Water and ice regimes of the rivers of European Russia under climate change

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Abstract Specific features of the water and ice regimes of the rivers of the European territory of Russia, as well as their spatial and temporal variability, were studied using up-to-date hydrometeorological data. Variations in the characteristics of the water and ice river regimes over the last 125 years are analysed. For some rivers, changes in the dates of the appearance of floating ice and then the break-up, due to changes in the air temperature and the rate of streamflow in rivers, are assessed. Special attention is paid to the factors that affect the formation of ice jams and their spatial and temporal variability for the northern rivers. Trends of ice regime changes within the territory under study during recent decades have been revealed. It is shown that changes of ice regime are mainly defined by features of the water regime. The basic feature of modern changes in the hydrological regimes of rivers over a large part of the country is a significant increase of low flows, especially in winter. Within the European territory of Russia, for the majority of the rivers considered, significant positive trends of increased winter and summer–autumn low flows are apparent. It was concluded that there is an increase of natural regulation of river drainage.

Key words ice and water regime; climate change; European Russia

INTRODUCTION

The analysis of river ice and water regimes in the European territory of Russia (ETR) (Fig. 1) is an important scientific and practical task. The scientifically-based estimations of present and possible future changes of the water and ice regimes of the rivers under the influence of natural and anthropogenic factors are important in working out strategies for rational use and protection of water resources, planning and realization of expensive water economic actions. For the middle latitudes of the Northern Hemisphere intensive warming since the second half of the 1970s has been observed (Federal Service for Hydrometeorology and Environmental Monitoring, 2008).

The current study analyses river ice and water regimes of rivers of the ETR to determine their possible changes due to global warming. The large extent of the territory considered, the variety of forms of atmospheric circulation, complexity of relief, variety of landscapes and climatic variations cause important distinctions in the formation of river runoff and its causal factors in the natural zones of this territory. The results of this study allowed trends to be identified and conclusions on possible qualitative and quantitative changes in river hydrological characteristics to be made.

DATA

As the source data for analysis of the ice regime, dates of river ice occurrence and break-up, and their anomalies ΔD (difference between actual value and annual averaged) for large river basins in the ETR, or for their parts, have been taken. As a rule, the duration of ice phenomena observation series is about 100 years. Furthermore, information on monthly and mean annual discharges from more than 300 stations, as well as data on air temperature and precipitation from weather stations located in the study region, were used.

CHANGE OF CLIMATE FEATURES IN THE EUROPEAN TERRITORY OF RUSSIA

According to the Russian Federal Service for Hydrometereology and Environmental Monitoring, for the whole of Russia, the most significant rise of temperature of the bottom air layer was observed in 1976–2007 and amounted to nearly 1.4°C.

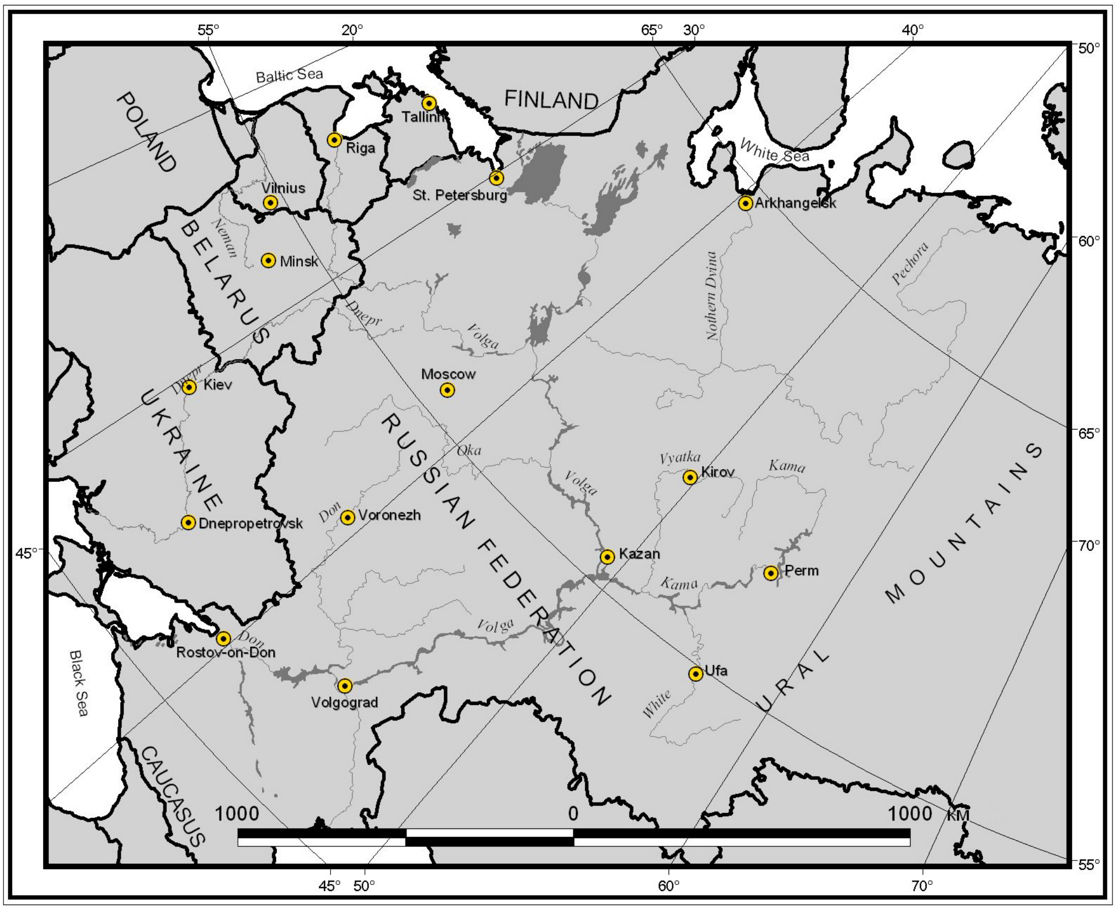

Fig. 1 Map of the study region.

In the ETR, the increase of mid-annual air temperature is the most intensive (0.4–0.6°C/10 years) and statistically significant compared with other regions of Russia (Federal Service for Hydrometeorology and Environmental Monitoring, 2008). An increase in average air temperature for the cold season (November–March) is distinctly traced for all of the ETR. The average temperature of air for the warm season also tends to increase; however, this increase in many cases is not statistically significant. The rise of air temperature in the cold season has resulted in more frequent winter thaws, a decrease in the depth of seasonal soil frost, and snowmelt from winter thaw feeds the groundwater. Also, in 1976–2006, an increase in the annual sums of precipitation was established across almost all the territory of Russia. Comparison of the precipitation of the warm and cold seasons shows the opposite tendencies to those in ETR. As a rule, negative trends in the warm season are noted or they are in general absent, and positive trends are noted in the cold season (Federal Service for Hydrometeorology and Environmental Monitoring, 2008).

IMPACT OF CLIMATE CHANGE ON RIVER ICE REGIME

The analysis of the time variability of the occurrence and break-up of river ice has been carried out for the observation period (1900–2005) and also for the last 30 years during which appreciable warming of the climate for all the ETR was observed. As an example, Fig. 2 shows long-term fluctuations of anomalies of ice-related phenomena on the rivers of the Lower Oka basin. To reveal the monotonic trend for the investigated range (increasing or decreasing), Spearman's non-parametric criterion has been used. The criterion uses estimation, r_S, of the correlation factor between ranks of members of a range and numbers of corresponding years. These estimations are tabulated in Table 1. According to Table 1, ranges of long-term fluctuations of anomalies

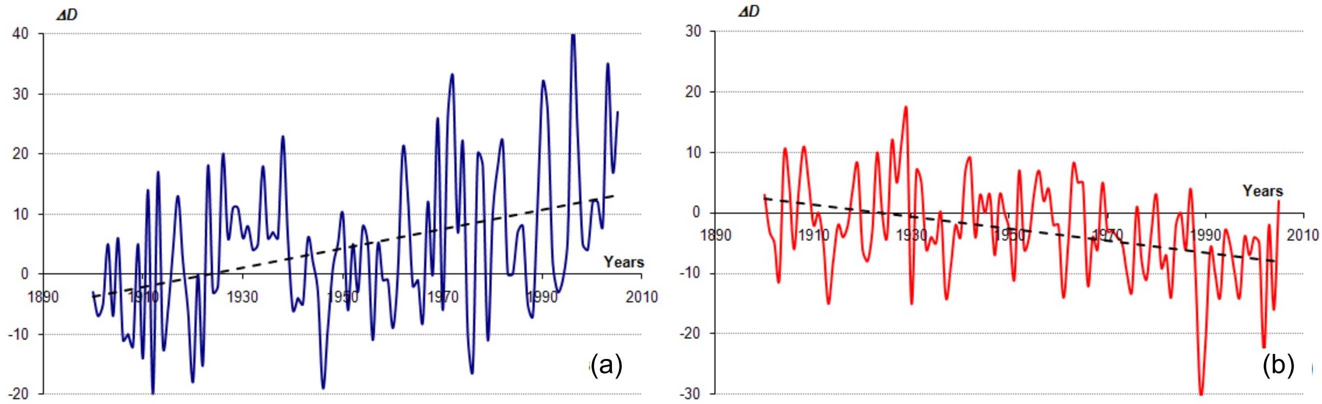

Fig. 2 Changes in Δ*D* (days) for: (a) anomalies of dates of floating ice appearance, (b) anomalies of break-up dates, for lower reaches of the Oka for period 1900–2005 (dashed lines indicate linear trends).

Table 1 Changes of dates of floating ice appearance and break-up for ETR for the period 1900–2005.

River basin	Changes of dates of:		r_S:	
	Floating ice appearance	Break-up	Floating ice appearance	Break-up
Pechora	1	2	0.02	0.06
Northern Dvina	6	–2	**0.20**	–0.11
Rivers of the Northwest	7	–9	0.12	**–0.30**
Neman	15	–10	**0.18**	–0.12
Upper Dnepr	13	–16	**0.32**	**–0.35**
Middle Dnepr	13	–11	**0.35**	**–0.23**
Rivers of Black Sea Coast	15	5	**0.23**	0.03
Upper Don	23	–10	**0.46**	**–0.19**
Lower Don	22	–25	**0.47**	**–0.38**
Upper Volga	13	–11	**0.32**	**–0.36**
Northern Volga tributaries	4	0	**0.18**	–0.03
Upper Oka	5	–10	**0.20**	**–0.27**
Lower Oka	16	–10	**0.39**	**–0.35**
Kama, Vyatka	9	–3	**0.25**	**–0.23**
White River	12	–2	**0.42**	–0.10
Lower Volga	9	–6	**0.31**	**–0.18**

r_S is Spearman's correlation coefficient; significant factors of correlation are highlighted.

of the times of ice break-up in the rivers of the northwest ETR and the basins of the Dnepr, Don, Oka and Volga show an obvious decreasing trend, and the ranges of long-term fluctuations of the times of development of floating ice on almost all rivers of the ETR show an obvious increasing trend.

For the last century, the change of the time of occurrence of ice is, in general, more significant than for the time of break-up. For the rivers of the centre and the south of ETR, the times of occurrence of ice are on average 5–15 days later (except the rivers of the Don basin – here changes are more than 20 days later). A similar picture is typical for break-up dates. On average, for all rivers of Russia, ice appearance occurs 6–7 days later, and break-up 4–5 days earlier, than was the case a hundred years ago.

Research has shown that not only the timing of the ice phenomena is changing, but also the recurrence of the dangerous ice phenomena of ice-jam increases. This process is typical, especially for the north of the investigated territory (Agafonova & Frolova, 2007; Frolova & Alekseevskiy, 2010). When the temperature regime in the north of the study region becomes milder, low water flows at the beginning of autumn are observed more frequently, which leads to early freeze-up dates. Air temperature fluctuations during autumn may cause a return of positive temperatures in November and result in floods due to snowmelt and rain. High water levels during this period stimulate later freeze-up, an increase of autumn ice and sludge drift duration, and formation of ice jams. The milder winter conditions due to climate change result in the decreasing sum of negative air temperatures, an increasing volume of solid precipitation and an increasing number of positive air temperature events that cause thawing spells (for many weather stations, the analysis of meteorological time series points to the existence of statistically meaningful trends in these characteristics). On one hand, thawing spells lead to winter break-ups that are accompanied by catastrophic ice jams due to increased discharge and associated volumes of ice sludge along river channels. Ice jams developed during such periods may cause subsequent spring ice jams. On the other hand, longer thaws result in thin ice cover and decreasing snow supply. High water levels during ice-jam periods and large volumes of ice sludge form favourable conditions for hazardous ice jams during break-ups. In recent years, an increasing tendency in the speed of break-up and clearance front propagation has become obvious on most rivers. As the regional climate becomes milder, longer reaches break-up simultaneously. This increases the probability of ice jam hazards and their severity.

IMPACT OF CLIMATE CHANGE ON RIVER WATER REGIME

Change in climatic conditions has led to considerable changes in the characteristics of the water regime of the rivers of the ETR, and thereby changes in annual and seasonal runoff. Research has shown that during recent decades, increased runoff was observed over much of the ETR (Shiklomanov, 2008). The most significant runoff increase (15–30%) was observed in the left-bank tributaries of the upper and middle reaches of the Volga and in a major part of the Kama basin. Runoff from Volga tributaries in the forest-steppe zone has also considerably increased. Annual runoff is 10–15% above the average in the upper part of the Northern Dvina basin, the upper reaches of the Dnepr, the left-bank tributaries of the Don and the rivers of the mountainous part of the Kuban basin. In the rest of the ETR, recent changes in runoff are not significant.

The basic feature of the recent changes in water regime of the rivers of most of the ETR is essentially an increase of low flows, especially in winter. For the majority of the considered rivers, significant trends of runoff increase in the winter and summer–autumn low-water periods are apparent. The degree of increase in low flow rises from northern areas to southern areas. So over the last 30 years, low flow in the Northern Dvina basin has increased by 20–30%, in the Volga basin by 50–70%, and in the Don basin by 40–60% (Fig. 3).

The "synchronization" of changes of low flow over these large regions and the scale of the changes are not ordinary and are unprecedented in the 20th century. The increase in low flows in the last 25–30 years has caused an increase in water resources even in the river basins where there was a reduction in runoff during the spring flood season. The analysis of observed data for the last 100 years has allowed the conclusion that such a situation has developed for the first time, because earlier all considerable low-water and high-water phases were defined, first of all, by spring flood runoff.

The observed water regime changes could be explained by the change in the sums of precipitation for the cold and warm seasons, and their proportions. Research has essentially shown a reduction of maximum water discharges and the share of snowmelt flood in annual runoff (Fig. 4). The beginning of spring flood in the Volga and Don basins has shifted by 10–15 days to earlier dates. If in the past (before 1970) the flood comprised 65–70% of the annual runoff, since 1970 this proportion has decreased to 45–50%. Thus, in the ETR there is a decrease in seasonal variations of runoff and an increase in its natural regulation.

It is necessary to emphasize that for the rivers of the southwest of ETR and a part of the Volga basin, there were changes in their flow in 1978–2005, caused by reduction of spring runoff and increase of low flow.

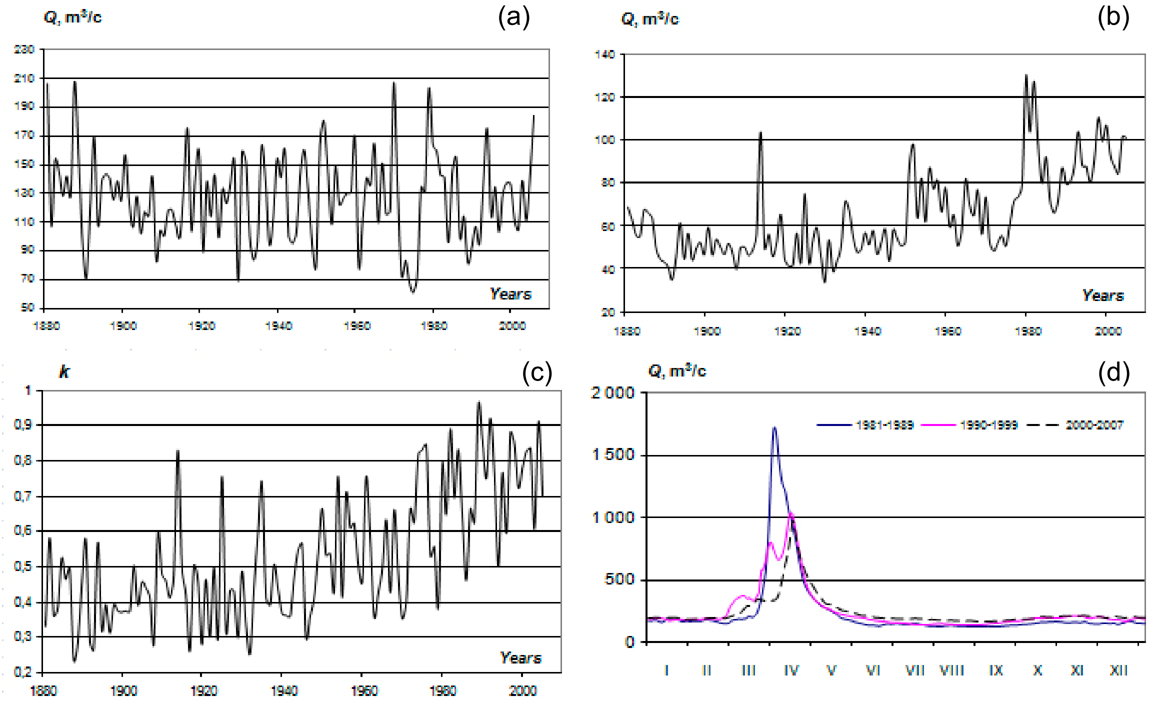

Fig. 3 Change in: (a) annual and (b) low-water runoff (Q, m^3/s), (c) share of the low flow in the annual runoff k for 1880–2005 years, (d) average hydrographs for 1981–1989, 1990–1999, 2000–2007 for the River Don in Liski.

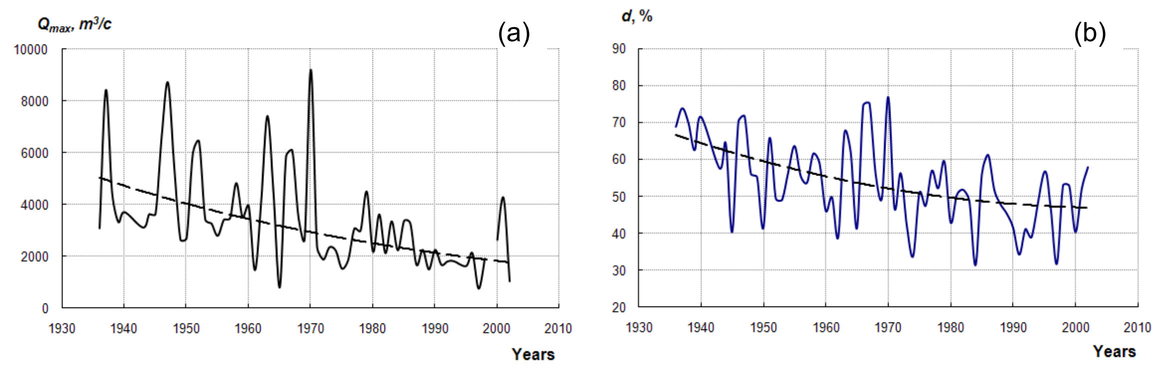

Fig. 4 (a) Change in the maximum discharge Q_{max}, m^3/s, and (b) share of the snowmelt flood in the annual runoff d, % for the River Oka at Kaluga.

Before the second half of the 1970s, according to M. I. Lvovich's classification, the rivers of the ETR were, due to their flow generation sources and within-year variation of runoff, considered as "mainly snow" fed. However, at the end of the 20th century there was a category transition of the rivers to the type "mixed feed" or even "mixed with prevalence of underground feed" (Shiklomanov, 2008). This means that the share of groundwater in river flows had significantly increased by the end of the 20th century. These processes have led to a significant growth of natural regulation of river flow, comparable to the influence of water reservoirs on seasonal regulation. Analysis of low-flow dynamics and the observation data from the water balance stations has shown that such an increase in runoff is caused, first by an increase in the frequency and duration of thaw periods, and also by a reduction of the depth and duration of frost in soils; and secondly, by an increase of recharge to and rise of groundwater levels, thus providing the baseflow of the rivers during low-flow periods (Shiklomanov, 2008).

The trends of change in the water regime of the rivers of the ETR, noted from the middle of the 1970s, may remain, at least for the next 10–15 years. In the centre, in the northwest and south of the ETR, the increase in winter runoff may reach 60–90%, and in summer 20–50%.

CONCLUSIONS

The statistical analysis of changes of meteorological characteristics has shown the increase of average air temperatures during the cold season for all of European Russia. Average temperatures in the warm season have also tended to increase, but in many areas the trend is statistically insignificant. As a result of the rise in air temperature in the cold season, winter thaws have become more frequent and the depth of the seasonal frost in the unsaturated zone of soils has decreased. The increase in humidity of an active layer of soils and the groundwater recharge is connected with the snowmelt runoff during winter thaws. Comparison of precipitation of warm and cold half-year periods shows opposite trends for the considered territory. As a rule, negative trends are marked during the warm season or they are absent in general, and positive trends are marked in the cold season. The increase in the amount of precipitation in the cold season is more reliable. Climate changes observed in recent decades in the mid-latitudes of the European territory of Russia have considerably affected and changed the characteristics of ice and water regimes, and the quantities of surface water and groundwater resources. For the rivers of the centre and the south of European Russia, the time of development of river ice is, on average, 5–15 days later (except for rivers of the Don basin where ice development if more than 20 days later). A similar picture is typical for break-up dates. Research has also shown that in recent decades there have been more phases of high runoff across most of the ETR. The most significant increase of low flows (15–40 %) is observed on the rivers of the ETR located approximately between the 56 and 60 parallels. An annual runoff increase of, on average, 10–15% is observed in the upper part of Northern Dvina basin, in the upper courses of Dnepr, on the left-bank inflows of Don, and on the rivers of the mountain part of Kuban basin. As a result of the developing climatic situation, favourable conditions for an increase of seepage feed to groundwater has been created that has led to the growth of groundwater flows to the rivers and the groundwater contribution to low flows. Therefore, the basic feature of modern changes of the water regime of the rivers of the ETR is significant increase in the winter low-water runoff. For the majority of the ETR rivers considered, there are significant (at a significance value of 95%) positive trends of increase in winter and summer–autumnal low-water runoff. Changes in the genesis of the flow to the rivers, caused by reduction of the spring runoff and the increase of low-water runoff, have led to significant growth of natural regulation of runoff.

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