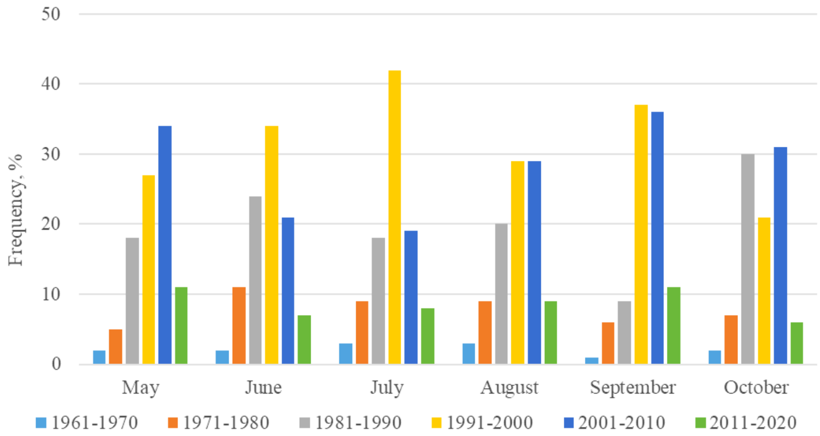

Fig. 1. Frequency of change-point years in individual decades.

Current water temperature varies during the year from 0 to 27°C, and in some years the mean July temperature may exceed 30°C. Most of the studied rivers are characterized by ice cover lasting from 7–9 months in the North of Central Siberia to 3–5 months in the South of Siberia and Primorye. For rivers of the North Caucasus, freezing is almost uncharacteristic, largely due to the turbulent nature of the flow, the widespread occurrence of karst, and the absence of glacial feeding in winter. However, water temperatures can be below 1°C even in the foothills, where negative air temperatures are rarely observed during the winter.

Water temperature in the Arctic and permafrost zone of Russia increases from northeast to southwest. A tendency toward a slight increase in water temperature in zones of discontinuous permafrost can be noted, compared to nearby zones of continuous permafrost (Fig. 2). Note that these differences are leveled out during the period of maximum river water heating, in July and August. A certain decrease in water temperature is observed in permafrost-free areas adjacent to territories occupied even by isolated permafrost. This is especially noticeable in the North of the European territory of Russia and on the Kola Peninsula.

Nevertheless, at the macroregional level, the more significant factors in the formation of the spatial distribution of water temperature are latitude and, to a great extent, elevation, as well as, possibly, the orientation of mountain slopes. This is especially evident in Southeastern Russia, where submeridionally oriented mountain ranges are widespread.

This relationship is equally evident in the Caucasus. It should be noted that for small rivers within the permafrost zone, generally lower temperatures are characteristic compared to other rivers in the regions, which is clearly seen in Kamchatka, Sakhalin, and Primorye.

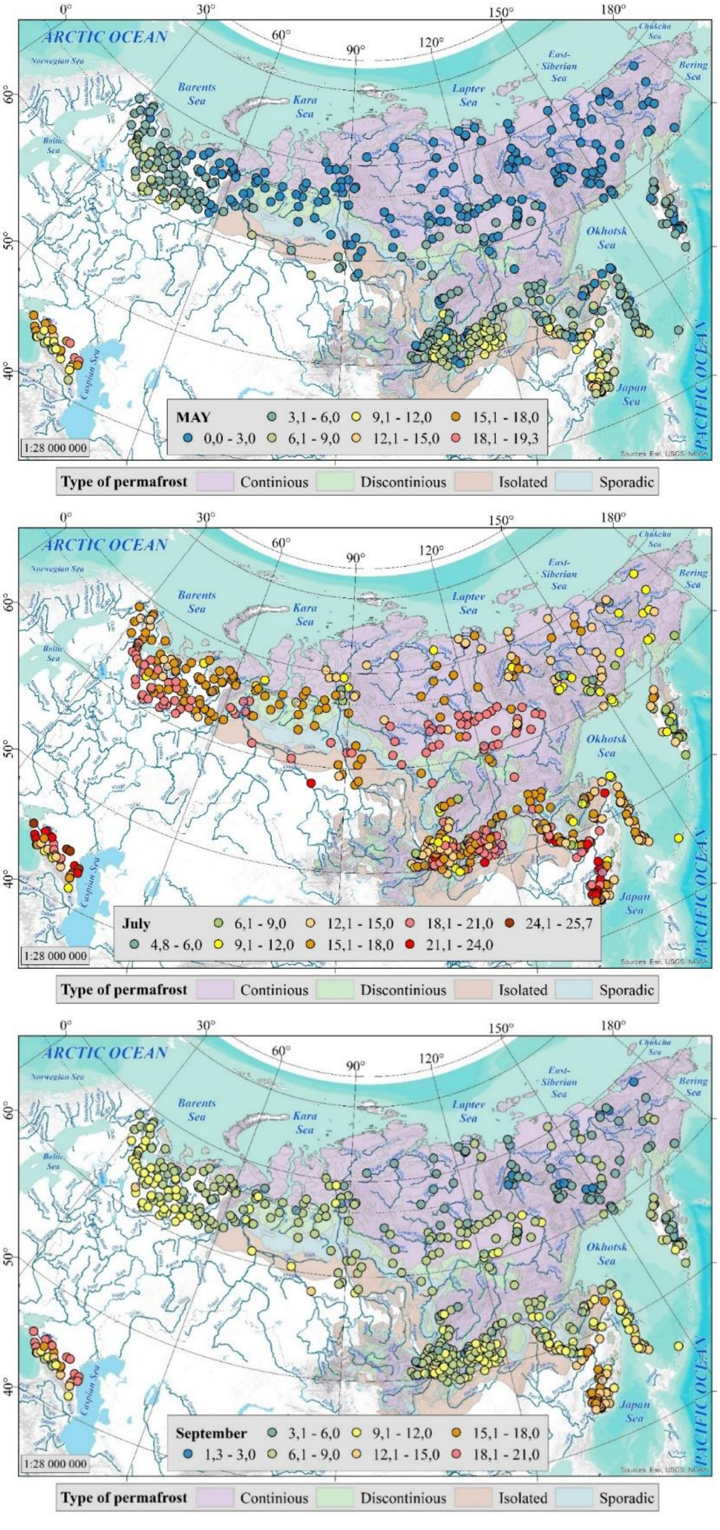

Fig. 2. Mean water temperature (℃) in rivers in 1991–2020.

Long-term changes in water temperature in the permafrost zone are generally small (Tab. 1). The greatest changes are characteristic of the North of Western Siberia, primarily the basins of the Nadym, Pur, and Taz Rivers, as well as the tributaries of the lower Yenisei and rivers draining the Putorana Plateau. A relatively large magnitude of changes is observed in regions with widespread discontinuous permafrost or its absence. Another important factor appears to be the relatively warm maritime climate.

Table 1

Magnitudes of changes in mean monthly water temperature in rivers of selected regions in 1991–2020 compared to 1961–1990

Region/Month	May	June	July	August	September	October
North-East	0.3	0.1	0.2	0.4	0.6	0.3
Kamchatka Reg.	0.3	0.2	0.4	0.2	0.2	0.3
Sakha Reg.	0.4	0.8	0.8	0.5	0.3	0.1
Sakhalin Isl.	0.1	–0.2	–0.4	–0.2	0.2	0.5
Amur basin	0.1	0.4	0.2	–0.2	0.5	0.5
Primorskiy Reg.	0.7	0.7	0.5	0.3	0.3	0.5
Baikal basin	0.8	1.2	1.2	0.7	0.5	0.3
Yenisey basin	0.5	1.4	0.6	0.2	0.2	0.4
North of West Siberia	1.1	2.5	0.3	0.5	0.6	0.6
North of European part	0.9	1.1	0.3	0.3	0.8	0.9
Karelia	1.2	0.5	0.5	0.5	1.2	1.2
Kola peninsula	1.3	1.3	0.7	0.8	1	0.7
North of Kaucasus	0	0.4	0.7	1	0.7	0.9

The Arctic and permafrost zone of Russia are characterized by a statistically significant increase in river water temperature over the long-term period. This is especially pronounced in the continuous permafrost zone, particularly in the Lena River basin (Fig. 3). In areas with potentially large influence of marine air masses during the warm period, practically no trends were detected (the Kolyma, Penzhina, and Anadyr basins). Relatively fewer trends were detected in discontinuous permafrost zones and in permafrost-free zones. It is important to note that the largest number of gauges with a monotonic increase in water temperature were detected in the transitional seasons, in May–June and September–October. At the same time, trends were practically not detected anywhere in the period 1991–2020 and in the period after the change-point years, which indicates a rather slow change in the thermal regime of rivers.

It is important to note the existence of significant decreasing trends in water temperature, which occur almost everywhere in the study area, both with and without permafrost, indicating that they are primarily determined by local factors.

The magnitude of changes in water temperature is generally quite small and ranges from 0.1℃/decade to 0.5℃/decade. Water temperature increases somewhat more intensively in June–September, the warmest months of the year. The greatest increase in water temperature is observed in lowland areas with discontinuous permafrost (Tab. 2).

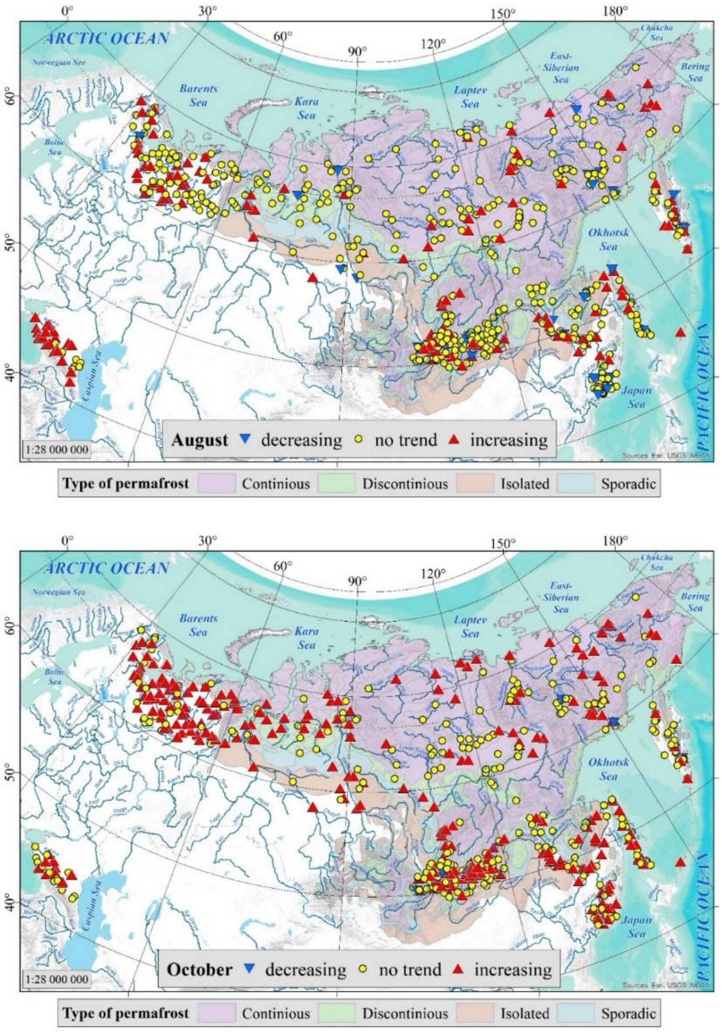

Fig. 3. Presence or absence of significant trends in river water temperature in 1961–2020 (in August, October) for individual months of the warm period.

From the territory of Russia, about 62.7 *EJ*/year reach the lower reaches and estuarial areas of the Arctic Ocean rivers in the period after 1981 [21]. The largest heat input is contributed by the Lena (16.5 *EJ*/year), Yenisei (15.1 *EJ*/year), and Ob (13.9 *EJ*/year). More than 1 *EJ*/year is also contributed by the Yana (1.4 *EJ*/year), Indigirka (2.2 *EJ*/year), Kolyma (3.6 *EJ*/year), Khatanga (1.9 *EJ*/year), Pechora (2.8 *EJ*/year), and Severnaya Dvina (3.1 *EJ*/year). In total, within the Arctic permafrost zone, excluding the largest rivers listed above, the heat flux generated during the year is about 14 *EJ*/year.

In the Lake Baikal basin, the heat flux generated during the year is about 2.5 *EJ*/year. More than 70% is contributed by the Selenga, and about another 15% by several large tributaries. A comparable amount of heat flux is generated over 12 months in the North Caucasus. More than half of it flows into the Caspian Sea.

Table 2

The magnitude of changes in water temperature during the period 1961–2020 in the presence of a significant trend

Region/Month	May	June	July	August	September	October
North-East	0.2	0.5	0.4	0.3	0.3	0.1
Kamchatka Reg.	0.2	0.3	0.3	0.3	0.2	0.1
Sakha Reg.	0.2	0.6	0.4	0.3	0.3	0.1
Sakhalin Isl.	0.3	0.5	0.5	0.4	0.3	0.2
Amur basin	0.3	0.4	0.4	0.4	0.3	0.3
Primorskiy Reg.	0.4	0.4	0.5	0.5	0.4	0.2
Baikal basin	0.3	0.4	0.4	0.3	0.3	0.2
Yenisey basin	0.2	0.7	0.4	0.3	0.4	0.2
North of West Siberia	0.3	0.7	0.6	0.3	0.3	0.2
North of European part	0.5	0.6	0.5	0.4	0.3	0.4
Karelia	0.6	0.4	0.4	0.4	0.3	0.4
Kola peninsula	0.4	0.4	0.3	0.3	0.3	0.2
Kaucasus	0.4	0.4	0.4	0.4	0.3	0.4

In the Pacific Ocean basin, the heat flux generated during the year is 34 *EJ*/year, of which about 30 *EJ*/year is generated in the Amur River basin. The heat flux of the Amur itself is 18.5 *EJ*/year at 600 *km* from the mouth. Another about 1 *EJ*/year is contributed to the Amur by the Amgun River before the estuarial area, but the degree of transformation of the heat flux of the Amur itself downstream of Komsomolsk, where the river turns North, remains unclear. In any case, more than half of the heat flux of this Pacific basin is accumulated by the Amur and discharged in a localized manner into the Amur Liman. The spatial distribution of heat flux for the entire study area is shown in Fig. 4.

On the presented map, one can first note a tendency for heat flux to increase as rivers emerge into the foothills of the Caucasus. In part, this, as in the Arctic and Southeastern Russia, is explained by an increase in water discharge.

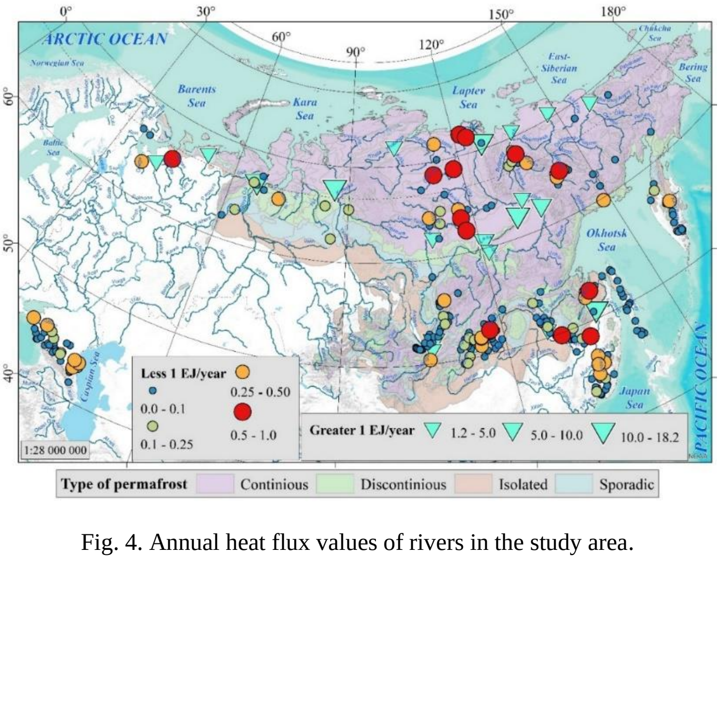

Fig. 4. Annual heat flux values of rivers in the study area.

The intra-annual distribution of river heat flux varies significantly across the study area. The maxima of heat flux occur during the calendar summer period and in many cases are associated with the period of maximum discharge, as in the Amur basin and Lake Baikal basin, or with the recession of the flood, as in the North of the European part and the North of Western Siberia. It is important to note that in the rivers of Southeastern Russia, the intra-annual distribution of heat flux is somewhat more uniform, i.e., the differences between individual months of the warm period are smaller than in the Arctic, including in the continuous permafrost zone.

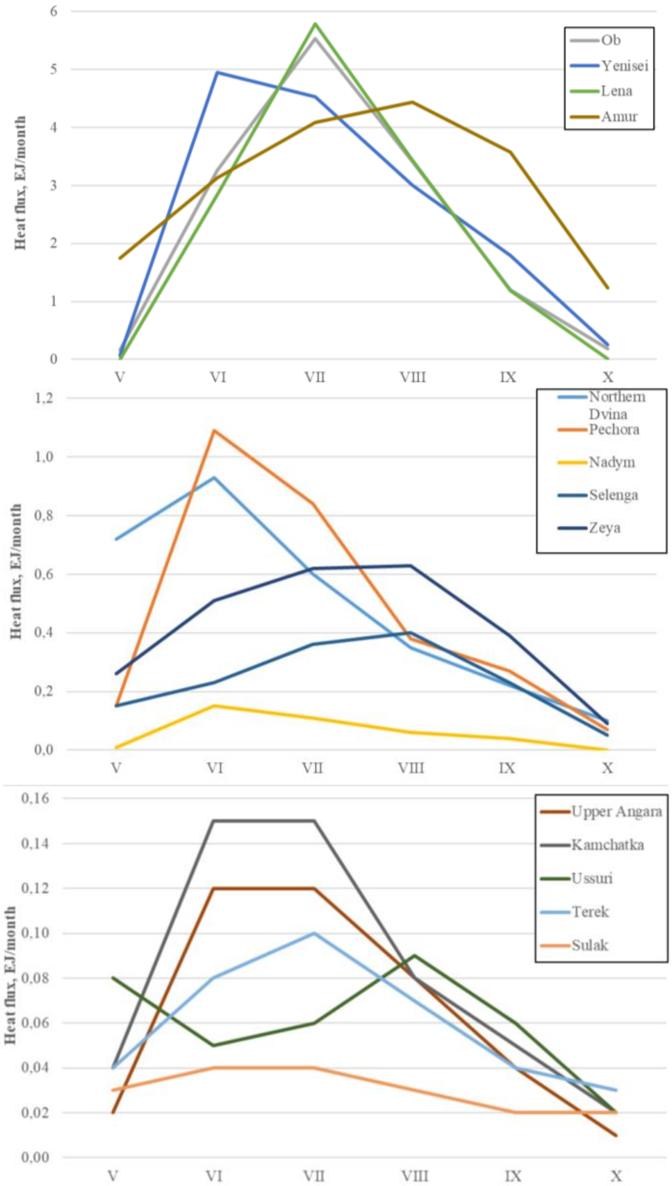

Fig. 5. Intra-annual distribution of heat flux in rivers of the study area.

At the same time, significant intra-annual fluctuations in the heat flux of the Ussuri River, located in a monsoon climate with small areas of permafrost on its tributaries in the mountains, are noteworthy. Also noteworthy are the sharp increase in heat flux in spring, its stability in summer, and a rather sharp decline in autumn on the Kamchatka River and the Verkhnyaya Angara River, which, despite being geographically far apart, both have mountainous headwaters with significant distribution of various permafrost types.

It is important to note that several large rivers among those studied are regulated by reservoirs. For Arctic Rivers, it has been shown that at the present stage, the anthropogenic reduction in heat flux has been overcome in the last decade. For reservoirs in the Amur basin, no such assessments exist. Likewise, the impact of irrigation systems and small reservoirs on the thermal regime of rivers in the North Caucasus has not been assessed.

Discussion. The study shows that water temperature in rivers of the permafrost zone is somewhat lower than in rivers in permafrost-free areas. Differences in water temperature are also observed within the permafrost zone itself, between areas with different permafrost types.

However, no linear relationship between the spatial distribution of water temperature and permafrost characteristics was detected at the study scale considered. Presumably, the spatial distribution of water temperature is largely determined by the same factors as the formation of permafrost, i.e., a combination of landscape and climatic conditions. Such conclusions are primarily based on the significant amount of data examined; however, estimates for the Arctic, in its Asian part, appear somewhat less reliable due to the lower density of hydrological gauges. The presence of permafrost apparently plays a more significant role in water temperature changes, which are lower in the continuous permafrost zone than in discontinuous permafrost zones. A large heat flux is generated in the permafrost zone, most of which, however, enters the Arctic Ocean, as well as the Okhotsk and Japan Seas. It is worth noting that the heat flux of the Amur River, part of whose basin is located outside the permafrost zone, is comparable to the heat flux of the Lena River, most of whose watershed is in the continuous permafrost zone. Presumably, mountainous areas with widespread distribution of various permafrost types reduce the total heat flux of the Amur.

Conclusion. During this work, the largest database on the thermal regime of rivers was compiled. This allowed for an analysis of the spatiotemporal distribution of water temperature in rivers. For the first time, an assessment of water temperature characteristics at the level of individual months has been made for the entire permafrost zone of Russia. An assessment of the role of permafrost in the formation of water temperature is provided. For the first time in the last 50 years, the heat flux to the Pacific Ocean from the territory of Russia has been estimated. A comparison of rivers in the permafrost zone and rivers with significant glacial feeding in the North Caucasus is presented for the first time.

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ՌՈՒՍԱՍՏԱՆԻ ԱՐԿՏԻԿԱԿԱՆ ԵՎ ՀԱՎԵՐԺԱԿԱՆ ՍԱՌՑԱԿԱԼԱԾ ՏԱՐԱԾՔՆԵՐԻ ԳԵՏԵՐԻ ԺԱՄԱՆԱԿԱԿԻՑ ՋԵՐՄԱՅԻՆ ՌԵԺԻՄԸ

Ամփոփում

Հոդվածում ներկայացված են հավերժական սառցակալած գոտիներում հոսող գետերի ջերմային ռեժիմի ուսումնասիրության արդյունքները, այդ թվում՝ Կովկասի լեռնային հավերժական սառցակալած գոտին և Ռուսաստանի արկտիկական գոտին: 1961–2022 թվականների 635 հիդրոլոգիական կայաններից ստացված տվյալների հիման վրա պարզվել է, որ ջրի ջերմաստիճանի շարքերում շրջադարձային կետերը տեղի են ունեցել հիմնականում 1990–2000-ական թվականներին, ինչը վկայում է գետերի արձագանքի ուշացման մասին՝ մթնոլորտային կլիմայի փոփոխության սկզբի համեմատ: Ներկայիս ջրի ջերմաստիճանը տատանվում է 0-ից մինչև 27°C, որտեղ ամենացածր արժեքները բնորոշ են անընդհատ հավերժական սառցակալած գոտիներին, իսկ ամենաբարձր արժեքները՝ անընդհատական հավերժական սառցակալած տարածքներում: 1991–2020 թվականների ընթացքում 1961–1990 թվականների համեմատ ջերմաստիճանի ամենամեծ դրական փոփոխությունները դիտվել են Արևմտյան Սիբիրի հյուսիսում, Կարելիայում և Պրիմորյեում: Անցումային եղանակներին (մայիս–հունիս և սեպտեմբեր–հոկտեմբեր) գերակշռում են ջրի ջերմաստիճանի բարձրացման վիճակագրորեն նշանակալի միտումները, սակայն 1991 թվականից ի վեր վիճակագրորեն նշանակալի չեն: Գնահատվել է ամենամեծ գետերի՝ Լենայի, Ենիսեյի և Օբի ջերմային հոսքը (ավելի քան 13–16 *ԷՋ*/տարի), ինչպես նաև 50 տարվա ընթացքում առաջին անգամ՝ Ամուրի (մոտավորապես 18,5 *ԷՋ*/տարի): 50 տարվա ընթացքում առաջին անգամ գնահատվել է Խաղաղ օվկիանոսի ավազանի գետերի ջերմային հոսքը, և համեմատություն է կատարվել հավերժական սառցակալած գոտու և Հյուսիսային Կովկասի գետերի միջև:

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СОВРЕМЕННЫЙ ТЕРМИЧЕСКИЙ РЕЖИМ РЕК В РОССИЙСКИХ АРКТИЧЕСКИХ И ВЕЧНОМЕРЗЛЫХ РАЙОНАХ

Резюме

Представлены результаты исследования термического режима рек, протекающих в криолитозоне, в том числе в горной криолитозоне Кавказа и арктической зоне России. На основании данных 635 гидрологических постов за период 1961–2022 гг. установлено, что переломные годы рядов температуры воды приходятся преимущественно на 1990–2000-е годы, что свидетельствует о запаздывании реакции рек относительно начала климатических изменений в атмосфере. Современная температура воды варьирует от 0 до 27°C, причем наиболее низкие значения характерны для зоны сплошной мерзлоты, а повышенные – для областей прерывистой мерзлоты. Наибольшие положительные изменения температуры за период 1991–2020 гг. по сравнению с 1961–1990 гг. отмечены на севере Западной Сибири, в Карелии и Приморье. Статистически значимые тренды повышения температуры воды преобладают в переходные сезоны (май–июнь и сентябрь–октябрь), однако после 1991 г. они статистически не значимы. Оценен тепловой сток крупнейших рек: Лены, Енисея и Оби (более 13–16 *EJ*/год), а также Амура, впервые за 50 лет (около 18,5 *EJ*/год). Впервые за 50 лет дана оценка теплового стока рек бассейна Тихого океана и выполнено сравнение рек криолитозоны и Северного Кавказа.