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Long-term Changes of Water Flow, Water Temperature and Heat Flux of the Largest Siberian Rivers

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Abstract: Long – more than 15 to 20 years – phases of increased and decreased water flow, water temperature and heat flux with respect to the average values, calculated for the entire period of observation in the largest rivers of Siberia (Ob', Yenisei and Lena) were analysed. Time delimitation of the contrasting phases (change point detection) was determined via statistical criteria (Mann-Whitney-Pettit test, cumulative deviation test, sequential regime shift detector) as well as by normalized cumulative deviation curves. The identified phases display statistically significant differences in average values for the considered characteristics. The long-term changes in water flow and heat flux, which occurred in the last 70 to 80 years, are mainly characterized by two major long phases with a border in the 1970s to 1990s with the exception of the Yenisei, where additional phase of increased heat flux presents. The long-term changes in water temperature have more complex behaviour. On the Lena, there were also two contrasting phases, whereas on the Yenisei and the Ob', apart from the two main phases, there were respectively one and two additional phases. In addition, the contribution of anthropogenic impact and climate change to total changes in the water flow and heat flux was estimated during the period of the most intense anthropogenic impact (since the 1960s), mainly related to the operation of the water reservoir system.

Zusammenfassung: Lange, mehr als 15 bis 20 Jahre dauernde Phasen mit zunehmendem und abnehmendem Wassertransport, Wassertemperatur und Wärmefluss bezogen auf die durchschnittlichen Werte der gesamten Beobachtungsperiode wurden für die größten sibirischen Flüsse, die Flüsse Ob, Jenissei und Lena, untersucht. Die zeitliche Abgrenzung kontrastierender Phasen (Erkennung von Änderungspunkten) wurde statistisch ermittelt. Die identifizierten Phasen zeigen statistisch signifikante Unterschiede in den Durchschnittswerten der betrachteten Charakteristika.
Die langfristigen Wechsel im Wasserfluss und Wärmefluss, die in den letzten 70 bis 80 Jahren auftraten, sind hauptsächlich charakterisiert durch zwei lange Phasen mit einer Grenze in den 1970ern bis 1990er Jahren, ausgenommen der Jenissei wo zusätzliche Phasen erhöhten Wärmeflusses auftreten. Die langfristigen Wechsel der Wassertemperatur zeigen ein komplexeres Verhalten. Bei der Lena zeigen sich ebenfalls zwei gegensätzliche Phasen, während beim Jenissei und Ob, abgesehen von den zwei Hauptphasen, sich eine, beziehungsweise zwei zusätzliche Phasen zeigen. Zusätzlich wurde der menschliche Einfluss und der des Klimawandels auf den gesamten Wechsel in Wasserfluss und Wärmefluss für den Zeitraum der intensivsten menschlichen Nutzung seit den 1960er Jahren abgeschätzt, der hauptsächlich durch den Betrieb der großen Staudammsysteme entsteht.

INTRODUCTION

The total water flow and heat flux from the three largest rivers of Eurasia: the Ob', Yenisei and Lena, which drain the Siberian region of about 8 million km^2, comprise the main input of "geo-runoff" (a term proposed by MURAVEYSKY 1960) components into the Arctic Ocean.

The watersheds of the rivers in question are distinctly differentiated by natural factors related to the water regime. For example, the proportion of permafrost areas and permafrost types differ significantly from basin to basin (Tab. 1). The natural features of the river basins determine distinctions in water balance, river runoff coefficients and other hydroclimatic characteristics (Tab. 2), and intra-annual flow distribution in the largest Siberian rivers. The water regimes in these river basins are characterized by high spring–summer flooding, which is determined by large snow water storage, except for the northern and central parts of the river basins (especially in the Lena River), where snow water storage is extremely small (Tab. 3). Approximately 80-90 % of the annual water flow occurs in the warm season. Anthropogenic factors have also a notable impact on the hydrological characteristics of the rivers. Among them, the most significant role plays flow regulation by reservoirs. The role of reservoirs in water regime formation is very important, particularly for the Yenisei, where their total storage capacity amounts to 369 km^3, as well as for the Ob' (69 km^3) and Lena (36 km^3) river basins.

Numerous studies have been published on the long-term water flow changes in the Ob', Yenisei and Lena rivers. These have mainly analysed the linear trends of flow change, and have estimated differences in stream flow before and after the onset of the rapid air temperature growth in the Siberia region in 1970s to 1980s (e.g., GEORGIADI & KASHUTINA 2011, 2014, SHIKLOMANOV 2008, SHIKLOMANOV et al. 2013, STUEFER et al. 2011, YANG et al. 2002). Additionally, the correlations of water flow changes with atmosphere macroscale circulation have been established (e.g., BABKIN 2004, PETERSON et al. 2002, POPOVA 2004). Far less attention has been paid to the study of long-term changes of heat flux and water temperature (e.g., GEORGIADI et al. 2016, LAMMERS et al. 2007, MAGRITSKY 2009, 2015, MAGRITSKY et al. 2007, ODROVA 1987).

This article focuses on the long phases of increased and decreased with respect to the mean, calculated for the entire period of observation, water flow, water temperature and heat flux of the Ob', Yenisei and Lena rivers at their outlets Salekhard, Igarka and Kyusyur stations accordingly, over a period of observation from the 1930s to 2000s, and the impact of anthropogenic factors on these. The phases for the long-term annual and seasonal behaviours, were considered separately. Specific phases are characterized by statistically significant differences in mean water flow, water temperature, heat flow and pronounced length – usually 15 to 20 years or more – of duration. Particular attention was paid to identifying the years (change points) in which changes in such phases occurred. Note, that the mentioned phases represent a characteristic

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River, gauging station	Basin area, 10^3 km^2	Proportion of basin area covered by permafrost (%)			
		Permafrost all types	Permafrost continuous	Permafrost discontinuous	Permafrost sporadic
Ob’, Salekhard	2450	36	7.4	2.4	26.2
Yenisee, Igarka	2470	83.7	29.6	13	41.1
Lena, Kyusyur	2430	93.8	78.8	12.3	2.7

Tab. 1: Proportion of basin area covered by permafrost of the different types. *Estimated on the basis of the Circum-Arctic map (Brown et al. 1998).

Tab. 1: Einzugsgebiete der Flüsse Ob, Jenissei und Lena mit der Verbreitung der verschiedenen Permafrost-Typen; auf der Basis Brown et al. (1998).

River outlet gauge station	Average long-term value							
	Volume (1) annual river water flow (km^3) (1)	Depth (2) annual river water flow (mm) (1)	Depth (2) annual total precipitation (mm) (1)	Depth (2) annual evaporate (mm) (1)	Runoff coefficient (3)	Average water temper. May-October (°C)	Heat flux May-October (10^{15} kJ)	Annual temperature (°C) (4)
Ob’ Salekhard	390	159	674	515	0.24	8.6	13.2	0.3
Yenisei Igarka	568	230	515	285	0.45	8.4	16.4	-3.3
Lena Kyusyur	505	208	460	255	0.45	6.4	15.2	-7.5

Tab. 2: Hydrological and climatological characteristics of the river basins. Note (1): According to Protas’ev (1967); (2): Volume of annual river water flow, total atmospheric precipitation and evaporation divided on the area of river basin; (3): Volume of annual river water flow divided on annual total atmospheric precipitation; (4): Mean annual air temperature averaged for the river basin according to ArcticRIMS (web source).

Tab. 2: Hydrologische und klimatologische Charakteristika der Einzugsgebiete von Ob, Jenissei und Lena. Beachte (1): nach Protas’ev (1967); (2): Volumen des jährlichen Wasser Abflusses, des gesamten Niederschlags und der Verdunstung bezogen auf das Einzugsgebiet; (3): Volumen des jährlichen Wasserabflusses bezogen auf den gesamten jährlichen Niederschlag; (4): mittlere Jahrestemperatur für das Einzugsgebiet nach ArcticRIMS (Internet).

River gauging stat.	Annual water flow	Winter water flow (Nov-April)	warm period water flow (May-October)	Snowmelt flood flow (May-August)
Ob’ Salekhard	100	18	82	66
Yenisei Igarka	100	17	83	68
Lena Kyusyur	100	8	92	73

Tab. 3: Seasonal structure of river water runoff of Ob’, Yenisei and Lena (%).

Tab. 3: Saisonale Verteilung des Wasserabflusses der Flüsse Ob. Jenissei und Lena (%).

feature of the rivers long-term changes under natural conditions (Georgiadi et al. 2014). Accounting for these phases for Ob’, Yenisei and Lena rivers is necessary for the long-term planning of the water resources usage and forecasting of the water and heat inflow into the Arctic Ocean.

METHODOLOGY OF THE STUDY

The approach used to analyse long phases of multi-year changes of mean annual and seasonal water flow, water temperature and heat flux of warm season induced by climate change and anthropogenic impacts, was based on the naturalization (i.e., eliminating of the anthropogenic changes) of river flow and heat flux datasets, and applying of several statistical criteria to determine the transitions from one phase to another (change point or shift point detection). The time delimitations of the water flow seasons were identified by analysing monthly flow hydrography over the entire observation period. Information on the average dates of the snow-melt flood start/finish and freeze/thaw was also used. For the water flow calculations, the winter low-water season was defined from November of the previous year to April of the current year, and the spring–summer flood period was set from May to August. Heat flux was calculated for the period from May to October.

Methods for naturalization of the water flow and heat flux

Long-term series of observed annual and seasonal water flow in the studied rivers were heterogeneous, in terms of anthropogenic impacts on the flow, and consist of two parts. The first part of the series includes long-term data relating to the period prior to the initiation of marked anthropogenic impacts. The second is a long-term data series in which the flow changed, to different degrees, due to anthropogenic impacts – mostly connected to water flow regulation by reservoirs and irretrievable water consumption by various economic sectors. If the anthropogenic component is excluded from the second data series flow, a series in which the changes are dependent purely on climatic factors results. Such water flow data series are called “conditional-natural” or “naturalized”. The water flow was naturalized by two methods. First method is based on approach suggested by A.I. Shiklomanov et al. (Arcticnet, web source, Shiklomanov et al. 2011, Shiklomanov et al. 2013). It was applied to the Ob’, Yenisei and Lena water flow data. According to it the long-term series of daily water discharge using the hydrograph routing method, based on the Duhamel integral approach and the function of influence suggested by Kalinin & Milyukov (1958), were generated. Its parameters were calibrated against the data from the upstream and downstream gauges (taking into account the river inflow between them) taken from parallel observations over the years with no evident effects of anthropogenic factors. Values of the Nash-

Sutcliffe (1970) coefficient, used to estimate the accuracy of the flow naturalization, were within 0.82-0.98 (Shiklomanow pers. comm. 2016) indicative of sufficiently reliable calculations. The obtained series of naturalized daily water discharge were used to study the long phases of decreased/increased values of annual and seasonal water flow and heat flux. These data were supplemented with the naturalized snow-flood water flow of the Lena River at Kyusyur Station, obtained by the second method so-called “rivers – indicators of climate change" approach (Georgiadi et al. 2014). In this case, this method provided a more correct result with respect to the succession of long-term phase changes. This method relies upon multiple linear regressions between the main river flow and the flow of tributaries and the upstream parts of the main river, characterized by relatively weak human-induced disturbances of the water regime.

Part of the long-term flow series naturalized by one of the above methods was combined with the other part, where the flow was undisturbed by anthropogenic impacts. Thus, the general series of naturalized stream flow was assembled. The obtained series of naturalized water discharge were used to study the long phases of decreased/increased annual and seasonal naturalised water flow and heat flux.

Every element of the naturalized heat flux (H_{nat}) time series was calculated using a modified version of the known formula:
$H_{nat} = C_{\rho} \cdot \rho \cdot T \cdot Q_{nat}$, (1)
where $C\rho$ is the specific water heat capacity (4.174-4.212 kJ/kg · ºC at T = 0-30 ºC) and ϱ is water density (0.99985-0. 99999 kg/m^3); T is observed water temperature, averaged for the considered time interval, in ºC; Q_{nat} is the water flow volume over the considered time interval from the naturalized dataset, in m^3. Note, that for the construction of the *observed* heat flux time series we used the same formula, but based on *observed* water flow volume.

As demonstrated by a number of studies (e.g., Magritsky et al. 2007, Magritsky 2015), the water temperature at the outlets (located up to the river mouth) of the Ob’, Yenisei and Lena rivers has not been exposed to marked anthropogenic impacts. Hence, the observed values could be used to estimate the naturalized heat fluxes. It should be noted that, due to deviations in water temperature measured close to the river-bank and at the water surface from the average temperature of the entire river flow at the considered cross-section the multiyear observation data contain respective errors (Antonov 1941, Koren’kov & Nazarov 1991, Reinberg 1938, Zhilyaev & Fofonova 2016). However, we believe that these errors do not distort the conclusions of the current article.

Methods for change point detection

The methods presented in this subsection (sequential regime shift detector, Mann-Whitney-Pettit and cumulative deviation tests, and normalized cumulative deviation curves) allowed us to reveal the statistical heterogeneity of the data series by average values, to evaluate the statistical significance of these average values and to define the years (change points) when the long phases of the increased/decreased values compared to the long-term average of the hydrological characteristics switched.

The sequential regime shift detector method represents the sequential version of the partial cumulative sum of the normalized anomalies approach, which is combined with the two-tailed Student t-test (Rodionov 2004, 2015). It allows to detect several periods (multiple change points), with statistically significant differences in mean values. There are two parameters, in particular, the target significance level and the cut-off length, which control the change points detection. The sequential regime shift detector approach can be found in freely available Regime Shift Detection Software (see references). The software is designed to automatically detect statistically significant shifts in the mean level and the magnitude of fluctuations in time series (Rodionov 2004, 2015).

For detection of single change-point Mann-Whitney-Pettit test (Pettit 1979) and cumulative deviation test (Buishand 1982) were used. Mann-Whitney-Pettit test (M-W-P) is a rank-based non-parametric test for a change in the mean of a series with unknown exact time of change. It is based on the Mann-Whitney test. It uses cumulative sums to test the null hypothesis of no change. It divides data into two groups and investigates if they come from the same distribution (Xie et al 2014). It is rather popular test, mostly because it is assumed to be distribution-free and insensitive to outliers and skewness in the data (Hedberg 2015, Yeh et al 2015, Sharma & Singh 2017). The cumulative deviation (CUMDEV) test is based on the rescaled cumulative sum of the deviations from the mean. The test is relatively powerful (Kundzewicz & Robson 2004) in comparison with other tests (e.g. Worsley likelihood ratio test; Buishand 1982) for a change-point that occurs towards the centre of the time series. The basic test assumes normally distributed data.

Besides the above mentioned statistical methods, pure normalized cumulative deviation curves (CDC), were constructed. They allow to demonstrate graphically different long phases of the hydrological characteristics. Values of the normalized cumulative deviation curve were calculated by the following formula:

$$\begin{aligned} \boldsymbol{CDC}_{\tau} &= \frac{1}{\boldsymbol{C_v}} \sum_{i=1}^{\tau} \left(\boldsymbol{K_i} - 1 \right) \\ \boldsymbol{K_i} &= \boldsymbol{E_i} / \boldsymbol{E_m} \\ \boldsymbol{C_v} &= \frac{\sigma}{\boldsymbol{E_m}} \\ \sigma &= \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \left(E_i - E_m \right)^2} \end{aligned} \qquad (2)$$

where CDC_{τ} is the coordinate value of the cumulative deviation curve at time moment τ; E_i is the value of the i-th term of the series (i = 1, n); *n* is the number of terms in the series; E_m is the long-term annual mean of the series; K_i is the modular coefficient of the i-th term of the series; C_v is the coefficient of variation of the series; and σ is the standard deviation of the series. These curves represent the cumulative sum of deviations of a certain characteristic from its long-term annual average value, calculated for the entire observation period. In most considered cases, the change points of the desired long phases can be determined based upon their so-called main or global minimal and maximal CDC coordinate values.

LONG PHASES IN THE MULTIYEAR WATER CHARACTERISTIC CHANGES

We should mention here that all considered water characteristics (water flow, water temperature and heat flux) experience statistically significant (significance level varies from 0.1 to 0.01) linear trends of a monotonic increase except for warm season water flow in the Ob' and Yenisei rivers, and water temperature and heat flux in the Yenisei River based on the Mann-Kendall, Spearman's and linear regression tests. Presence of statistically significant linear trend during the whole period considered ensures presence of minimum two contrasting phases. However, the inter-annual variation of the considered characteristics is larger than the resulting straight line-trend. Also, it is clear that there are a lot of non-linear effects that have a correlation with the considered characteristics. It leads to the fact that quite often the considered characteristics do not have significant increasing trend on a background within one long phase. Therefore, the consideration of the phases for the large river water characteristics is more advantageous and correct compared to the pure linear trend analysis. Also, note that the results concerning the shift point positions obtained using different methods are coincided with each other, which gave us a possibility to establish distinctly the phase boundaries.

Water Flow

Naturalized water flow

Table 4 provides the data on the long phases, shift points and their significance level, illustrating the distinctions among the hydroclimatic characteristics of the Ob', Yenisei and Lena rivers at their outlets. The shift points, detected by statistical tests and cumulative deviation curves, coincided in most cases. During the period of observation – from the 1930s to 1940s until the early 21st century – the studied rivers featured two long phases of change in the annual flow, winter low flow, spring–summer flooding and the entire warm season. The phase of decreased values was replaced by the increased flow phase over a broad interval in the 1970s to 1990s. Note that the second phase continues until the present (Fig. 1, Tab. 4). Although the duration of the existing time series – except some series of water temperature – does not allow us to determine the beginning of the phase of decreased water flow, or the end of the phase of increased values, it does allow us to talk about shift points.

The time delimitation for the switch between decreased/increased phases of naturalized river flow varies markedly between annual and seasonal water flows, both within the

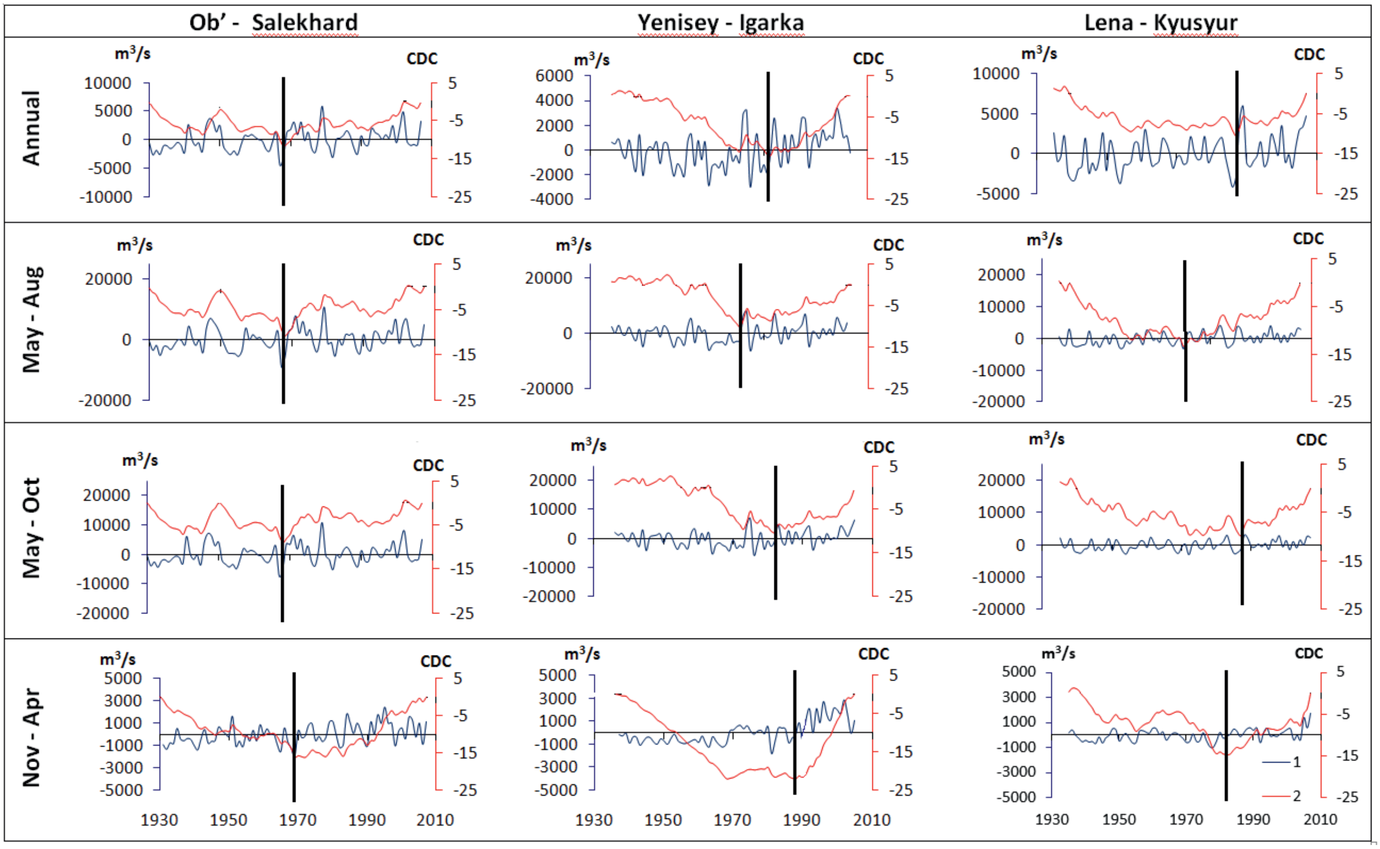

Fig. 1: Long-term changes in naturalized mean annual water flow, snow flood flow (May to August), warm season water flow (May to October) and winter water flow (November to April). (1)/blue: as deviations from their long-term mean values (m^3/s) (1), and (2)/red: in a form of the normalized cumulative deviation curves in the Ob' River at Salekhard, the Yenisei River at Igarka and the Lena River at Kyusyur. The vertical black lines show phase boundaries (shift points) of increased/decreased values of the naturalized water flow compared to the mean value, calculated for the entire period of observation.

Abb. 1: Langfristige Wechsel der mittleren jährlichen Abflüsse unter Ausschluss menschlicher Einwirkungen („naturalized") zur Schneeschmelze (Mai bis August), Sommerphase (Mai bis Oktober) und Winterphase (November bis April) der Flüsse Ob am Pegel Salekhard, des Jenissei am Pegel Igarka und der Lena am Pegel Kyusyur. (1) blaue Kurve: Standardabweichung vom Normalwert (m^3/s); (2) rote Kurve: kumulative Normalverteilung (CDC). Der vertikale schwarze Balken beschreibt die Phasengrenze von Zunahme/Abnahme des Abflusses nach Ausschluss menschlicher Einwirkungen im Vergleich zum Durchschnittswert der gesamten Beobachtungszeit.

River, gauge station	Ob'at Salekhard		Yenisei at Igarka		Lena at Kyusyur	
Method	Shift point	*p* Value	Shift point	*p* Value	Shift point	*p* Value
annual water flow						
CDC&Student' test	1968	0.01	1982	0.01	1987 (1957)*	0.05
CUMDEV TEST	1969	0.05	1983	0.05	1988	0.1
M-W-P Test	1969	0.1	1983	0.01	1958	0.1
snow flood flow						
CDC&Student' test	1968	0.05	1973	0.1	1972	0.01
CUMDEV TEST	1969	0.1	1974	0.1	1973	0.01
M-W-P Test	1969	0.1	1974	0.1	1973	0.01
warm season water flow						
CDC&Student' test	1968	0.05	1982	>0.1	1987 (1973)*	0.05
CUMDEV TEST	1969	0.1	1983	0.1	1988	>0.1
M-W-P Test	1969	0.1	1983	0.05	1977	0.1
winter water flow						
CDC&Student' test	1969	0.01	1988	0.01	1982	0.05
CUMDEV TEST	1973	0.01	1983	0.01	1983	0.01
M-W-P Test	1970	0.01	1983	0.01	1983	0.01
water temperature						
CDC&Student' test	1950 1965 1987	0.01	1957 1999	0.05	1997	0.05
CUMDEV TEST	1988	0.05	1999	>0.1	1997	0.1
M-W-P Test	1988	0.05	1999	0.1	1997	0.05
Sequential regime shift detector	1951 1966 1988	0.1 0.1 0.1	1958 1999	0.1 0.1	**	-
heat flux						
CDC&Student' test	1990	0.05	1953 1982 (1998)*	0.01	1972	0.05
CUMDEV TEST	1993	0.1	1983	0.1	1973	>0.1
M-W-P Test	1993	0.05	2000	0.1	1973	0.1
Sequential regime shift detector	-	-	1954 1982	0.05 0.05	-	-
annual air temperature						
CDC&Student' test	1980	0.05	1987	0.05	1987	0.05
CUMDEV TEST	1981	0.01	1988	0.01	1988	0.01
M-W-P Test	1981	0.01	1988	0.01	1988	0.01

Tab. 4: Shift points for hydroclimatic characteristics of the Ob, Yenisei and Lena rivers at their outlets. * Possible additional shift points are indicated in parentheses; ** ,-‘ means that the Sequential regime shift detector method was not applied due to case simplicity.

Tab. 4: Wendepunkte der hydroklimatischen Charakteristika von Ob, Jenissei und Lena an ihren Mündungen. * mögliche weitere Wendepunkte in Klammern.

same river and between rivers. The duration also varies considerably over a wide range, from 22 to 52 years (Fig. 1, Tab. 4). The most notable differences in the water flow between the two different phases are observed in the winter (Fig. 2). This difference in mean values reaches 40 % for the Yenisei River, with about 20 % for the Ob' and Lena rivers. Differences in other water flow characteristics are within 10 %.

Anthropogenic impacts

The influence of anthropogenic factors – primarily flow regulation by reservoirs – caused the time shift of the transition between long phases of decreased/increased winter flow to earlier years (Georgiadi & Kashutina 2016). This is particularly noticeable for the Yenisei River – more than a ten-year shift – but manifests weakly in the cases of the Lena and Ob' rivers – a three-year shift.

Most considerably, the anthropogenic factor reduces snow flood flow, and, to a lesser degree, annual flow due to seasonal flow regulation by reservoirs, water losses for their dead storage capacity filling, additional evaporation from free-water-surface of reservoirs as compared to land surface evaporation before dams' construction and consumptive water use.

It essentially increases the winter flow when reservoirs water capacity is used for hydropower generation.

Notably, the period of intensified anthropogenic impact almost coincided with the long phase of increased annual and seasonal flow caused by climatic changes. The contribution of climatic and anthropogenic factors to changes in the water flow can be evaluated by comparing the flow for the period prior to the noticeable anthropogenic impact (base period) with the observed – human-induced modifications – and naturalized flow during the subsequent period of significant anthropogenic impact on the water regime. The time delimitations of base period and period of human-induced water regime were defined through comparison of the annual flow hydrography for the different periods, as well as data on the start of operations of the large reservoirs. This allowed to determine the years when noticeable changes in flow were initiated to be traced. We compared averaged flow for the periods: 1930s to 1960s – base period or period of conditional-natural water regime – and 1961 to 2007 – period of significant human-induced modification of the water regime – for the Ob' River at Salekhard; and, correspondingly, 1936 to 1966 and 1967 to 2004 for the Yenisei River at Igarka; and 1936 to 1967 and 1968 to 2007 for the Lena River at Kyusyur. The most significant increase in the annual flow during the period of human-induced water flow occurred in the Yenisei and Lena rivers (Fig. 3). As mentioned above, anthropogenic factors reduce snow-flood flow and annual flow, and increase winter flow. Thus, in the case of winter-flow, climatic and anthropogenic factors act uni-directionally to increase it, and, in the case of snow-flood flow and annual flow, they produce an opposite impact. As result snow-flood flow was decreased in the Ob', and especially in the Yenisei, due to the predominant influence of anthropogenic factors. In all other cases, climatic factors dominate, which leads to increased flow.

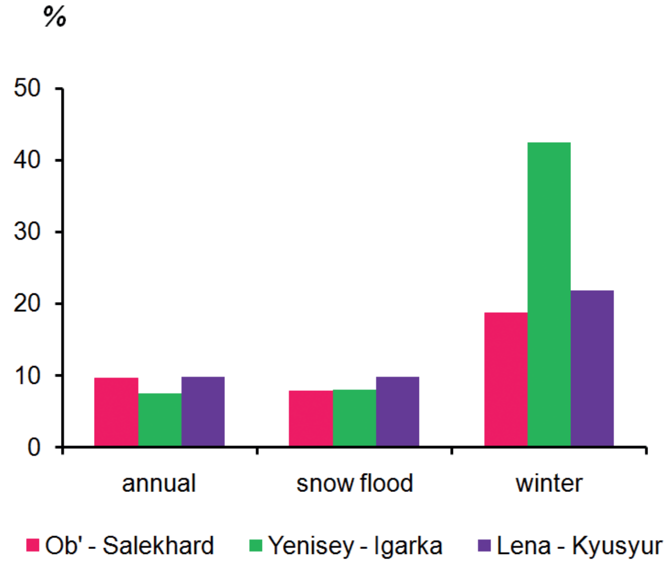

Fig. 2: Difference in naturalized water flow within long phases of its increased/decreased values in the Ob' River at Salekhard, the Yenisei River at Igarka and the Lena River at Kyusyur, in (%).

Abb. 2: Unterschied des Wasserabflusses unter Ausschluss menschlicher Einwirkungen („naturalized") in langen Phasen von Zunahme/Abnahme (Jahr - Schneeschmelze - Winter) in den Flüssen Ob am Pegel Salekhard, Jenissei am Pegel Igarka, Lena am Pegel Kyusyur in (%).

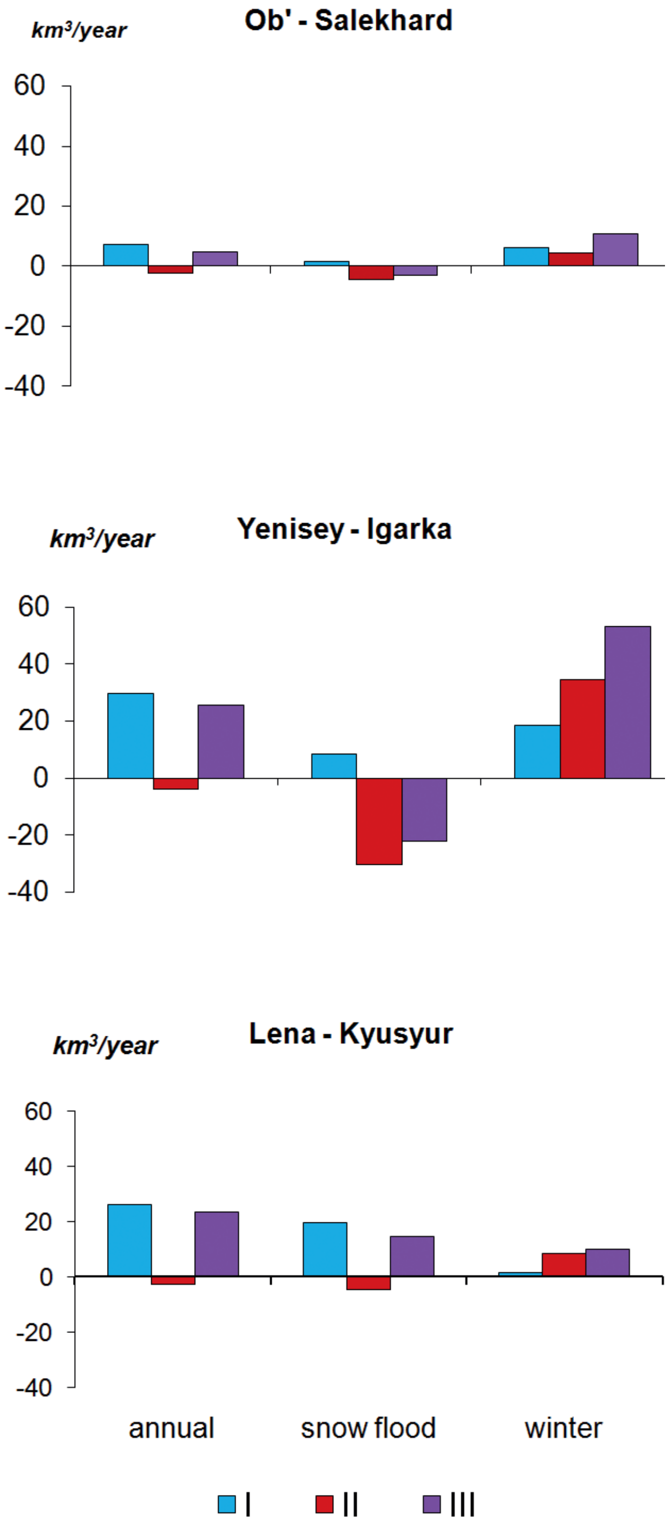

Fig. 3: Climatic and anthropogenic changes in water flow (W, km^3/year) Top: in the Ob' River at Salekhard (during 1961-2007 compared to the base period 1930-1960). Middle: in the Yenisei River at Igarka (during 1967-2004 compared to the base period 1936-1967). Middle: in the Lena River at Kyusyur (during 1968-2007 compared to the base period 1936-1967); I/blue: climatic changes, II/red: anthropogenic changes, III/purple: total changes.

Abb. 3: Klimatisch und anthropogen verursachte Wechsel im Wasserfluss (W, km^3/Jahr); oben: im Ob bei Salekhard (im Zeitraum 1961 bis 2007 im Vergleich zur Basis 1930 bis 1960); Mitte: Im Jenissei bei Igarka (im Zeitraum 1967 bis 2004 im Vergleich zur Basis 1936 bis 1967); unten: In der Lena bei Kyusyur (im Zeitraum 1968 bis 2007 im Vergleich mit der Basis 1936 bis 1967). I/blue: klimatischer Wechsel; II/rot: anthropogen verursachter Wechsel; III/lilafarben: Gesamt.

Long phases of multiyear changes in water temperature and heat flux

Water temperature

In the Lena River, two long phases of statistically significant distinct water temperatures – averages for May–October – were identified (Fig. 4, Tab. 4). A phase of cooler river waters lasted from at least the start of observations until 1995, and after that, it was replaced by a phase of increased water temperature. Four contrasting phases were observed in the Ob' and three in the Yenisei. Note that the first two different phases in the Ob' were identified against a background of a statistically significant trend of rising water temperature.

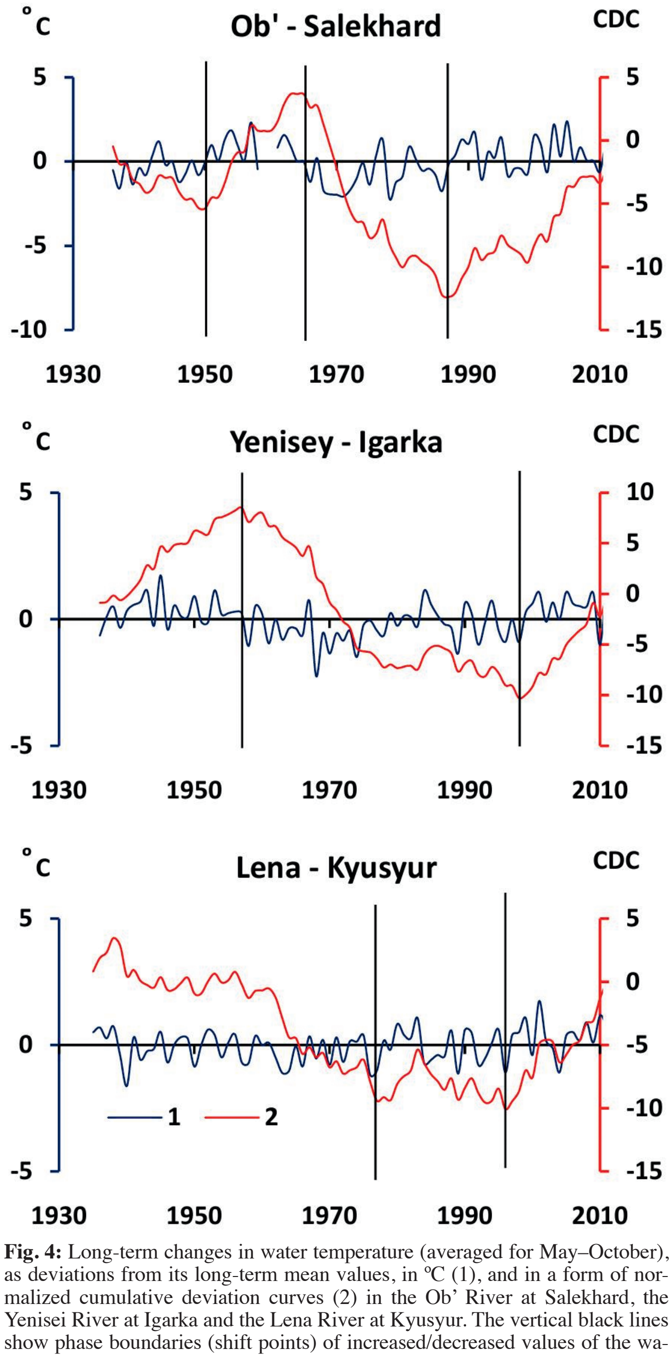

Fig. 4: Long-term changes in water temperature (averaged for May–October), as deviations from its long-term mean values, in ºC (1), and in a form of normalized cumulative deviation curves (2) in the Ob' River at Salekhard, the Yenisei River at Igarka and the Lena River at Kyusyur. The vertical black lines show phase boundaries (shift points) of increased/decreased values of the water temperature compared to the average value, calculated for the entire period of observation.

Abb. 4: Langfristige Wechsel der Wassertemperatur (Durchschnitt für Mai bis Oktober) in den Flüssen Ob am Pegel Salekhard, Jenissei am Pegel Igarka und Lena am Pegel Kyusyur; (1) blaue Kurve: als Abweichung vom Normalwert in (°C) und (2) rote Kurve: als kumulative Normalverteilung (CDC). Die vertikalen schwarzen Linien beschreiben Phasengrenze von Zunahme/Abnahme der Wassertemperatur im Vergleich zum Durchschnittswert der gesamten Beobachtungszeit.

The duration of the contrasting phases in the Ob' River is approximately equal, at about 20 years. In the Yenisei and Lena rivers, the phase of decreased water temperatures was more than twice as long as the phase of increased values within considered period. The difference in water temperature between these long phases of increased and decreased values is 1.5 ºC in the Ob' River, 0.7 ºC in the Yenisei River, and 0.5 ºC in the Lena River.

Naturalized heat flux

Two long phases of decreased/increased heat flux were identified in the Ob' and Lena rivers characterized by statistically significant difference in mean value (Fig. 5, Tab. 4). The switch between contrasting phases occurred in the 1970s (the Lena) and the 1990s (the Ob'). The duration of these phases in frame of the considered time interval were approximately equal in the Lena River, whereas in the Ob' – and the Yenisei – the phase of decreased heat flux values was longer; however, two long phases of increased heat flux were found in the Yenisei River – the first in 1936 to 1953, the second from 1983 until the present – as well as one phase of decreased flux, which started in 1954. The difference in heat flux between the long phases of increased/decreased values is about 10 % in the Lena River and 15 % in the Ob' and Yenisei rivers.

Anthropogenic-induced changes in heat flux

The most notable change caused by anthropogenic factors was observed for the Yenisei heat flux, whereas in the Lena and Ob' rivers, its impact is weak. Comparison of the observed and naturalized long-term series of heat flux from 1967 to 2004 – the period of the most intense anthropogenic impact, mainly related to the operation of the reservoir system on the Yenisei and Angara Rivers – showed that anthropogenic factors led to a decreased average long-term heat flux, by 12 % and 6 %, respectively, for the entire period of observation.

ASSOCIATIONS BETWEEN LONG PHASES OF MULTI-YEAR CHANGE IN WATER FLOW / WATER TEMPERATURE / HEAT FLUX AND AIR TEMPERATURE

Large-scale climate changes, including air temperature, have a decisive influence on the long-term dynamics of water flow, water temperature and heat flux in the largest Russian Arctic rivers. Hydroclimatic changes on different scales are characterized by different degrees of contiguity. Despite the complex nature of the effects of changes in air temperatures on the hydrological characteristics under study, a certain degree of consistency in the long-term phases of their decreased/increased values, with a duration of 15 to 20 years or more, is observed. This is especially true for long-term changes in the water flow and heat flux, and, to a lesser extent, water temperatures.

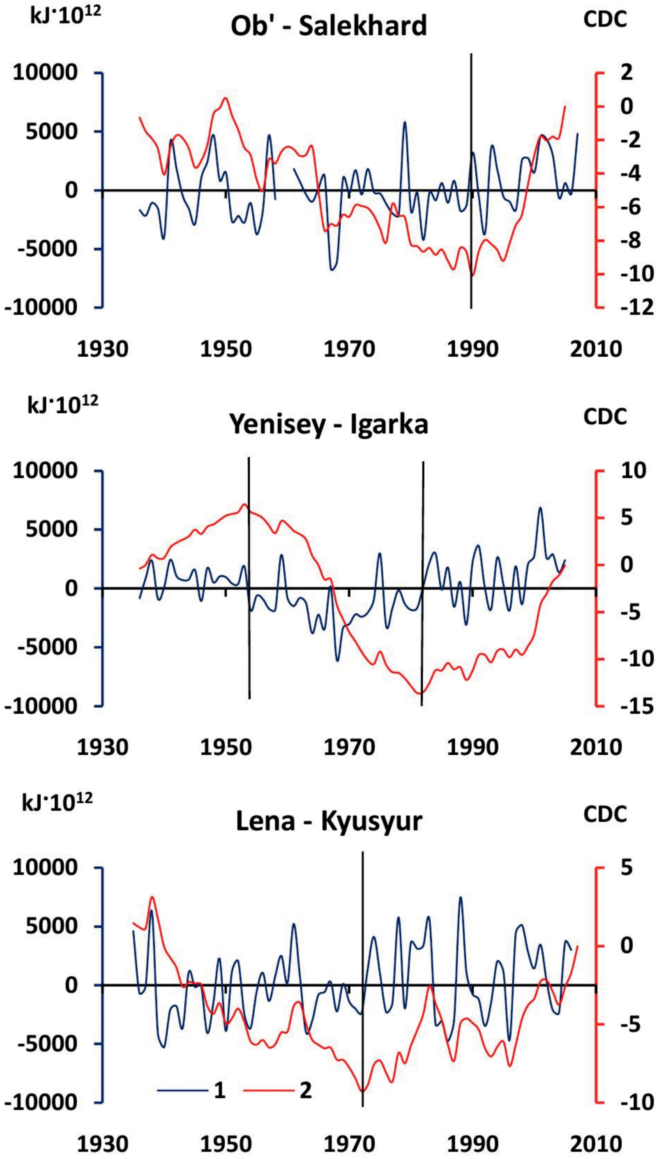

Fig. 5: Long-term changes in naturalized heat flux (averaged for May–October), in kJ·10^{12} (1), and in the form of the normalized cumulative deviation curves (2) in the Ob' River at Salekhard, the Yenisei River at Igarka and the Lena River at Kyusyur. The vertical black lines show phase boundaries (shift points) of increased/decreased values of the naturalized heat flux compared to the mean value, calculated for the entire period of observation.

Abb. 5: Langfristige Wechsel des Wärmeflusses mit ausgeschlossenen menschlichen Auswirkungen („naturalized") im Durchschnitt für die Zeit Mai bis Oktober für die Flüssen Ob am Pegel Salekhard, Jenisse am Pegel Igarka und Lena am Pegel Kyusyur; (1) blaue Kurve: als (kJ·10^{12}) und (2) rote Kurve: als kumulative Normalverteilung (CDC). Die vertikalen schwarzen Linien beschreiben Phasengrenze von Zunahme/Abnahme des Wärmeflusses nach Ausschluss menschlicher Auswirkungen im Vergleich zum Durchschnittswert der gesamten Beobachtungszeit.

The hydrological changes discussed above occurred against a backdrop of long phases of decreased – from the 1930s to 1940s – and increased – from the 1970s to 1980s – values of annual temperature (Fig. 6, Tab. 4). It should be noted that similar long-term changes in air temperature have been observed across the entire Arctic Ocean continental watershed since the 1930s to 1940s (GEORGIADI & KASHUTINA 2011). Differences in the average basin air temperature during phases of their increased/decreased values in each river basin were about 1 ºC for the annual temperature.

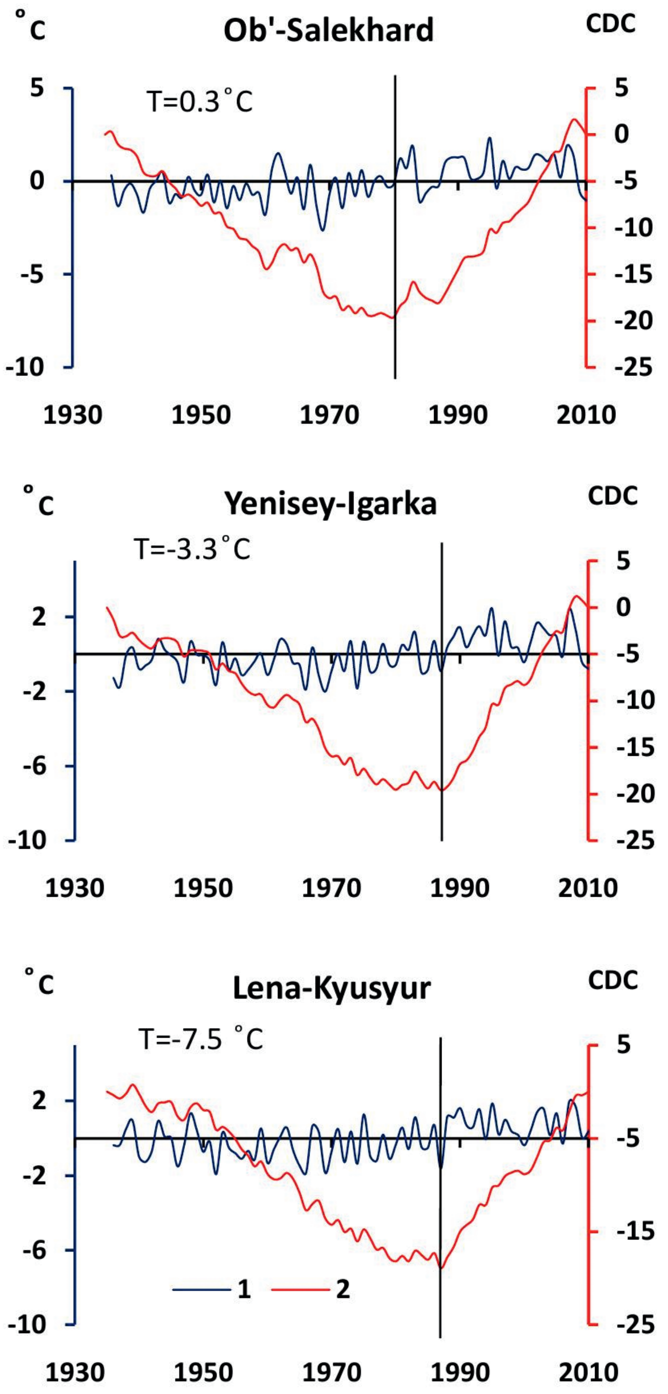

Fig. 6: Long phases of increased/decreased mean annual air temperatures in coordinates of normalized cumulative deviation curves, averaged by basin, for the Ob' River at Salekhard, the Yenisei River at Igarka and the Lena River at Kyusyur, based on database of the World Data Center (meteo.ru). T: mean annual long-term average air temperature. The vertical lines show the shift points between the different phases.

Abb. 6: Langfristige Phasen von Zunahme/Abnahme der mittleren Jahrestemperatur als kumulative Normalverteilung (CDC) gemittelt für das Einzugsgebiet der Flüsse Ob bei Salekhard, Jenissei bei Igarka und Lena by Kyusyur (nach World Data Center, meteo.ru). T: mittlere langfristige Jahrestemperatur. Die vertikalen schwarzen Linien beschreiben die Schaltpunkte zwischen den verschiedenen Phasen.

CONCLUSIONS

(1) The long phases of increased and decreased with respect to the mean, calculated for the entire period of observation, water flow, water temperature and heat flux of the Ob', Yenisei and Lena rivers at their outlets, over a period of observation from the 1930s to 2000s, and the impact of anthropogenic factors on these were investigated. The specific phases are characterized by statistically significant differences in mean values of considered hydrological characteristics and pronounced length (usually 15 to 20 years or more) of duration. The mentioned phases represent a characteristic feature of the rivers long-term changes under natural conditions.

(2) During the period of observation, two long phases of decreased and increased naturalized – i.e., excluding anthropogenic changes, mainly due to flow regulation by reservoirs – water flow were revealed in the largest rivers (Ob', Yenisei and Lena) of the Arctic Ocean continental watershed. The shift point, between the phases occurred in the 1970s to 1980s. The difference between the average values within different phases varies from 10 to 20 % reaching a maximum of 40 % in the Yenisei River during the wintertime.

(3) The period of intensified anthropogenic impact (since the 1960s) almost coincides with a long phase of increased naturalized annual and seasonal flow caused by climatic changes. Most considerably, the anthropogenic factor reduces snow flood flow, and, to a lesser degree, annual flow due to seasonal flow regulation by reservoirs, water losses for their dead storage capacity filling, additional evaporation from free-water surface of reservoirs as compared to land surface evaporation before dams' construction and consumptive water use. It essentially increases the winter flow when reservoirs water capacity is used for hydropower generation.

(4) In the Lena River, two long phases of water temperature change – averages for May–October – were identified. Four contrasting phases were observed in the Ob' River, and three in the Yenisei River. The difference in water temperature between the long phases of increased/decreased values is 1.5 ºC in the Ob' River, 0.7 ºC in the Yenisei River and 0.5 ºC in the Lena River.

(5) Two contrasting long phases in the multiyear change in heat flux were identified in the Ob' and Lena rivers. A phase of decreased values lasted for 35 to 55 years within considered period of time. This was replaced by a phase of increased values, which started in the Lena River in the 1970s to 1980s, and in the Ob' River in the 1990s. Two long phases of increased heat flux were found in the Yenisei River– the first, from 1936 to 1953, the second from 1983 until the present – as well as a phase of decreased flux, beginning in 1954. The difference between the averaged heat flux values over the contrasting long phases is about 10 % in the Lena River and 15 % in the Ob' and the Yenisei rivers. The most notable man-induced heat flux changes (a 12 % reduction) were observed in the Yenisei River during the period of intensified anthropogenic impact.

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ArcticRIMS <http://rims.unh.edu/>

Regime Shift Detection Software <https://sites.google.com/site/climatelo gic/home>