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Long-term changes of water flow, water temperature and heat flux of two largest arctic rivers of European Russia, Northern Dvina and Pechora

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Abstract

The phases of long-lasting (more than 10–15 years) increased and decreased water flow, water temperature and heat flux values in the Northern Dvina River and the Pechora River were studied for the observation period from the 1930s to 2020. To distinguish between different phases, statistical homogeneity tests and normalized cumulative deviation curves were used. Generally, the identified phases displayed statistically significant differences between average values of the measured characteristics. During contrasting phases, the general pattern of water temperature during the warm season, water runoff and heat flux in the Northern Dvina and Pechora River Basins differed considerably. The number of the identified phases varied between the studied rivers and ranged from two to four contrasting phases in the Northern Dvina River exceeded those of the Pechora River. Consequently, the duration of the phases also varied quite significantly. The difference in mean values of the hydrological characteristics during the contrasting phases in the Northern Dvina River exceeded those of the Pechora River. The longest phases of increased and decreased heat flux nearly coincide with contrasting periods of water runoff and water temperature. The phases of simultaneous increased or decreased values of all hydrological characteristics were associated with corresponding periods of increased or decreased air temperature (on average for a year and for the open water period) and annual precipitation values. Those long-lasting phases of simultaneously increased or decreased values of river flow, heat flux, and water temperature were associated with changes of the global thermal regime, regional cryosphere variations, and long-term periods of intensification or weakening of the atmospheric circulation over the North Atlantic, characterised by variability in macrocirculation indices such as the North Atlantic Oscillation and Scandinavian circulation pattern.

1. Introduction

Currently, the various aspects of the long-term variability of heat flux and water temperature series in rivers—including those of the Arctic region—have been in the focus of numerous studies (Elshin 1981, Lammers *et al* 2001, 2007, Tananaev *et al* 2019, Yang *et al* 2021). However, studies focusing on long-lasting contrasting phases of other geo-flux components, including heat flux and its factors, are limited (Reid *et al* 2016, Georgiadi *et al* 2018, Georgiadi *et al* 2021). The heat flux and thermal regime of Arctic rivers are important factors that determine hydro-ecological state, ice regime, channel processes and coastal reshaping in areas where permafrost is widely spread; additionally, these factors influence the ice regime and ecological state of the Arctic Ocean and its seas. This article is devoted to the study of contrasting geo-flux phases during the open water season of the Northern Dvina and Pechora Rivers, as well as to the climatic conditions that characterize these phases.

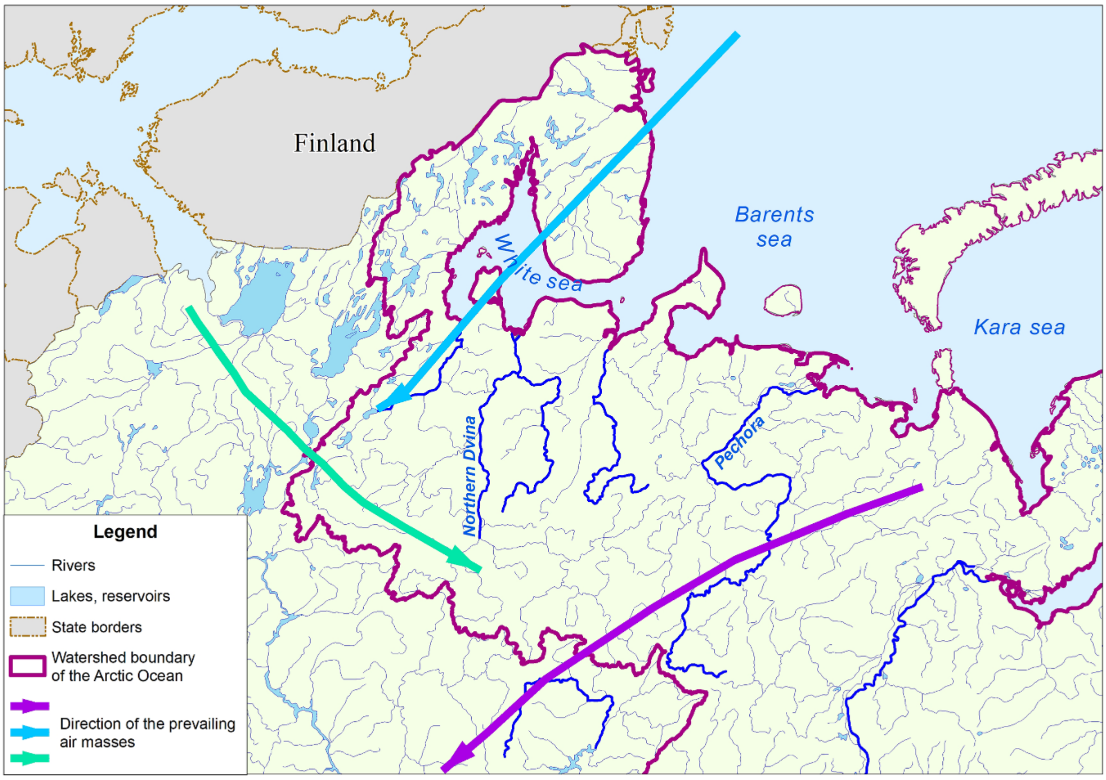

Figure 1. The Arctic Ocean Basin boundary within European Russia and directions of three dominant air mass movements: maritime Arctic air (blue line), maritime subarctic air (green line), and continental Arctic air (purple line); figure is prepared on the basis of the text description of the former Union of the Soviet Socialistic Republics climatic regions by Alisov (1956).

'Geo-flux' is a term describing the combination of water, sediment, chemical, biological and heat fluxes from a catchment area (Muraveisky 1960). The total water flow and heat flux from the Northern Dvina River and the Pechora River in Russia comprise 10% of the input of these geo-flux components into the Arctic Ocean. Those parameters are considered quite sensitive to ongoing climate change effects, which, along with anthropogenic impact, are the major driving factors for long-term changes in geo-flux around the world (Gordeev 1996, Peterson *et al* 2002, Shiklomanov and Shiklomanov 2003, Hinzmann *et al* 2005, Lammers *et al* 2007, WRRU 2008, Georgiadi *et al* 2011, 2014, 2018, Holmes *et al* 2012, Shiklomanov *et al* 2013, Smirnov 2015, Vihma *et al* 2016, Magritsky 2009, 2015, Magritsky *et al* 2018, AHPE 2021, Vasilenko *et al* 2020, Yang *et al* 2021). At the same time, the long-term changes in geo-flux components of the Arctic rivers, as well as those in other regions, are characterized by contrasting periods or phases, according to the terminology adopted in Russia (Andreyanov 1959) of their increased and decreased values with various durations. A large amount of long-term variability exists: some long-lasting periods can be distinguished by a duration of 10–15 years, while others last many decades (WRRU 2008, Georgiadi *et al* 2011, Georgiadi *et al* 2014, 2018, 2020, Shi *et al* 2019). These contrasting phases are characterized by specific, relatively steady water regimes and ecosystem conditions of river, lake and marine waters (Rodionov and James 2005, North *et al* 2013).

This article is devoted to the study of long-lasting periods (phases) of increased and decreased heat flux, water temperature, and river runoff during the open water season over the Eastern European part of the Arctic Ocean Basin. Namely, over the basins of the two largest rivers in the region within Russian borders, Northern Dvina and Pechora Rivers. During the cold season those river basins, while geographically neighbouring each other, are affected by distinctively different air masses. Whereas the Northern Dvina River basin is mainly a subject of maritime air masses coming from mostly ice-free Barents and Baltic Seas, the Pechora River basin is influenced mainly by continental Arctic air masses originating in the regions adjacent to the Kara Sea which remains ice-covered during most of the year (figure 1). This difference, as it will be shown further, may explain the dissimilar behaviour of geo-flux phases in two rivers.

The consequent distinguished replacements of the phases with contrasting water regimes represent an important feature of the long-term hydrological dynamics caused by climate change. Moreover, the differences between average values of geo-flux components related to contrasting phases in most cases have been shown to be statistically significant (Hedberg 2015, Yeh *et al* 2015, Sharma and Singh 2017, Georgiadi *et al* 2018).

The long-term phases of annual and seasonal runoff of such major Arctic rivers as the Ob, Yenisei and Lena have been identified and studied (Georgiadi *et al* 2018, Shi *et al* 2019). However, the climatic conditions of the formation of long contrasting phases of water flow and other components of geo-flux, including the features of atmospheric circulation, have not been practically studied. Although it should be noted that there are already some results of a qualitative assessment of the conjugacy of long-term changes in the water flow of the largest Arctic rivers and various indices of atmospheric circulation (Peterson *et al* 2002, Georgiadi and Kashutina 2016), as well as the first quantitative estimates of the influence of atmospheric circulation on various characteristics of the water flow of Arctic rivers and rivers of other regions, expressed in such indices as AO (Kryjov and Gorelits 2019) and North Atlantic Oscillation (NAO) (Popova and Georgiadi 2017). Contrasting phases of annual and seasonal water runoff have been studied in detail for different regions of the Earth, including the Arctic rivers (e.g. Water Resources of Russia and their Use 2008). Considerable attention has been paid to methodological approaches used to identify the boundaries and properties of contrasting phases within long-term series of river runoff. This includes using various criteria in statistical homogeneity testing to identify transitions from one phase to another, called 'shift points' (Kundzewicz and Robson 2004, Rodionov 2004, 2015, Yeh *et al* 2015, Sharma and Singh 2017, Georgiadi *et al* 2018).

2. Data and region description

The basins of the largest Arctic rivers of European Russia—the Northern Dvina River at Ust-Pinega and Pechora River at Ust-Tsilma—were chosen as the study objects in this research (figure 2). Data from the 1930s to 2020 period were used for these basins. Particular attention was paid to the identification of the years (shift points) when the changes between the contrasting long phases occurred.

The physico-geographic description of these basins is placed in supplementary material of this section. Table 1 contains their major long-term mean hydrological and climatologic characteristics.

Three characteristics of the global climate change were used to assess its impact on the hydrological cycle of the study region.

Results of the surface air temperature analysis for the past 100 years were provided by the Climate at a Glance NCEI NOAA website (www.ncei.noaa.gov/cag/global/time-series/europe/land/; NCEI 2022). This dataset provides evidence of the global air temperature changes. It shows the increase in annual mean temperature over Europe reaching up to 1.5 °C per century. Moreover, the rate of annual warming here increased threefold during the past 40 years (up to 0.47 °C per decade during the 1980–2021 period). In the study area located in the northeastern part of Europe, this increase is even more pronounced than over the rest of Europe (EEA 2020). This warming affected the hydrological cycle of the region by shifting the dates of the spring onset and increasing the duration of the vegetation season (Callaghan *et al* 2011).

The NAO index is defined as the difference in sea level pressure (SLP) between two 'centers of action', Azores High and Icelandic Low. An increase in this difference during the cold seasons intensifies the westerly air flows over the North Atlantic, thus increasing the storm track activity that brings precipitation over Northwestern Europe. The second index, Scandinavian circulation pattern (SCAND), characterizes the so-called Scandinavian pattern, which has a primary SLP center of action over western Norway with an opposing center of action over the Northeastern Atlantic near Greenland. During winter, NAO and SCAND indices accounted for, approximately, 33% and 14% of the total sea level pressures variance over the North Atlantic region, respectively (Dixon *et al* 2000). The long-term series of atmospheric pressure at sea level for the winter period (December–March) between Gibraltar and Stykkishólmur/Reykjavík (Iceland) were used for the study of long-term changes in NAO (Jones *et al* 1997). The SCAND index is available since 1950 and was downloaded from www.cpc.ncep.noaa.gov/data/teledoc/scand.shtml.

3. Methods of regime shift (change point) detection

Delimitations between separate long-lasting phases of increased and decreased values of the considered characteristics were determined using normalized cumulative deviation curves, CDCs (Andreyanov 1959, Georgiadi *et al* 2018), combined with the statistical homogeneity assessments of series means using Student's t-test and Mann–Whitney–Pettitt (MWP) tests (Cramer 1946, Pettitt 1979, Stepanek 2008, Xie *et al* 2014, Lemeshko *et al* 2018). The estimates of the contrasting phases' shift points determined by different methods have predominantly coincided with the findings that have been previously made by the authors (Georgiadi *et al* 2018). Supplementary material of this section has more detailed description of the used methods.

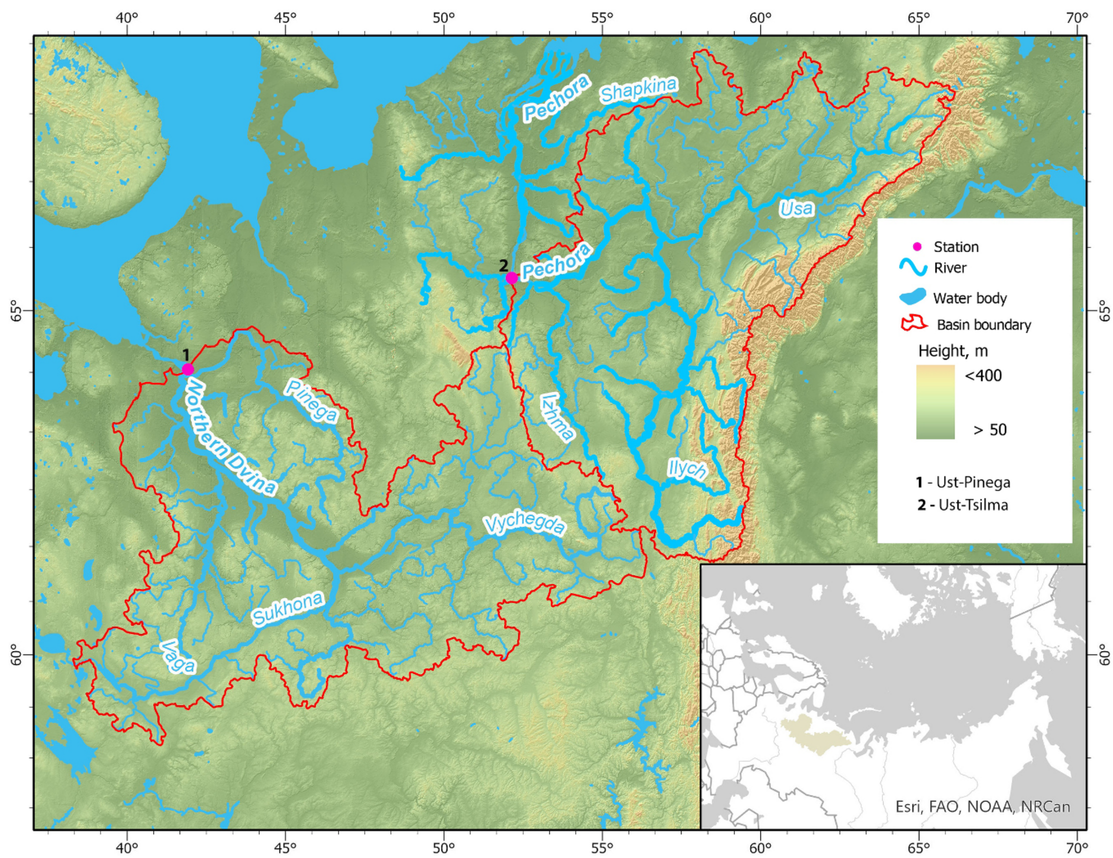

Figure 2. Location of the Northern Dvina and Pechora River Basins and the gage river stations used in the study. 1 – The Ust-Pinega gage station on the Northern Dvina River is located at the delta head, 137 km from the sea edge of the delta, immediately downstream of the confluence with the Pinega River. It encloses a catchment area of 348 000 km^2, which is 97.5% of the total catchment area. 2 – Ust-Tsilma gage station is located 425 km from the mouth of the Pechora River, and it encloses a catchment area of 248 000 km^2, which is 77% of the entire catchment area.

Table 1. Long-term mean hydrological and climatologic characteristics of the studied river basins.

	Average long-term value					
River outlet gauge station	Annual air temperature[a], °C	Annual total atmospheric precipitation[a], mm	Annual water discharge[b], m^3 s^{-1}	Water discharge in May–October[b], m^3 s^{-1}	Water temperature, May–October[b], °C	Heat flux, May–October[c], 10^{15} kJ
Northern Dvina, Ust-Pinega	1.2	617	3243	4966	11.37	2.87
Pechora, Ust-Tsilma	−3.3	534	3505	6100	8.3	2.74

[a] According to authors' estimation based on data of Climatic Research Unit—Groups and Centres (www.uea.acuk/web/groups-and-centres/climatic-research-unit/data).

[b] According to authors' estimation based on data of Hydrological Yearbooks. A small number of data gaps were filled for water discharges from neighboring gage stations or by year-analogues, for water temperature in relation to the air temperature at the nearest weather stations.

[c] According to authors' estimation.

4. Results

4.1. Shift point analyses

Comparison of the determined shift points obtained using normalized CDCs (figure 3) and using criteria of statistical homogeneity (supplementary material) confirmed the previously drawn conclusion (Georgiadi *et al* 2018) that these methods give similar results. The single significant difference in defined shift points using both methods was related to the transition from a phase of decreased water runoff to a phase of increased water runoff in the Pechora River. In this case, the shift point determined using the normalized cumulative deviation curve suggested

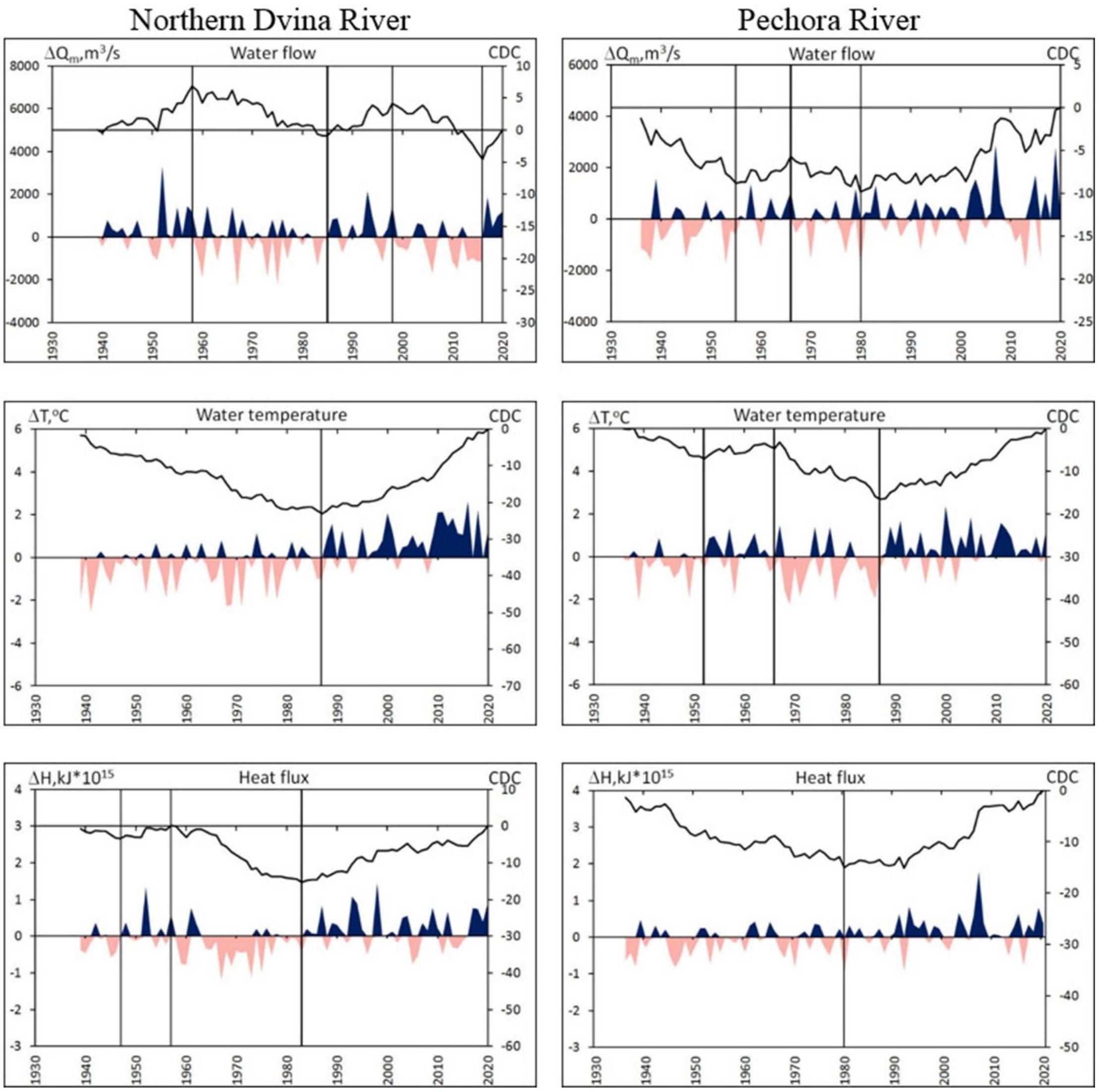

Figure 3. Long-term changes in water flow, water temperature and heat flux of the Northern Dvina at Ust-Pinega and Pechora at Ust-Tsilma for warm season (May–October) in a form of the normalized cumulative deviation curves (black line) and in deviations from their long-term mean values, $m^3 s^{-1}$ (dark blue – positive deviations and red – negative deviations). The vertical black lines in this Figure show phase boundaries (shift points) of increased/decreased values of the water flow compared to the mean value, calculated for the entire period of observation.

the transition occurred in 1981, while the Student's t-test criterion proposed strong transition that occur 10 years later. This discrepancy may have happened due to a dramatic change in the atmospheric circulation in North Atlantic in the early 2000s with Islandic Low shifted northeastward into the Barents Sea, generated the so-called Arctic Rapid change Pattern (ARP) that in its negative phase amplified the heat transport into the central Arctic (Zhang *et al* 2008) and directly impacted the humidity of the continental Arctic air that mostly controlled the Pechora River Basin precipitation (cf, figure 1). For the other cases, several shift points were found using the criteria of statistical homogeneity (especially based on the Student's t-test criterion) and the normalized CDC method, with no significant differences between tests. For all cases, the shift points obtained using the normalized CDC approach were used for initial (eyeball) assessment and the MWP test was employed in further analysis.

4.2. Long-lasting phases for two rivers

4.2.1. Water flow

The features of long-lasting phases of increased and decreased water flow during the open water season of the year differ significantly between the Northern Dvina River and Pechora River (figure 3, table 2). The Northern Dvina River is characterised by four distinctive phases with almost identical duration of 13–27 years (excluding the last period, which is ongoing as of data analysis). In the Pechora River, four such phases differing in duration were distinguished. Along with a longer phase of increased water flow from 1981 to 2020, a lengthy period of decreased runoff was observed from 1936 to 1955. Another two short contrasting successive phases were observed

Table 2. Characteristics of contrasting phases of water flow, water temperature and heat flux for the open water season (May through October) of the Northern Dvina at Ust-Pinega and Pechora at Ust-Tsilma. For each variable and phase, the table shows phase boundary, phase duration, and the average value of the variable. Phases with decreasing values (DV) and increasing values (IV) are shown separately.

Long phase	Water discharge, $m^3 s^{-1}$	Water temperature, °C	Heat flux, 10^{15} kJ per May–October season
	Phase boundaries/phase duration/average value of characteristics		
The Northern Dvina at Ust-Pinega			
DV	1959–1985/27/4672	1939–1987/49/10.8	1939–1947/9/2.68
DV	1999–2016/18/4274	—	1958–1983/26/2.57
IV	1939–1958/20/5366	1988–2020/33/12.2	1948–1957/10/3.05
IV	1986–1998/13/5199	—	1984–2020/37/3.09
Average values of each characteristic for each type of phase, their absolute and relative differences			
$IV_{average}$	5324	12.2	3.08
$DV_{average}$	4604	10.8	2.6
$IV_{average}–DV_{average}$	720	1.4	0.48
$IV_{average}–DV_{average}$, in % relative to $DV_{average}$	16	13	18
Pechora at Ust-Tsilma			
DV	1936–1955/20/5690	1936–1952/17/7.8	1936–1980/45/2.59
DV	1967–1980/14/5820	1968–1987/20/7.6	—
IV	1956–1966/11/6366	1953–1967/15/8.8	1981–2020/40/2.91
IV	1981–2020/40/6329	1988–2020/32/8.7	—
Average values of each characteristic for each type of phase, their absolute and relative differences			
$IV_{average}$	6337	8.7	2.91
$DV_{average}$	5743	7.7	2.59
$IV_{average}–DV_{average}$	594	1.0	0.32
$IV_{average}–DV_{average}$, in % relative to $DV_{average}$	10	13	12

'—' means that phases have not been revealed.

from 1956 to 1966 (increased flow) and 1967 to 1980 (decreased flow). Furthermore, from the 1930s until the mid-1950s, in 1961–1966 and in 2001–2007, the water runoff on both studied rivers changed out of phase with each other, while the hydrological situation developed quasi-synchronously since that time until 1998 and after 2009.

4.2.2. Water temperature

Like water runoff, the features of long-lasting phases of increased and decreased water temperature for the May to October period and its variability is significantly different between the Northern Dvina and Pechora Rivers (figure 3). Only two such periods could be distinguished for the Northern Dvina River. The most prolonged of them is characterised by lower water temperature values and was observed from 1939 to 1988, when it was replaced by a period with a higher water temperature which continues until recent years (table 2). The water temperature time series for the Pechora River shows four contrasting phases. The first three of these were found to be approximately equal in length. They were replacing one another starting with a period of low water temperature in 1936–1952 (figure 3, table 2). Since 1988, the current phase of increased water temperature has been observed, which is the longest of the distinguished periods.

Only two long-lasting periods of simultaneously increased (1988–1998) or decreased (1959–1985) water temperature and water runoff were observed for the Northern Dvina River during the entire observation period. In the other two periods, the water runoff was increased while the water temperature was lowered (1939–1958) or the opposite was observed (1999–2016). In the Pechora River, two periods were identified when both the water temperature and water runoff were increased (1956–1966, 1988–2020) and another two when those characteristics were decreased (1936–1952, 1968–1980). However, unlike the Northern Dvina River, the Pechora River experienced several relatively short periods of increased water temperature and decreased water flow (1953–1955) or vice versa (1981–1987). This happened due to a mismatch between the time limits of contrasting phases for different studied characteristics.

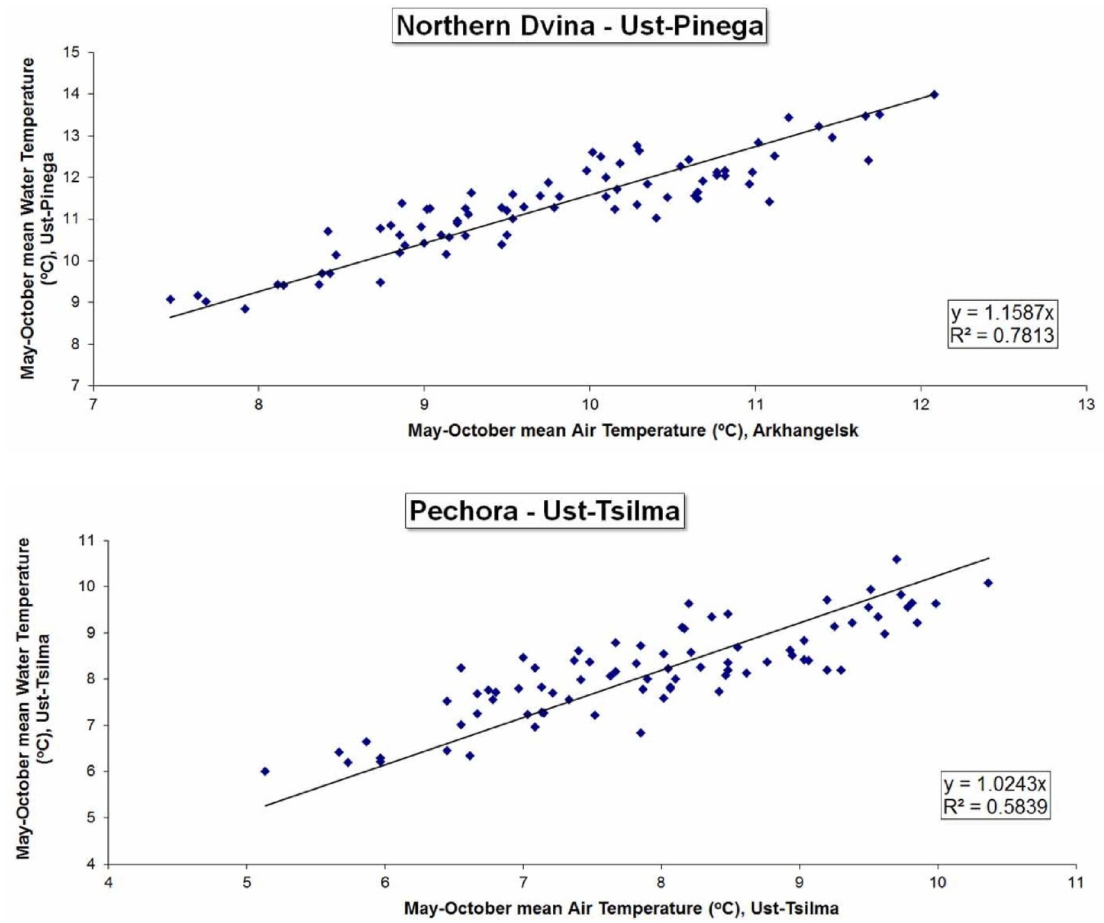

Figure 4. The relationships between open water season water and air temperature at Ust'-Pinega hydrometric gage and meteorological station in Arhangelsk and hydrometric gage and meteorological station in Ust-Tsilma.

Additionally, it was noted that on average, the difference in water temperature between contrasting periods was greater in the Northern Dvina River (table 2).

The long-term increase of the water temperature in these two rivers corroborates well with the general surface air warming over the region (figure 4). The correlation rate is higher for the Northern Dvina Basin, which could be explained by its flat terrain and, thus, more homogeneous climate conditions. Similar relationships have been identified for many other rivers, including those in the Arctic region (Yang and Peterson 2017).

4.2.3. Heat flux

The features of the long-term heat flux dynamics are influenced by the long-term variability in water flow and water temperature during the open water season (cf, equation S2). For both the Northern Dvina River and the Pechora River, two main long-lasting periods of decreased (1958–1983 and 1936–1980, respectively) and increased (1939–1958 and 1984–2020, respectively) heat flux were revealed (figure 3). In the Northern Dvina River, there were also observed relatively short periods of decreased (1939–1947) and increased (1948–1957) heat flux.

4.3. Conjugation of contrasting phases of water flow, water temperature and heat flux

Generally, phases of increased heat flux of the rivers in this study—especially the longest ones—have coincided with phases of increased water runoff and water temperature. The same applies to phases with decreased values. Phases of decreased (1959–1983) and increased (1988–2012) values for all three characteristics were observed in the Northern Dvina River. A similar situation was found in the Pechora River (figure 3, table 2). The decreased values were recorded in 1936–1952 and 1968–1981 while the increased values were observed in 1988–2020. The heat flux was also found to adopt higher values during shorter periods with multidirectional deviations in water flow and water temperature (figure 3). Such short periods were observed in both the Northern Dvina River (e.g. 1939–1958 and 1999–2016) and the Pechora River (1953–1955). It was found that relative difference in the heat flux between the contrasting phases in both rivers was greater than for water runoff (table 2).

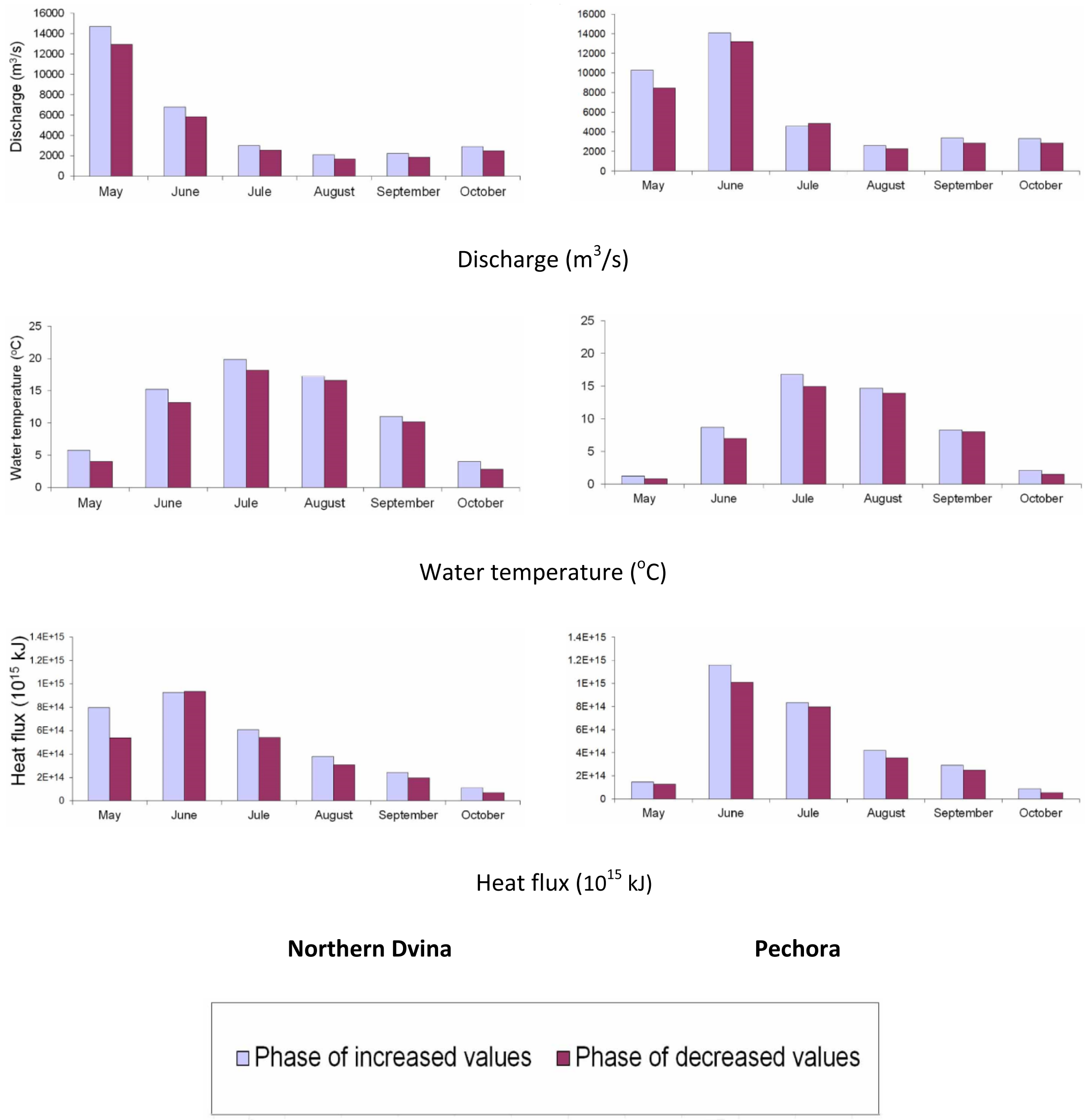

Figure 5. The distribution of monthly water flow, water temperature and heat flux within open water season (May–October) averaged for long phases of its increased and decreased values in the Northern Dvina River at Ust-Pinega and the Pechora River at Ust-Tsilma.

4.4. Dynamics of water flow, water temperature and heat flux in the open water season during the long-lasting phases of increased and decreased values

The greatest differences in the time distribution of mean monthly values during the open water season for the studied characteristics of the Northern Dvina and Pechora River flows occurred for water flow and heat flux, while the water temperature on these rivers was changed similarly (figure 5). Moreover, the features of this distribution do not differ significantly for contrasting phases. Although the period of increased water flow in both the Northern Dvina River and the Pechora River was observed from May to June, the maximum runoffs in those rivers were clearly distinguished in May and June, respectively. Furthermore, the difference in water runoff in these months was greater in the Northern Dvina River than in the Pechora River. This circumstance determines the differences between the heat flux for both rivers from May to June. Although the greatest heat flux, both on the Northern Dvina and on the Pechora Rivers is observed in June, but the heat fluxes in May and June in the Northern Dvina River are comparable to each other, whereas heat flux in the Pechora River in May is significantly lower than in July–September and slightly exceeds the flux in October. The maximum heat flux of the Northern Dvina River was observed in June, while the maximum water temperature was bound to July and the maximum water runoff was formed in May. The highest water temperature in the Pechora River was also observed in July; however, the maximum values of water runoff and heat flux were found in June.

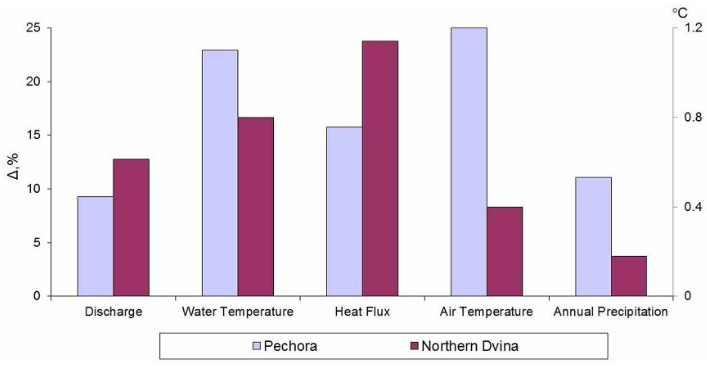

Figure 6. Average difference in open water season water discharges and heat flux (in %), water temperature and air temperature (in °C) as well as annual sum of atmospheric precipitation (in %) between long phases of its increased/decreased values in the Northern Dvina River at Ust-Pinega and the Pechora River at Ust-Tsilma.

4.5. Climate conditions during the phases of increased and decreased values of water flow, water temperature and heat flux

Figure 6 shows the difference between the characteristics in the phases of their decreased and increased values for cases (for parts of the phases) when phases of decreased or increased values of all characteristics were observed simultaneously. The open water season air temperature and the annual atmospheric precipitation values in the both river basins were higher during long-lasting phases of simultaneously observed increased values of the hydrological characteristics established in section 4.1 (figure 6). The relative differences between the contrasting phases in the Pechora River were greater than those of the Northern Dvina River for all hydroclimatic characteristics except heat flux.

4.6. Association between long-lasting phases of long-term variability in water flow, water temperature and heat flux, and macroscale atmospheric circulation

The variability of macroscale atmospheric circulation was analysed using the NAO and SCAND indices, which indicate changes in the intensity of zonal circulation (NAO) and anticyclonic conditions (SCAND) over the study region. The major feature of the SCAND pattern consists of a high pressure over the Scandinavian Peninsula (Barnston and Livezey 1987). Thus, the dominance (anomalously high frequency of occurrence) of the SCAND pattern implies the prevalence of the anticyclonic conditions in the northeastern Europe eastward, first of all over the Northern Dvina River Basin.

The index values estimated for the winter period were analysed in association with the studied rivers because this is the season during which the main stage of snowmelt flood formation occurs, and, consequently, that of increased heat flux. Normalized CDCs were used to identify the long-lasting phases of the NAO and SCAND indices long-term variability. The long-term fluctuations of the NAO index since 1930s comprise several contrasting phases (figure 7(a)).

Table 3 presents a correlation matrix built for all parameters considered in this study observed during the 1951–2020 period. Abbreviations ND and P stand for Northern Dvina and Pechora, respectively. Abbreviations Tw, Qow, and H stand for open water season water temperature, discharge, and heat flux, respectively. Time variable (years) is included in this table to show the contribution of linear trends (warming) on Tw and H values for both rivers. A high correlation between discharge and heat flux in studied rivers (0.77 and 0.83) is essential and was anticipated from equation (S2). Surprisingly, the water temperature variability, while also being part of equation (S2), is not contributing towards heat flux variations in Northern Dvina and Pechora rivers (see also, section 4.2.3 above). Detrended NAO index values do not correlate significantly with Tw and H for both rivers. This is despite previously observed continuous period of sufficiently high correlation between NAO index and Tw in both studied basins (not shown) during the 1951–2000 period prior to the shift of the Icelandic Low Centre northeastward into the Barents Sea (section 4.1).

Being negatively correlated with the NAO index, the SCAND index has a statistically significant negative correlation with discharge and heat flux of the Northern Dvina River. Moreover, the control of this index over the hydrological parameters in the study region did not deteriorate in the past two decades (opposite to the NAO index) after the establishment of the ARP in the North Atlantic.

Periods of long-term increased and decreased values of NAO and SCAND indices during the 1939–2020 (NAO) and 1951–2020 (SCAND) periods are shown in figure 7. The features of hydrological characteristics variability in the two studied rivers during these periods could be found in table 4. The water temperature values are not presented in this table. Prior to 1995, high NAOs correspond to Tw in the Northern Dvina warmer by 0.5 °C compared

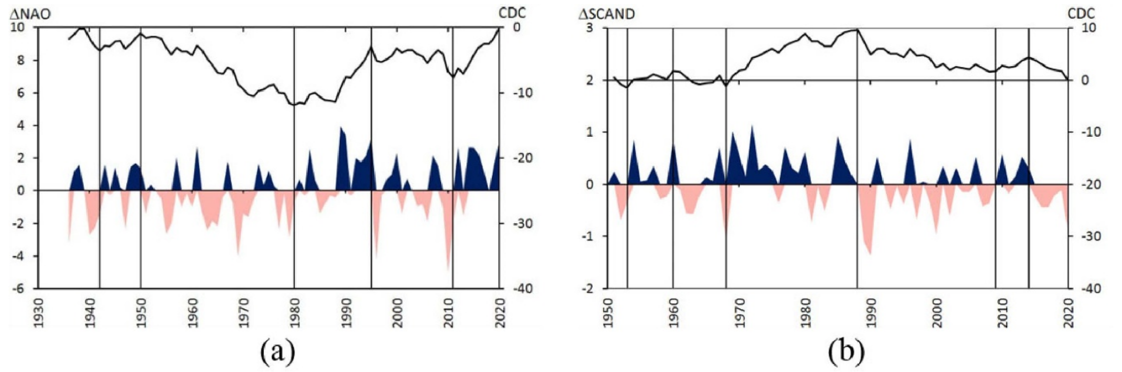

Figure 7. Long-term changes in (a) NAO and (b) SCAND indices estimated for winter (December–March) in a form of the normalized cumulative deviation curves (black line) and in deviations from their long-term mean values (dark blue – positive deviations and red – negative deviations).

Table 3. Correlations among three hydrological variables for two rivers considered in this study, NAO and SCAND indices for the common 1951–2020 period. Correlations with absolute values ⩾0.25 are shown in bold.

	Years	ND_Tw	ND_Qow	ND_H	P_Tw	P_Qow	P_H	NAO XII–III
Years	1	—	—	—	—	—	—	—
ND_Tw	**0.54**	1	—	—	—	—	—	—
ND_Qow	−0.07	**−0.43**	1	—	—	—	—	—
ND_H	**0.27**	0.06	**0.77**	1	—	—	—	—
P_Tw	**0.25**	**0.70**	−0.09	0.21	1	—	—	—
P_Qow	0.17	−0.23	**0.28**	0.23	−0.20	1	—	—
P_H	**0.27**	0.02	0.21	**0.34**	0.10	**0.83**	1	—
NAO XII–III	**0.27**	0.24	0.17	**0.29**	**0.30**	0.16	0.17	1
SCAND XII–III	−0.17	−0.01	**−0.35**	**−0.36**	−0.22	−0.21	−0.12	**−0.49**

Table 4. Differences in the geo-flux characteristics of the Northern Dvina and Pechora Rivers during the periods of long-term increased and decreased values of NAO and SCAND indices for the 1939–1995 (NAO) and 1951–2020 (SCAND). Due to deterioration of the used in this study definition of the NAO index, we restricted its use in this analysis during the post-1995 period.

	Units and %	ND_Qow	ND_H	P_Qow	P_H
Values with high minus	Difference in geo-fluxes	142	0.3	85	0.04
low NAOs	Difference/average, %	2.9	9.9	1.4	1.5
Values with high minus	Difference in geo-fluxes	−346	−0.3	−548	−0.28
low SCANDs	Difference/average, %	−7	−10.0	−9	−10.2

to the long-lasting periods of low NAO values. For the Pechora, there are no differences in Tw between the two types of NAO periods. High SCANDs correspond to lower Tw values in the Northern Dvina and Pechora than during the low SCAND long-lasting periods (by 0.35 °C and 0.5 °C, respectively). For both rivers, table 4 shows a considerable decrease in geo-flux components with transition from negative to positive SCAND phases (by 7%–10%). Only heat flux increases by 10% in the Northern Dvina River upon a shift from negative to positive NAO phases. The impact of this shift on the river discharge, on the other hand, is quite small (3%) and is completely unnoticed in the Pechora River geo-flux components.

5. Discussion

Reid *et al* (2016) identified a shift in the early 1980s for various characteristics within the Earth's 'biophysical systems from the upper atmosphere to the depths of the ocean and from the Arctic to the Antarctic and occurred at slightly different times around the world'. Twenty-nine co-authors of this paper compiled a compendium of changes in atmosphere, world ocean, cryosphere, hydrosphere, and biosphere. It is worth noting that the shift points for most of hydrological parameters studied during this research, including the NAO index, are located in the 1980 and a few years after it (figures 3 and 7). For Tw in the Northern Dvina River, and for H at the Pechora River, the vicinity of this year was the only shift point revealed during the past 80 years.

In Northeast Europe, prolonged cold winters with an abundance of snowfall generate pulses of spring freshet that dominate in the seasonal runoff cycle (figure 5). The warm season droughts there are infrequent. As a result, an interannual memory (soil moisture, water accumulated in lakes) plays an insignificant role in changes of the Northern Dvina River discharge. Ground ice (permafrost and glaciers) and mountain snowpack have some multiannual effects on the Pechora River discharge (Brown *et al* 1997). Low discharge values (e.g. in September) could serve as indirect proof of this effect. The lowest discharge values in the Pechora are, however, still 50% higher than those for the Northern Dvina. Nonetheless, these are only small fractions of the rivers' discharge. Thus, in order to find the origin of multiannual phases in various hydrological parameter values for studied rivers, it is necessary to assess other factors that might cause them. Unfortunately, there are plenty of possible sources which could possibly explain observed long-lasting phases in studied hydrological characteristics. Below, we list some of them.

- During the last 80 years, surface air warming manifests itself in Northeast Europe stronger than over the globe. Annual temperature rise here has been more than 2 °C (National Center for Environmental Information 2022). That's why we observe increase in the water temperature closely connected with the regional surface air temperature (figures 3, 4 and table 3).
- Warming throughout the open-water season as well as earlier onset of spring (Groisman *et al* 2003) causes an increase in evapotranspiration and, therefore, may reduce the river runoff in the study region, especially, during the past decades when the warming was the most prominent.
- Global warming affects the Arctic sea ice extent and concentration as well as seasonal snow cover extent, thickness, and distribution (SWIPA 2011). Retreat/thinning/defragmentation of sea ice over the White and Kara Seas opens additional access of evaporated water vapour into the Arctic Ocean atmosphere that has enabled increase in precipitation from the Arctic air masses that move southward (figure 1).
- The cold season precipitation in many regions of Russia has increased since 1966 (Bulygina *et al* 2009, 2011, SWIPA 2011). In particular, Bulygina *et al* (2009) reported an increase in a number of days with snow cover exceeding 1 cm for the 1966–2007 period in the Pechora River basin, while in the Northern Dvina River basin these numbers decreased. The difference in the snow cover variability over two neighbouring river basins can explain differences in freshet discharge trends between the two rivers.
- Global warming may affect the major features of atmospheric circulation (e.g. trajectories of cyclones) shifting them 'slightly' but consistently (Vinnikov and Kovyneva 1983). Such displacement could thereafter affect the precipitation patterns and other components of the hydrological cycle. In the next paragraph, an example of one of such shifts is discussed related to the studied region (see also section 4.1).
- The long-lasting phase of increased NAO index values observed since the late 1980s. However, since the mid-1990s, the variability of hydrological characteristics in the Northern Dvina and the Pechora Rivers has gone out of phase with the fluctuations of the NAO index regarding the contrasting period occurrences. We can explain this new feature by the changes in the core driving force of NAO, the gradient between two specific points or 'centres' of atmospheric circulation over the Northern Atlantic. Many years ago, Groisman (1983) studied the changes in the positions of the 'centres of action' of the Northern Hemisphere circulation for the 1900–1970 period in relation to the contemporary changes in the hemispheric surface air temperature. He found that a small 0.5 °C hemispheric warming (at the time there were no other global temperature changes) may result in a significant displacement of the Azores High eastward by about 20° of longitude. At that time, the Azores High was indeed located in the vicinity of the Azores Islands and the SLP at Ponta Delgada on the São Miguel Island was used to characterise it. Now it is characterised by the SLP in Lisbon or Gibraltar. At the end of the 20th century, the time came to reallocate the official Iceland Low position and its characteristic Reykjavik SLP data somewhere further to the northeast. Meanwhile, the traditional indicators of the NAO began to 'malfunction' while using previously established relationships between the NAO index and regional hydrologic parameters values.

6. Conclusions

We investigated the long-lasting phases of increased and decreased water flow, water temperature and heat flux of the Northern Dvina and the Pechora Rivers from the late 1930s to 2020. The contrasting phases are characterized by statistically significant differences in mean values of the hydrological characteristics with prolonged duration of these phases, usually 10–15 years or more. The phases represent a characteristic feature of the long-term variability in both rivers.

The features of long-lasting phases of increased and decreased values of water flow, water temperature and heat flux during the open water season in the Northern Dvina and Pechora Rivers are significantly different and the duration of these phases varied significantly, from 9 to 45 years. The difference in the average values of the considered hydrological characteristics in contrasting phases relative to the phase of decreased values ranged from 11% to 18%.

Phases of increased heat flux, especially the longest ones, almost coincide with periods of increased water runoff and water temperature. The same applies to periods with decreased values. Thus, simultaneous contrasting phases for all three studied characteristics were observed. For the Northern Dvina River, it was a period of decreased (1959–1983) and increased (1988–2012) values of all characteristics. For the Pechora River, decreased values were recorded for 1936–1952 and 1968–1981 periods, and increased values were observed for the 1989–2020 period. The water runoff and water temperature are negatively correlated. However, while in May–June the freshet discharge leads the heat flux dynamics, during the next four months, the water temperature becomes the leading factor and the freshet discharge of the snowmelt cold water does not control **H** anymore.

The greatest differences in the monthly mean open water season values distribution of the studied characteristics for the Northern Dvina and Pechora Rivers were bound to water runoff and heat flux, while the water temperature of these two rivers changed similarly and overlay with the regional surface air warming tendencies.

Periods of simultaneously observed increased values of all studied hydrological characteristics were associated with periods of increased air temperatures (annual mean and open water season average) and annual precipitation.

From the 1930s until the mid-1990s, the long-lasting phases of simultaneously increased or decreased values of the studied hydrological characteristics were generally associated with the respective deviations in the zonal circulation, expressed as changes in the NAO index. However, since the mid-1990s, the variability of water flow and heat flux have gone out of phase with the NAO index fluctuations. This can be explained by the significant shift in the 21st century of the 'Icelandic Law' position to the northeast that made the NAO definition obsolete for characterization of the zonal circulation over North Atlantic.

SCAND index associated with the anticyclonic conditions over Northern Europe and more frequent blocking of the zonal atmospheric circulation, has not demonstrated consistent changes (trends). Its negative impact on the geo-flux components in the Northern Dvina River Basin remains unchanged during the entire 70 years long study period.

One can speculate that the reason for the emerging of the long contrasting phases in the regional hydrological cycle may be a feature of the stochastic nature due to the nonlinear nature of oscillations with changes in amplitude and frequency (Hurst 1951, Koutsoyiannis 2003). This way of thinking helps to find a comfortable refugium when no deterministic answers are found. Our analyses left us somewhere in the middle. We see that some shifts from one contrasting phase to another are associated with the global Earth system shift in early 1980s. We found that the other phase switches can be modulated by variations of the large-scale regional macrocirculation indices, such as pre-1995 NAO and SCAND, and finally, we see some low-frequency variations in the regional hydrological cycle that have just happened and we, so far, cannot attribute them to low frequency variations of other environmental characteristics.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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