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Assessment of Changes in Ice Regime Characteristics of Russian Lakes and Rivers under Current Climate Conditions

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Abstract

This article deals with assessment of changes in ice cover duration and maximum ice cover thickness for the last three decades compared with the previous period by the example of observation data for 28 hydrometric stations on rivers and 10 hydrological stations on lakes. Estimations of homogeneity and trends of long term serious of above mentioned rivers and lakes ice regime characteristics for three time periods were carried out using Student and Fisher criteria. Assessment of changes in ice regime characteristics for the period 1980-2010 compared with the period of stationary climate (from the beginning of observations until 1979) using two methodological approaches was made. The results can be used for solving problems of economy branches adaptation in case of rivers and lakes used in winter conditions.

Keywords

Rivers, Lakes, Ice Cover Duration, Maximum Ice Cover Thickness, Assessment of Changes, Last Three Decades

1. Introduction

In recent decades, the issue of assessing changes in hydrological regime of surface water bodies in a non-stationary climate has become especially relevant. Over the past 100 years, average annual temperatures on the territory of the Russian Federation have risen by 1.2˚C, which resulted in noticeable changes in hydrological regime of many rivers and lakes of the country. Studies of these changes are mainly focused on water resources and water balance of rivers as these are two major factors shaping the dynamics of water use both annually and inter-annually, which is critically important in planning and implementation of different water management projects in river basins. Very few studies are focused on surface water bodies' ice regime characteristics. However, it is known that such characteristics of river and lake ice regime as dates of ice-on and ice-off, duration of ice cover and ice thickness are highly important and sometimes limiting factors in winter operation of these water bodies. The dates of ice-on and ice-off and duration of ice cover determine navigation, hydraulic construction in cold period, construction of ice roads and bridges. Ice thickness is a major factor in evaluating the bearing capacity and duration of river and lakes ice bridges and roads. It is for this reason that the issue of assessing changes in ice regime of lakes and rivers, both in current and possible future climate conditions, is of undoubted importance. This issue is not being addressed; it will not be possible to maximize the efficiency of operation of rivers and lakes in cold and winter periods when ice phenomena are favorable for some economic activities and at the same time restrictive for others.

2. Status of Research

In the Russian Federation, research in the field of climate change impact on surface water bodies ice regime has begun relatively recently—since the early 1990s. Scientists from the Hydrometeorological centre of Russia (B.M. Ginzburg, I.I. Soldatova) who had studied long-term variations of freeze-up and break-up dates in different geographical zones of Russia in 1891-1985 and their relationship with air temperature fluctuations in the Northern Hemisphere revealed unidirectional trends in variations of freeze-up and break-up dates with similar ice regime conditions [1].

Since the end of the 1990s, research in changes of ice regime of surface water bodies began at the State Hydrological Institute (St. Petersburg, Russia). Case studies of individual rivers and water bodies were used initially also with respect to freeze-up and break-up dates. In general, trends in long-term changes of the freeze-up and break-up dates over the past 50 - 100 years were analyzed [2]. Over the subsequent 10 years, the scope of characteristics to be analyzed was extended to include changes in ice cover duration and maximum ice thickness. It was found that the period since the beginning of the 1980's has seen the sharp rise in the degree of changes in water bodies ice regime [3] [4]. These changes are diverse for water bodies located in different natural zones. The main focus in these studies was on the Arctic rivers of Russia [5].

Outside Russia, since the end of the 1990s, the most extensive research was done in Canada, Finland and the USA [6] [7] [8]. In the last decade of the XX century, scientists from the USA initiated an international project on assessment of historical trends of freeze-up and break-up dates on rivers and lakes in the Northern Hemisphere. The project involved scientists from Canada and Finland and the outputs were published in the Science Journal [9]. Further studies in this field were mainly done in Canada (T. Prowse, B. R. Bonsal, C. R. Duguay).

An important step in international research activities was the establishment of the SWIPA (Snow, Water, Ice and Permafrost in the Arctic) project under the auspices of AMAP (Arctic Monitoring and Assessment Programme). The findings of the project have been summarized in a fundamental monograph with a specific chapter *Lake and river ice* addressing changes in the ice regime of the Arctic surface water bodies [10] [11] [12]. The author of the present article was the co-author of the chapter. It should be noted that research conducted outside Russia mainly focus on freeze-up and break-up dates and assessment of their trends.

Looking at the Russian research activities, one can outline the following major findings:

1. Determined are the features of long-term changes in river and lake ice regime, both for separate natural regions and for individual water bodies.

2. Revealed is a clear trend towards strengthening of the gradient of changes in ice regime characteristics since the early 1980's. The role of the climate component in these changes is not so clear.

3. There have been only general efforts to assess future changes in surface water bodies ice regime. The methodology for such assessment is currently at an early stage of development.

In view of the above, there is a need to enhance the research, first, in further development of methodologies to assess past and, especially, expected future changes in river and lake ice regime in close connection with climate indicators and their projected changes. Secondly, the scope of the research should be extended to include more rivers and lakes of Russia for which such assessments are made, including for the next 15 - 20 years.

The present article describes the findings of the research in changes of the ice regime characteristics of rivers and lakes located in the main natural zones of Russia over the past three decades.

3. Methodology and Input Data

Long-term series of ice cover duration and maximum ice thickness from the Water Cadastre of Russia were used as input data. Ice cover duration is a period since the appearance of stationary ice on a river or lake in autumn until the start of ice drift in spring.

Data from 28 gauging sites on 21 river and 10 observing sites on 8 lakes in all major natural regions of Russia were used in the assessment. All input information and data were downloaded in a special electronic database. **Figure 1** provides a sketch map of observing sites on rivers and lakes used in the assessment.

The criteria for selection of sites was the length of time series which were generally not shorter than 55 - 56 years ending in 2010 (in some cases in 2008 or 2009). **Table 1** presents information on observing sites in rivers used for the assessment.

The information on lake sites used in the assessments is presented in the **Table 2**.

To assess changes in ice regime characteristics a comparative analysis of mean values as well as their trends was made for the three specific periods (entire pe-

Table 1. Observing sites on rivers and length of observation periods.

N°	River-site	Catchment area, km²	Observation period	
			Ice cover duration	Maximum ice thickness
		European Russia		
1.	Luga-Tolmachevo	6350	1937-2010	1954-2010
2..	Onega-Turchasovo	42,800	1933-2010	1953-2010
3.	Northern Dvina-Kotlas	88,300	1933-2010	1954-2010
4.	Mezen'-Marakaib	6450	1932-2010	1953-2010
5.	Mezen'-Malonisogorskaya	56,400	1945-1979	1935-2010
6..	Pechora-Ust'-Unya	4430	1945-2010	1955-2010
7.	Pechora-Troitsko-Pechorsk	35,600	1914-2010	1955-2010
8.	Don-Serafimovich	204,000	1980-2008	1951-2008
9.	Volga-V. Lebyazhye	1,360,000	1980-2008	1943-2008
10.	Samara-Elshanka	22,800	1980-2008	1945-2008
		Asian Russia		
11.	Ural-Verkhneuralsk	2650	1980-2010	1945-2010
12.	Ob'-Kamen-na-Obi	216,000	1980-2009	1954-2009
13.	Ob'-Oktyabrskoye	2,190,000	1980-2009	1954-2008
14.	Ob'-Salekhard	2,950,000	1980-2009	1954-2009
15	Yset'-Ysetskoye	56,000	1980-2008	1943-2008
16.	Biya-Biysk	36,900	1980-2008	1945-2008
17.	Tom'-Tomsk	57,000	1980-2008	1947-2008
18	Yenisei-Kyzyl	115,000	1980-2010	1954-2010
19.	Yenisei-Selivanikha	2,340,000	1980-2010	1954-2010
20.	Lena-Macha	538,000	1980-2010	1955-2010
21.	Lena-Sangari	1,680,000	1980-2010	1955-2010
22.	Lena-Kyusyur	2,430,000	1980-2010	1955-2010
23.	Barguzin-Mogoito	9350	1980-2008	1945-2008
24.	Shilka-Sretensk	175,000	1980-2009	1955-2009
25.	Kolyma-Zyryanka	287,000	1980-2010	1941-2010
26.	Naiba-Bykob	679	1980-2008	1955-2008
27.	Ussuri-Kirovskiy	24,400	1980-2010	1956-2010
28.	Ingoda-Ulety	12,500	1980-2009	1955-2009

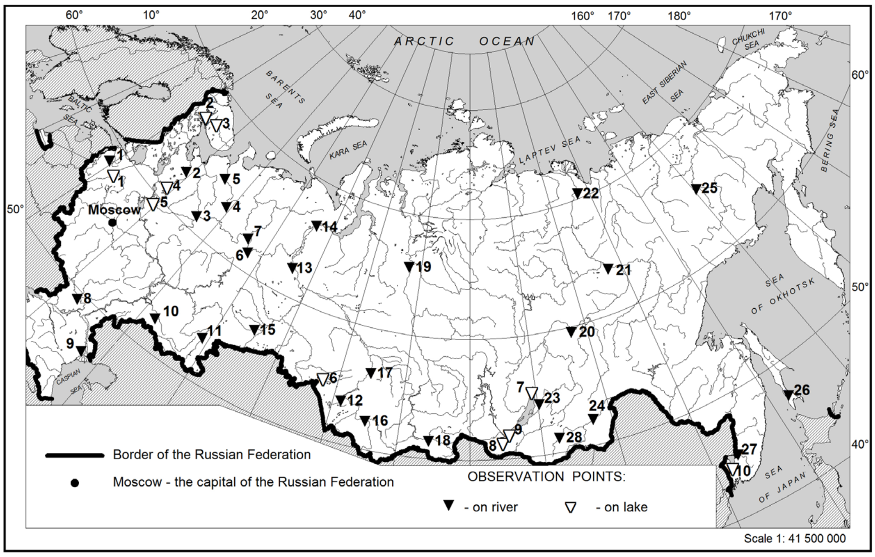

Figure 1. Observing sites on rivers and lakes.

Table 2. Observing sites on lakes and length of observation periods.

N°	Lake-site	Area, km^2	Observation period	
			Ice cover duration	Maximum ice thickness
1.	Ilmen'-Voitsy	982	1916-1980	1946-1980
2.	Imandra-Zasheek	876	1945-2008	1945-2008
3.	Lovozero-Lovozero	200	1946-2008	1946-2008
4.	Lacha-Nokola	356	1918-2008	1940-2008
5.	Kubenskoye-Korobovo	370	1931-2008	1932-2008
6.	Chany-Kvashnino	1030	1933-2010	1943-2010
7.	Baikal-Nizhneangarsk	31,500	1936-2008	1946-2008
8.	Baikal-Baikal	31,500	1926-1980	1945-2009
9.	Baikal-Peschanaya Bukhta	31,500	1931-2008	1945-2008
10.	Khanka-Astrakhanka	4070	1936-2008	1945-2008

riod—since the beginning of observations until 2010, first stationary climate period—since the beginning of observations until 1979 and second non-stationary climate period—1980-2010).

4. Assessment of Homogeneity of Long-Term Ice Regime Series

Two general criteria were used to assess the homogeneity of long-term series of ice cover duration and maximum ice thickness, namely the Student's t-test (assessment of homogeneity hypothesis by true mean (expectation)) and the Fisher's F-test (assessment of homogeneity hypothesis by dispersion). Both criteria were used for 5% level of significance. The initial series included two abovementioned periods—from the beginning of observations until 1979 and from 1980 to 2010. Table 3 below provides the results of long-term series homogeneity assessments for maximum ice thickness on rivers.

Analysis of data in Table 3 demonstrated that for maximum ice cover on rivers the homogeneity hypothesis has proved not to be true by both criteria for seven gauging sites (Luga-Tolmachevo, Northen Dvina-Kotlas, Mezen'-Marakaib, Pechora-Ust'-Unya, Ob'-Oktyabrskoye, Biya-Biysk and Lena-Kyusyur). Looking ahead, one can mention that for the above gauging sites the analysis of trends (to be discussed below) demonstrated either multidirectional trends in the first and second periods (Northen Dvina-Kotlas, Pechora-Ust'-Unya, Ob'-Oktyabrskoye, Biya-Biysk) or highly different trend gradients when comparing two periods (Luga-Tolmachevo, Mezen'-Marakaib, Lena-Kyusyur). The same

Table 3. Homogeneity tests for long-term series of maximum ice thickness on rivers.

Site	Fisher's test			Student's test		
	Calculated value	Critical value	Result	Calculated value	Critical value	Result
Luga-Tolmachevo	2.717	2.098	non-homogeneous	3.699	2.467	non-homogeneous
Onega-Turchasovo	1.499	2.253	homogeneous	0.768	2.222	homogeneous
Northern Dvina-Kotlas	2.984	2.064	non-homogeneous	3.783	2.289	non-homogeneous
Mezen'-Marakaib	2.170	2.074	non-homogeneous	3.227	2.325	non-homogeneous
Mezen'-Malonisogorskaya	1.001	2.099	homogeneous	1.165	2.014	homogeneous
Pechora-Ust'-Unya	5.769	2.080	non-homogeneous	2.221	2.047	non-homogeneous
Pechora-Troitsko-Pechorsk	1.889	2.076	homogeneous	1.413	2.017	homogeneous
Volga-V.Lebyazhye	1.323	1.878	homogeneous	0.239	2.042	homogeneous
Samara-Elshanka	1.553	1.938	homogeneous	5.790	2.631	non-homogeneous
Ural-Verkhneuralsk	1.986	2.492	homogeneous	7.564	4.147	non-homogeneous
Ob'-Kamen-na-Obi	1.341	2.469	homogeneous	3.485	2.645	non-homogeneous
Ob'-Oktyabrskoye	2.969	2.265	non-homogeneous	3.258	2.564	non-homogeneous
Ob'-Salekhard	1.370	2.170	homogeneous	2.313	2.222	non-homogeneous
Biya-Biysk	2.399	2.043	non-homogeneous	4.310	2.956	non-homogeneous
Tom'-Tomsk	1.448	1.879	homogeneous	0.080	2.178	homogeneous
Yenisei-Kyzyl	1.869	3.120	homogeneous	3.364	3.572	homogeneous
Yenisei-Selivanikha	2.161	2.740	homogeneous	0.853	2.040	homogeneous
Lena-Macha	1.226	2.051	homogeneous	1.511	2.203	homogeneous
Lena-Sangari	1.645	2.827	homogeneous	6.071	3.995	non-homogeneous
Lena-Kyusyur	3.557	3.453	non-homogeneous	6.882	4.863	non-homogeneous
Barguzin-Mogoito	1.025	1.886	homogeneous	0.348	2.265	homogeneous
Shilka-Sretensk	1.043	1.974	homogeneous	0.804	2.200	homogeneous
Kolyma-Zyryanka	1.263	1.980	homogeneous	1.163	2.438	homogeneous

reasons lie behind cases when non-homogeneity is determined by one of the criteria. The homogeneity hypothesis by the Student's test has proved not to be true for the cases when trend gradients vary greatly for two periods (Ob'-Kamen'-na-Obi, Ob'-Salekhard, Ural-Verkhneuralsk, Lena-Sangary), which can be explained by differences in mean values for both periods.

In regard to the long-term series of ice cover duration on rivers, the homogeneity hypothesis has proved not to be true by both criteria only for the Mezen'-Marakaib gauging site (as well as for the maximum ice thickness).

Long-term series of ice thickness on lakes have proved to be homogeneous by both criteria for five gauging sites. It is only for one site (lake Kubenskoye-Kubenskoye) that the hypothesis has proved not to be true by both criteria. The main reason for that are different trend gradients for both periods. The same reason lies behind non-homogeneity by Student's test of maximum ice thickness long-term series of the lakes Lacha-Nokolo and Khanka-Astrakhanka.

Long-term series of ice cover duration for six lake observing sites have proved to be homogeneous by both criteria. It is only for two sites (lake Baikal-Baikal and lake Khanka-Astrakhanka) that the time series have proved non-homogeneous by the Student's t-test, which, judging by the trend analysis, can be explained by differences in trend gradients for both periods and, accordingly, by differences in mean values for both periods.

Summarizing the results of the assessment, a very important trend can be observed: if time series of maximum ice thickness of an observing site are non-homogeneous by both criteria, the same is the case for the time series of duration of ice cover by both or only one criteria. The examples of such sites on rivers are Luga-Tolmachevo, Northen Dvina-Kotlas and Mezen'-Marakaib. This can be explained by the fact that sharp fluctuations of average ice cover duration for a long period are usually accompanied by changes in average maximum ice thickness for the same period. For example, if a series of harsh winters with prolonged ice cover duration is observed, average maximum ice thickness increases for the same period and vice versa.

5. Assessment of Trends of Long-Term Series of Ice Regime Characteristics

Trends of long-term series were assessed by the Student's t-test for three time intervals. Table 4 provides the results of the assessment for maximum ice thickness.

The table provides the following values needed to check the trend significance (*i.e.* to test the hypothesis of the ice regime characteristics linear regression coefficient equal zero):

$$t = a/S_a$$

where a—the regression coefficient, S_a—its root-mean-square deviation, $t_{0.05}(m)$—critical value to test the hypothesis of regression coefficient with 5% level of significance (inverse t-Student distribution) equal zero; m—degree of freedom for t-test (number of terms in a series minus 2).

Table 4. Assessment of trends of long-term series of maximum ice thickness on rivers.

Site	Maximum ice thickness								
	until 1980			since 1980			entire period		
	T	$t_{0.05}(m)$	m	t	$t_{0.05}(m)$	m	t	$t_{0.05}(m)$	m
Luga-Tolmachevo	−1.449	2.069	24	**−4.101**	**2.052**	27	**−6.522**	**2.007**	55
Onega-Turchasovo	−0.942	2.060	25	−1.765	2.086	20	**−3.734**	**2.012**	56
Northern Dvina-Kotlas	**−2.543**	**2.064**	24	1.228	2.045	29	**−3.945**	**2.004**	55
Mezen’-Marakaib	1.848	2.060	25	−1.305	2.080	21	**−4.224**	**2.011**	56
Mezen’-Malonisogorskaya	−0.305	2.060	24	−0.957	2.080	21	−1.655	2.011	55
Pechora-Ust’-Unya	−0.311	2.069	23	0.402	2.080	21	−1.588	2.013	54
Pechora-Troitsko-Pechorsk	−0.178	2.069	23	−2.026	2.048	28	−0.294	2.006	54
Don-Serafimovich	−0.409	2.056	27	−1.249	2.093	19	**−2.338**	**2.012**	56
Volga-V.Lebyazhye	0.578	2.035	35	**−3.630**	**2.074**	22	−1.044	2.002	64
Samara–Elshanka	**−2.077**	**2.035**	33	−1.770	2.056	26	**−7.118**	**2.000**	62
Ural-Verkhneuralsk	**−3.388**	**2.035**	33	**−3.632**	**2.042**	30	**−10.277**	**1.997**	64
Ob’-Kamen-na-Obi	−0.485	2.069	24	−1.483	2.048	28	**−4.139**	**2.006**	54
Ob’-Oktyabrskoye	−0.678	2.069	24	0.516	2.069	23	**−2.055**	**2.011**	53
Ob’-Salekhard	**−3.623**	**2.069**	24	−0.004	2.069	23	**−2.352**	**2.011**	54
Yset’-Ysetskoye	−0.946	2.030	35	−1.808	2.080	21	**−4.251**	**2.002**	64
Biya-Biysk	−1.967	2.035	33	0.541	2.056	26	**−3.978**	**2.000**	62
Tom’-Tomsk	1.428	2.042	31	−1.447	2.056	26	−0.305	2.002	60
Yenisei-Kyzyl	−1.638	2.074	24	−1.017	2.045	29	**−6.522**	**2.006**	55
Yenisei-Selivanikha	−0.333	2.080	24	0.557	2.045	29	−0.755	2.007	55
Lena-Macha	1.747	2.074	23	−0.821	2.042	30	−1.733	2.005	54
Lena-Kyusyur	−1.895	2.074	23	**−2.440**	**2.042**	30	**−8.249**	**2.005**	54
Barguzin-Mogoito	−1.529	2.037	37	1.387	2.060	25	0.619	2.001	52
Shilka-Sretensk	−0.961	2.069	23	−0.513	2.052	27	−1.337	2.007	53
Kolyma-Zyryanka	**−2.387**	**2.040**	31	−0.015	2.045	29	−1.156	1.999	68
Naiba-Bykob	−1.769	2.069	23	0.198	2.069	23	−0.925	2.011	52
Ussuri-Kirovskiy	1.045	2.074	22	−0.541	2.045	29	−0.647	2.006	53
Ingoda-Ulety	−0.129	2.074	23	0.731	2.052	27	−1.241	2.008	53

The test of hypothesis of the regression coefficient equal zero consisted in comparison of absolute value t with $t_{0.05}(m)$. If $|t| > t_{0.05}(m)$, the hypothesis is discarded with error probability 0.05 (trend is significant). If not, there is no reason to discard the hypothesis (the trend is insignificant).

Calculated and critical statistical values for the periods with statistically significant trends are shown in bold.

The analysis of trends demonstrated that maximum number of statistically significant trends of long-term series of maximum ice thickness on rivers (14 cases out of 28) are obtained for the entire period. As for the two separate periods, the number of statistically significant trends is much smaller (four trends for the first period and three—for the second). It is noteworthy that statistically significant trends for complete time-series have been obtained for many gauging sites with non-homogeneous long-term series (Luga-Tolmachevo, Northen Dvina-Kotlas, Mezen'-Marakaib, Ob'-Oktyabrskoye, Biya-Biysk, Lena-Kyusyur), which is indicative of past changes in maximum ice thickness formation conditions in the past 60 - 70 years. Figure 2 shows as an example a diagram of changes in maximum ice thickness on the Lena river at Kyusyur site which gives visual representation of the trend for 1955-2010.

As for long-term series of ice cover duration, it is only for seven gauging sites that total assessment of trends was made for all the three periods. For the rest of the sites, assessment was made only for the second period due to absence of data.

For all the three periods, statistically significant trends were obtained for the same sites as they were obtained for maximum ice thickness but not always for the same periods. For example, for the Luga-Tolmachevo site, statistically significant trend was obtained for the entire period, while for the Northen Dvina-Kotlas, Mezen'-Marakaib and Pechora-Troitsko-Pechorsk they were obtained only for the first period (Figure 3) and for Ural-Verkhneuralsk—for the second one.

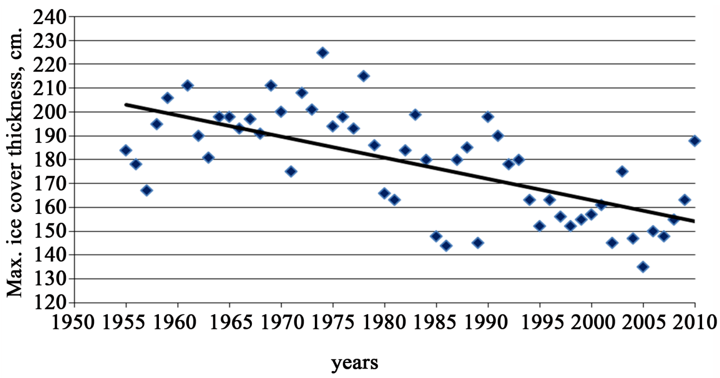

Figure 2. Changes in annual maximum ice thickness in 1955-2010 (Lena-Kyusyur).

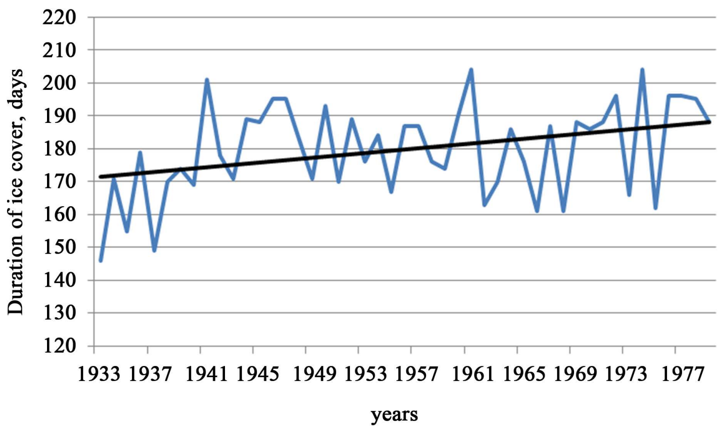

Figure 3. Changes in annual ice cover duration in 1933-1979 (Northen Dvina-Kotlas).

For those sites which had time-series only for the second period, statistically significant trends were obtained for the sites Iset'-Isetskoye, Yenisei-Selivanikha, Lena-Macha, Lena-Kyusyur, Ussuri-Kirovskiy and Kolyma-Zyryanka. It is worth noting that for four out of six abovementioned sites statistically significant trends were obtained also for time-series of maximum ice thickness.

Statistically significant trends in long-term series of maximum ice thickness on lakes were obtained for the lakes Ilmen-Voitsy and Kubenskoye-Korobovo (entire series and second period), Imandra-Zasheek, Lovozero-Lovozero (second period) and Chany-Kvashnino (entire period) (**Figure 4**).

For the series of ice cover duration, statistically significant trends were obtained for the lakes Imandra-Zasheek, Lovozero-Lovozero (first period), Chany-Kvashnino, Khanka-Astrakhanka (entire series and second period) and Baikal-Baikal (entire series). It is easy to show that for three abovementioned lakes statistically significant trends were obtained for both maximum ice thickness and ice cover duration (Imandra-Zasheek, Lovozero-Lovozero, Chany-Kvashnino. It should also be noticed that long-term series of maximum ice thickness for Kubenskoye-Korobovo, for which a significant trend was obtained, proved to be non-homogeneous as well as ice cover duration series with significant trends for Baikal-Baikal and Khanka-Astrakhanka.

6. Assessment of Changes in Ice Regime Characteristics of Rivers and Lakes for Non-Stationary Climate Period

Changes in ice regime characteristics were assessed for the second period 1980-2010 relative to the first period of conditionally stationary climate (since the beginning of observations until 1979). Large scale chronological graphs of annual values of ice regime characteristics with frequent divisions of vertical axis spacing for 1980-2010 for all sites on lakes and rivers were used for this purpose. Trend lines were plotted on the graphs and values corresponding to the last and the first years in the series were taken. Difference of these two relative to a num-

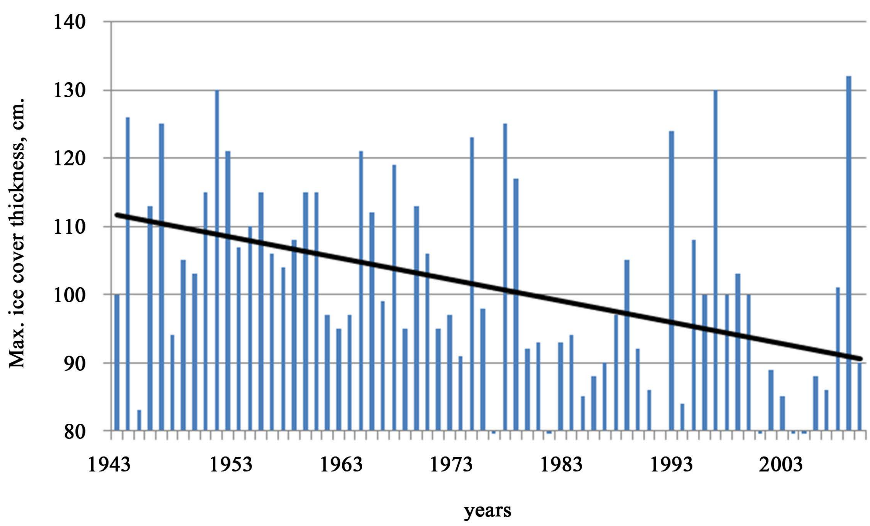

Figure 4. Changes in annual maximum ice thickness in 1943-2010 (Chany-Kvashnino).

ber of years in a series defines the gradient (Δ) of temporal changes of a parameter. For the sake of convenience, the gradients were calculated relative to a decade and expressed either in cm/decade (for maximum ice thickness series) or in day/decade (for ice cover duration series). In order to evaluate the degree of significance of the obtained trends they were related to mean values of the corresponding characteristics calculated for the stationary climate period (since the beginning of observations until 1979). Table 5 and Table 6 provide changes in ice regime characteristics of rivers (%) characterized by coefficient K calculated as a reminder of the gradient obtained for the series since 1980 (expressed as ΔX_2 for maximum ice thickness and ΔY_2, for ice cover duration) and average value of a characteristic for the series until 1979 (expressed as X_1 for maximum ice thickness and Y_1 for ice cover duration).

Table 5. Changes in ice regime characteristics of rivers K(%) by trends for the second period relative to their mean values for the first period.

River site	Maximum ice thickness			Ice cover duration		
	$X_{1,cm.}$	$\Delta X_{2,cm}$	K, %	$Y_{1,days}$	$\Delta Y_{2,days}$	K, %
Luga-Tolmachevo	42	−15	35	115	−9	8
Onega-Turchasovo	62	−9	14	169	−21	12
Northern Dvina-Kotlas	73	+6	8	180	−12	7
Mezen’-Marakaib	78	−5	6	204	−4	20
Mezen’-Malonisogorskaya	80	−6	7	201	−9	4
Pechora-Ust’-Unya	72	+3	4	204	−15	7
Pechora-Troitsko-Pechorsk	68	−9	13	192	0	
Volga-V. Lebyazhye	43	−24	56			
Samara-Elshanka	49	−12	24			
Ural-Verkhneuralsk	94	−24	25			
Don-Serafimovich	43	−18	42			
Ob’-Kamen-na-Obi	89	−9	10			
Ob’-Oktyabrskoye	85	+6	7			
Ob’-Salekhard	105	0				
Yset’-Ysetskoye	72	−21	29			
Biya-Biysk	64	0				
Tom’-Tomsk	82	−12	15			
Yenisei-Kyzyl	158	−15	9			
Yenisei-Selivanikha	90	+2	2			
Lena-Macha	116	−9	8			
Lena-Kyusyur	192	−15	8			
Barguzin-Mogoito	117	+18	15			
Shilka-Sretensk	124	−18	14			
Kolyma-Zyryanka	97	0				
Naiba-Bykob	79	0				
Ussuri-Kirovskiy	85	−5	6			
Ingoda-Ulety	135	+9	7			

Table 6. Changes in ice regime characteristics (%) obtained from trends for the second period relative to their mean values for the first period.

Site	Maximum ice thickness			Ice cover duration		
	$X_{1,cm}$	$\Delta X_{2,cm}$	K, %	$Y_{1,days}$	$\Delta Y_{2,days}$	K, %
Ilmen'-Voitsy	65	−3	5	175	+5	3
Imandra-Zasheek	79	−21	26	200	−14	7
Lovozero-Lovozero	93	−18	19	225	+15	7
Lacha-Nokola	99	+6	6	177	−15	8
Kubenskoye-Korobovo	67	−12	18	155	+7	4
Chany-Kvashnino	107	0		199	+14	7
Baikal-Nizhneangarsk	100	−12	12	142	+3	2
Baikal-Baikal	83	−2	2	116	−15	13
Baikal-Peschanaya Bukhta	91	−4	4	113	+3	3

For some rivers, parameters related to ice cover duration are not reflected in Table 5 due to absence of data needed to calculate mean values of a parameter for the first period.

Analysis of data in Table 5 demonstrates that for many rivers gradients of changes in maximum ice thickness relative to mean value of a parameter for previous period amount to 15% and more. Such gradients are especially significant for southern rivers of the European Russia (Volga-Verkhnee Lebyazhye—56%, Samara-Elshanka—24%, Don-Belyaevsky—42%). First, for these rivers mean values of the parameters for the first period are small (43 - 49 cm) compared with the same values, for example, for the Siberian rivers (2 - 3 times greater for maximum ice thickness). Secondly, for many rivers of the Asian Russia these gradients are equal to or 10% greater than mean values for the previous period (Ob'-Kamen-na-Obi, Tom'-Tomsk, Yset'-Ysetskoye, Barguzin-Mogoito, Shilka-Sretensk), although these mean values themselves are quite large amounting to 80 - 120 cm.

As for the relations of gradients of ice cover duration to mean values of this parameter for the first period, they do not exceed 10% - 15% for the rivers in question, from which it can be concluded that changes in maximum ice thickness for the past 30-year period occur more intensively than those in ice cover duration.

Data in Table 6 indicate that maximum values of coefficient K for maximum ice thickness are typical for lakes of the Kola Peninsula (Imandra-Zasheek—26%, Lovozero-Lovozero—19%) and for the lake Kubenskoye-Korobovo (18%). For the rest of the lakes these coefficients do not exceed 10% - 12%.

Interestingly, as opposed to rivers, the range of changes in mean values of maximum ice thickness for the first period for lakes of both European and Asian Russia is much smaller and varies within 65 - 107 cm. Values of the coefficient K for the lakes in question vary mainly from 2% to 8% (only for the lake Baikal-

Baikal it amounted to 13%), which proves the previous conclusion that for rivers changes in maximum ice thickness for the past 30 years occur more intensively compared with changes in ice cover duration.

A comparison was made of mean values of the characteristics in question obtained from time series of the second period with mean values of the same characteristics obtained from the first period time series. The results of the comparison are given in Table 7.

Analyzing data in Table 7 one can observe that in most cases values of changes in both maximum ice thickness and ice cover duration are negative. The largest negative changes are typical for rivers of the Asian Russia, e.g. for the site Ural-Verkhneuralsk they amounted to −35 cm, for Yenisei-Kyzyl and Lena-Kyusyur −38 cm. In most cases, the above changes for rivers do not exceed 10 - 12 cm. The latter is typical also for data on ice cover duration on rivers— negative changes in mean values for the second period relative to the first one are in the range of 10 days except for the Luga-Tolmachevo site for which it was 29 days.

For lakes, all the obtained changes in mean values of ice regime characteristics are negative and relatively small. For maximum ice thickness they were equal to 1 to 13 cm and for ice cover duration 3 to 12 days.

Three cases demonstrated positive values of changes for both maximum ice thickness (Yenisei-Selivanikha +1 cm; Barguzin-Mogoito +19 cm.) and ice cover duration (Onega-Turchasovo +3 days). It is worth noting that positive changes in mean values over the past period are not always indicative of positive trend of a parameter for the entire period (since the beginning of observations until 2010). It appeared negative for two out of three abovementioned sites (Yenisei-Selivanikha—1 cm/decade; Onega-Turchasovo—2 cm/decade) and only for the site Barguzin-Mogoito the trend of maximum ice cove thickness changes was positive for the entire period (+2 cm/decade).

In order to integrate assessments of changes in ice regime parameters of all the abovementioned rivers and lakes in 1980-2010, data on trends for the second period (Table 5 and Table 6) were integrated with assessment of changes in mean values for the non-stationary period (1980-2010) relative to mean values for the previous period (Table 7). Integrated values of changes in maximum ice thickness and ice cover duration over non-stationary period (1980-2010) relative to the previous period are given in Table 8.

7. Summary

The study found that maximum ice thickness on the rivers of the European Russia in 1980-2010 decreased in general by 10% - 15%. It is only for the Luga-Tolmachevo site that this decrease amounted to more than 30% compared with the previous period (42 cm). For the rivers of the Asian Russia, decrease in maximum ice thickness amounted to 10% - 20% except for the site Ural-Verkhneuralsk where it is estimated at 25% - 35%.

Ice-cover duration on the rivers of the European Russia decreased by 5% - 10%. It is estimated at 29% only for the Luga-Tolmachevo site.

Table 7. Changes in mean values of maximum ice thickness and ice cover duration for the period of non-stationary climate (1980-2010) relative to mean values for the previous period.

Water body—site	Changes in mean values of maximum ice thickness for the second period (1980-2010) relative to the first period, cm	Changes in mean values of ice cover duration for the second period (1980-2010) relative to the first period, days
Luga-Tolmachevo	−12	−29
Onega-Turchasovo	−7	+3
Northern Dvina-Kotlas	−11	−7
Mezen’-Marakaib	−9	−11
Mezen’-Malonisogorskaya	−5	−10
Pechora-Ust’-Unya	−5	−8
Pechora-Troitsko-Pechorsk	−2	−3
Volga-V. Lebyazhye	−3	
Don-Serafimovich	−8	
Samara-Elshanka	−10	
Ural-Verkhneuralsk	−35	
Ob’-Kamen-na-Obi	−18	
Ob’-Oktyabrskoye	−6	
Ob’-Salekhard	−2	
Yset’-Ysetskoye	−12	
Biya-Biysk	−10	
Tom’-Tomsk	−2	
Yenisei-Kyzyl	−38	
Yenisei-Selivanikha	+1	
Lena-Macha	−23	
Lena-Sangari	−23	
Lena-Kyusyur	−38	
Barguzin-Mogoito	+9	
Shilka-Sretensk	−4	
Kolyma-Zyryanka	−1	
Naiba-Bykob	−2	
Ussuri-Kirovskiy	−2	
Ingoda-Ulety	−8	
Ilmen’-Voitsy	−9	−3
Imandra-Zasheek	−1	−3
Lovozero-Lovozero	−9	−9
Lacha-Nokola	−2	−12
Kubenskoye-Korobovo	−2	−11
Chany-Kvashnino	−13	−12
Baikal-Nizhneangarsk	−8	−8
Baikal-Baikal	−11	−8
Baikal-Peschanaya Bukhta	−7	−4
Khanka-Astrakhanka	−7	−10

Table 8. Assessment of changes in maximum ice thickness and ice cover duration over non-stationary climate period (1980-2010) relative to the previous period.

Water body-Observing site	Maximum ice thickness, cm	Ice cover duration, cm
Luga-Tolmachevo	−12 – 15	−9 – 29
Onega-Turchasovo	−7 – 9	+ 3 – 21
Northern Dvina-Kotlas	+6 – 11	−7 – 12
Mezen’-Marakaib	−5 – 9	−4 – 11
Mezen’-Malonisogorskaya	−5 – 6	−9 – 10
Pechora-Ust’-Unya	+3 – 5	−8 – 15
Pechora-Troitsko-Pechorsk	−2 – 9	0 – 3
Don-Serafimovich	−8 – 18	
Volga-V. Lebyazhye	−3 – 24	
Samara-Elshanka	−10 – 12	
Ural-Verkhneuralsk	−24 – 35	
Ob’-Kamen-na-Obi	−9 – 18	
Ob’-Oktyabrskoye	−2 – 6	
Ob’-Salekhard	0 – 2	
Yset’-Ysetskoye	−12 – 21	
Biya-Biysk	0 – 10	
Tom’-Tomsk	−2 – 12	
Yenisei-Kyzyl	−15 – 38	
Yenisei-Selivanikha	−1 + 2	
Lena-Macha	−9 – 23	
Lena-Sangari	−21 – 23	
Lena-Kyusyur	−15 – 38	
Barguzin-Mogoito	+9 + 15	
Shilka-Sretensk	−4 – 18	
Kolyma-Zyryanka	0 – 1	
Naiba-Bykob	0 – 2	
Ussuri-Kirovskiy	−2 – 5	
Ingoda-Ulety	−8 + 9	
Ilmen’-Voitsy	−3 – 9	−3 + 3
Imandra-Zasheek	−1 – 21	−3 – 12
Lovozero-Lovozero	−9 – 18	−9 + 15
Lacha-Nokola	−2 + 6	−12 – 15
Kubenskoye-Korobovo	−2 – 12	−11 + 7
Chany-Kvashnino	0 – 13	−12 + 12
Baikal-Nizhneangarsk	−8 – 12	−8 + 3
Baikal-Baikal	−2 – 11	−8 – 15
Baikal-Peschanaya Bukhta	−4 – 7	−4 + 3
Khanka-Astrakhanka	−6 – 7	−5 – 10

Maximum ice thickness on the above lakes decreased by 10% - 15% in 1980-2010. As for decrease in ice cover duration, the negative gradient is estimated at 5% - 10% compared with the previous period.

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