Impact of global warming on the conditions of the Siberian rivers discharge formation: significance of atmospheric transport

A Vyazilova, G V Alekseev, N Kharlanenkova, N Glok
Arctic and Antarctic Research Institute, St. Petersburg, Russia

Abstract. Impact of climate change on the Ob, Lena and Yenisei runoff is under discussion. Indexes of zonal, meridional and general circulation were used to assess the effect of changes in atmospheric circulation. Correlations between the indexes and surface air temperature, precipitation, atmospheric moisture content in the regions of catchment areas confirmed the influence of atmospheric transport in the cold part of the year. Assessment of the relationship between changes of climatic conditions in the catchment areas and interannual changes of river runoff parameters indicated that annual runoff increases and mostly is affected by increase of average annual precipitation. Frequency of maximum river discharges during climate warming is reduced.

1. Introduction
Fresh water content (FWC) in the Arctic Ocean and its variations are under great attention as the main source of fresh water flowing into the north part of Atlantic Ocean and influencing the thermohaline convection [1–3]. Annual fresh water inflow to the Arctic Ocean is defined mainly by river runoff (42%), inflow through the Bering Strait (32%) and net precipitation (26%) [4]. Earlier Aagaard & Carmack (1989) [5] assessed the contribution of river runoff as 56% with 28% for inflow through Bering Strait and 15% for net precipitation. Half of annual river runoff into the Arctic accounts for the 3 large Siberian rivers: Ob, Yenisei and Lena. Changes of these 3 rivers discharge characterize the climatic changes of river runoff into the Arctic Ocean.

There is no consensus on the causes of runoff changes that is especially significant in the last two decades, in particular, regarding the role of atmospheric circulation and the associated changes in precipitation and air temperature in the catchment areas and their impact on runoff.

For example, in the article [6] the influx of 72 rivers into the Arctic was studied for the period 1975–2015. The results defined the general increasing of runoff and the rise is more notable for Eurasian rivers than for North American rivers. There was not found out any significant impact of climatic parameters such as Arctic Oscillation(AO), North Atlantic Oscillation (NAO) and Pacific Decadal Oscillation (PDO) on river runoff.

Oshima et al. [7] note that although the influx of waters from the main Siberian rivers is a large source of fresh water in the Arctic Ocean, the reason for the long-term changes in their discharges is still unclear. They found a multidirectional effect of climatic factors, in particular, atmospheric circulation in the areas of Ob and Lena runoff formation in summer.
In [8] increasing trends of air temperature and precipitation for the cold period (November – March) of the year with coefficients of 0.3–0.52 °C / 10 years and 14–16 mm / 10 years were noted in the Lena basin. The warm season was also followed by an increase of average temperatures and precipitation. It was previously established [9] that the runoff of the river Lena increased from 1936 to 2001 due to the average annual precipitation observed above the norm.

The purpose of our study is to assess the impact of global and regional changes in atmospheric circulation, precipitation and air temperature on the formation of three major Siberian rivers runoff.

2. Data and methods
Surface air temperature and atmosphere moisture content reanalysis data NCEP (1948-2018) [10], ERA/Interim (1979-2018) [11], global land precipitation data PREC/L [12], global precipitation climatology GPCC (Global Precipitation Climatology Center) [13] were used. Rivers discharge for the period 1936-2018 was received from the datasets R-ArcticNet [14], ArcticGRO [15].

Catchment areas and total catchment area of 3 rivers were approximate by the geographical regions: Ob catchment area: 51.25-68.75°N, 61.25-88.75°E, Yenisei catchment area: 51.25-68.75°N, 91.25-108.75°E, Lena catchment area 51.25-68.75°N, 111.25-131.25°E., total catchment area: 70° – 50° N, 60°- 160° E.

Monthly mean surface air temperature and precipitation were defined for selected regions of rivers catchment. Indexes of zonal, meridional and general circulation in the northern hemisphere were calculated according to the monthly mean surface air temperature at the nodes of the geographical grid [16]. Methods of multidimensional mutual-correlation and mutual-spectral analysis, EOF decomposition, construction of frequency distribution of values less than 10% and more than 90% probability were used.

3. Results

3.1. Influence of atmospheric circulation on climatic conditions in catchment areas
With an increase of the zonal and meridional transport of heat and moisture by atmospheric circulation the spatial contrasts of the near-surface air temperature decrease, but with weakening of the transport the spatial contrasts increase. On this basis indexes were proposed [17, 18] to assess the effect of atmospheric transport fluctuations on the mean surface air temperature in the Northern hemisphere, on the Earth as a whole and single regions.

Index of zonal circulation impact DZ is figured out by formula:

$$D_Z = \frac{1}{2\pi(\sin \phi_2 - \sin \phi_1)} \int_{\phi_1}^{\phi_2} \cos \phi \int_{-\infty}^{\infty} (T_{\varphi \lambda} - T_{\varphi})^2 d\lambda d\phi$$

(1)

Index of meridional circulation impact DM is defined by:

$$D_M = \langle (T_{\varphi} - \langle T_{\varphi} \rangle)^2 \rangle_{\varphi}, T_{\varphi} = \langle T_{\varphi \lambda} \rangle_{\lambda}, \langle T_{\varphi} \rangle = \langle T_{\varphi \lambda} \rangle_{\lambda}$$

(2)

and characterizes the variability of air temperature distribution along the meridian from the equator to the pole. Angle brackets mean averaging over latitude φ, or longitude λ. The index of the joint influence of zonal and meridional circulation or general circulation is defined by:

$$D = (D_Z + D_M)^{\frac{1}{2}}.$$  

(3)

The mean squared deviation of the surface air temperature from the corresponding average in the formulas for DZ and DM is included in the determination of the available potential energy in the atmosphere [19, 20]. Changes in the available potential energy correspond to an increase or decrease of the kinetic energy of the atmosphere or the intensity of atmospheric circulation.

In the article [21] the connection of the proposed indexes with the mean temperature is indicated. It is based on the difference between the heat capacities of the ocean and land, as a result of which the increase in zonal and meridional circulation is accompanied by transport of sensible and latent heat from
the oceanic areas and leads to a noticeable increase of air temperature over land with a slight temperature decrease of the ocean surface.

Figure 1 shows the distribution of the correlation coefficients between the indexes $D_Z$, $D_M$, and surface air temperature in the Northern Hemisphere for the winter of 1948-2012. The zonal transport has the most noticeable effect on the surface air temperature in Asia north of 40° N and the effect of meridional transport appears more in the northern areas, including the Arctic basin. The areas of zonal and meridional transports impact on surface air temperature including the catchment basins of Siberian rivers and, therefore, transport could affect the climatic conditions at the catchments regions. Note that zonal transport has a warming effect only in the cold part of the year from October till March.

**Figure 1.** Correlation coefficient $R$ between zonal $D_Z$ (a) and meridional $D_M$ (b) circulation and surface air temperature in the cold period of year 1948–2012 (NCEP reanalysis data).

Calculations of the correlations between the indexes and climatic parameters at the catchment areas confirmed this assumption (tables 1-3). The tables show the correlations between the indexes and mean values of air temperature, atmosphere moisture content and precipitation in the catchment areas of every single river and the total catchment.

**Table 1.** Correlation coefficients $R$ between $D_Z$, $D_M$, $D_Z+D_M$ and air temperature in Ob, Yenisei, Lena catchment areas (ERA/Interim 1980–2018 reanalysis data). The level of 95% significance is 0.32.

| Index     | Ob       | Yenisei  | Lena     | 3 rivers  | Note                                      |
|-----------|----------|----------|----------|-----------|-------------------------------------------|
| $D_Z$     | -0.66    | -0.66    | -0.64    | -0.65     | Between averages for November-March       |
|           | -0.71(11)| -0.86(11)| -0.79(11)| -0.77(11) | Maximum between monthly averages (month)  |
| $D_M$     | -0.57    | -0.50    | -0.49    | -0.62     | Between averages for November-March       |
|           | -0.76(3) | -0.81(3) | -0.75(3) | -0.82(3)  | Maximum between monthly averages (month)  |
| $D_Z+D_M$ | -0.67    | -0.63    | -0.63    | -0.74     | Between averages for November-March       |
|           | -0.77(3) | -0.84(3) | -0.77(1) | -0.84(3)  | Maximum between monthly averages (month)  |
Table 2. Correlation coefficients R between DZ, DM, DZ+DM and total column water (tcw) in Ob, Yenisei, Lena catchment areas (ERA/Interim 1980–2018 reanalysis data). The level of 95 % significance is 0.32.

| Index | Ob     | Yenisei | Lena    | 3 rivers | Note                                      |
|-------|--------|---------|---------|----------|-------------------------------------------|
| DZ    | -0.53  | -0.61   | -0.52   | -0.64    | Between averages for November-March       |
|       | -0.69(1) | -0.82(11) | **0.83(11)** | -0.73(11) | Maximum between monthly averages (month)  |
| DM    | -0.48  | -0.46   | -0.47   | -0.67    | Between averages for November-March       |
|       | -0.51(3) | -0.67(3) | -0.66(3) | -0.66(3) | Maximum between monthly averages (month)  |
| DZ+DM | -0.57  | -0.59   | -0.57   | -0.75    | Between averages for November-March       |
|       | -0.64(12) | -0.72(1,3) | -0.76(1) | -0.71(3) | Maximum between monthly averages (month)  |

Table 3. Correlation coefficients R between DZ, DM, DZ+DM and precipitation in Ob, Yenisei, Lena catchment areas (ERA/Interim 1980–2018 reanalysis data). The level of 95 % significance is 0.32.

| Index | Ob     | Yenisei | Lena    | 3 rivers | Note                                      |
|-------|--------|---------|---------|----------|-------------------------------------------|
| DZ    | -0.38  | -0.31   | -0.59   | -0.37    | Between averages for November-March       |
|       | **-0.70(3)** | -0.51(3) | -0.68(1) | -0.65(3) | Maximum between monthly averages (month)  |
| DM    | -0.40  | -0.35   | -0.47   | -0.47    | Between averages for November-March       |
|       | -0.42(3) | -0.25(4) | -0.35(11) | -0.34(3) | Maximum between monthly averages (month)  |
| DZ+DM | -0.45  | -0.39   | -0.59   | -0.51    | Between averages for November-March       |
|       | -0.57(3) | -0.35(3) | -0.57(11) | -0.49(3) | Maximum between monthly averages (month)  |

All correlation coefficients confirm the significant impact of atmospheric transports in the cold period of the year on surface air temperature, atmosphere moisture content and to a lesser extent on precipitation.

In summer amplification of zonal circulation is accompanied by decreasing of air temperature in the catchment areas and meridional transports enhance the air temperature even more than in winter. If winter zonal transport form similar changes of mean air temperature, moisture content and precipitation in all regions of catchment areas, then in summer the changes in the Ob and Lena catchment areas have no connection and are not opposite (table 4), that was previously noted in [7].

Table 4. Correlation coefficients between monthly mean climatic parameters in the catchment areas of Ob and Lena (ERA/Interim reanalysis 1980-2018). The level of 95% significance is 0.32.

| Month/season | Temperature | Total column water | Precipitation |
|--------------|-------------|--------------------|---------------|
| January      | **0.73**    | **0.73**           | 0.30          |
| February     | 0.59        | 0.48               | 0.42          |
| March        | **0.72**    | **0.66**           | 0.28          |
| April        | 0.53        | 0.38               | -0.03         |
| May          | -0.11       | -0.07              | 0.30          |
| June         | 0.11        | -0.02              | -0.51         |
3.2. **Connection between climate conditions in catchment areas and river runoff**

Impact of surface air temperature and precipitation changes on the river runoff is estimated by correlation coefficients between mean air temperature, mean precipitation in the catchment areas and annual river discharge (Table 5).

It could be noted that mostly mean annual precipitation affect the river runoff, especially discharge of the river Lena, and also summer precipitation in June and July impact on rivers runoff.

**Table 5.** Correlation coefficients between annual river discharge (R-ArcticNet, ArcticGRO data) and parameters of climatic conditions in the catchment areas (ERA/Interim reanalysis data 1979–2018). The level of 95% significance is 0.31.

| Annual discharge | Mean SAT in catchment area | Mean precipitation in catchment area |
|------------------|-----------------------------|--------------------------------------|
|                  | Annual (11-03) Max R(month) | Annual (11-03) Max R(month)          |
| Ob               | 0.03 0.17 0.14 (3)           | 0.58 0.58 0.60 (6)                   |
| Yenisei          | 0.38 0.16 0.40 (10)          | 0.51 0.31 0.48 (6)                   |
| Lena             | 0.30 0.16 0.38 (9)           | **0.77** 0.40 0.51 (7)              |

Impact of air temperature changes on the rivers discharge is more noticeable while meaning the air temperature for the total area of 3 rivers. Especially the connection is more significant when the annual temperature is used. The highest correlation coefficient (0.49) is defined between sum of annual rivers discharge and annual surface air temperature in the total catchment area. The correlation coefficient between sum of annual rivers discharge and surface air temperature in March and in the cold period of the year is 0.43.

The main contribution to the connection between climatic parameters and river runoff is made by trends that show the single sign changes. Maximum positive trends of mean air temperature and precipitation in the catchment areas are observed in springs. Trend coefficient of mean air temperature in April is 0.11° C/year in the Ob catchment area, 0.08° C/year in the Lena catchment area, 0.10° C/year in the Yenisei catchment area. The highest rise of precipitation is noted in March in the Ob catchment area (0.67 mm/year) and in May in the regions of Lena (0.63 mm/year) and Yenisei (0.32 mm/year) catchments. Annual and average for the cold period air temperature and precipitation in the catchment areas are also increasing as annual river runoff.
3.3. Long-term changes in river discharge and climatic parameters in catchment areas

Positive trend coefficients indicate the increase of annual discharges of Ob, Lena and Yenisei. Trends are maximum for the discharges of Lena (500.41 m$^3$ year$^{-1}$ during the period 1936-2018 and 1079.73 m$^3$ year$^{-1}$ during the period 1979-2018). Total annual discharge of 3 rivers also increase during the period 1936-2018 (figure 2a) with linear trend of 2.216 km$^3$ year$^{-1}$ and absolute maximum in 2007. Monthly discharges of 3 rivers increased mostly in May. In June, when generally maximum discharge of 3 rivers is noted, discharges were decreasing during the periods 1936-2018 and 1979-2018 (figure 2b). Trend coefficients of maximum discharges in 1979-2018 are -51.77 m$^3$ year$^{-1}$ for Ob, 98.86 m$^3$ year$^{-1}$ for Lena, -387.36 m$^3$ year$^{-1}$ for Yenisei. Correlation between maximum monthly discharge and annual discharge is the highest for the river Ob (0.71).

Figure 2. Total annual discharge of 3 rivers in 1936-2018 (a), monthly mean discharge trend coefficients, m$^3$ year$^{-1}$ in 1979-2018 (b)

Maximum discharges and associated spring floods on rivers are a hazard to the population living in river valleys. From this point of view, a decrease in maximum discharges is a favorable consequence of warming. Another important indicator of spring floods impact is floods frequency under climate changes. To assess the frequency of the maximum monthly mean discharges changes, the integral frequencies of small values less than 10% and large values more than 90% of coverage were calculated (figure 3).

The figure shows an increase of the number of small maximums in the periods of 1940-50s and in the 2000s and an increase of maximum discharges in the 1970s and 1980s. It can be assumed that during periods of warming lower maximums dominate, while cooling the number of maximum discharges increases. The calculations of air temperature frequency in the catchment areas of three rivers (figure 4) confirm this speculation.

Figure 3. The number of (a) small (less 10% probability), (b) large (more 90% probability) discharge maximums of three rivers, 9-year running intervals
4. Conclusions

Climatic conditions in the catchment areas of the main Siberian rivers are formed under the influence of atmospheric circulation, bringing heat, moisture and precipitation.

Atmospheric transport affect most of all in the cold part of the year, especially in November and March. In summer, an increase in zonal circulation is accompanied by a decrease of air temperature in the area of catchments, and meridional transport enhance the temperature.

Atmospheric transport in winter form similar changes in mean values of temperature, moisture content and precipitation in catchment areas, while in summer changes are not related or opposite in the area of catchments of the Ob and Lena.

The greatest influence on runoff is exerted by the increase of average annual precipitation, especially on Lena's runoff. The effect of temperature changes is noticeable when annual temperature is averaged over all three basins.

The annual discharge of rivers increases, especially the discharge of Lena. Sum of 3 rivers annual runoff was increasing during 1936-2018 with the speed of 2.216 km³/year⁻¹, but maximum discharge was decreasing in 1979-2018 with the speed of 0.14 km³/year⁻¹ (Ob) and 1.0 km³/year⁻¹ (Yenisei).

In the 2000s frequency of discharge maximums occurrence of less than 10% probability increased, while large highs of more than 90% probability decreased. The maximum occurrence of large maximums is in the 1970s – 1980s. Such a distribution of the discharge maximums occurrence frequency is associated with climate warming in the 2000s and a cooling in the 1970s.

This study was supported by the Russian Found for Basic Research projects 18-05-60107.

References
[1] Karcher MJ, Gerdes R, Kauker F, Köberle C and Yashayaev I 2005 Arctic Ocean change heralds North Atlantic freshening. Geophys. Res. Lett. 32(21):L21606
[2] Jahn A, Aksenov YO, de Cuevas BA, De Steur L, Häkkinen S, Hansen E, et al. 2012 Arctic Ocean freshwater: How robust are model simulations? J. Geophys. Res. 117
[3] Fedorov A, Barreiro M, Boccaletti G, Pacanowski R and Philander SG 2007 The Freshening of Surface Waters in High Latitudes: Effects on the Thermohaline and Wind-Driven Circulations. J. Phys. Oceanogr. 37(4):896–907
[4] Serreze MC, Barrett AP, Slater AG, Woodgate RA, Aagaard K, Lammers RB, et al. 2006 The large-scale freshwater cycle of the Arctic. J. Geophys. Res. Ocean 111(C10):1–19.
[5] Aagaard K and Carmack EC 1989 The role of sea ice and other fresh water in the Arctic circulation. J. Geophys. Res. 94(C10):14485–98
[6] Durocher M, Requena AI, Burn DH and Pellerin J. 2019 Analys is of trends in annual strea mflow to the Arctic Ocean. Hydrol. al Process 1–9
[7] Oshima K, Ogata K, Park H and Tachibana Y 2018 Influence of atmospheric internal variabili ty on the long-term Siberian water cycle during the past 2 centuries. Earth Syst. Dynam. 9:497–506
[8] Dzhamalov R G, Krichevets G N and Safronova T I 2012 Current Changes in Water Resources in Lena River Basin Water Resources 39(2):131–145 [In Russian]

[9] Berezovskaya S, Yang D and Hinzman LD 2005 Long-term annual water balance analysis of the Lena River. Glob. Planet Change 48:84–95

[10] Kalnay E, Kanamitsu M, Kistler R, Collins WD, Deaven D, Gandin L, et al. 1996 The NCEP/NCAR 40-year reanalysis project. Bull. Am. Meteorol. Soc. 77:437–71

[11] Dee DP, Uppala SM, Simmons AJ, Berrisford P, Poli P, Kobayashi S, et al. 2011 The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. Q J R Meteorol. Soc. 137:553–97

[12] Chen M, Xie P, Janowiak JE and Arkin P 2002 Global Land Precipitation: A 50-yr Monthly Analysis Based on Gauge Observations. J. Hydrometeorol. 3(3):249–66

[13] Adler RF, Huffman GJ, Chang A, Ferraro R, Xie P-P, Janowiak JE, et al. 2003 The Version-2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979–Present). J. Hydrometeorol. 4(6):1147–67

[14] Lammers RB, Shiklomanov AI, Vörösmarty CJ, Fekete BM and Peterson BJ 2016 R-ArcticNet, A Regional Hydrographic Data Network for the Pan-Arctic Region (ISO-image of CD-ROM). PANGAEA. Available from: https://doi.org/10.1594/PANGAEA.859422

[15] Shiklomanov AI, Holmes RM, McClelland JW, Tank SE and Spencer RGM 2018 Arctic Great Rivers Observatory. Discharge Dataset, Version 20190402. Available from: https://www.arcticrivers.org/data

[16] Alekseev G V 2014 Arctic dimension of global warming Ice and snow 54(2):53—68 [In Russian]

[17] Alekseev G V, Podgornyi I A, Svyaschennikov P N 1991 Changes of the warming influence of oceans to the global climate Doklady Akademii Nauk. Proc. of the Academy of Sciences 320(1):70–3 [In Russian]

[18] Alekseev G V, Podgornyi I A, Svyaschennikov P N 1990 Adveective and radiation changes of climate Doklady Akademii Nauk. Proc. of the Academy of Sciences 315(4):824–827 [In Russian]

[19] Van Mijem J 1977 Energetic of the atmosphere ed Matveev L T Leningrad: Hydrometeoizdat Publ. 327 p [In Russian]

[20] Lorenz E N 1970 The Nature and Theory of the General Circulation of the Atmosphere Leningrad: Gidrometeoizdat Publ. 259 p [In Russian]

[21] Alekseev G V 2014 Dinamic amplification of global warming Proceedings of the international conference dedicated to the memory of academician A.M. Obukhov. Moscow: GEOS p 290–306 [In Russian]