

Impact of Global Warming on River Inflow to the Arctic Seas

A. E. Vyazilova^{a*}, G. V. Alekseev^a, and N. E. Kharlanenkova^a

^aArctic and Antarctic Research Institute, ul. Beringa 38, St. Petersburg, 199397 Russia

*e-mail: vae@aari.ru

Received July 22, 2020

Revised September 10, 2021

Accepted November 25, 2021

Abstract—An impact of global warming on river runoff into the Arctic seas is discussed. River runoff is one of the main components of the Arctic freshwater balance. Annual total river runoff is determined as the sum of runoff of six rivers: the Ob, Yenisei, Lena, Kolyma, Indigirka, and Mackenzie. The indices of zonal, meridional, and general circulation were calculated to assess the effect of atmospheric circulation. Correlations between the indices and surface air temperature and precipitation in the catchment areas confirmed the most significant influence of atmospheric transport on climatic conditions in the cold season. It was stated that annual total river runoff increased during 1979–2019, but the occurrence of peak discharges was reduced.

DOI: 10.3103/S1068373922060048

Keywords: River runoff, Arctic Ocean, global warming, atmospheric circulation

INTRODUCTION

Great attention has been paid to the freshwater content in the Arctic basin, which is the source of desalinated water flowing into the North Atlantic and affecting the thermohaline circulation [16, 19, 21]. The average annual freshwater inflow to the Arctic Ocean is determined by river runoff (42%), the inflow through the Bering Strait (32%), and precipitation minus evaporation (26%) [24]. The authors of [7] evaluated the contribution of river runoff at 56%, with 28% of the inflow through the Bering Strait and 15% of pure precipitation. At the same time, a half of the average annual river inflow to the Arctic Ocean is contributed by the three largest Siberian rivers: the Ob, Yenisei, and Lena [7]. Total runoff of the three major Siberian rivers and the largest North American river (the Mackenzie) is equal to ~1900 km³ per year, or ~60% of the average annual volume of freshwater flowing into the Arctic seas [9, 17]. There is no single opinion about the reasons of runoff changes, which have been especially noticeable in the recent two decades, in particular, about the role of atmospheric circulation and related changes in precipitation and air temperature in the catchment areas and their effects on runoff. For example, the authors of [15] investigated the inflow of 72 rivers to the Arctic Ocean over the period from 1975 to 2015. The results demonstrated a general increase in runoff, and this increase is more noticeable for the Eurasian rivers than for the North American ones. No significant effect of such climatic indicators as the Arctic Oscillation, North Atlantic Oscillation, or Pacific Decadal Oscillation on runoff of rivers providing the largest freshwater inflow to the Arctic Ocean was found.

The authors of [23] noted that although the inflow of the major Siberian rivers is a significant source of freshwater in the Arctic Ocean, the cause for long-term changes in their runoff is still unclear. Differently directed impacts of climatic factors, in particular, of the atmospheric circulation in the areas of the Ob and Lena river runoff formation in summer were reported.

The authors of [5] noted the positive air temperature and precipitation trends for the Lena basin in the cold season (November–March), with the coefficients of 0.3–0.52 C/10 years and 14–16 mm/10 years. The warm season was also characterized by the increase in the mean values of temperature and total precipitation. It was established earlier [10] that the Lena runoff from 1936 to 2001 increased because average annual precipitation was above the normal. The results of [9] demonstrated that total runoff of the Ob, Lena,

Table 1. Stream gages at the outlets and catchments areas of the rivers

River	Stream gage	Latitude	Longitude	Catchment area, km ²
Ob	Salekhard	66.63 N	66.60 E	2929051
Lena	Kyusyur	70.68 N	127.39 E	2467694
Yenisei	Igarka	67.43 N	86.48 E	2518210
Kolyma	Kolymskoe, Kolymsk-1	68.73 N	158.72 E	657254
Indigirka	Vorontsovo	69.57 N	147.53 E	343569
Northern Dvina	Ust'-Pinega	64.13 N	41.92 E	348728
Mackenzie	Arctic Red River	67.45 N	133.74 W	1805884

Yenisei, and Mackenzie rivers increases at a rate of 89 km³ per decade and rose approximately by 14% during the 30-year period from 1980 to 2009. Total average annual river runoff in northern Canada also increased during 1989–2013, which was associated with the impact of the Arctic Oscillation [14]. According to [18], total river runoff to the Arctic Ocean in 2000–2010 increased by ~300 km³ per year relative to the mean for 1980–2000.

The objective of the present paper is to estimate variations in the river inflow to the Arctic Ocean in the recent four decades and to reveal the impact of global and regional changes in the atmospheric circulation, precipitation, and air temperature on these variations.

DATA AND METHODS

The inflow of river water to the Arctic seas is determined as the sum of runoff of six rivers: the Ob, Yenisei, Lena, Kolyma, Indigirka, and Mackenzie, which make the main contribution to the river inflow to the Arctic Ocean. The Northern Dvina River runoff was also considered but was not included to the estimate of total runoff as it does not contribute to the Arctic freshwater balance. River discharges of the Indigirka River from 1999 to 2019 were retrieved due to the absence of observational data for this period in the R-ArcticNet [22] and ArcticGRO datasets [25] utilized in the present study. The coordinates of stream gages at which river runoff data were obtained, as well as the area of the catchments, are presented in Table 1. The position of the catchments is shown in the map (Fig. 1) according to the Interactive Database of the World's River Basins (<http://riverbasins.wateractionhub.org/>).

Data on surface air temperature from the NCEP (1948–2018) [20], ERA-Interim (1979–2018) [13], ERA5 (1979–2019) reanalyses [12], PREC/L land precipitation data [11], and GPCP (Global Precipitation Climatology Project) precipitation fields [8] were used to assess the effects of global and regional changes in the atmospheric circulation, precipitation, and air temperature on runoff formation.

The monthly mean values of surface air temperature and precipitation were calculated for the areas including the river catchments. Based on the data on monthly mean surface air temperature at the points of the geographic grid covering the Northern Hemisphere, the indices of zonal, meridional, and general circulation in the Northern Hemisphere were calculated using the formulas proposed in [1]. The calculation of the indices was based on the fact that the spatial contrasts of surface air temperature decrease when the heat and moisture transport by the atmospheric circulation intensifies and, on the contrary, the contrasts increase if the transport weakens. The indices are intended for assessing the effect of atmospheric transport intensity variations on the mean surface air temperature for the hemisphere, the globe, and separate regions.

The index of zonal circulation D_z was calculated using the formula

$$D_z = \frac{1}{2} \frac{\int_0^{2\pi} \cos^2(\theta) (T(\theta) - \langle T \rangle)^2 d\theta}{\int_0^{2\pi} (\sin^2(\theta) - \sin^2(\theta_1)) d\theta}.$$

The index of the impact of meridional circulation D_m is determined by the formulas

$$D_m = \left\langle (T - \langle T \rangle)^2 \right\rangle, \quad T = \langle T \rangle, \quad \langle T \rangle = \langle T \rangle$$

and characterizes non-uniformity of the temperature distribution along the meridian from the equator to the pole. The angle brackets mean the averaging with respect to latitude or longitude. The index of the coupled impact of zonal and meridional (or general) circulation is determined as follows:

$$D = (D_z + D_m)^{1/2}.$$

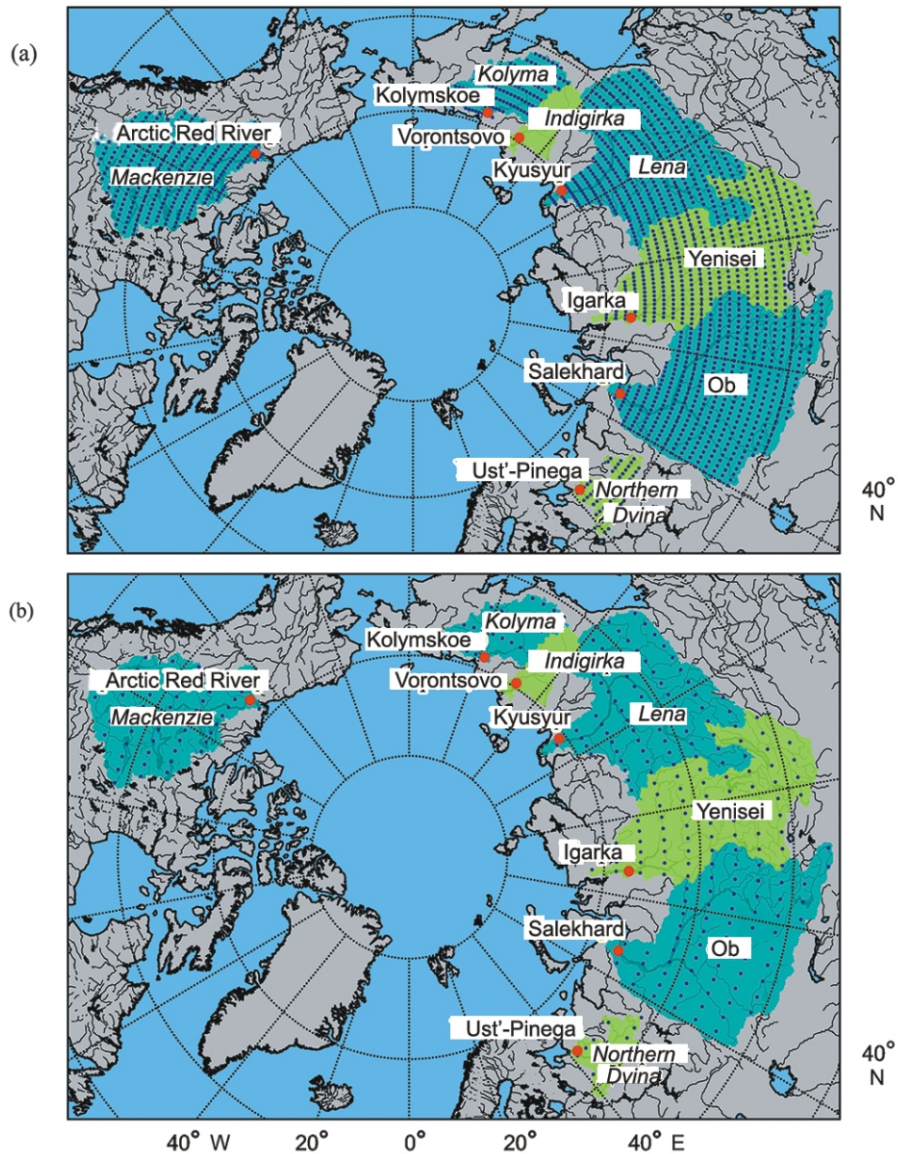


Fig. 1. The catchments of the Ob, Yenisei, Lena, Kolyma, Indigirka, Mackenzie, and Northern Dvina rivers and the grid points of (a) the ERA5 reanalysis and (b) GPCP project dataset for averaging the parameters.

The mean squared deviation of surface air temperature from the corresponding means in the formulas for D_z and D_m was included to the determination of available potential energy in the atmosphere [4, 6]. The changes in available potential energy correspond to an increase or decrease in kinetic energy of the atmosphere or in the intensity of atmospheric circulation.

The calculated indices are presented at the website of Arctic and Antarctic Research Institute (<http://www.aari.ru/main.php?lg=0&id=466>).

The relationships between the climatic parameters were evaluated by the multidimensional cross-correlation analysis. The frequencies of high and low values of peak monthly mean discharges are determined using the p -quantile ($p = 0.1$). Hence, small discharges will be below the quantile $x_{0.1}$ and large discharges will be above $x_{0.9}$. The values of the quantile for each river are determined using the set of order statistics [3] of annual maximum discharges. The order statistics $x(i)$ (the i th value of the set), where $i = N(np + 1)$ is the largest integer number in $(np + 1)$; n is the length of the series; N is the integer number operator; p , the order of quantile, is used to determine the year when the peak monthly mean discharge in a given river was below the specified quantile x_p . Similarly, $x(i)$ where $i = N(n(1 - p) + 1)$, is used to determine the year when the peak discharge was above x_{1-p} . Counting the total number of cases for all rivers when a given year was

within the half-interval ($<x_{0.1}$ or $>x_{0.9}$) gives the occurrence of such cases in a given year on the “Number of cases–Year” diagram. To enhance the reliability of the occurrence values, their moving summing over 9 years was carried out with attributing the resulting sum to the middle of the interval.

The monthly mean, annual mean, and seasonal mean values of surface air temperature in the catchments were obtained by averaging the ERA5 reanalysis data (1° × 1° grid) in the catchment areas of the Ob, Lena, Yenisei, Northern Dvina, Kolyma, and Mackenzie rivers. Monthly mean and annual mean total precipitation over the warm and cold seasons in the catchments were obtained by averaging the GPCC data (2.5° × 2.5° grid) in the area of each basin (Fig. 1). Monthly mean and annual mean precipitation were used to assess changes in climatic conditions and the effect of atmospheric circulation on climatic conditions in the catchments; warm- and cold-season precipitation was used to evaluate the impact of the changes in climatic conditions on river runoff.

RESULTS

Climate change in the catchment areas. The monthly and annual mean values of air temperature and precipitation, trend coefficients, indices of zonal, meridional, and general circulation in the Northern Hemisphere, coefficients of correlation between the indices and climatic parameters were used to assess changes in climatic conditions in the river catchments.

Monthly mean air temperatures in all catchments of the analyzed rivers rise, except for the areas of the Lena and Yenisei in December, the Ob and Kolyma in January, and the Kolyma in February. Maximum coefficients of the temperature trend significant at the level of 95% are observed in March and April (0.1 °C/year for the Yenisei in April and for the Kolyma in May), as well as in November (0.12 °C/year for the Kolyma). The largest precipitation growth is observed in the catchment areas of the Ob and Northern Dvina in March (the trends are significant at the level of 95%). Precipitation in the Kolyma catchment is characterized by the maximum positive trends in the autumn months (significant at the level of 95%).

Effects of atmospheric circulation on climatic conditions in the catchment areas. The zonal transport has the most noticeable effect on surface air temperature in Asia north of 40° N. The impact of meridional transport is observed in more northern regions, including the Arctic basin [1]. The areas of the impact of zonal and meridional transport on surface air temperature include the catchment basins of the rivers, hence, the atmospheric transport affects climatic conditions in the catchments.

The calculation of the coefficients of correlation between the indices and climatic parameters in the catchments confirmed this statement. Table 2 presents the coefficients of correlation between the indices and the mean values of temperature in the catchment areas of individual rivers. It should be noted that the zonal transport has a warming effect only in the cold season (October to March).

Climatic conditions in the catchments of the Kolyma, Mackenzie, and Northern Dvina rivers are more affected by the meridional transport. The maximum correlation coefficients are observed between the annual mean indices of meridional and general circulation and the annual mean values of air temperature in the Kolyma and Northern Dvina catchments.

The calculation of the coefficients of correlation between the circulation indices and mean precipitation demonstrated that the zonal and meridional transport has the most significant effect on precipitation in the Lena catchment areas in the cold season. The maximum coefficient of correlation between the zonal circulation index and mean precipitation in November is -0.72 , and the coefficient for cold-season mean precipitation is -0.58 (with D_z), -0.53 (with D_m), and -0.63 (with D).

The coefficients of correlation between the North Atlantic Oscillation (NAO) index and the climatic parameters in the catchments were calculated. The effect of the NAO on cold-season air temperature was revealed only for the Northern Dvina catchment. The coefficient of correlation between the cold-season mean values is 0.61, the coefficient of correlation between the winter means is 0.78, and the coefficient of correlation between the mean values of air temperature and the index in March is 0.77.

Correlation between climatic conditions in the catchment areas and annual river runoff. The impact of the changes in surface air temperature and precipitation in the catchments on river runoff was estimated by the coefficients of correlation between monthly mean air temperatures, cold- and warm-season total precipitation in the catchments, and the monthly mean discharge, as well as annual river runoff.

For air temperature, the maximum correlation coefficients were obtained between temperature in April and May and river runoff in May and June. The highest positive correlation coefficients are typical of the months when the discharge increases, and high negative coefficients were revealed for runoff in June, when

Table 2. The coefficients of correlation between the indices of zonal (D_z), meridional (D_m), and general circulation (D) and air temperature in the basins of the Arctic rivers according to the ERA-Interim, ERA5 reanalysis for 1979–2018

Index	Parameter	Ob	Yenisei	Lena	Kolyma	Mackenzie	Northern Dvina
D_z	November–March	–0.62	–0.66	–0.62	–0.07	–0.27	–0.43
	Max	–0.66	–0.84	–0.76	0.35	–0.44	0.66
		(December)	(November)	(November)	(June)	(February)	(April)
	Year	–0.42	–0.50	–0.29	0.03	–0.34	–0.14
D_m	November–March	–0.51	–0.49	–0.57	–0.58	–0.23	–0.54
	Max	–0.69	–0.79	–0.75	–0.64	–0.65	–0.59
		(March)	(March)	(March)	(March)	(January)	(July)
	Year	–0.57	–0.57	–0.75	–0.82	–0.39	–0.75
D	November–March	–0.62	–0.63	–0.68	–0.49	–0.27	–0.58
	Max	–0.73	–0.83	–0.79	–0.64	–0.65	–0.54
		(March)	(March)	(January)	(March)	(January)	(December)
	Year	–0.65	–0.68	–0.78	–0.76	–0.46	–0.74

The maximum values are bolded. The 95% significance level of the coefficients is 0.32. The coefficients of correlation are presented between the mean values for November–March (the line “November–March”), the maximum monthly mean values (the line “Max,” the month is given in brackets), as well as the annual mean values (the line “Year”).

the discharge is characterized by the decreasing trend. The changes in mean air temperature in April in the Ob catchment and mean discharge of the Ob in May are presented in Fig. 2a.

The coefficients of correlation between river runoff and total precipitation in the catchment areas showed that warm-season (April–October) total precipitation has the most significant effect on river runoff. Mean warm-season precipitation has the greatest effect on the annual flow of the Lena (the correlation coefficient $R = 0.76$, Fig. 2b), Northern Dvina ($R = 0.65$), Ob ($R = 0.58$), and Mackenzie ($R = 0.47$). Annual runoff of the Ob and Kolyma is affected by cold-season precipitation ($R = 0.51$ and 0.55 , respectively).

Long-term changes in river runoff parameters. Positive trend coefficients indicate an increase in annual runoff for all six rivers. Total annual mean runoff of the six rivers (the Ob, Lena, Yenisei, Kolyma, Mackenzie, and Indigirka) increases at a rate of $4.51 \text{ km}^3/\text{year}$, and the annual mean discharge grows at a rate of $143 \text{ m}^3/\text{s}$ per year, the trends are significant at the level of 95%.

Maximum total annual runoff of the six rivers was observed in 2007 and was equal to $2391 \text{ km}^3/\text{year}$. Interdecadal changes in the river inflow to the Arctic seas (Table 3) show the maximum inflow in the 2000s, which corresponds to the increased freshwater content in the upper layer of the Arctic basin during this decade [2].

Peak discharges of the Ob, Lena, Yenisei, and Mackenzie (observed mainly in June) decrease, the trends in peak discharges are significant at the 95% level. The Yenisei discharge is reduced most significantly, the maximum discharge trend coefficient is $-369 \text{ m}^3/\text{s}$ per year during 1979–2019. Peak discharges of the Northern Dvina also decrease and, unlike peak discharges of the Siberian rivers, are registered in May.

Significant discharges and related river floods are dangerous for population living in river valleys. From this point of view, the decreasing occurrence of significant discharges and the increasing frequency of small discharges are the favorable consequences of the warming. To assess such changes, the frequencies of significant and small discharges were computed using the set of order statistics formed of the series of peak monthly mean discharges for each river.

The calculation was performed for the discharge of the six rivers in 1979–2019. The results of the calculation showed (Table 4) that the increase in the number of small peak discharges falls on the 2000s and 2010s, and the increase in the number of significant peak discharges falls on the 1980s and 1990s. Hence, smaller peak discharges dominate during the warming, and a greater number of significant peak discharges was observed during the cooling in the preceding period.

CONCLUSIONS

Climatic conditions in the catchment areas of the analyzed rivers are formed under the influence of atmospheric circulation, which carries heat, moisture, and precipitation. The atmospheric transport mainly

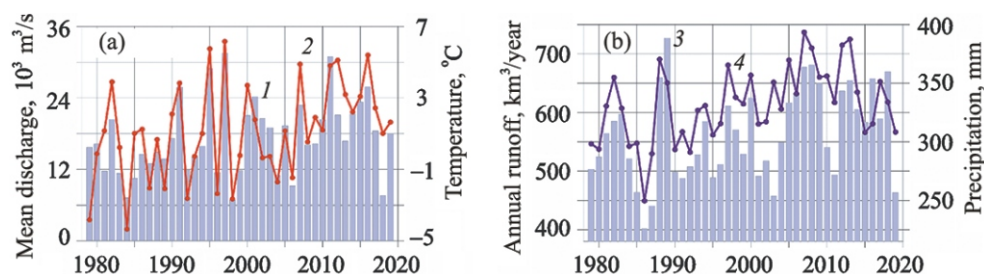


Fig. 2. The correlation between (a, 1) the mean discharge of the Ob River in May and (2) mean air temperature in April in the Ob catchment area, (b, 3) annual mean runoff of the Lena River and (4) mean warm-season total precipitation in the Lena catchment. The correlation coefficient (a) $R = 0.80$ (after removing the trend, 0.78); (b) $R = 0.76$ (0.72).

Table 3. Mean decadal annual runoff of the six rivers and the trend coefficient for annual river runoff

Period	Ob	Lena	Yenisei	Kolyma	Mackenzie	Indigirka	Total of six rivers
Mean annual runoff, km ³ /year							
1980–1989	376	548	582	97.8	273	52.8	1930
1990–1999	405	532	613	105	283	53.4	1991
2000–2009	417	590	641	106	304	55.0	2113
2010–2019	419	590	579	109	280	55.6	2033
Trend coefficient, km ³ /year							
1979–2019	0.81	2.28	0.40	0.40	0.45	0.17	4.51

Table 4. The number of small (n) and significant (N) peak monthly mean discharges for the six rivers and average annual air temperatures in the catchment areas in 1979–2019

Period	Peak discharge		Average annual temperature	
	n	N	n	N
1980–1989	5	10	22	2
1990–1999	7	11	6	4
2000–2009	4	4	0	7
2010–2019	14	5	2	17

affects climatic conditions in the cold season, especially in November and March. In summer, the intensification of zonal circulation is accompanied by the air temperature drop in the catchment areas, and the meridional transport leads to the temperature rise. The greater influence on climatic conditions in the Ob, Lena, and Yenisei catchments is exerted by the zonal transport, and the meridional transport has more significant effects in the Kolyma, Mackenzie, and Northern Dvina catchments.

Air temperature in the Northern Dvina catchment is affected by the North Atlantic Oscillation, especially in the cold season.

The effect of air temperature changes on river runoff is the most noticeable in May, when river discharges increase, also, air temperature in spring is noticeable in all catchment areas.

The increase in annual mean precipitation has the greatest effect, especially for the Lena River. Total annual runoff of the six rivers (the Ob, Yenisei, Lena, Mackenzie, Indigirka, and Kolyma) increased in

1979–2019 at a rate of 4.51 km³/year, and peak river discharges decreased, except for the Kolyma discharge. The Yenisei peak discharge decreased most (at a rate of 369 m³/s per year).

In the 2000s, the occurrence of small peak discharges increased, and the frequency of significant discharges decreased. The significant occurrence of high peak discharges falls on the 1980s. Such distribution of the frequencies of annual peak monthly mean discharges may be associated with climate warming in the 2000s–2010s and with the cooling in the 1970s–1980s.

The air temperature rise, especially in the spring months, when floods are mainly observed on the analyzed rivers, is accompanied by the subsequent increase in monthly mean discharges. Despite a decrease in peak river discharges, annual mean river runoff at the outlets increases, as well as the volume of freshwater flowing into the Arctic seas. The revealed runoff growth is an effect of global warming, at which the atmospheric transport of heat and moisture intensifies, and this trend will be maintained as the warming develops.

FUNDING

The research was supported by the Russian Foundation for Basic Research (grant 18-05-60107).

REFERENCES

1. G. V. Alekseev, "Arctic Dimension of Global Warming," *Led i Sneg*, No. 2 (2014) [in Russian].
2. G. V. Alekseev, A. V. Pnyushkov, A. V. Smirnov, A. E. Vyazilova, and N. I. Glok, "Effects of Atlantic Inflow on Freshwater Content in the Upper Layer of the Arctic Basin," *Problemy Arktiki i Antarktiki*, No. 4 (2019) [in Russian].
3. L. N. Bol'shev and N. V. Smirnov, *Tables of Mathematical Statistics* (Nauka, Moscow, 1968) [in Russian].
4. J. van Miehem, *Atmospheric Energetics*, Ed. by L. T. Matveev (Gidrometeoizdat, Leningrad, 1977) [Transl. from English].
5. R. G. Dzhamalov, G. N. Krichevets, and T. I. Safronova, "Current Changes in Water Resources in Lena River Basin," *Vodnye Resursy*, No. 2, **39** (2012) [*Water Resour.*, No. 2, **39** (2012)].
6. E. N. Lorenz, *The Nature and Theory of the General Circulation of the Atmosphere* (Gidrometeoizdat, Leningrad, 1967) [Transl. from English].
7. K. Aagaard and E. C. Carmack, "The Role of Sea Ice and Other Fresh Water in the Arctic Circulation," *J. Geophys. Res.*, No. C10, **94** (1989).
8. R. F. Adler, G. J. Huffman, A. Chang, R. Ferraro, P. P. Xie, J. Janowiak, B. Rudolf, U. Schneider, S. Curtis, D. Bolvin, A. Gruber, J. Susskind, P. Arkin, and E. Nelkin, "The Version-2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979–Present)," *J. Hydrometeorol.*, No. 6, **4** (2003).
9. R. Ahmed, T. Prowse, Y. Dibike, B. Bonsal, and H. O'Neil, "Recent Trends in Freshwater Influx to the Arctic Ocean from Four Major Arctic-draining Rivers," *Water (Switzerland)*, No. 4, **12** (2020).
10. S. Berezovskaya, D. Yang, and L. Hinzman, "Long-term Annual Water Balance Analysis of the Lena River," *Glob. Planet. Change*, No. 1–3, **48** (2005).
11. M. Chen, P. Xie, and J. E. Janowiak, "Global Land Precipitation: A 50-yr Monthly Analysis Based on Gauge Observations," *J. Hydrometeorol.*, No. 3, **3** (2002).
12. *Copernicus Climate Change Service (C3S) (2017): ERA5: Fifth Generation of ECMWF Atmospheric Reanalyses of the Global Climate*. Copernicus Climate Change Service Climate Data Store (CDS), <https://cds.climate.copernicus.eu/cdsapp#!/home>.
13. D. P. Dee, S. M. Uppala, A. J. Simmons, P. Berrisford, P. Poli, S. Kobayashi, U. Andrae, M. A. Balmaseda, G. Balsamo, P. Bauer, P. Bechtold, A. C. M. Beljaars, L. van de Berg, J. Bidlot, N. Bormann, C. Delsol, R. Dragani, M. Fuentes, A. J. Geer, L. Haimberger, S. B. Healy, H. Hersbach, E. V. Hylm, L. Isaksen, P. Kellberg, M. Kohler, M. Matricardi, A. P. McNally, B. M. Monge-Sanz, J.-J. Morcrette, B.-K. Park, C. Peubey, P. de Rosnay, C. Tavolato, J.-N. Thepaut, and F. Vitart, "The ERA-Interim Reanalysis: Configuration and Performance of the Data Assimilation System," *Quart. J. Roy. Meteorol. Soc.*, No. 656, **137** (2011).
14. S. J. Dery, T. A. Stadnyk, M. K. MacDonald, and B. Gauli-Sharma, "Recent Trends and Variability in River Discharge across Northern Canada," *Hydrol. Earth System Sci.*, No. 12, **20** (2016).
15. M. Durocher, A. I. Requena, D. H. Burn, and J. Pellerin, "Analysis of Trends in Annual Stream Flow to the Arctic Ocean," *Hydrol. Processes*, No. 7, **33** (2019).
16. A. Fedorov, M. Barreiro, G. Boccaletti, R. Pacanowski, and S. G. Philander, "The Freshening of Surface Waters in High Latitudes: Effects on the Thermohaline and Wind-driven Circulations," *J. Phys. Oceanogr.*, No. 4, **37** (2007).
17. W. E. Grabs, F. Portmann, and T. Couet, *Discharge Observation Networks in Arctic Regions: Computation of the River Runoff into the Arctic Ocean, Its Seasonality and Variability*, Ed. by E. L. Lewis (Kluwer, Dordrecht, The Netherlands, 2000).

18. T. W. N. Haine, B. Curry, R. Gerdes, E. Hansen, M. Karcher, C. M. Lee, B. Rudels, G. Spreen, L. Steur, K. Stewart, and R. Woodgate, "Arctic Freshwater Export: Status, Mechanisms, and Prospects," *Glob. Planet. Change*, **125** (2015).
19. A. Jahn, Y. O. Aksenov, B. A. de Cuevas, L. de Steur, S. Hakkinen, E. Hansen, C. Herbaut, M. Houssais, M. Karcher, F. Kauker, C. Lique, A. Nguyen, P. Pemberton, D. Worthen, and J.-Z. Zhang, "Arctic Ocean Freshwater: How Robust are Model Simulations?," *J. Geophys. Res.*, **117** (2012).
20. E. Kalnay, M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne, and D. Joseph, "The NCEP/NCAR 40-year Reanalysis Project," *Bull. Amer. Meteorol. Soc.*, No. 3, **77** (1996).
21. M. Karcher, R. Gerdes, F. Kauker, C. Koberle, and I. Yashayaev, "Arctic Ocean Change Heralds North Atlantic Freshening," *Geophys. Res. Lett.*, No. 21, **32** (2005).
22. R. B. Lammers, A. I. Shiklomanov, C. J. Vorosmarty, B. M. Fekete, and B. J. Peterson, "R-ArcticNet, a Regional Hydrographic Data Network for the Pan-Arctic Region (ISO-image of CD-ROM)," PANGAEA (2016).
23. K. Oshima, K. Ogata, H. Park, and Y. Tachibana, "Influence of Atmospheric Internal Variability on the Long-term Siberian Water Cycle during the Past 2 Centuries," *Earth Syst. Dyn.*, No. 2, **9** (2018).
24. M. C. Serreze, A. P. Barrett, A. G. Slater, R. A. Woodgate, K. Aagaard, R. Lammers, M. Steele, R. E. Moritz, M. Meredith, and C. M. Lee, "The Large-scale Freshwater Cycle of the Arctic," *J. Geophys. Res. Oceans*, **111** (2006).
25. A. I. Shiklomanov, R. M. Holmes, J. W. McClelland, S. E. Tank, and R. G. M. Spencer, *Arctic Great Rivers Observatory. Discharge Dataset, Version 20190402* (2018), <https://www.arcticrivers.org/data>.