Ice regime of rivers of the Arctic zone of Russia in modern and future climate conditions

A N Vasilenko¹, S A Agafonova¹ and N L Frolova¹

Department of Land Hydrology, Lomonosov Moscow State University, GSP-1, Leninskie Gory, 119991, Moscow

E-mail: saiitia24@mail.ru

Abstract. The article devoted to renewal the data about spatial distribution of different parameters of river ice regime in modern climate conditions which are under influence of climate changes. Also, it is an attempt to estimate the future river ice regime under simulation of global warming in the middle of the 21st century.

1. Introduction

Due to the geographical position of Russia, ice events and ice cover occur on the overwhelming majority of rivers in the northern part of Eurasia, lasting for 1 month every year. On the rivers flowing northwards off 60N, ice events have longer duration. The ice regime of rivers should be taken into consideration when analyzing the hydrological processes occurring on the rivers and during the economic development planning. Ice phenomena has both positive and negative sides. On the one hand, ice roads and ice bridges are built and maintained in conditions of steady ice cover, and on the other hand there exists a number of hazardous hydrological phenomena associated with the ice. The most common of them are ice jams. The winter ice cover also inhibits oxygen invasion and prevents solar radiation from penetrating into the river water during the winter period. Thus, the biological productivity of the river ecosystems is limited, with some of their biogeochemical processes, and among them self-purification, inhibited.

The studies of the ice regime of rivers in Russia began in the late 19th century. During the 20th century, significant progress was achieved in the study of ice formation, the processes of freezing and breaking-up of rivers, the formation of ice jams, as well as in ice conditions forecasting. The analysis of the spatial distribution of the ice phenomena was also carried out. The main results of these studies were published in the monographs [1] and [2]. They show that the ice regime of rivers is primarily determined by a combination of hydrometeorological factors. The climate change, observed since the 1980s, has led to changes in a number of parameters of the ice regime. At the same time, the existing generalizations of the ice regime of rivers are outdated and require undating.

This article analyzes results of studying the ice regime of the rivers flowing northwards 60N in Russia, in the current and future climatic conditions.
2. Materials and methods

The original data for the analysis were taken from 184 hydrological stations. Their geographical position is presented in Figure 1. These hydrological stations are located mainly on medium and large rivers.

The ice regime phases were analyzed for the following parameters:

1. Ice appearance date (Diap);
2. Freeze-up date (Dfr);
3. Ice drift start date, spring (Dids);
4. Ice drift completion date (Didc);
5. Freezing duration (Tfr);
6. Ice cover duration (Ticov);
7. Ice breakup period duration (Ticl);
8. Ice events period duration (Tie).

Processing of the series of the observations of ice phenomena is challenged by their incompleteness for many of the hydrological gages. This is explained by the fact that the discovery of a large number of observation gages occurred in the mid-1950s, while in the 1990s there was a significant reduction in the observations network. To extend the series explored, the method of hydrological analogy was used. With it, the corresponding omissions in the series of observations have been restored, provided that the series of observations are highly correlated.

![Figure 1. Geographical position of hydrological stations](image_url)

The analysis of the obtained series of observations covered the period from 1951 to the early 1930s, which marked the start of the “modern» climate norm established by WMO (1981-2010). [5].

For each series, the homogeneity of the mean values for periods 1951-1980 and 1981-2014 was determined using the non-parametric Mann-Whitney test. The presence or absence of trends in data series were determined using the Spearman's rank correlation coefficient. To determine the actual changes in the considered quantities, the difference of average values in both time periods was used.
Variability in the series was determined by standard deviation (SD). The transformation of the ice regime was determined for each of the 8 parameters listed above.

Also, data on the early and late stages of the onset of the ice regime phases, the minimum and maximum phase durations for the period 1936-2014 – from the beginning of the Hydrological Yearbooks on the area under study – were reviewed.

With regard to ice regime forecasts, our calculations targeted the dates of the onset of various phases of the ice regime of the rivers, namely, the date of ice appearance, the date of freezing (freeze-up), the date of the ice drift start, and the date of ice clearance. Our predictors were the dates when the air temperatures became consistently below 0°C. Where data on rivers’ monthly runoff was available, the interrelations between values were established using multiple regression equations.

The data on monthly water discharges were obtained from 40 hydrological stations. Possible changes in the runoff were interpreted in percentage rates of 10%, 20%, 30%, 40%, and 50%. Data on daily air temperatures were obtained from TCR NOAA reanalysis [6]. The dates when the air temperatures became consistently below 0°C were selected using D.A. Ped method. [4].

To construct regression models, the data series were averaged by a moving average of 20 years. In our case, if the coefficient of determination R2 between the obtained series of terms of ice phenomena and the timing of the transition of air temperature through 0°C remained less than 0.7, the rebounding or extreme values of the transition dates were removed from the initial series. Removal of extreme values is justified, since the maximum values of the natural phenomena under consideration usually have a more specific genesis compared to ordinary conditions. [3]. In cases of using water flow as a predictor, multiple regression equations with a coefficient of determination of not less than 0.8 were used. As a result, 126 equations were obtained.

3. Modern ice regime

Over the past 30 years, the duration of the period with ice events has decreased on the rivers of the Arctic zone of Russia by 10-13 days in the western part (North of the European part of Russia (EPR), Kola Peninsula, north of Western Siberia) and 2-4 days in the eastern (Taimyr, north of Eastern Siberia, Chukotka Peninsula).

The first ice formations (skim ice and border ice) appear on the rivers of Taimyr and Chukotka in the middle of September. In the first decade of October, ice is formed in Eastern Siberia, in the middle of October - in Western Siberia. The appearance of ice in the north of the EPR takes place at the end of October, and in early November ice forms in the south of Karelia. It is important to note that many rivers, especially mountain ones, have a long freezing period and carry a large amount of skim ice. The west of the Arctic zone is characterized by significant variability of the date of the appearance of ice, where it varies within 1-2 weeks. At the same time, anomalies in Eastern Siberia and Chukotka do not exceed a week. Thus, the earliest dates of ice appearance can be observed on Taimyr in early September, and in the north of the EPR in the second decade of October. The latest dates of ice formation occur in the period from the first week of October to the second decade of November. Under the conditions of observed climatic changes, ice appears later for 1-4 days in Siberia and for 4-8 days in the north of the EPR (figure 2). The variability of the date of ice appearance also decreased by 1-2 days for about half of the territory under consideration. In the north of the EPR, in Western Siberia and on the Taimyr, this characteristic increased by 1-3 days, and in the Onega river basin - by 4-6 days.

The freezing period is rather long over the whole territory - about 2 weeks. Only in Taimyr it does not exceed 10 days, while in the north of the EPR and in Chukotka it can last up to 3 weeks. The variability of freezing period duration varies from west to east from 20 to 8 days. Thus, rivers can freeze everywhere in 1-3 days. The maximum noted in freezing period duration is 3-4 weeks in Siberia, 5 weeks in Chukotka, 2-3 months in southern Karelia. On a number of rivers, primarily mountainous, the ice cover fails to form itself. Practically everywhere in Arctic zone of Russia there is a trend for freezing period to shorten itself by several days.
The duration of ice cover period in the Arctic zone varies from 5 to 9 months. In Eastern Siberia (without the Indigirka and Alazei basins), the duration of ice cover period is sub-latitude increasing from 260 days on Taimyr to 200-210 days south of the Polar Circle. In the Indigirka basin and in Chukotka, rivers remain ice-covered during 221-230. In this area, even the largest rivers freeze over and aufices are widespread. In the north of Western Siberia and in the lower reach of the Yenisei, ice cover persists for 211-220 days, in the areas southwards from it – 201-210 days on both slopes of the Urals. In the north of the EPR, the ice cover period duration decreases from east to west from 191–200 days in the western part of the Pechora basin to 181–190 days in the Mezen basin to 171–180 days in the central part of the Northern Dvina basin. In the Onega basin, in Karelia and on the Kola Peninsula, ice cover period duration is minimal - 161-170 days. The ice cover period duration varies from 7–9 days in the northern and eastern parts of Siberia and in the north-east, to 10–12 days in Central Siberia and the Gydan Peninsula. On the rivers of the southern coast of the White and Barents seas (without the coast of the Kola Peninsula) the variability is 16-18 days, in Karelia and on the Kola Peninsula - 19-21 days. In most parts of the north of the EPR, in the Ural Mountains and in the west of Siberia the ice cover period duration varies by 13–15 days. Thus, the duration of freeze-up can vary from 4 to 9 months. In recent decades, the duration of ice cover period has reduced almost everywhere: 52% of the surveyed stations show that the reduction is significant. Most manifest are changes in the Onega and Pechora basins, as well as in the eastern part of the Kola Peninsula (11-13 days). In the other parts of the north of EPR and in Western Siberia, the reduction is 8-10 days, in the north of Siberia - 5-7 days, and in the Eastern Siberia 2-4 days. At the same time, average SD of the considered characteristics has increased for almost of the entire territory, with the exception of the western Kola Peninsula and the Pechora Basin. In the North of the EPR and in the Eastern Siberia, the standard deviation (SD) tends of decrease – by 0-2 days; in the Western Siberia by 3-5 days. The most prominent change occurred in the central parts of the Kola Peninsula – 6-8 days, and manifest are the changes in South Karelia – 3-5 days. In the west of the Kola Peninsula and in the Pechora basin, the variability has decreased by 4-6 and 1-3 days, respectively.

![Figure 2. Shifts in the dates of ice appearance in the Arctic zone of Russia over 1981-2014 period compared to 1951-1980 (days)](image-url)
duration can be 5-7 days on the entire territory, except the areas between the Northern Dvina and Yenisei rivers, where it may reach 8-12 days. Thus, the ice drift can begin on the rivers of the western part of the Arctic zone of Russia anytime from the second decade of April to the end of May. In Siberia, the ice drift begins anytime from the end of May to the beginning of June. In the past 30 years, the ice drift tends to start 2-4 days earlier everywhere on the area in question. In some territories, changes can be less manifest (Taimyr, Western Siberia). While in the Ob and Yenisei basins the SD has increased by 1-3 days, in the rest of the territory the SD some is what lower.

In today’s conditions, ice breakup rivers tend to occurs in May or the first decades of June. The period with ice events ends first in Karelia, then in the north of the EPR, and then in Siberia. In June, ice breakup is usually observed on Taimyr and northern Siberia. SD is large enough - from 4 to 6 days in the Asian part up to 7-9 days in the European. The greatest variability is observed in the Pechora basin - 10-12 days. Therefore, ice breakup can occur on rivers in the last decade of April at the earliest and in the last decade of May or late May-early July at the latest. After the onset of climate change in the late 1980s, the ice breakup date tends to shift earlier for the entire Arctic zone – 1-2 days on Taimyr and in the Lena basin, 3-5 days in the rest of the area (Fig.3). In Central and Western Siberia, SD increased by 1-3 days and decreased in Eastern Siberia and in the EPR by 1 and 2-4 days, respectively. Along with changes in the timing of the ice phenomena, there have also been changes in the frequency of occurrence of the most dangerous ice phenomena - ice jams, leading to flooding and significant damage in the economy. The study shows that in the Kola Peninsula, the frequency of ice jams on rivers increased from 1981 to 2014 compared with the period 1951-1980 on average by 23%, in Karelia - by 11%. On the territory of the North part of the EPR, the frequency decreased by an average of 5%, but on some rivers, including the major ones like the Mezen, this parameter increased by 17%.

In the Arctic part of Western Siberia, a decrease in the number of ice jams is also observed on average by 14%. On the Nadym river, in this case, the frequency of occurrence of ice jams increases. In the Yenisei region, the parameter increases by 6%, while on small rivers, as well as on both Tunguska rivers this parameter is a decrease (in some cases by 30%). In the area of Lena, there was a reduction in the frequency of occurrence of ice jams by 6%, but in the Olenek basin, at the same time, its growth by 14% is observed. In most of the rivers of Chukotka, the frequency of occurrence also increases.

![Figure 3. Shift in ice breakup dates in Arctic zone of Russia over 1981-2014 compared to 1951-1980](image)

4. Evaluation of future ice regime
According to our calculations, under climate change scenario RCP8.5, the period with ice events is likely to shorten in the north of the EPR almost by half and in the Asian part of the Arctic zone of Russia by 3-4 months by the 2050s (2041–2060).

The ice appearance on the rivers in the north of the EPR may occur in the second half of November, and on the Kola Peninsula the ice appearance may shift to a later date, compared with the north of EPR. On the Kola Peninsula, a 50% increase in the river runoff in the autumn months may shift the dates of ice appearance to the first decade of December. In the north of the EPR, the possible increase in the runoff does not have any effect on our projected estimates.

In future climatic conditions, the freeze-up may occur in the second decade of November in the absence of changes in the runoff. Its shift to later dates can range from 10 days to 3 weeks. Later dates, as in the case of ice formation dates, might be observed on the Kola Peninsula. a 50% increase in the river runoff may lead to even greater shift in the freezing time – by 3 to 4 weeks or even more in the north.

The ice drift is projected to start in the end of March or the first half of April. It means that in the absence of an increase in the runoff, a shift to 25–40 days earlier can occur in the North of the EPR and the Kola Peninsula, whereas a 50% rise in the runoff is likely to cause ice drift to start another 3-4 days earlier. Similar projections were obtained for the ice breakup dates.

The total duration of ice event period may reduce to 110-150 days, a reduction likely to be experienced also by the freeze-up process.

The results of calculations covering the north of EPR and Kola Peninsula are presented in Table 1.

Table 1. Estimated dates of onset of different phases in the river ice regime for Kola Peninsula and the North of EPR in the mid-21st century (2041-2060)

| Region          | Phase of ice regime | Modern date (day.month) | Increasing discharge for          |
|-----------------|---------------------|-------------------------|-----------------------------------|
| Kola Peninsula  | Ice appearance      | 23.10                   | 28.11 30.11 21.12 5.12 7.12 9.12 |
| North of the EPR|                     | 24.10                   | 14.11 14.11 14.11 14.11 14.11 14.11 |
| Kola Peninsula  | Freezing            | 7.11                    | 29.11 2.12 4.12 6.12 8.12 10.12 |
| North of the EPR|                     | 6.11                    | 16.11 17.11 18.11 19.11 20.11 22.11 |
| Kola Peninsula  | Ice run             | 8.5                     | 30.13 29.3 28.3 28.3 27.3 26.3 |
| North of the EPR|                     | 12.5                    | 15.4 15.4 14.4 13.4 12.4 12.4 |
| Kola Peninsula  | Ice clean           | 15.5                    | 22.3 21.3 21.3 20.3 19.3 18.3 |
| North of the EPR|                     | 14.5                    | 12.4 11.4 11.4 11.4 10.4 10.4 |

The date of ice appearance on the rivers of the Asian part of the Arctic zone can shift to later dates - by 45 days (Western Siberia) to 70 days (the Lena basin), falling on the end of November or the first decade of December. Similar trends are indicated by some of our estimates for hydrological gages, based on the runoff data. A 50% increase in the runoff may increase the shift by another 3-7 days.

Smaller shifts are observed for freeze-up dates – 30 to 40 days, practically falling on the period of ice appearance. The estimates taking into account changes in the runoff are indicative of the results similar to those for ice appearance dates.
The ice drift start and completion dates are projected to fall on the last decade of March or early April. The shift to earlier dates ranges from 50 days (the Lena basin) to 70 days (Western Siberia). However, our estimates taking into account the changes in the runoff show that the ice drift start date falls on the end of April and the date of ice drift completion dates is close to current.

The results of calculations for the regions of the Asian part of the Arctic zone are presented in Table 2.

Table 2. Estimated dates of onset of different phases in the river ice regime for Asian part of the Arctic zone of Russia in the middle of 21 century (2041-2060)

| Region          | Ice appearance (day.month) | Freezing-up (day.month) |
|-----------------|----------------------------|-------------------------|
|                 | Modern 2041-2060 Modern 2041-2060 |                          |
| Western Siberia | 13.10 27.11 21.10 01.12      |                         |
| Yenisei         | 12.10 29.11                |                         |
| Lena            | 01.10 09.12 26.10 28.11     |                         |
| Chukotka        | 04.10 02.12 12.10 23.11     |                         |

| Region          | Ice run (day.month) | Ice cleaning (day.month) |
|-----------------|---------------------|--------------------------|
|                 | Modern 2041-2060 Modern 2041-2060 |                      |
| Western Siberia | 01.6 24.3 02.6 29.3    |                         |
| Yenisei         | 26.5 21.3 04.6 29.3    |                         |
| Lena            | 02.6 10.4 06.6 04.3    |                         |
| Chukotka        | 26.5 28.3 30.5 23.3    |                         |

5. Conclusions
It has been found that on the territory of the Arctic zone of Russia, there is a softening of the ice regime of the rivers that manifests itself in the reduction of the duration of the period with ice events by 10-13 days in the western part of the territory and by 2-4 days in the eastern one, and in earlier onset of ice formation process. Ice events on the rivers of the Arctic zone can be observed over longer periods of time - from 5 to 9 months.

Evidence was obtained that the duration of the freeze-up and the ice drift processes may show opposite tendencies: the freezing period is reduced by 0-2 days in the east and 3-5 days in the west of the territory, while the duration of ice drift may increase by 1-2 days in one area and reduce by 1-2 days in another. Over the most of the territory, there is an increase in variations in the ice regime on rivers, which increases the risk of their early or late onset.

Based on the equations obtained using the climate modeling data, an attempt was made to forecast the ice regime on the rivers of the Arctic zone in the mid-21st century. According to our projections, under RCP8.5 global warming scenario, the ice regime may soften even more, with probability for ice events period to reduce two-fold.

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