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DETECTION OF THE CHANGE POINT IN ICE FORMATION DATES

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Abstract. In recent years, there has been an increasing interest in studies related to the impact of climatic changes on the ice regime of water bodies. This paper aims to detect the change point in the ice formation dates for Kamskoe Reservoir. This is done with the use of an improved methodological approach. The results revealed that the greatest deviations are observed when comparing time intervals after 1995. The last decade of the observation period (2008–2018) was characterized by significant changes in late dates. According to the Data Series Smoothing method, the change point for the observation series falls on 1996. Differential Integral Curves of the ice dates show that the beginning of the significant climatic changes is noted in 1995–1997. The rejection of the randomness hypothesis indicates the presence of significant changes in the ice dates for 1956–2018 for all gauges, except Berezniki. The deviation of the homogeneity hypothesis for the ice dates in 1956–1995 and 1996–2018 shows the presence of statistically significant changes at the turn of 1996. Thus, the impact of modern climatic changes on the ice dates has been observed over the last 25 years, with the change point falling on 1996.

Keywords: ice dates, dates variability, climatic changes, ice dates variability, change point, statistical hypothesis testing

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ОПРЕДЕЛЕНИЕ ГОДА НАЧАЛА ВЛИЯНИЯ ВЫРАЖЕННЫХ КЛИМАТИЧЕСКИХ ИЗМЕНЕНИЙ НА СРОКИ ЛЕДООБРАЗОВАНИЯ

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Аннотация. В последние годы возрастает интерес к исследованиям, связанным с влиянием климатических изменений на ледовый режим водных объектов. Целью данной работы является определение начала выраженных изменений (момента разладки) в рядах наблюдений сроков ледообразования на гидрологических постах Камского водохранилища. Момент разладки был определен с помощью усовершенствованного методологического подхода, представляющего собой последовательную проверку рядов наблюдений и их частей на случайность и однородность с использованием статистических методов. Результаты показали, что наибольшие отклонения наблюдаются при сравнении временных интервалов после 1995 г. Последнее десятилетие (2008–2018 гг.)

оказало существенное влияние на изменение поздних дат. По методу скользящих средних значений начало выраженных изменений сроков ледообразования приходится на 1996 г. На разностно-интегральных кривых видно, что начало периода значительных климатических изменений по разным гидрологическим постам также приходится на 1995–1997 гг. Отклонение гипотезы случайности для всех постов, кроме Березников, за 1956–2018 гг. свидетельствует о наличии существенных изменений в сроках ледообразования. Отклонение гипотезы однородности сроков ледообразования для периодов 1956–1995 и 1996–2018 гг. показывает наличие статистически значимых изменений после 1996 г. Таким образом, влияние современных климатических изменений на сроки ледообразования наиболее ярко выражено в последние 25 лет.

Ключевые слова: сроки ледообразования, изменчивость дат, климатические изменения, точка перегиба, проверка статистической гипотезы

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Introduction

Climate change can determine the features of the hydrological regime of water bodies. Ice phenomena are sensitive to incremental changes in air temperature and can be used as indicators of systematic changes in climate. The study of the pronounced changes in the ice regime is important and relevant, and it can be performed using ice dates.

There are numerous publications devoted to studies into the long-term fluctuations of the ice regime. The first studies dealt with the fluctuations in ice dates due to climate change. For example, G.P. Williams [50] considered the break-up dates of lakes and rivers as an indicator of climate change. Later, similar issues were investigated in M. Tanaka and M.M. Yoshino [44] for Lake Suva in Japan and in J.A. Maslanik and R.G. Barry [30] for lakes in Finland and Canada.

In 1990, the Intergovernmental Panel on Climate Change (IPCC) published the Scientific Assessment [18]. After its publication, the number of articles devoted to climate change and related changes in the ice regime has significantly increased. As to specifically Russian research, century-long changes in the ice regime of rivers were analyzed in few studies [14, 15, 40, 41]; there was conducted research aiming to assess the climate change impact on the ice regime of lakes in a temperate climate [42] and also numerical modeling of the ice regime changes due to climatic conditions [16, 43, 46]. In the 1990s, the number of studies increased 7 times compared to the previous decade.

The majority of the authors compared average characteristics and their trends for two periods – before (stationary climate) and after (nonstationary climate) pronounced climatic changes. As to the comparison periods, the authors used different time intervals, which were selected depending on the availability of data and the year of publication. Some studies were focused on 1961–1990 because this period was recommended by the World Meteorological Organization (WMO) for data averaging in the current climate [1, 2, 11, 13, 41]. At the same time, I.I. Soldatova [41] used data for this period as being up-to-date with respect to 1893–1960. Other researchers considered 1961–1990 as basic and compared it with data for the modern period. For example, B.M. Ginzburg [13] explored 1997–2003, S.A. Agafonova and N.L. Frolova [1] examined 1991–2007, S.A. Agafonova et al. [2] and N.L. Frolova et al. [11] focused on 1991–2014. Some scientists [34, 49] took the early 1980s as the time of a noticeable increase in the average global air temperature based on research [4]. V.K. Smakhtin [39] used data for 1975–2012 due to the Second Assessment Report of Roshydromet on Climate Changes and Their Consequences [45]. According to this report, the most intense warming was observed since the mid-1970s. Other scientists did not compare the two observation periods (periods of stationary and non-stationary climate); their studies were based on the analysis of the examined characteristics averaged with different steps: 12 years [9], 20 and 50 years [12], or 30 years [10], and identified the period where the examined characteristics showed the greatest deviations.

Some investigations applied different statistical methods for the detection of the change point and analysis of long-term changes in the ice regime. D.M. Livingstone [26, 27] determined the time series change-point in the study of the break-up dates of lakes.

Several studies examined long-term changes in the ice regime characteristics and looked for the statistical significance of particular trends. Trends were tested in different ways: using the nonparametric Mann-Kendall trend test [8, 10, 12, 21, 22, 23, 24], linear least-squares regression and non-parametric methods [7]. Some studies checked the trend's significance in the ice regime data using the one-sample t-test [33, 37, 39, 48, 49], the Wilcoxon signed-rank test [7, 32, 49].

Data homogeneity was assessed only in a few studies [41, 34, 48, 49]. Several works examined data for spatial autocorrelation which was found to be present and could result in underestimated confidence intervals [7, 12, 17, 23, 24].

The overview of recently published research shows the absence of unified methodology for determining the change point in the ice regime time series. Studies on the climate change impact on the ice regime of water bodies apply different statistical techniques. Thus, the primary objective of our study is to determine the change point in the ice formation dates using the methodological approach proposed in V.G. Kalinin and V.V. Chichagov [20].

More specifically, this paper addresses the following questions:

1. How are the ice dates in time intervals different from the dates in 1956–2018?
2. When is the change point in ice formation dates observed?
3. Do the observation series before and after identification of the change point are characterized by homogeneity disturbance?

Study area

Kamskoe Reservoir catchment is located in Perm Krai (region) in the western part of the Urals. It was constructed on the Kama River. The reservoir is a cascade regulator because it is the first in the Kama cascade and has a water head of 22 m. The filling of the reservoir began in 1954 and ended in 1956. At a retention water level (RWL), the water surface area is 1719 km^2, the total volume is 10.7 km^3, the active storage is 8.36 km^3, the average depth is 6.2 m, the maximum depth is 28.1 m. The reservoir is fed by river runoff and has crenelated shoreline and large bays. Kamskoe Reservoir provides seasonal, weekly, and daily storage of flow.

Heat is unevenly distributed in the study area from north to south. During the year, the northern part receives 15% less solar heat than the southern part. Even greater changes in the values of total solar radiation are observed over the seasons. In the summer, the catchment area receives 80% of the annual amount of heat, and in the winter – about 20% [38]. The northern location of the area contributes to the frequent invasion of cold Arctic air masses, which determine the climate severity. Cyclones determine a sharp change in the weather – from warm to cold. The sharp drop in air temperatures is especially pronounced when the average daily air temperatures are close to 0°C. During such periods, the first ice forms on rivers and reservoirs in the autumn. The average air temperature from September to October drops by 7-8°C. In October, the air temperature falls below 0°C. The 0ºC isotherm dates are observed within 1-1.5 months (September 26-November 13).

Data and methods

1. Data sources

Data were extracted from different sources: for 1956–1985 – from the Hydrological Yearbooks [6]; for 1986–2007 – from the archives in the Perm Center for Hydrometeorology and Environmental Protection; for 2008–2018 – from an open access database in the Automated Information System for Water Bodies' State Monitoring [5]. The collected data contain *in situ* observations for 63 years from 11 gauges on Kamskoe Reservoir. The ice formation dates were selected uniformly from daily water level tables for all gauges according to the method given in 3.2.1.

2. Analysis methods

2.1. Identification of the stable ice dates

The stable ice formation dates (ice dates) in the autumn were selected as an ice regime parameter for the study. The ice dates were determined as follows: if the period with ice was longer than the subsequent period without ice, then the first date with ice was taken as the stable date of ice formation; if the period with ice was shorter, then the first date after period without ice was taken as the stable date of ice formation. To enable the comparability and averaging, the ice dates were represented by natural numbers as the number of days from September 1st.

2.2. Analysis of long-term fluctuations

Since *the primary objective* of this study is to detect the change point in the ice formation dates for Kamskoe Reservoir, a decision was taken to examine it through long-term fluctuations in the stable ice dates. The long-term average, early and late ice dates for a representative 40-year period (1956–1995) were previously calculated and analyzed by V.G. Kalinin [19]. In our study, the observation period was increased by 1.5 times, covering 63 years (1956–2018). First, changes in the average long-term ice dates were analyzed for both subperiods (1956–1995 and 1956–2018), because we needed to check if the average dates had changed over the last subperiods. It was also checked whether the extreme (early and late) ice dates had changed. The average ice dates were also calculated for different time intervals (with a 5-year step) and compared with average dates for the whole period (1956–2018). That was made in order to control in which period the greatest deviations in the average ice dates were observed.

2.3. Detection of the change point

An analysis of the ice dates long-term fluctuations cannot properly determine the trends and the change point for the time series (the beginning of intraseries changes). Therefore, the studied dates were smoothed with the Moving Average method [47] to level out interannual fluctuations. Smoothing was done over the odd periods: 3, 5, 7, 9, 11, etc. up to 31, with a one-year step.

The Differential Integral Curve method was used to assess the cyclic fluctuations of many hydrological parameters [3]. In the context of ice dates analysis, this method determines cyclical fluctuations and identifies periods of earlier and later ice dates. This includes identification of the change point, where the influence of climatic changes on the ice regime is noticeable. According to the method, first the modular coefficient $K = \frac{x}{\bar{x}}$ was calculated (where x is the dates of the series, $\bar{x}$ is the average date of the series), then the values *K-1* were determined. After that, an integral curve was plotted by consecutive summing of those values.

2.4. Justification of the change point with statistical methods

The observation series were analyzed with the methodological approach outlined in V.G. Kalinin and V.V. Chichagov [20] using statistical methods. Since long-term fluctuations are random, these methods can be used. The methodological approach is as follows:

1). Available series and their parts were tested for randomness with the Mann Reverse Arrangements Test [29]. There are nonparametric tests for trend. This procedure is easy to apply and useful for detecting underlying trends in random data records.

The reverse arrangements test is applied to determine the number of inversions. It consists in calculating the number of pairs of elements in the series under study for which the sequence is violated. A violation of the sequence is understood as the presence of a pair of lower rank for a larger element. The number of inversions should not be too small or large if the dataset behaves like an independent random sample. Time series are independent if the zero hypothesis passes the test at *p*-level >0.05. It is checked whether the data are independent and whether the results can be obtained during observations of the same random variable.

2). The first 15 values of the autocorrelations and the p-values with the Ljung–Box test were calculated to identify a relationship between the data in the time series. For *p*-level >0.05, the zero hypothesis is accepted. This evidences the absence of autocorrelations.

3). The normality hypothesis of the ice dates was tested with three different criteria: Kolmogorov–Smirnov One-Sample test, Lilliefors and Shapiro–Wilk tests [25, 36]. N.M Razali and Y.B. Wah [35] shows that the Shapiro–Wilk test is the most powerful of these three criteria when testing for normality.

4). Applying the homogeneity criteria to the analysis of two parts of the data series without prior checking their randomness using the reverse arrangements test can lead to erroneous results. That is why testing with the homogeneity criteria: t- and F-tests and Mann–Whitney, Kolmogorov–Smirnov, and Wald–Wolfowitz Runs tests [31] is possible in case of accepting the randomness hypothesis for the parts of the data series under comparison. The studied parts of the series are considered homogeneous if the zero hypothesis of p-level is >0.05.

It should be noted that when testing the randomness and homogeneity hypotheses in a data series, the values of p-level can be close to 0.05 (0.03 or 0.07). Therefore, in the analysis, the values of p-level were separated: the zero hypothesis works at p-level >0.075; it does not work at p-level <0.025; the values are boundary at $0.025<p$-level<0.075.

Results and discussion

1. Analysis of long-term fluctuations

The spatial distribution of average long-term ice dates on Kamskoe Reservoir for 1956-2018 is shown in Fig. 1. Ice phenomena begin in the shallow bay and gradually reach waters of the reservoir where cooling occurs most rapidly. The formation of ice starts in the reservoir's upper reaches in Chusovskoy (Nizhnie Chalygi) and In'vinskii (Maikor) bays, then from north to south– from Berezniki to Chermoz (Fig. 1).

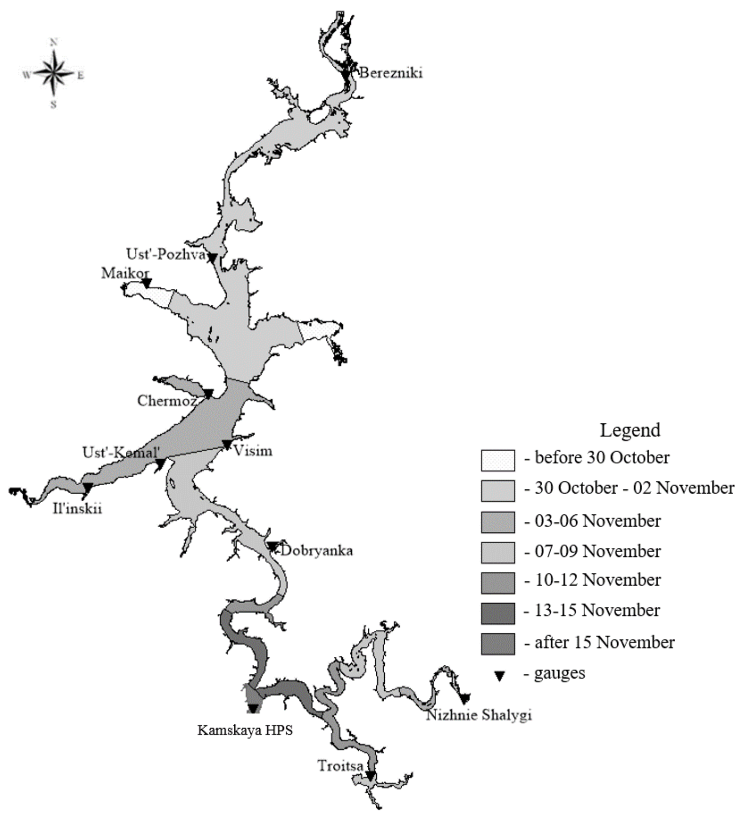

Fig. 1. Average (1956–2018) ice dates at the gauges on Kamskoe Reservoir
Рис. 1. Средние (1956–2018 гг.) даты появления льда на г/п Камского водохранилища

At the same time, ice formation processes are observed in Obvinskii (Il'inskii) and other small bays in the central part of the reservoir. Further, ice formation spreads to the reservoir's central part (Visim, Sludka, Dobryanka gauges) and is simultaneously observed in the Chusovskoy (Vetlyany) and Sylvinsky (Troitsa) reaches. Ice formation ends in the near-dam deep-water part of Kamskoe Reservoir (Fig. 1). Thus, the general pattern of ice formation is from north to south and from the reaches to the central part. According to the long-term average data for 1956–2018, ice phenomena form from October 30th to November 3rd. It should be noted that ice dates significantly fluctuate on an annual basis, different gauges show synchronous fluctuations, while ice dates tend to shift to the later side in recent decades (Fig. 2).

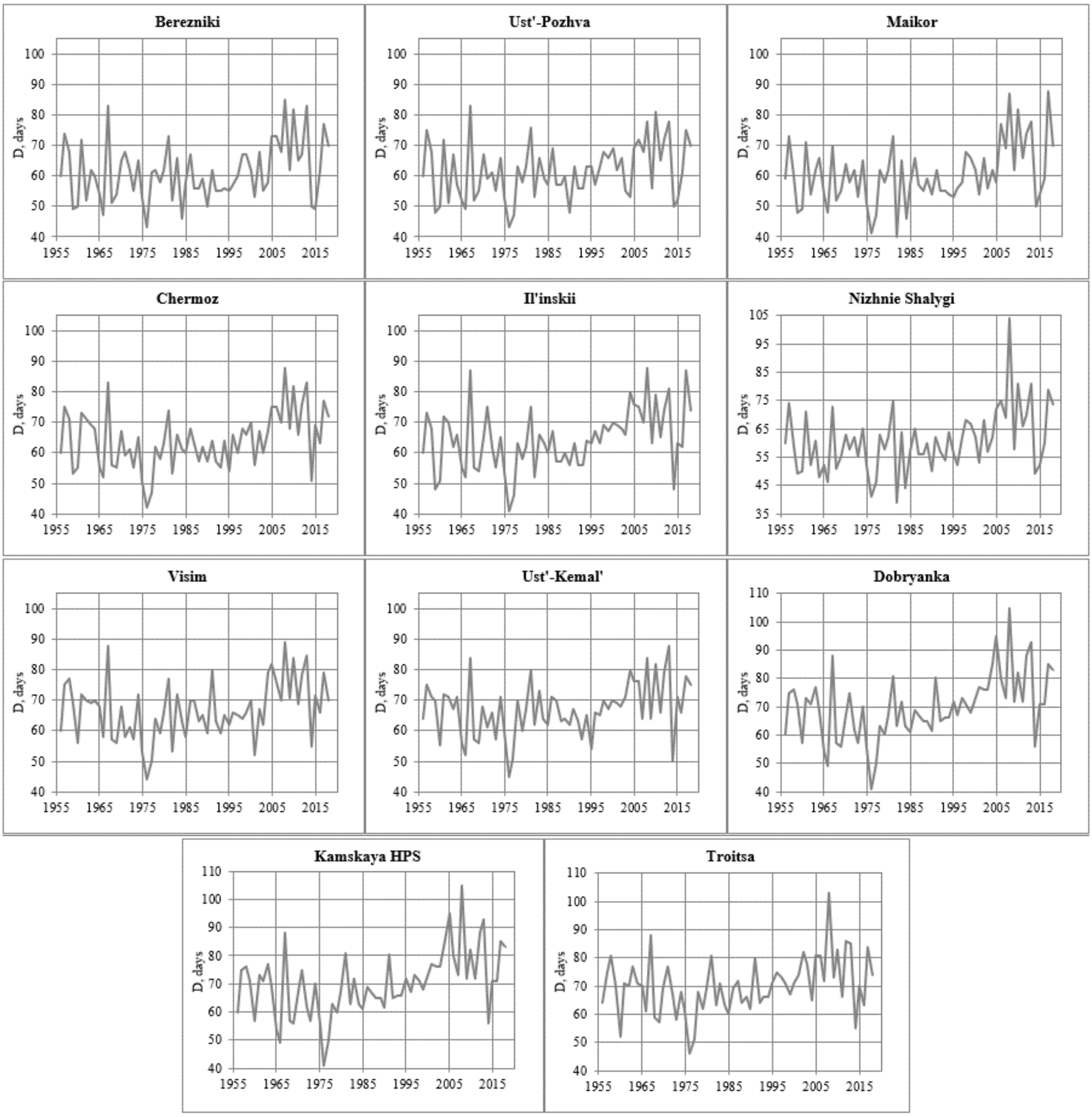

Fig. 2. Long-term fluctuations of the ice dates (D, days) (in the numbers of days from September 1st) for 1956–2018
Рис. 2. Многолетние изменения дат появления льда (*D*, дни) (в числах от 1 сентября) за 1956–2018 гг.

The average long-term ice dates for 1956–1995 and 1956–2018 are presented in Table 1. Analysis of this table shows that the average dates for all gauges shifted to the late side by 2-4 days. The change by ±2 days is within the accuracy of determining these dates. At the Maikor, Chermoz, Ust’-Kemal’, Il’yinski, Dobryanka, Nizhnie Shalygi, and Troitsa gauges, the average ice dates changed by 3–4 days. At Dobryanka, the shift to the late side by 4 days can be explained by an increase in warm water discharge from the Permskaya Hydro-Recirculating Power Plant (Permskaya HRPP). This shift in days is associated with the commissioning of new power units in 1987, 1990, and 2017.

Table 1

Long-term average, early and late ice dates for 1956–1995 and 1956–2018
Среднемноголетние, ранние и поздние даты появления льда за 1956–1995 и 1956–2018 гг.

Gauge	*Average date**	*Early date**		*Late date**	
		Date	*Year*	*Date*	*Year*
Berezniki	$\frac{29\ Oct}{31\ Oct}$ (+2)	$\frac{13\ Oct}{13\ Oct}$ (-)	$\frac{1976}{1976}$ (-)	$\frac{22\ Nov}{24\ Nov}$ (+2)	$\frac{1967}{2008}$ (+)
Ust'-Pozhva	$\frac{29\ Oct}{31\ Oct}$ (+2)	$\frac{13\ Oct}{13\ Oct}$ (-)	$\frac{1976}{1976}$ (-)	$\frac{22\ Nov}{22\ Nov}$ (0)	$\frac{1967}{1967}$ (-)
Maikor	$\frac{27\ Oct}{30\ Oct}$ (+3)	$\frac{10\ Oct}{10\ Oct}$ (-)	$\frac{1982}{1982}$ (-)	$\frac{12\ Nov}{27\ Nov}$ (+15)	$\frac{1957,1981}{2017}$ (+)
Chermoz	$\frac{31\ Oct}{03\ Nov}$ (+3)	$\frac{12\ Oct}{12\ Oct}$ (-)	$\frac{1976}{1976}$ (-)	$\frac{22\ Nov}{27\ Nov}$ (+5)	$\frac{1967}{2008}$ (+)
Visim	$\frac{03\ Nov}{05\ Nov}$ (+2)	$\frac{14\ Oct}{14\ Oct}$ (-)	$\frac{1976}{1976}$ (-)	$\frac{27\ Nov}{28\ Nov}$ (+1)	$\frac{1967,1995}{2008}$ (+)
Ust'-Kemal'	$\frac{03\ Nov}{06\ Nov}$ (+3)	$\frac{15\ Oct}{15\ Oct}$ (-)	$\frac{1976}{1976}$ (-)	$\frac{23\ Nov}{27\ Nov}$ (+4)	$\frac{1967,1995}{2013}$ (+)
Il'inskii	$\frac{31\ Oct}{03\ Nov}$ (+3)	$\frac{11\ Oct}{11\ Oct}$ (-)	$\frac{1976}{1976}$ (-)	$\frac{26\ Nov}{27\ Nov}$ (+1)	$\frac{1967,1995}{2008}$ (+)
Dobryanka	$\frac{04\ Nov}{08\ Nov}$ (+4)	$\frac{11\ Oct}{11\ Oct}$ (-)	$\frac{1976}{1976}$ (-)	$\frac{27\ Nov}{14\ Dec}$ (+17)	$\frac{1967}{2008}$ (+)
Kamskaya HPS	$\frac{13\ Nov}{15\ Nov}$ (+2)	$\frac{29\ Oct}{29\ Oct}$ (-)	$\frac{1966}{1966}$ (-)	$\frac{01\ Dec}{15\ Dec}$ (+14)	$\frac{1991}{2008}$ (+)
Nizhnie Shalygi	$\frac{27\ Oct}{31\ Oct}$ (+4)	$\frac{09\ Oct}{09\ Oct}$ (-)	$\frac{1982}{1982}$ (-)	$\frac{14\ Nov}{13\ Dec}$ (+29)	$\frac{1981}{2008}$ (+)
Troitsa	$\frac{06\ Nov}{09\ Nov}$ (+3)	$\frac{16\ Oct}{16\ Oct}$ (-)	$\frac{1976}{1976}$ (-)	$\frac{27\ Nov}{12\ Dec}$ (+15)	$\frac{1967}{2008}$ (+)

* Date format is $\frac{X_1}{X_2}(X_2\text{-}X_1)$, where X_1 and X_2 are the ice dates for 1956–1995 and 1956–2018, respectively; (-) – date/year did not change; (+) – date/year changed.

* Формат дат $\frac{X_1}{X_2}(X_2\text{-}X_1)$,, где X_1 и X_2 – даты появления льда за 1956–1995 гг. и 1956–2018 гг. соответственно; (-) – дата/год не изменились; (+) – дата/год изменились.

It is worth noting that trends toward late ice dates (warmer climate) persist at all gauges. The late ice dates at Maikor and Troitsa shifted by 15 days, and at Nizhniye Shalygi ice started to appear 29 days later. The last decade (2008–2018) had a significant impact on the change in late dates. The warmest years were 2008, 2013, and 2017. A significant change in the late ice dates also occurred at the Dobryanka (+17 days) and the Kamskaya HPS (+14 days) gauges due to the heated waters from the Permskaya HRPP. Overall, spatial correlation between the later dates of ice formation and years was observed at all gauges except Ust'-Pozhva. While the early ice dates and the years when early dates were observed did not change.

A similar pattern is observed in trends toward later freeze-up dates which are consistent consistent with changes found by other researchers [10, 22, 26, 27, 28]. M.N. Shimaraev et al. [37] and N.L. Frolova et al. [11] noted that climatic changes had been observed since the mid-1970s, which was associated with the restructuring of the atmosphere and confirmed by an increase in air and ocean temperatures.

The results, as shown in Table 2, indicate that for the first part of the time intervals the deviations of the ice dates have a "-" sign. That means the average dates for particular time intervals fall on earlier dates (cold climate) compared to the dates for the whole period (1956–2018). For the second part of the time intervals, these deviations have a "+" sign. That means the average dates fall on later dates (warm climate).

The least deviations (up to 2 days) in the average long-term ice dates are observed for the 1–4th time intervals. For the 5–7th time intervals, these deviations increase to 3–4 days, and for 8–11th time intervals – up to 5–7 days for the second part of the time intervals. This indicates that in the last two decades ice dates were determined by the climatic conditions. The largest deviations (up to 10 days) are shown by Maikor and Nizhnie Shalygi in the 10th time interval. These gauges are located in shallow bays, where water masses cool very quickly.

Table 2

Deviation (in days) of the average ice dates from the average dates for the whole period (1956–2018)
Отклонение (в днях) средних дат появления льда от средних за весь период (1956–2018 гг.)

#	*Time intervals*	*Number of years*	*Berezniki*	*Ust'-Pozhva*	*Maikor*	*Chermoz*	*Visim*	*Ust'-Kemal'*	*Il'inskii*	*Nizhnie Shalygi*	*Troitsa*	*Kamskaya HPS*	*Average*
1	1956–1960	5	-1	-1	-3	-1	0	0	-4	-2	-2	-3	-2
	1961–2018	58	0	0	0	0	0	0	0	0	0	0	0
2	1956–1965	10	-1	-2	-1	+1	2	0	-2	-3	0	+1	-1
	1966–2018	53	0	0	0	0	0	0	0	+1	0	0	0
3	1956–1970	15	-1	-1	-2	0	+1	-1	-2	-3	-1	-1	-1
	1971–2018	48	0	0	0	0	0	0	+1	+1	0	0	0
4	1956–1975	20	-1	-2	-2	-1	-1	-2	-2	-3	-2	-1	-2
	1976–2018	43	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1
5	1956–1980	25	-2	-3	-3	-3	-3	-3	-4	-4	-4	-3	-3
	1981–2018	38	+1	+2	+2	+2	+2	+2	+2	+2	+2	+2	+2
6	1956–1985	30	-2	-2	-3	-3	-3	-2	-3	-4	-3	-3	-3
	1986–2018	33	+2	+2	+3	+2	+3	+2	+3	+3	+3	+2	+3
7	1956–1990	35	-2	-2	-3	-3	-3	-2	-3	-4	-3	-3	-3
	1991–2018	28	+3	+3	+4	+3	+3	+3	+4	+5	+4	+3	+4
8	1956–1995	40	-3	-2	-3	-3	-3	-3	-3	-4	-3	-2	-3
	1996–2018	23	+4	+4	+6	+5	+4	+5	+6	+6	+5	+4	+5
9	1956–2000	45	-2	-2	-3	-2	-2	-2	-3	-3	-3	-2	-2
	2001–2018	18	+5	+4	+7	+6	+6	+6	+7	+7	+6	+6	+6
10	1956–2005	50	-2	-2	-3	-2	-2	-1	-2	-3	-2	-1	-2
	2006–2018	13	+7	+6	+10	+8	+7	+6	+7	+10	+7	+6	+7
11	1956–2010	55	-1	-1	-1	-1	-1	-1	-1	-1	0	-1	-1
	2011–2018	8	+4	+4	+7	+6	+5	+5	+4	+5	+3	+4	+5

2. Detection of the change point

Smoothing of the ice dates over 3, 5, and 17–31-year periods did not allow us to reveal the change point (the beginning of intraseries changes) due to too short and too long averaging periods, respectively. At the same time, for the 7, 9, 11, 13 and 15-year periods the change point is clear (Fig. 3). For three smoothing periods (11, 13, and 15-year), the year of the change point does not change and is likely to fall on 1996.

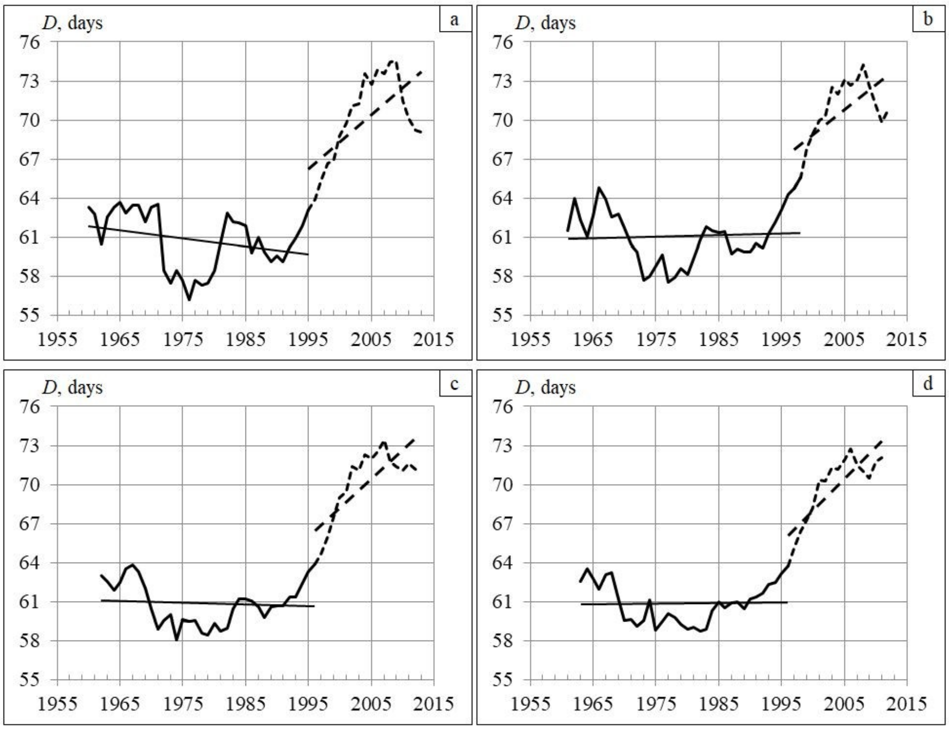

Fig. 3. Smoothed ice dates curves (D, days) for 9-year (a), 11-year (b), 13-year (c), and 15-year periods at Il'inskii (solid line – stationary climate; dashed line – nonstationary climate)

Рис. 3. Сглаженные кривые дат появления льда (*D*, дни) для 9-летнего (а), 11-летнего (б), 13-летнего (в) и 15-летнего (г) на г/п Ильинский (сплошная линия – стационарный климат; пунктирная линия – нестационарный климат)

Fig. 4 apparently shows that ice was formed at earlier dates and later dates before and after 1997, respectively. Therefore, there is a split into two oppositely directed periods. This confirms the results of the change point detection obtained above. Thus, under the conditions of Kamskoe Reservoir, the period of significant climatic changes starts in 1995–1997 in the autumn.

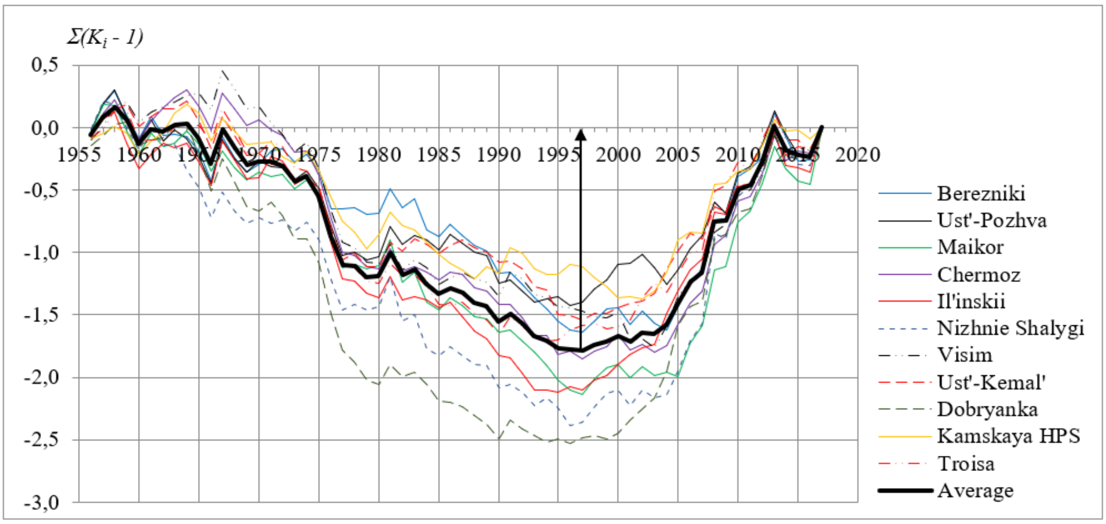

Fig. 4. Differential integral curves of the ice dates for 1956–2018

Рис. 4. Разностно-интегральные кривые дат появления льда за 1956–2018 гг.

There are no similar studies devoted to the change point detection. Only papers related to trend detection in ice dates show that trends with freeze-up dates for a group of lakes were most significant in 1971–2000 [10]. X. Zhang et al. [51] showed widespread trends toward earlier freeze-up over

1967-1996. Thus, the influence of modern climatic changes on the ice dates is likely to be most pronounced in the last 25 years.

3. Justification of the change point with statistical methods

Application of the reverse arrangements test (Table 3) showed that the randomness hypothesis for the observation series for 1956–2018 is rejected (the significance level is no more than 0.046) for all gauges except Berezniki. This indicates significant changes in these data.

In addition, the randomness hypothesis is accepted for all gauges with a high level of significance, with rare exceptions for the 1956–1975, 1956–1995, and 1996–2018 observation series. However, for 1976–2018 the randomness hypothesis is usually rejected. This means that statistically significant changes in the observation series began to occur from the mid-90s. Therefore, in Table 3 we compare the observation series for 1956–1995 and 1996–2018.

Table 3

Values of the significance level of the reverse arrangements test
Значения уровня значимости критерия инверсий

Gauge	*1956–1975*	*1976–2018*	*1956–1995*	*1996–2018*	*1956–2018*
Berezniki	0.823	**0.027**	0.270	0.319	0.090
Ust'-Pozhva	0.823	*0.011*	0.790	0.432	**0.035**
Maikor	0.631	*0.008*	0.189	0.207	**0.046**
Chermoz	**0.064**	*0.000*	0.153	0.114	*0.017*
Visim	*0.024*	*0.001*	0.260	**0.057**	**0.041**
Ust'-Kemal'	0.165	*0.003*	0.174	0.207	**0.042**
Il'inskii	0.501	*0.000*	0.438	0.754	*0.004*
Dobryanka	0.113	*0.000*	0.862	0.464	*0.000*
Kamskaya HPS	0.386	*0.001*	0.826	0.227	**0.028**
Nizhnie Shalygi	0.974	*0.004*	0.917	0.248	*0.006*
Troitsa	0.098	*0.001*	0.336	0.754	*0.022*

Note: the observation series with the accepted randomness hypothesis with significance levels less than 0.025 are italicized; the observation series with the accepted randomness hypothesis with significance levels in the range from 0.025 to 0.075 are bolded; the observation series with the accepted randomness hypothesis with significance levels greater than 0.075 are given in roman type.

Примечание: курсивом выделены ряды наблюдений с принятой гипотезой случайности с уровнем значимости менее 0,025; жирным шрифтом выделены ряды наблюдений с принятой гипотезой случайности с уровнями значимости в диапазоне от 0,025 до 0,075; ряды наблюдений с принятой гипотезой случайности с уровнями значимости выше 0,075 воспроизведены прямым шрифтом.

The hypothesis about the absence of the first 15 autocorrelations was checked with the Ljung Box test, which gave the following results (only the smallest p-values are indicated below). For 1956–1995, the zero hypothesis is accepted for all gauges (the minimum value of the real significance level was found to be 0.07 for the Ust-Pozhva gauge, the real significance level was more than 0.1). In 1996–2018, the zero hypothesis was accepted for all gauges (the minimum value of the real significance level was found to be 0.08 for the Ust-Kemal gauge, the real significance level was more than 0.25 for the rest of the gauges). Thus, for the observation series for all gauges for 1956–1995 and 1996–2018, it is justifiable to test the hypothesis of homogeneity.

To test the homogeneity hypothesis using t- and F-tests, we verified that the observation series can be described in terms of normal distribution law. The results of testing the normality hypothesis of the ice dates with three different criteria are presented in Table 4. It shows that the hypothesis of homogeneity can be tested for all gauges using t- and F-tests.

Table 4

Significance level of acceptance of the normality hypothesis for ice formation dates according to the Lilliefors and Shapiro-Wilk tests
Уровень значимости принятия гипотезы нормальности дат появления льда по тестам Лиллиефорса и Шапиро-Уилка

Gauge	*Lilliefors*		*Shapiro–Wilk*	
	1956–1995	*1996–2018*	*1956–1995*	*1996–2018*
Berezniki	p> 0.20	p> 0.20	0.48611	0.67761
Ust'-Pozhva	p> 0.20	p> 0.20	0.76538	0.68079
Maikor	p> 0.20	p> 0.20	0.77412	0.22098
Chermoz	p> 0.20	p> 0.20	0.85040	0.91905
Visim	p> 0.20	p> 0.20	0.89905	0.86134
Ust'-Kemal'	p> 0.20	p> 0.20	0.91307	0.41866
Il'inskii	p> 0.20	p <0.10	0.61162	0.31576
Dobryanka	p> 0.20	p <0.10	0.99631	0.13099
Kamskaya HPS	p <0.05	p <0.10	0.12755	**0.05411**
Nizhnie Shalygi	p> 0.20	p> 0.20	0.83244	**0.07161**
Troitsa	p <0.20	p> 0.20	0.80580	0.38671

Note: the significance levels are italicized, bold and roman fonts correspond to the Note to Table 3.
Примечание: уровни значимости выделены курсивом, полужирным и прямым шрифтом соответствуют примечанию в табл. 3.

The results of testing the homogeneity hypothesis for observation series using the homogeneity criteria of two-sample t-, two-sample F-, Mann–Whitney and Kolmogorov–Smirnov One-Sample and Two-Sample tests are presented in Table 5.

Table 5

Statistical characteristics of ice dates for 1956–1995 and 1996–2018
Статистические характеристики дат появления льда за 1956–1995 и 1996–2018 гг.

Gauge	*Mean-1*	*Mean-2*	*pS*	*SD-1*	*SD-2*	*pF*	*pMU*	*pKS*	
Berezniki	58.9	65.8	*0.005*	8.38	10.03	0.318	0.006	*0.022*	**0.043**
Ust'-Pozhva	58.6	65.5	*0.007*	9.70	8.72	0.607	0.007	*0.015*	**0.030**
Maikor	57.4	66.2	*0.000*	7.99	10.68	0.112	0.002	*0.012*	**0.025**
Chermoz	61.0	69.3	*0.000*	8.23	8.65	0.765	0.000	*0.000*	*0.001*
Visim	64.4	71.3	*0.005*	8.75	9.28	0.729	0.006	*0.014*	**0.027**
Ust'-Kemal'	64.4	71.5	*0.001*	8.01	8.29	0.831	0.002	*0.005*	*0.011*
Il'inskii	60.9	70.4	*0.000*	8.75	8.91	0.897	0.000	*0.000*	*0.001*
Dobryanka	65.4	77.6	*0.000*	9.35	10.60	0.483	0.000	*0.000*	*0.000*
Kamskaya HPS	74.1	80.6	*0.007*	8.51	9.25	0.632	0.008	*0.005*	*0.010*
Nizhnie Shalygi	57.1	66.8	*0.000*	8.54	12.24	**0.048**	0.001	*0.001*	*0.002*
Troitsa	67.0	75.3	*0.001*	8.47	9.87	0.395	0.000	*0.001*	*0.003*

Note. Mean-1, SD-1 are the mean and standard deviations of ice dates in 1956–1995, respectively; Mean-2, SD-2 are the average and standard deviations of these dates in 1996–2018; pS, pF, pMU, pKS are the significance levels of the two-sample t-, two-sample F-, Mann–Whitney, and Kolmogorov–Smirnov One-Sample and Two-Sample tests. The significance levels are italicized, bold and roman fonts correspond to the Note to Table 3.
Примечание. Mean-1, SD-1 – среднее и стандартное отклонение дат появления льда за 1956–1995 гг. соответственно; Mean-2, SD-2 – среднее и стандартное отклонение этих дат за 1996–2018 гг.; pS, pF, pMU, pKS – уровни значимости двухвыборочного t-, двухвыборочного F-, одновыборочного и двухвыборочного критериев Манна – Уитни и Колмогорова – Смирнова. Уровни значимости выделены курсивом, полужирным и прямым шрифтом в соответствии с примечанием к табл. 3.

The results, as shown in Table 5, indicate that the homogeneity hypothesis for 1956–1995 and 1996–2018 should be rejected for all gauges. This confirms the stated assumption that significant climatic changes at Kamskoe Reservoir are likely to have started in 1995-1997 in the autumn.

Conclusions

1. The average long-term, early, and late ice dates analysis for Kamskoe Reservoir for 1956–1995 and 1956–2018 showed that the average dates for 1956–2018 were shifted at all gauges to the late side by 2–4 days. The last decade (2008–2018) had a significant impact on the change in the late dates. The warmest years were 2008, 2013, and 2017. The early ice dates and the years when they were observed did not change.

2. Comparison of the average dates for different time intervals with the average for the whole observation period revealed that ice dates were observed earlier for the first part of the time intervals. The average dates fall on later dates for the second part of the time intervals. The greatest deviations are noted when comparing time intervals after 1995.

3. The change point is clearly detected on the smoothed curves with a one-year step over a 7–15-year period. When considering only 11–15-year smoothing, the first signs of change are observed in 1996.

4. The beginning of the significant climatic changes in ice dates is noted in 1995–1997 on differential integral curves.

5. The rejection of the randomness hypothesis for 1956–2018 for all gauges, with the exception of Berezniki, indicates the presence of significant changes in these data. Moreover, for 1956–1995 and 1996–2018 for all gauges the randomness hypothesis is accepted with a high level of significance. Hence, no statistically significant changes were detected in the observation series.

6. Rejection of the homogeneity hypothesis for the observation series in 1956–1995 and 1996–2018 shows the presence of statistically significant changes at the turn of 1996.

Thus, the influence of modern climatic changes on the dates of ice formation in Kamskoe Reservoir is likely to have started within the period of the last 25 years.

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