RESEARCH PAPER

FEATURES OF A LONG-TERM HEAT FLUX FORMATION OF THE LARGE RUSSIAN ARCTIC RIVERS AND ITS TRANSFORMATIONS IN ESTUARIES UNDER THE INFLUENCE OF CLIMATE-INDUCED AND DAM-INDUCED EFFECTS

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ABSTRACT. The heat flux of large rivers flowing into the Arctic seas of Russia is relatively high and plays an important role in the thermal state of the lower reaches and mouths of these rivers. It influences the ice regime, navigational conditions during spring and autumn seasons, and hydro-ecological conditions of the Arctic, as well as the climate of river valleys and individual parts of the region. It has also an important contribution to the bank erosion processes. Heat flux is a function of water temperature and water flow. Water flow and water temperatures have mostly increased since the 1970s-1990s. However, as was shown in our research, the water temperature increase in many rivers is not statistically significant. Nevertheless, this increase led to an increase in heat flux and its role in hydro-meteorological processes in the Arctic. However, heat flux changes in the large rivers of the Russian Arctic are also statistically insignificant. Notable changes were observed in the Russian Arctic rivers regulated by large reservoirs. In order to assess these changes and identify their spatial and temporal patterns, hydrological data from multiple gauging stations were analyzed for a period up to 2018. Another point of the research was the study of the transformation of water temperature and heat flux along the length of regulated rivers and in their mouths.

KEYWORDS: river, mouth, gauge, water temperature, heat flux, climate change, reservoir

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INTRODUCTION

River heat flux plays an important role in hydrological and ecological state of rivers, as well as their thermal and ice regime (Alekseevskiy 2000, 2012). It also contributes to bank erosion in the permafrost zone (Costard et al. 2003). The heat, which is transported from the South to the North with large rivers, is an important factor that determines the climate of river valleys, along with the ice and thermal regime in near-shore zones of the Arctic Ocean (Golubeva et al. 2015, Park et al. 2020). The role of heat flux depends on thermal conditions, geographical location and area of the basin, flow direction, water regime, morphological structure of deltas etc.

River heat flux is a function of water flow and water temperature. The annual water flow of the Russian Arctic rivers after the 1970-1990s has increased by 7-10%, but statistically significant changes were observed only in the North-East of Russia (Frolova et al. 2022). A great range of models, both global and regional, show that the water flow of these rivers will increase by 10-40% by the end of the 21st century, with a reduction in spring flood and an increase in summer and autumn water flow (Gelfan et al. 2022). Water temperatures, meanwhile, are controlled by air temperatures on monthly and annual time scales (Hannah and Garner, 2015). Significant air temperature increase after the end of the 1970s is observed all around Russia (Doklad… 2022). Significant warming in the Arctic is more intensive than in more southern regions (IPCC 2014, IPCC 2022) with an annual air temperatures increase of 0.8-1.1^0/decade, and seasonal air temperatures increase of 0.4-1^0/decade in the Russian Arctic (Doklad… 2022). This warming tends to increase from South-West to North-East. According to the IPCC report (IPCC 2022), global river water temperature between 1901 and 2010 increased from -1.21^0 to 1.076^0, also in the Arctic region, where an annual river water temperature increase in the past decades was observed (in the Russian part) (Vasilenko et al., 2020) and modeled (Wanders et al., 2019). Therefore, changes in heat flux are also expected.

The studies of heat flux of the Arctic rivers began in 1907 (Polinov, 1907) and 1914 (Shostakovich 1914). However, its first reliable estimations were obtained in the USSR during the active economic development, which included expeditions and scientific research in the Arctic. A series of manuscripts (Antonov 1936, Zaikov 1936, Zotin 1947, Korovkin 1940, 1941, Kashcheev et al. 1937, Khmyznikov 1934) presented heat flux values of some large rivers, as well as estimations of the total heat flux to the Arctic Ocean from the Soviet part of the basin. There were also several conclusions about the role of heat flux in the ice regime of the Arctic Sea. The next important stage of heat flux studies corresponded to the release of the series of monographs "Surface water resources of the USSR" (Surface water resources of the USSR 1969, 1970, 1972 a,b, 1973 a,b) in 1960-1980. This period was marked by the expansion of the monitoring network, construction of dams of the great Asian reservoirs, and projects for the partial transfer of river water resources to the south. A range of studies was dedicated to scientific support of these activities (Antonov 1976, Elshin 1981, 1988, Gottlieb et al. 1976, Ivanov, Nikiforov 1976, Ivanov, Kurzhunov 1980, Kurzhunov 1984, Nikiforov et al. 1980, Odrova 1984, 1987, Orlova 1984, Soviet Arctic 1970).

In the 21st century, a new stage of studies began. New hydrological and meteorological data, the construction of new reservoirs, an increase in the scale of nature management within the catchments of the Arctic rivers, and regional climatic changes required a new assessment of the heat flux and thermal regime of these rivers. The research primarily focused on analyzing the adaptation of the thermal regime to these processes, clarification of spatial and temporal patterns, and assessment of the contribution of climate-induced and anthropogenic factors to the observed changes.

New estimates of the heat flux in the lower reaches and estuaries of the main Arctic rivers, heat inflow into the Arctic seas, and new conclusions about long-term trends and cycles in water temperature and heat flux were presented in (Geoecological state…, 2007, Kosmakov 2001, Magritsky 2009, 2015, Magritsky et al. 2004, Vasilenko et al. 2020, Georgiadi et al. 2018, Lammers et al. 2007, Liu 2004, Liu et al. 2005, Park et al. 2017, Yang et al. 2005). Dam-inducted changes in water temperatures and heat flux of the Asian Arctic rivers were analyzed in (Geoecological state… 2007, Kosmakov 2001, Magritsky 2009, 2015, Magritsky et al. 2004, Yang et al. 2004, Ye et al. 2003, Liu et al. 2005). The estimations of decreasing heat flux in the multichannel delta of the Lena River were obtained by D.V. Magritskiy in 2018 (Magritsky et al. 2018). A range of new methods to estimate river heat flux from areas that do not have gauging stations was developed (Geoecological state … 2007, Magritsky 2009, 2015, 2021, Lammers et al. 2007, Liu et al. 2005, van Vliet et al. 2011), as well as multiple complex models, which could be used for future projections of water temperatures and heat flux (Mohseni et al. 1998, Park et al. 2017, Toffolon and Piccolroaz 2015, van Vliet et al. 2011). These models were mostly tested by the data from key gauges at the Ob, Yenisei, and Lena rivers (Park et al. 2017, van Vliet et al. 2011). The dominant role of the thermal factor in the erosion of river banks in permafrost regions was first experimentally confirmed by Costard F. (Costard et al. 2003).

Despite this, there are some issues that were not previously considered, which are related to the thermal state and heat flux of rivers flowing into the Arctic seas, the patterns of their changes over the area and along large rivers, as well as anthropogenic influence on these characteristics. The estimates of heat flux in earlier papers were obtained based on short time series, which covered the period only until the late 1990s - early 2000s, and for a relatively small number of gauging stations. In our study, we prolong hydrological data to 2018/2019 and used more monitoring stations. The changes in water temperatures and heat flux downstream of the basin outlet stations of the Arctic rivers are considered in more detail.

MATERIALS AND METHODS

River water temperature data

Water temperature is measured on gauging stations of the Russian (and former Soviet) Hydrology and Meteorology service (ROSHYDROMET) twice a day, at 8 a.m. and 8 p.m. (local time). On coastal sea stations of ROSHYDROMET (within the river mouths), the temperature is measured 4 times a day – at 00, 06, 12, and 18 UTC. Measurements at river stations are not carried out in winter when the rivers are frozen. In spring, observations often start a few days after ice breaking, sometimes in the near-shore polynya. Therefore, the annual observation period for the studied territory is usually from 4 to 8 months. In autumn, measurements are interrupted when the water temperature reaches 0°C or is less than 0.2°C for a few days. It is usually connected with the autumn ice run. In May and April, all sea coastal waters are characterized by a negative monthly temperature, and November water temperature is also mostly negative.

An important problem with the temperature data is related to the period when it was measured only once a day - in the morning. This was a common practice until the 1950s. According to E.M. Sokolova (Sokolova 1951), morning temperature differs from the average temperature as it is closer to the daily minimum value. On rivers with high water runoff, the difference between the morning and daily average temperature does not exceed 0.1–0.5°C (for monthly values), while on small rivers it can reach 1–2°C. Therefore, we analyzed most of the records only after 1960. Observations are usually conducted close to the river bank with flowing water and a depth of at least 0.3–0.5 m. However, the water temperature measured near the shore does not always show the real mean stream temperature due to permafrost rocks, plant shadowing, groundwater inflow, or the influence of tributaries. Information about gauging stations (g.) on large rivers and the difference in temperatures in the near-shore zone and mean stream temperature was collected during field studies, conducted by the authors and other researchers (Magritsiy et al. 2022). As a result, water temperature data from several gauges were not used due to the great impact of tributaries. For other cases, which were not covered by field studies, we had to use water temperature, which was measured near the river bank. This temperature data was also used in previous studies (Lammers et al. 2007; Park et al. 2020).

For this research, we selected data from 55 out of 150 gauging stations from our database (Fig. 1). The resulting dataset consisted primarily of data for basin outlet stations and stations at the mouths of large rivers flowing into the Arctic seas of Russia. For the large regulated rivers of the Asian part of Russia (Ob, Yenisei, Vilyui, and Kolyma), the data from stations located along the river from the reservoir dam to the basin outlet station, were also used. This accounted for a total of 28 stations from the dataset. The remaining data corresponded to stations on rivers and main tributaries between the mouths of the large Arctic rivers. Due to gaps in the published water temperature data, in this research we only used stations, which had monthly water temperature records of at least 20 years in 1961-1991, and at least 15 years in 1991-2018/2019. Data on water temperature are published by ROSHYDROMET in their annual handbooks as 10-day and monthly average values together with maximum values and the dates of their occurrence.

For the largest rivers of the region, we used water temperature and water flow records from 1936 to 2018 and also calculated different statistics for the period before and after 1970. This year was chosen because water flow and air temperature changes began after 1970, and the great dams on the Ob and Yenisei rivers were built before 1970. The number of coastal stations decreases from the West to the East. Measurements in the river parts of estuaries and deltas are conducted for the Onega, Severnaya Dvina, Pechora, Ob, Yenisei, and Lena rivers. Coastal water temperature data for the Russian Arctic seas are available in open source mostly from 1977. Many stations, however, were closed in the 1980s and 1990s. Nearshore zone temperature data were collected from "The Unified State Information System on the situation in the World Ocean" (http://portal.esimo.ru/portal). We used the information from offshore coastal stations to analyze the seaward transformation of the temperature regime within river mouths.

River discharge data

Water discharge measurements in the Russian Arctic began in the 1880s on the rivers in the North of the European part of Russia. Measurements on most rivers began in the 1930s and 1940s. The highest quantity of discharge measurements with the greatest coverage of river basins was from the 1960s to 1980s. However, since the 1990s a lot of gauging stations were closed and at many stations discharge measurements were terminated. Measurements of water discharge are no longer carried out in the mouth reaches of the Taz, Pyasina, Khatanga, Yana, Indigirka, Alazeya, Kolyma (Kolymskoe-1), Amguema, and Anadyr rivers, as well as on other medium and small rivers flowing into the Arctic seas. At the mouth of the Yenisei (Igarka) and Lena (Kyusyur) rivers, water discharge measurements are occasional, while in the Lena River delta they are completely abandoned. At the mouths of the Nadym and Pur rivers, water discharge measurements were resumed after a long break in 2010 and 2013.

Water discharges are measured once every 10 days (RD 2020; Instructions… 1978) at gauges which have water discharge measurements in their program. Measurements can be more frequent during the period of high flow. Daily discharge values are calculated by regional ROSHYDROMET services based on established relationships between discharge and water levels, which are measured twice a day. 10-day mean water discharges are calculated as a mean of the daily discharge values for a period of 10 days. Monthly discharges are also calculated as a mean of the daily values. Previously obtained empirical relationships between water levels and discharges, as well as between water discharges at different gauging stations, continue to be officially used to calculate water discharges at some hydrological stations, where water discharges are either no longer measured, or are not measured every year. An example of this is the situation at the stations Igarka (Yenisei), Saskylakh (Anabar), and Kolymskoye–1 (Kolyma). Water discharge measurements are usually conducted within 1 km from the point of water temperature and water level measurements, at the most suitable place on the river. Water discharge data for each station are published in the annual hydrological handbook of ROSHYDROMET as daily, 10-day, monthly, and annual average values together with maximum and minimum values and the dates of their occurrence.

In total, data on water discharges from 35 stations for the period from 1930 to 2018 were used. Many of the selected long-term discharge time series had gaps, a late beginning (in the 1960s or 1970s) or an early end of observations (mostly in the 1990s). To solve this problem, the reconstruction of missing values and lengthening of time series was carried out using one-dimensional and sometimes multiple regression. Water discharges were reconstructed based on the data of equivalent stations, which were characterized by an empirical relationship with correlation coefficients (R) greater than 0.7-0.8.

Methods

Heat flux was calculated using the equation from (Elshin 1981; Magritsky 2009; Methodological recommendations … 1961): $W_T = c_p \rho W \bar{T}_w$, where W_T, is heat flux, Joule (for 10 days or a month); c_p is specific heat capacity, which is 4,174-4,212 Joule/(kg×°C) for T_w from 0 to 30 °C; p is fresh water density; W is water runoff, m^3 (for 10 days or a month); $\bar{T}_w$, is mean water temperature for the same time interval. Heat flux over a year or hydrological season is obtained by summing 10-day or monthly values of W_T. It was found that there is a difference between the values of annual heat flux calculated using monthly (main case) and 10-day values, which can be characterized by the coefficient $K_{d/m}=W_T$(10 days)/W_T(month) (Magritsky 2021). In the northeast of the Asian part of Russia, the coefficient $K_{d/m}$ varies from 0.90 to 1.05. For most stations, heat flux was calculated based on monthly data.

Identification and assessment of trends in long-term fluctuations of T_w and heat flux of rivers in the region were carried out using graphical and statistical methods. The first group of methods included plotting and analysis of

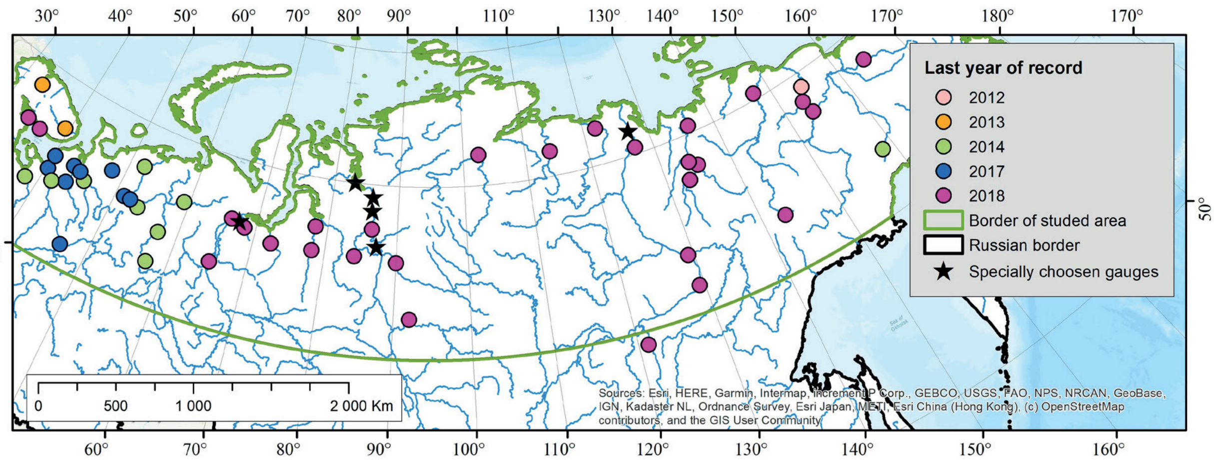


Fig. 1. Geographical location of analyzed gauging stations, and the last year in their water temperature records

the general time series graphs T_w=*f(t)*, W_T=*f(t)*, as well as the differential mass (*St*) and the total mass (Ss) curves. Ordinates of the differential mass curves were calculated as $St_i=\sum_i^t\left(x_i/\bar{x}-1\right)$, and for the total mass curves – as $Ss_i=\sum_i^t x_i/\bar{x}$, where x_i - is the value for a certain year. The second group of methods was necessary for quantifying the main hydrological characteristics, as well as for confirming the statistical significance of the identified trends and differences in average values and variance of the selected independent long-term periods. In this study, we analysed data series (with a significance level α = 5% for all tests) for homogeneity (using the F-test, t-test, and Mann-Whitney U-test). The Mann-Whitney test was used as the main one because it does not assume normal distribution and provides good results even for short records. The presence and statistical significance of trends were analysed using Spearman's rank correlation coefficient, which is close to the Mann-Kendall test. The Pettit test was used for detecting a "change point" in water temperature and heat flux records. This test is commonly used for detecting "change points" in water flow data for Russian rivers (Frolova et al. 2022), which provides an opportunity to compare changes in water and temperature regimes. This test allows to identify only one point in a time series, so local changes were analyzed using trends and by comparing statistical characteristics (mean and standard deviation) of the two nearest periods. The local increase or decrease in water temperatures and heat flux could occur in short time periods (less than 15-20 years). Due to the gaps in the 1990s and in the past years, the length of data could be not enough to calculate statistical significance, so we were somewhat cautious about some of the results obtained for the last decade (2011-2020) in the North of the European part of the Russian Arctic.

It was decided to consider 1961-1990 as the base period, and 1991-2018/2019 as the modern period. This was based on the recommendations of WMO, the features of the initial data on water temperature, and the analysis of graphs. To improve our estimations, we compared differences in the mean values of 1991-2018 and 1961-1990 with their standard error of the mean (SEM), and also with the SEM of 1960-2018 ($SEM=\sigma/\sqrt{n}$, where σ is standard deviation, n is the number of values in the series), which helped to separate changes driven by changing record length from changes, which were driven by other reasons.

The analysis of changes in water temperature and heat flux of rivers caused by large reservoirs was carried out by comparing changes in the values of T_W and W_T along their channel for two or three periods using both statistical and graphical tools. These periods were chosen based on the different magnitude of anthropogenic impact on the hydrological regime of rivers, but similar temperature conditions and annual/monthly river runoff.

Statistical tests were conducted using Python. Data was prepared with MS Office Excel. Data analyses were made both using Python and MS Office.

RESULTS AND DISCUSSION

Long-term fluctuations of water temperature and heat flux under climate change

From the performed analyses it was found, that water temperature in the lower reaches and estuaries of large rivers in the Russian Arctic is mainly increasing. However, there are differences in the magnitude of changes, as well as in periods of the most significant changes in water temperature and heat flux. The maximum water temperature on most rivers is observed in June.

The long-term variability of the temperature regime of the large rivers flowing into the White and Barents Seas is driven only by natural causes. The beginning of T_W increase in the lower reaches of these rivers corresponds to the beginning of noticeable climate changes, particularly in air temperature, which date back to the second half of the 1970s - early 1980s. The increase of T_W was found in all months of the warm season of the year. The greatest growth was recorded in June, during the decline of the spring flood. Compared to 1961-1990, the temperature in 1991-2018 increased by 1.5–2.1°C. The same changes of T_W were observed for most of the rivers of the Onega, Severnaya Dvina, Mezen, and Pechora watersheds, as well as on the Kola Peninsula.

However, the amount of statistically significant T_W changes (based on the U-test) is relatively small. The most significant changes in this part of the Russian Arctic were observed in June. The highest changes of T_W in June (2.0-3.0°C) were found in the Pechora watershed (but not in the Pechora itself). In other months of the warm period, T_W in all watersheds of the White and the Barents Seas changed by less than 1°C. The number of gauges with statistically significant changes of T_W account for 31-42% of gauges used in this research (in the Barents and the White Sea watersheds) for July and August, and 62-69% for May and October. Most of the gauges demonstrated significant changes in June (81%) and September (73%). In the Onega, Severnaya Dvina, and Mezen lowlands, significant changes in T_W (based on the U-test) were observed from June to September, while in the Pechora lowlands, significant changes in TW were observed in all warm months except July and August.

The largest rivers of the Asian Part of the Russian Arctic are regulated, but the rivers of their Arctic watersheds are still in natural conditions. T_W increase on gauges of this region was similar to the rivers of the White and Barents Seas watersheds. The highest changes were observed in June on large rivers of the Kara Sea watershed (2.0-3.0°C). In the upstream of the Pur river, the change in TW for June reached 4.0-5.0°C, however, there was a gap in observations in the 1990s, so this result is not as reliable as others.

Statistically significant changes in T_W of rivers in the Asian part of the Russian Arctic (based on the U-test) were observed for 30% of gauges only in May and June, while the number of gauges with significant changes from June to October is even lower. A significant increase in T_W in July and August was found only for a small group of medium rivers of the Laptev Sea watershed, particularly in the Yana and Indigirka watersheds.

Small statistically significant changes in T_W accompanied by a steady trend since 1961 without sharp changes were observed at most of the gauges, including gauges on large rivers (Fig. 2). Besides, it was found that long-term fluctuations of T_W, both annual and monthly, are gradual. This suggests that substantial T_W changes over a 20-30 years period could be caused by several extremely hot years. Therefore, differences in the mean values of the base period (1961-1990) and the modern period (1991-2018) are less than the differences between the base period and the second half of the modern period (Table 1). Significant trends are shown by the colors, presented at the bottom of Table 1. Two rows for each gauge correspond to the differences in T_W in 1991-2018 compared to 1961-1990, and in 2005-2018 compared to 1961-1990.

Table 1. Changes in the mean monthly water temperature of large rivers in the Russian Arctic in 1991-2018 compared to 1961-1990 and in 2005-2018 compared to 1961-1990

River – Gauging station	The period compared to 1961-1990	Month							
		April	May	June	July	August	Sept.	October	Nov.
Onega – Porog	1991-2018	0	**0.8**	**0.8**	0.9	**0.6**	0.9	0.8	0.3
	2005-2018	0.1	1.9	0.7	0.7	1.2	1.0	0.6	0.4
Severnaya Dvina - Ust-Pinega	1991-2018	0	**1.0**	**1.6**	**0.9**	**0.6**	**1.1.**	**1.2**	0.1
	2005-2018	0	0.8	0.4	0.3	0.9	0.4	0.4	0.3
Mezen – Dorogorskoe	1991-2018	0	**0.8**	**1.1**	0.3	0.2	0.2	**1.0**	0
	2005-2018	0	1.5	0.6	0.2	1.6	1.3	0.2	0.2
Pechora - Ust-Tsilma	1991-2018	0	**0.6**	**2.1**	**0.9**	**0.5**	**0.5**	**0.8**	**0.1**
	2005-2018	0	0.9	1.8	0.1	-0.1	0.2	1.0	0.1
Ob – Salekhard	1991-2018	0	**0.6**	**2.4**	**1.8**	**0.8**	**0.6**	**0.7**	**0**
	2005-2018	0	-0.1	0.8	0.6	-0.1	1.1	0.9	0
Nadym – Nadym	1991-2018	0	**1.1**	**2.4**	-0.3	0.1	0.2	**0.4**	0
	2005-2018	0	0.1	1.3	0.9	-0.1	1.5	0.6	0
Enisei – Igarka	1991-2018	0	**0.2**	2.5	1.2	-0.1	0.1	**0.6**	0
	2005-2018	0	0.1	1.9	1.5	-0.7	0.6	0.8	0
Khatanga – Khatanga	1991-2018	0	0	**1.6**	0.1	-0.4	0.4	**0.3**	0
	2005-2018	0	0	1.9	0.2	-0.1	0.8	0.2	0
Anabar – Saskylakh	1991-2018	0	**0.1**	**0.8**	-0.1	0.2	**0.6**	0	0
	2005-2018	0	0.1	2.2	0.8	0	0.9	0.1	0
Olenek – Taimylyr	1991-2018	0	0	**1.9**	**1.5**	**1.1**	**0.4**	0	0
	2005-2018	0	0	1.8	0	-0.1	0.8	0.1	0
Lena – Kyusyur	1991-2018	0	0	**0.9**	**1.2**	**1.1**	0.1	0	0
	2005-2018	0	0	1.5	0	0.4	-0.1	0.2	0
Yana – Yubileinaya	1991-2018	0	**0.1**	**0.7**	**0.8**	**1.3**	0.4	0.1	0
	2005-2018	0	0.1	1.7	-0.1	1.0	1.1	0.1	0
Indigirka – Chokurdakh	1991-2018	0	0	**1.2**	**1.0**	**0.9**	0.9	0.1	0
	2005-2018	0	0.1	1.5	-0.5	0.1	1.0	0,3	0
Kolyma – Srednekolymsk	1991-2018	0	0.1	0.1	**0.5**	**0.7**	**1.1**	**0.4**	0
	2005-2018	0	0.2	0.5	-0.3	0.6	0.9	0.1	0
	Significant trend only in 1961-2018								
	Significant trend in 1961-1990 and 1991-2018								
	Significant trend only in 1991-2018								
1.5	Changes are higher than the standard error in 1960-2018, 1961-1990, and 1991-2018								

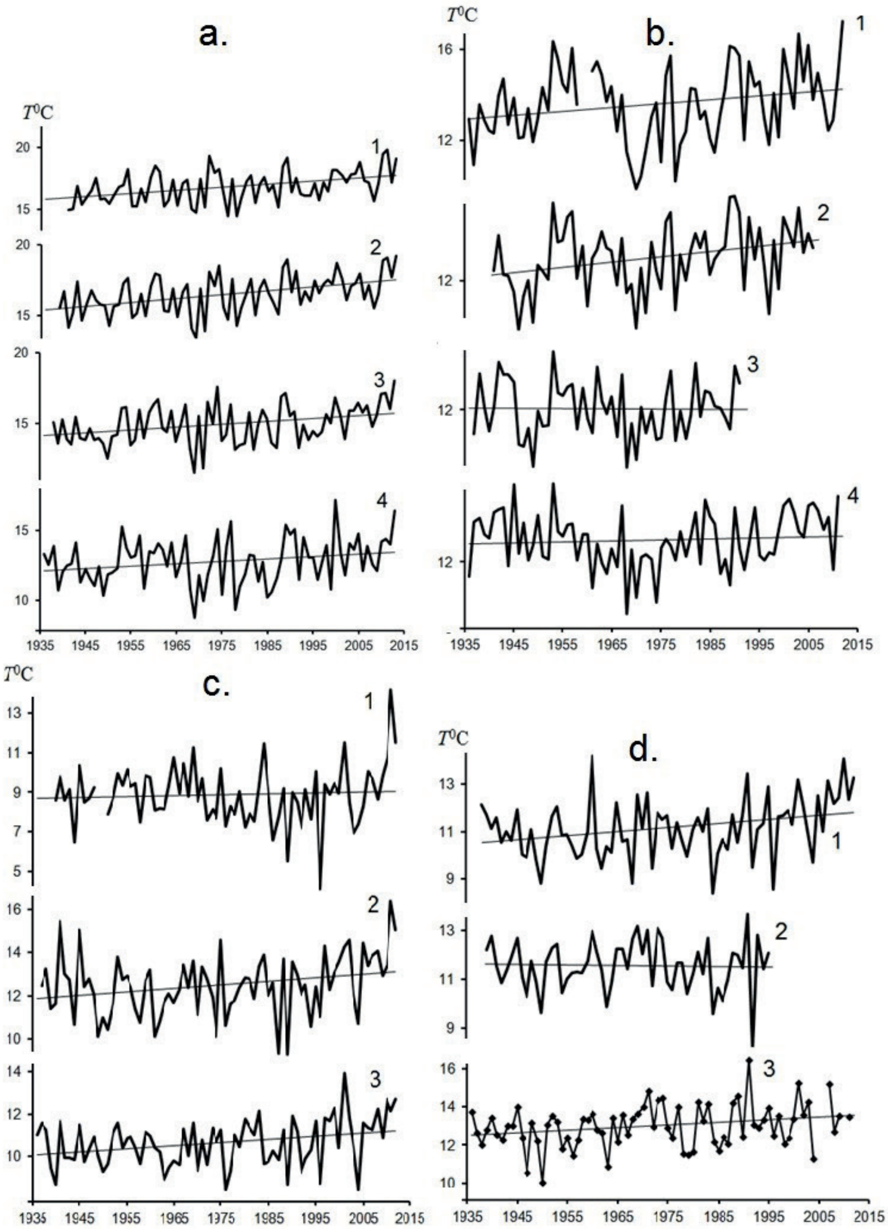


Fig. 2. Long–term changes in the mean water temperature in June–August at the basin outlet stations of the large rivers of the Russian Arctic: a. 1 – Onega (Porog), 2 - Severnaya Dvina (Ust–Pinega), 3 – Mezen (Malonisogorskaya), 4 – Pechora (Ust-Tsilma); b. 1 – Ob (Salekhard), 2 – Nadym (Nadym), 3 – Pur (Samburg), 4 –Yenisei (Igarka); c. 1 – Anabar (Saskylakh), 2 – Olenek (Sukhana), 3 – Lena (Kyushur); d. 1 – Yana (Yubileinaya), 2 – Indigirka (Vorontsovo), 3 – Kolyma (Srednekolymsk)

Some differences were found in the starting point of a steady increase in seasonal and monthly water temperatures (the Pettit test) after 1960. For the months from May to October (except for September) the median "change point" is between 1989 and 1996, while for September it is in 2000. The median for watersheds (or the Arctic parts of watersheds of large rivers) is in a range from 1983 to 2007. So, the main changes in the water temperature regime after 1960 occurred either close to the changes in air temperature, precipitation, and water flow, or started later (Frolova et al. 2022, Report… 2022). In any case, the increase in water flow and water temperature occur simultaneously at least in the past decade, but more often – since the end of the 1990s.

River heat flux (W_t) is currently either stable or decreasing, despite the increase in water temperatures. This is also affected by the selected periods for comparing the mean values of heat flux.

For example, together with the precipitation and air temperature increase, the annual flow of the Severnaya Dvina increased in 1991-2018 by almost 8.4 km^3 (mainly in the warm season of the year), which entailed a corresponding increase in heat flux (W_T) by 11% compared to 1961-1990 from 2.7 to 3 EJ/year (Table 2). The highest increase in the Wt of the Severnaya Dvina was observed in 1991-2004. In 2005-2014, the annual W_T was the same as in the base period – 2.7 EJ/year. However, it is expected to increase after 2014 due to several extremely hot summer periods in the North of the European part of Russia (Report 2022). The W_T of the Pechora increased by 8.4% (from 2.7 to 2.9 EJ/year). In 2005-2018 it increased further to 3.0 EJ/year. The W_T of the Onega and Mezen rivers in 1991-2018 changed slightly compared to the base period - by 1.5-2%.

At the same time, the heat flux of the Pechora in 1971-2018 increased significantly compared to 1936-1970 (by 11%). The Onega heat flux, meanwhile, did not change in these periods, and the Severnaya Dvina heat flux increased by 4%, which was found to be statistically insignificant (Fig. 3).

The conclusions are also affected by the selected statistical test for homogeneity. The Student t-test marks heat flux changes as significant for more rivers, than the Mann-Whithey U-test (Fig. 3). However, due to the varying normality of records, the results of the nonparametric analysis are more reliable.

The predominant role of natural factors in the fluctuations of heat flux (W_T) is characteristic of unregulated rivers flowing into the Kara Sea. The exceptions are the Yenisei River, regulated by the cascade of large Angara-Yenisei reservoirs, and, to a certain degree, the Ob River, regulated by the Novosibirsk reservoir and the cascade of the Irtysh River reservoirs. The major increase in T_W in this sector of the Russian Arctic was observed since the middle of the 1980s (Fig. 2b) and continues nowadays. The maximum increase in T_W was recorded in June (2.1-2.4 °C) (Table 1). In the remaining months, it was less than 1.1-1.2 °C. The Ob, Nadym, and Yenisei rivers are characterized by the acceleration of the TW increase in June over the last decade (2011-2018) and decreasing intensity of the T_W increase in other months, except May.

Long-term fluctuations of W_T are not so unambiguous. In the mouth of the Ob River, W_T changed by 9.2%. In the 1970s, 1980s, and the first half of the1990s, the W_T of the Ob River decreased (Fig. 3, Table 2). Since 1998, it increased in response to an increase in water runoff, while the water temperature began to rise earlier - from the second half of the 1980s. In the lower reaches of the Yenisei River, low values of W_T were observed from the 1960s to the late 1990s (Fig. 3), despite the positive runoff trend since the mid-1970s (Frolova et al. 2022). Here, the heat flux compared to 1936-1970 decreased by 7.2% (Fig. 3). Only since 1999/2000 W_T shows an increase, driven by a significant increase in both runoff and water temperature. Up to this point, T_W changes were positive, but insignificant due to a complex combination of variable fluctuations in spring and summer-autumn air temperatures in different parts of the watershed (http://seakc.meteoinfo.ru/about-centre/bulletin), which were also combined with the dam-induced effects. The main reason for the small long-term changes in heat flux of the Yenisei is the anthropogenic inter-seasonal redistribution of its runoff (Magritsky 2008). As a result, the relative discharges of the flood and the warm season in general decreased, and the winter runoff, on the contrary, increased. In 1991-2018, the annual heat flux of the Yenisei increased by 7.8%. However, it is also important to consider the construction of new reservoirs in the catchment area in recent years.

In the rivers, flowing into the western part of the Laptev Sea, changes in heat flux in some cases were caused by the multidirectional changes of T_W and water runoff, so far with the dominant role of the latter. T_W had a significant increase since the late 1990s – early 2000s in the lower reaches of the Khatanga, Anabar, and Olenek rivers, similar to the lower reaches of the Yenisei River (Fig. 2b). Moreover, in the lower reaches of the Anabar River, it was especially sharp after a long period with low TW (beginning in the mid–1970s). The maximum increase in river water temperature in all months was recorded in the lower reaches of the Olenek Rivers – by 1.9, 1.5, 1.1, and 0.4 °C in June, July, August, and September, respectively (Table 1). At the basin outlet stations of the Khatanga and Anabar rivers, a significant increase of T_W occurred only in June – by 1.6 and 0.8°C, respectively. In the remaining summer months, the changes were small. Anomalies of water flow in the warm period were positive from the mid-1980s to the mid-1990s after there was a decrease. As a result, since the beginning of the 2000s-2010s, there is a tendency of decreasing heat flux in the lower reaches of the Olenek River (Fig. 3). Nevertheless, in 1991-2018 heat flux of the Anabar and Olenek rivers increased by 22.3% and 18.4 %, respectively, compared to the base period (1961-1990).

The thermal state of the lower reaches of the Lena River is not affected by the operation of reservoirs on the Vilyui River, while the temperature regime of the tributary itself has undergone noticeable anthropogenic changes (Magritsky 2015). The heat flux of the lower Lena (Kyusyur) in 1991-2018 exceeded its value in 1961-1990 by 5%, increasing from 15.8 EJ/year to 16.7 EJ/year. However, this change was not statistically significant, as well as most changes in heat flux (Table 2).

Statistically significant climate-driven changes in heat flux were observed on the rivers between the Lena and Kolyma (Figure 3). The major increase began in the second

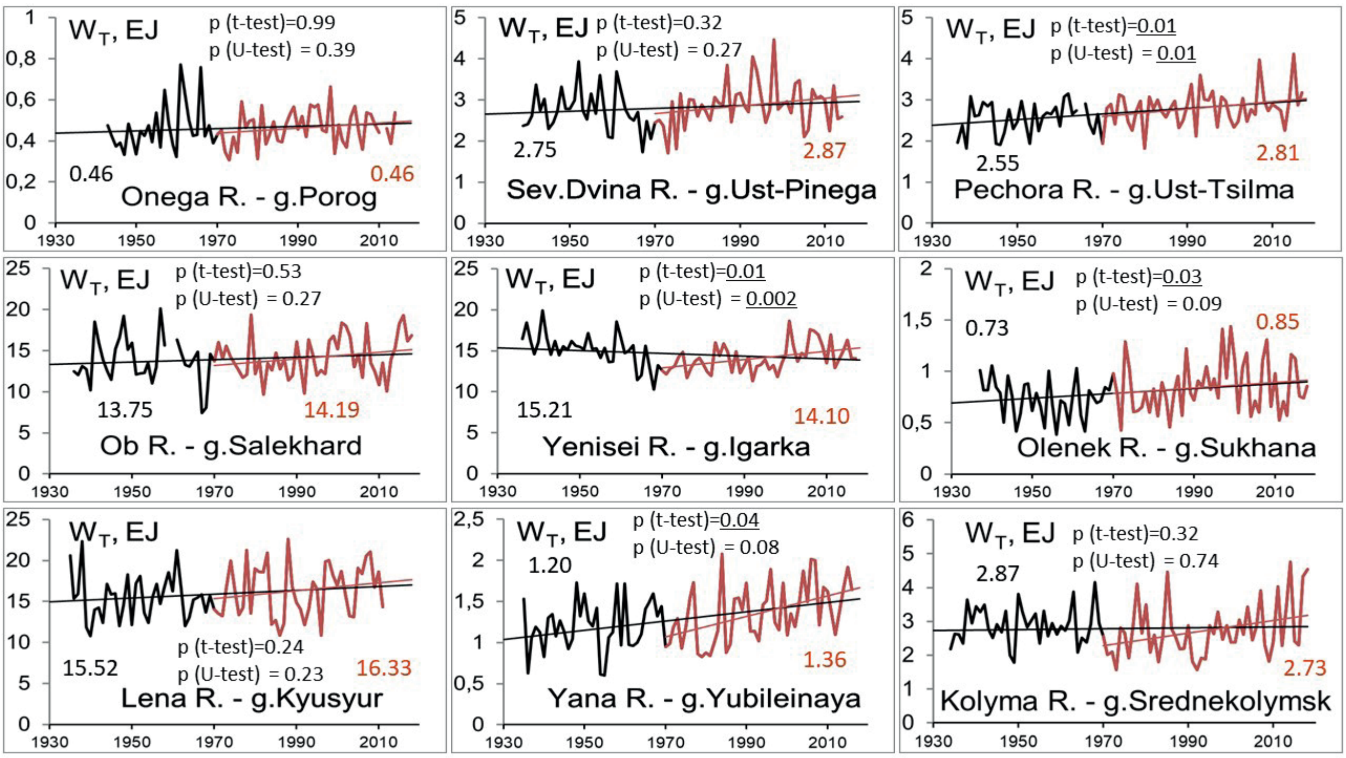


Fig. 3. Long–term changes of the annual heat flux (the mean heat flux for 1936-1970 is shown in black, and the mean heat flux for 1971-2018 is shown in red)

Table 2. Statistical characteristics of heat flux changes of large Russian Arctic rivers lowlands (significant changes due to U-test are marked with bold)

River – gauge	Mean W_T, EJ/year		Changes, %	U-statistics	p-value
	1961–1990	1991–2018			
Onega – Porog	0,47	0,48	2	304	0,46
Severnaya Dvina – Ust-Pinega	2,70	2,99	11	264	0,09
Pechora – Ust-Tsilma	2,69	2,91	8	294	0,11
Ob – Salekhard	13,40	14,63	9	319	0,12
Yenisei – Igarka*	**13,50**	**14,56**	**8**	**278**	**0,04**
Olenek – Sukhana	0,76	0,90	18	295	0,05
Lena – Kusur	15,85	16,65	5	260	0,29
Yana – Yubileinaya*	**1,23**	**1,47**	**20**	**220**	**0,01**
Koluma – Srednekolumsk	2,71	2,82	4	411	0,89

half of the 1990s, due to the increase in water flow and TW (Figure 2d). The hydrological and thermal regimes of the Kolyma River are influenced by the Kolymskoe reservoir (built in 1980) (Magritsky 2008, 2009) and the Ust-Srednekanskoe reservoir (built in 2013). T_W in the lower reaches of the Kolyma River increased in 1991-2018 in all months of the warm period. At the mouth of the Kolyma River, there is a positive trend in heat flux since the mid-1990s. The main reason for these changes is the climate-driven increase in summer and autumn temperatures, which is observed since the late 1980s, and an increase in water flow during the warm season, observed since the mid-1990s (Report 2022; Frolova et al. 2022). This, as well as the case of the lower Yenisei River, indicates an intensification of climate change in recent decades.

Calculation of heat flux in the mouths of large river based on observation data

The heat flux of the rivers flowing into the seas of the Russian Arctic is quite high, despite the relatively low T_W and the short season of the year with T_W ≥0-0.2 °C. Two factors help this. The first factor is the high water runoff of these rivers and the significant role of water runoff in the formation of heat flux. The second factor is the similarity of water and temperature regimes. Typical intra-annual changes of T_W in the Arctic zone of Russia consist of a gradual increase of T_W in spring, a maximum in July/August, and a slow decrease in autumn. Spring flood (characterized by high water discharges) takes place in spring-summer or only summer months. There are low discharges in the low flow season with high water temperatures, but rainfall floods increase the heat flux in summer.

The annual W_T of the large Arctic rivers is at least 62.09 EJ/year (1981-2012), of which 45.53 EJ/yr, or 70%, is the heat flux of the biggest rivers: Ob, Yenisei, and Lena. It is necessary to mention, that the error in the estimation of the Lena River mean annual heat flux (at Kyusyur gauge) varies from -0.79 EJ/yr (Magritsky et al. 2018) to 2.7·EJ/yr (Tananaev et al. 2019). There are no such estimations for the lower reaches of the Ob and Yenisei rivers. The heat flux of the estuaries of the White Sea is at least 4.25 EJ/yr. The share of the Severnaya Dvina is 3.06 EJ/yr, which is similar to the Pechora River. The heat flux from the Kola peninsula to the Barents Sea is at least 0.16 EJ/yr, however, the data for many rivers of this region was not available. The heat flux of the Yana and Indigirka rivers is less than 10% of the heat flux of the Lena River. W_T of the Indigirka and Kolyma rivers was almost the same until the construction of a new reservoir on the Kolyma River. As it was mentioned earlier, the total heat flux of individual rivers in past decades is increasing. It is important to note that in 2013-2018, the annual W_T of most rivers changed significantly with the maximum changes observed in the lower reaches of the Olenek River.

The W_T of the large rivers of the White Sea catchment is primarily formed in spring (April–May – 24-28%) and summer (June–August – 58-65%). In other sea catchments, summer months play the major role: 82% for the Pechora River, 85-92% for the Kara Sea, 89-96% for the Laptev Sea, 88-92% for the East Siberian Sea, and 96% for the Amguema River (the Chukchi Sea). The intra-annual distribution of heat flux in the mouths of large rivers is illustrated in Figure 4. The transit of heat with medium and small rivers of the Kola Peninsula is observed from May to September. The range of intra-annual fluctuations in monthly heat flux is small (0.03 EJ/year) due to the significant regulation of runoff by numerous lakes and reservoirs. By September, the heat flux of these rivers decreases to 0.01 EJ/year or less.

Patterns of the water temperature and heat flux variation along river channels

The patterns of T_W and W_T changes along the large regulated rivers, as well as downstream of the basin outlet stations were studied. The influence of large reservoirs on the thermal state of the main rivers flowing into the Arctic seas is observed in all seasons throughout hundreds of kilometers. The degree and range of this influence depend on the following factors: 1) the size of the reservoir, type of regulation, and discharge system of the hydroelectric power plant (HPP); 2) the flow direction of the river and conditions of the climate zones which it crosses; 3) hydrological and thermal regime of tributaries, and their spatial distribution; 4) channel morphology; 5) additional anthropogenic impact downstream from the reservoir.

The first consequence of the construction of large reservoirs on the Ob, Irtysh, Yenisei, Vilyui, and Kolyma rivers was a decrease in water runoff during the period with positive T_W (Magritsky 2008, 2015, Magritsky et al. 2018). The second consequence was a decrease in T_W in some months and an increase in others directly near the

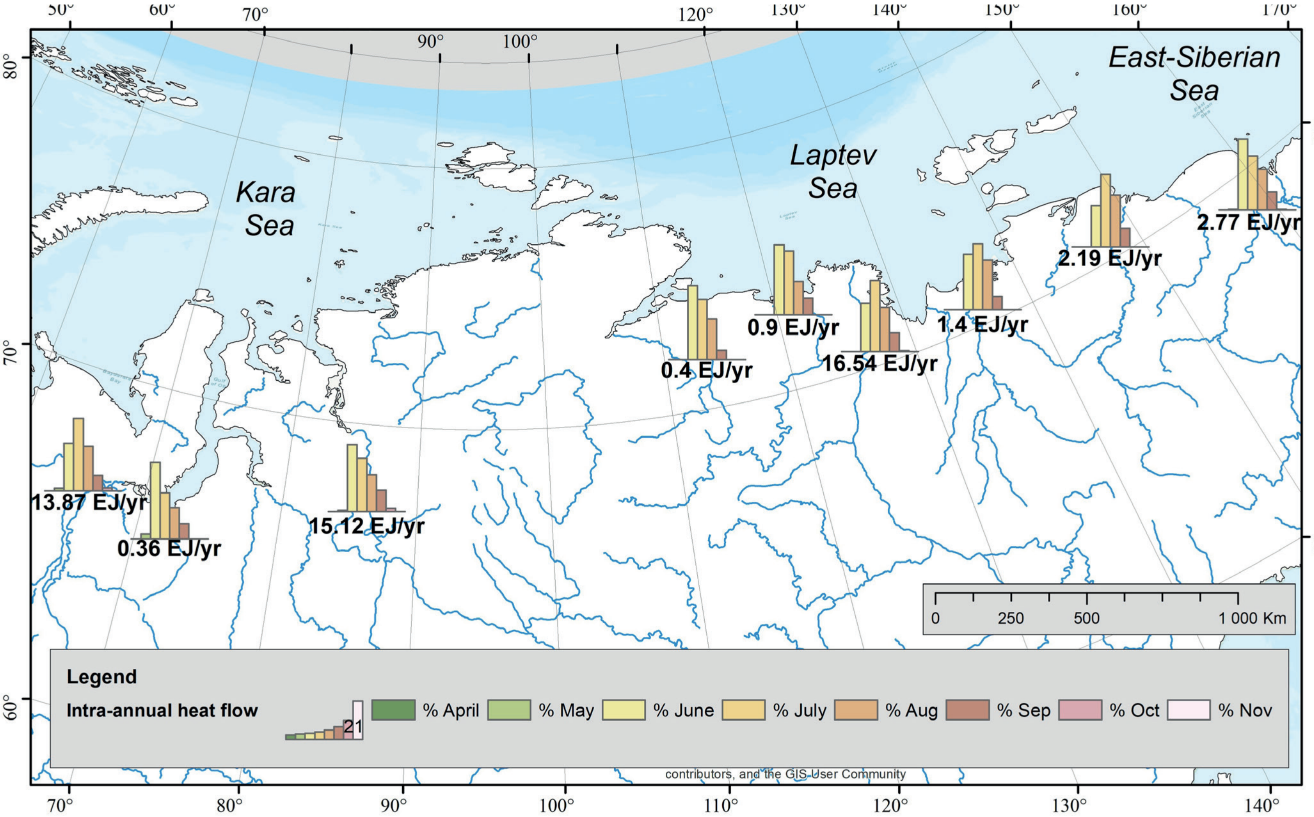


Fig. 4. Relative intra-annual distribution of heat flux in the mouths of Arctic rivers for the period 1981-2012

dams. For example, near the dam of the Krasnoyarsk HPP, T_W decreased in May-September (by 12.2°C in July and 1°C in September), while in January–March it increased by 1.3°C, and by 6°C in October–November. Positive winter TW is observed all the way until the mouth of the Angara River. Near the Kolyma HPP, T_W decreased by 6.4°C in June and July, and by 1.6°C in August. In September and November–May, the temperature increased by 0.5–1.9°C, and in October by 4.4°C. The decrease in water temperature in April, May, and June downstream of the Novosibirsk reservoir was about 0.4, 5.0, and 2.0°C, and its increase in August - November was in the range from 0.2 to 2°C. In July, the changes in T_W were insignificant.

The third consequence is the restoration of the natural temperature conditions at a significant distance from the dams. On the Yenisei River, the maximum intensity of temperature restoration corresponds to May–October, when it occurs over the first 400-600 km (Kosmakov 2001; Magritsky et al. 2004). In summer, the natural temperature conditions are restored at a distance of 700-750 km, and in winter – 400 km from the dam. On the Kolyma River, the ultimate restoration of water temperature was recorded in November–April at 40-100 km downstream of the Kolyma HPP, while in May–October it is restored 230-620 km downstream. In June, the influence of the reservoir may extend to a much greater distance. The influence of the Novosibirsk reservoir on T_W of the Ob River varies on average from 600-800 km in April, May, August–October to 150-400 km in June–July (Magritsky et al. 2019). The largest influence is observed in November, reaching the mouth of the Irtysh River (>1500 km). Larger distances are indicated in (Orlova 1984), and smaller ones – in (Beirom et al. 1973). The further extent of the observed violation of the temperature regime is caused by the changes in the water regime of the Ob, the changed role of tributaries, and the variability of climatic factors.

The fourth feature is a decrease in the heat flux of regulated rivers. Along the length of the Yenisei River, W_T increases both in natural and regulated conditions. This is due to an increase in water flow towards the mouth of the Yenisei River, which compensates for the anthropogenic decrease in W_T. Between Krasnoyarsk and Igarka (a distance of 1765 km), W_T in natural conditions increased almost 4 times. The contribution of the Angara River to the heat flux was 29%. Under the new conditions, W_T at a distance of 40, 448, 934, and 1805 km from the Krasnoyarsk HPP is equal to 45, 61, 79, and 90% of its natural value. At Igarka, a significant decrease in W_T was detected in 1964 and continued until 1998–1999. The impact of the Novosibirsk reservoir on heat flux also weakens along the length of the Ob River and remains almost unchanged downstream of Kolpashevo and under the combined influence of the Ob-Irtysh reservoirs. Near the Novosibirsk HPP, W_T is equal to 84% of its natural value. At 23, 564, 1834, and 2699 km downstream, W_T is 88, 95, 95, and 95%. Some aspects of the impact of reservoirs on thermal characteristics are gradually being leveled due to climate warming. For example, since the end of the XX century and at the beginning of the XXI century, an increase in heat flux has been recorded in the estuaries of the Yenisei and Kolyma rivers.

Downstream of the basin outlet stations of the Arctic rivers and towards the sea, a decrease in T_W and W_T usually prevails. The heat flux of the Ob and Lena rivers slightly increases in the pre-estuary sections by 0.87 and 3.4%, respectively. A great longitudinal transformation of W_T and T_W was found in the pre-delta reaches of the Yenisei River as T_W in May-July gradually decreases downstream of Igarka (Fig. 5). Moreover, in May and June, there is a slight increase in T_W near Potapovo, possibly related to the operation of the Ust-Khantaiskoe reservoir. In August-October, the maximum T_W is observed at Dudinka, however, we cannot exclude the influence of the Dudinka River and Dudinka seaport on the measurements at the gauging station. At the same time, heat flux decreases by 4.3 EJ/year. The decrease in W_T is especially noticeable in June (2.45 EJ/month), and its value gradually decreases by September.

In the Arctic river deltas, temperature conditions and heat flux change is influenced by 1) the distribution of runoff between delta branches, 2) the direction and length of the

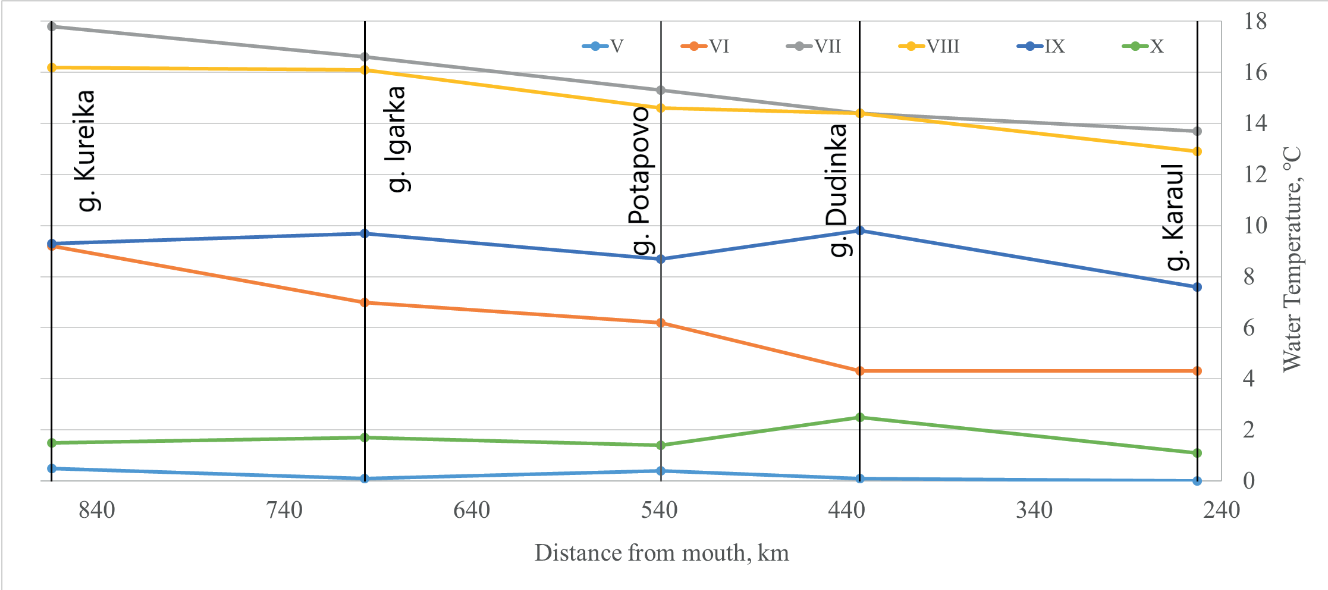
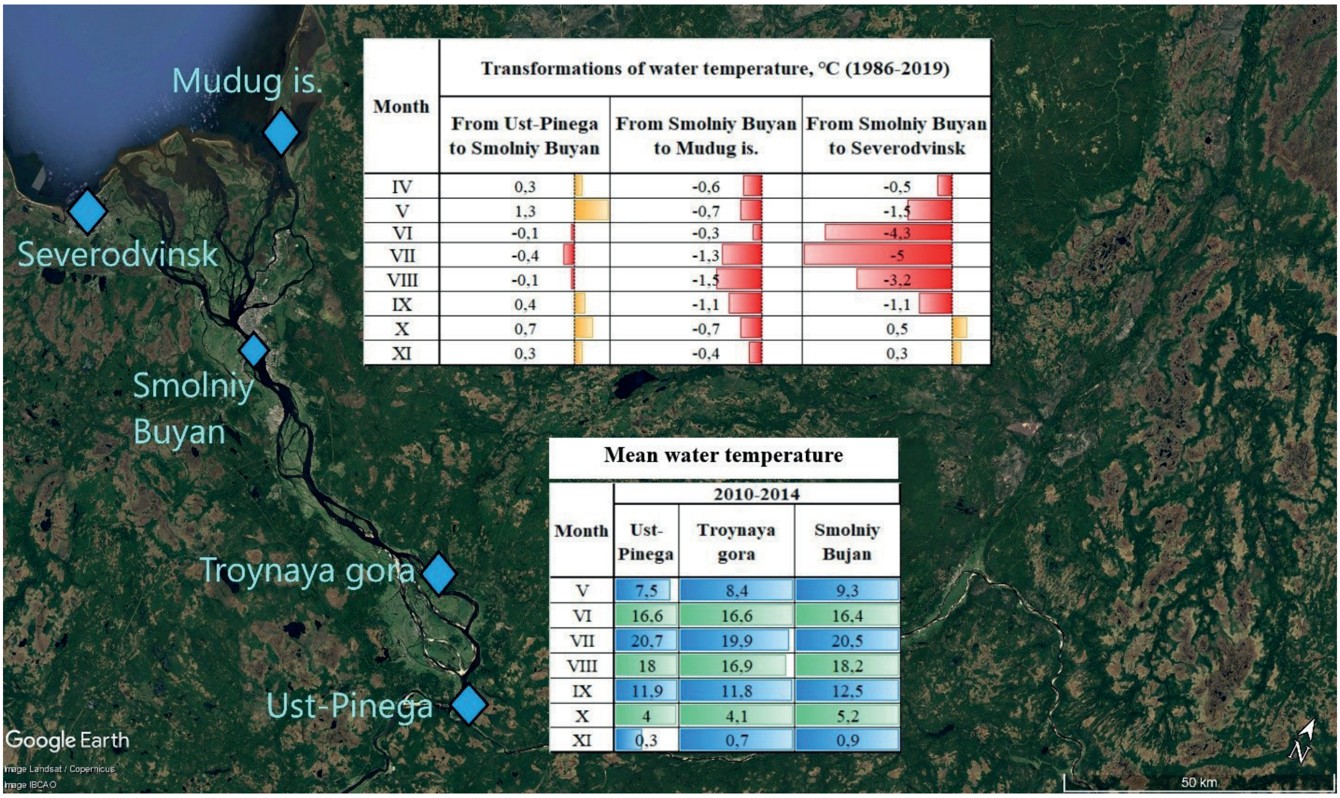


Fig. 5. Changes in the average monthly water temperatures from the mouth of the Kureika River to the Karaul gauge



Month	Transformations of water temperature, °C (1986-2019) From Ust-Pinega to Smolniy Buyan	From Smolniy Buyan to Mudug is.	From Smolniy Buyan to Severodvinsk
IV	0,3	-0,6	-0,5
V	1,3	-0,7	-1,5
VI	-0,1	-0,3	-4,3
VII	-0,4	-1,3	-5
VIII	-0,1	-1,5	-3,2
IX	0,4	-1,1	-1,1
X	0,7	-0,7	0,5
XI	0,3	-0,4	0,3

Month	Mean water temperature 2010-2014 Ust-Pinega	Troynaya gora	Smolniy Bujan
V	7,5	8,4	9,3
VI	16,6	16,6	16,4
VII	20,7	19,9	20,5
VIII	18	16,9	18,2
IX	11,9	11,8	12,5
X	4	4,1	5,2
XI	0,3	0,7	0,9

Fig. 6. Transformation of water temperature in the Severnaya Dvina River delta

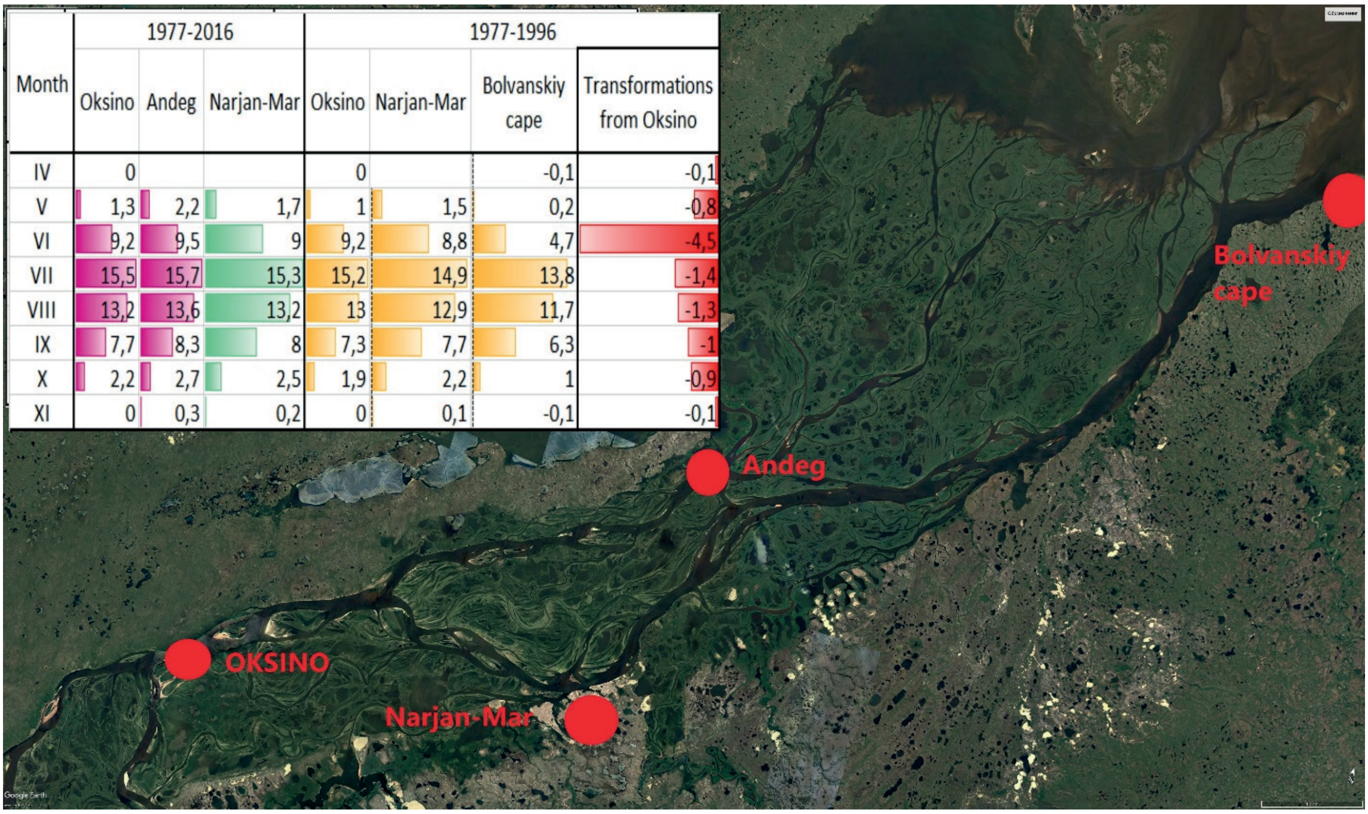
main delta branches, 3) the long-term preservation of river ice in the channel and on the banks and the presence of permafrost rocks cooling river waters, 4) marine factors, such as tidal and surge phenomena.

In the meso-tidal delta of the Severnaya Dvina, a comparison of T_w at the delta head (Smolny Buyan) and at the sea edge of the delta (Severodvinsk and Mudyug Island) in 1981-2016 shows a decrease in T_w towards the sea in almost all cases (Fig. 6).

A small increase in T_w, within 0.5°C, was observed only in October and November. At the same time, in the western part of the sea edge of the delta, the difference from the T_w at the delta head is much greater than in the eastern segment. The greatest difference in temperatures is -4.3 (June), -5 (July), and -3.2°C (August). The difference in temperatures between the delta head and Mudyug Island does not exceed 1.5 °C. Tides increase the daily range of T_w fluctuations, which increases towards the sea.

In the micro-tidal (tidal range is less than 2 m) delta of the Pechora, T_w is monitored at the delta head (Oksino), as well as on the delta branches of Bolshaya Pechora (Naryan-Mar and Bolvansky Cape) and Malaya Pechora (Andeg) (Fig. 7). T_w in Malaya Pechora is usually slightly higher than in the Pechora River before branching for Bolshaya and Malaya Pechora. In Bolshaya Pechora, T_w increases slightly towards Naryan-Mar in all months except June and July. All changes are quite small, within 0.5°C. However, towards the mouth of the Bolshaya Pechora, T_w in 1977-1996 decreased in all months. The largest decrease was observed in June (up to 4.5°C). In July and August, a decrease in T_w by 1.3-1.4°C also prevails. At the same time, June and July-August account for 41% of the annual heat flux of Pechora at Oksino.

Presumably, the heat flux decreases towards the sea together with water temperature, similar to the Yenisei lowlands, however, the data on water flow distribution in delta branches is currently available only for a part of the summer period (Alabyan et al. 2022).



Month	1977-2016			1977-1996			
	Oksino	Andeg	Narjan-Mar	Oksino	Narjan-Mar	Bolvanskiy cape	Transformations from Oksino
IV	0			0		-0,1	-0,1
V	1,3	2,2	1,7	1	1,5	0,2	-0,8
VI	9,2	9,5	9	9,2	8,8	4,7	-4,5
VII	15,5	15,7	15,3	15,2	14,9	13,8	-1,4
VIII	13,2	13,6	13,2	13	12,9	11,7	-1,3
IX	7,7	8,3	8	7,3	7,7	6,3	-1
X	2,2	2,7	2,5	1,9	2,2	1	-0,9
XI	0	0,3	0,2	0	0,1	-0,1	-0,1

Fig. 7. Transformation of water temperature in the Pechora River delta

CONCLUSION

The studies carried out on modern and extensive data made it possible to clarify previous estimates of the heat flux of the main rivers of the Russian Arctic to their estuaries. The major part of it is formed in the summer months. The long-term variability of heat flux is caused mostly by climatic factors, with the exception of the Ob, Yenisei, and Kolyma rivers. Rivers without reservoirs mainly demonstrate a long-term increase in water temperature and heat flux, particularly since the mid-1980s and late 1990s. The growth was noted both during the spring flood and low water seasons. However, the statistical significance of the water temperature and heat flux changes, as well as of changes in water flow, around the Russian Artic is still low. This suggests, that the reaction of hydrologic parameters to climate change is somewhat lagging.

The construction of dams on great rivers resulted in a group of consequences. First of all, it led to the reduction of water flow in the warm period. Secondly, it caused an increase in water temperatures downstream of HPPs in several winter and autumn months, and a water temperature decrease in other months. The natural water temperature regime is restored only at a high distance from dams, which can exceed 500 km. In general, the heat flux of large regulated rivers has reduced. However, nowadays due to climate-driven changes in hydrological and temperature regimes, it tends to increase again, with the exception of the Ob estuary, where a small heat flux decrease was observed.

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