A simulated distribution of Siberian river runoff in the Arctic Ocean

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Abstract. Continental runoff is one of the major sources of the Arctic freshwater budget. As is generally known, it influences water column stratification and maintains Arctic halocline, which isolates the sea ice and the cold, fresh upper layer from the warmer, saltier Atlantic waters of the Arctic Ocean. An increase in river runoff was observed in recent years. It is suggested that this will have an impact on Arctic water mass transformations. However, few details are known regarding river freshwater export to the Central Arctic Basin. It is assumed that river water pathways in vast shelf seas and deep basins are closely related to atmospheric variability. In this study, we use three-dimensional coupled regional ocean-ice model simulations forced by atmospheric reanalysis data to investigate the change in Siberian rivers freshwater pathways in the Arctic Ocean due to the variability of atmospheric dynamics. A numerical experiment with an increasing runoff of the largest Siberian rivers is carried out. The consequences of adding freshwater to particular regions of the Arctic Ocean are analysed.

1. Introduction

The Arctic river discharge is one of the major sources for the Arctic freshwater budget. The Arctic Ocean accounts for about 1\% of the global ocean volume but receives about 11\% of the global river discharge \[1, 2\]. Eight largest Arctic rivers, namely, Mackenzie, Yukon, Kolyma, Lena, Yenisey, Ob, Pechora, and Severnaya Dvina together, cover approximately two-thirds of the pan-Arctic drainage area and account for over 60\% of the river water inflow to the Arctic Ocean \[3\]. A long-term increasing trend for the Arctic river discharge, which is the greatest for the rivers of the Eurasian Arctic, has been well documented \[4, 5, 6, 3\]. Peterson et al. \[4\] show a 7\% increase in the Eurasian runoff over the period from 1936 to 1999. Overeem et al. \[6\] analyzed the observational records for 19 large rivers encompassing the Arctic region and found a consistent increase in the annual discharge (+9.8\%) over the entire region from 1977 to 2007. The authors show that a combined change in the river water discharge over 30 years exceeds the previous values obtained for the Canadian Arctic (+2\%) over 1964–2000 and for Eurasia (+7\%) over 1936-1999. An observation data analysis performed by Holmes et.al. \[3\] over 1976-2018 has shown that long-term trends in the annual discharge were $3.3\pm1.6\%$ per decade for the Eurasian rivers and $2.0\pm1.8\%$ per decade for the North American Arctic rivers.

Fresh water supplied by the Arctic rivers influences the Arctic Ocean stratification and the sea ice formation. The Arctic stratification is characterized by a cold and fresh surface layer, a relatively warm and salty Atlantic layer formed by Atlantic Waters entering the Arctic Ocean through the
Barents Sea and the Fram Strait, and an intermediate layer of cold water with a gradual increase in the salinity with depth known as the cold halocline [7, 8, 9]. Moving from the shelves to the Central Arctic Ocean, the river waters maintain the Arctic halocline, which isolates the sea ice from the warmer and saltier Atlantic layer. Changes in the river discharge can cause notable changes both inside and outside the Arctic Ocean as perturbations in the freshwater export from the Arctic Ocean have a potential for changing the dense water formation rate and the ocean convection in the North Atlantic [10].

It is generally known that the river water pathways over the vast shelf seas and the residence time are closely linked to the atmospheric dynamics [11, 12, 13]. To date not much is known regarding the river freshwater export into the Central Arctic Basin, and the distribution of the river water in the Arctic Ocean and beyond it. It is assumed that the variability of the Eurasian river runoff pathways is largely governed by the Arctic Oscillation (AO), the leading mode of atmospheric variability in the Northern Hemisphere [14]. Since the beginning of 2000 this issue has been debated in scientific papers.

The numerical modeling carried out by Harms et al. [15] investigates the role of the Siberian river runoff for transporting possible river contaminants in the Arctic Ocean. Based on the numerical results the authors have concluded that the Kara Sea river water dominates in the Siberian branch of the Transpolar Drift, whereas the Lena River water dominates in the Canadian branch. Analysis of the numerical results obtained has shown that the dissolved contaminants supplied by the river water would be able to reach the Canadian Archipelago in about 15 years after releasing into the Siberian estuaries. In a paper by Jahn et al. [16] it was shown that the fresh water exported through the western Canadian Arctic Archipelago mainly comes from the Pacific and North American runoff. The Eurasian runoff export through the Fram Strait occurs in the years with an anticyclonic circulation anomaly and it takes three years to reach the Fram Strait after leaving the shelf. Newton et al. [17] used a high-resolution numerical simulation of the Arctic Ocean to study the river runoff distribution in the Arctic Ocean in the 1990s characterized by an increased AO index. In the numerical results obtained the freshwater plumes have shifted eastward over the both shelves and the deep basin. The tracers migrate away from the Eurasian Basin; first to the Canadian side of the Lomonosov Ridge over the Makarov Basin, and then even further into the Beaufort Sea, north of the Canadian continental slope. Morison et al [18] argued that due to a cyclonic (anticlockwise) shift in the ocean pathway of the Eurasian runoff forced by strengthening of the west-to-east Northern Hemisphere atmospheric circulation in the 1990s, a large amount of the Eurasian river runoff was transported mainly into the Canada Basin, and caused an increase in the freshwater content in the Canada basin balanced by a decrease in the Eurasian basin.

In this study we aim at tracing the Siberian river runoff distribution over the Arctic Ocean and try to identify modifications in the river freshwater pathways due to variability of the atmospheric dynamics. We discuss the numerical results based on a three-dimensional coupled regional ocean-ice model forced by atmospheric reanalysis data. In our first experiment we analyzed the spatio-temporal scales of the distribution of particles periodically emitted at the shelves from the Siberian river mouths. In our second experiment we increased the discharge values of the Siberian Rivers and assumed that this has an impact on the Arctic water mass transformation. By analyzing the numerical results obtained we tried to understand the consequences of adding freshwater for particular regions of the Arctic Ocean.

2. Model

2.1. Coupled Ice-Ocean model

Our study is based on a three-dimensional regional coupled ocean-ice model called SibCIOM (Siberian Coupled Ice-Ocean Model) [19, 20] developed at the Institute of Computational Mathematics and Mathematical Geophysics (Siberian Branch of the Russian Academy of Sciences). The ocean model is based on the conservation laws for heat, salt, and momentum, as well as on
conventional approximations: the Boussinesq, hydrostatic, and “rigid lid” ones. The QUICKEST scheme is employed to approximate advection [21]. The multidimensional extension uses the COSMIS approach [22]. The vertical adjustment is considered to be a mixed layer parameterization based on the Richardson number [23].

The ocean circulation model has been coupled with the CICE v3 model of the thermodynamics of elastic viscous-plastic ice [24] and the multi-category sea ice thermodynamics [25]. The sea ice advection utilizes a semi-Lagrangian scheme [26]. The fast ice parameterization is the most simplified approach, and the ice velocity was set to zero in the shallowest part of the Laptev and East Siberian Seas (a depth of < 30 m) for the period from October 30 to June 1.

2.2. Particle Tracer Model
In order to numerically track the river water distribution we used the method of Lagrangian particles. Particles were individually and periodically emitted in the region of a certain source and moved within the numerical domain with a model velocity. The advective motion of particles was also accompanied by diffusion, which is considered to be a stochastic process. The position of a particle caught in the layer of convective or wind mixing was also stochastically determined based on a uniform distribution in the mixed layer. A particle of any river runoff was deployed in a way that it represents the volume km$^3$. This means that the time interval between two successive particle releases is determined as $\Delta t = V_0 / R(t)$, where $R(t)$ is the current river discharge rate in km$^3$/s.

2.3. Model domain
The model domain includes the Arctic and the Atlantic Ocean north of 20° S. The grid resolution for the North Atlantic is chosen to be 0.5° x 0.5°. At 65° N the North Atlantic spherical coordinate grid is merged with the displaced poles of the Arctic grid. The horizontal grid size in the Arctic varies from 10 to 25 km with an average grid spacing of about 18 km. The model version used here has 38 unevenly spaced vertical levels with a maximum resolution of 5 m in the upper 20-meter layer. The minimum depth of the shelf zone is taken to be 20 m.

2.4. Forcing
The model is forced by the CORE-II Reanalysis data [27]. The model takes into account the inflow of Bering Strait and the 52 largest rivers in the region, among which are the Siberian rivers Yenisei, Ob, Lena, Indigirka, Olenek, Yana, and Kolyma. Data on the average seasonal runoff from these rivers were obtained from hydrological station measurements [28]. In addition, according to the estimates by Aagaard and Carmack [1] the total runoff of the continental waters in the Arctic is approximately 1.3 times greater than that of the main rivers. Therefore, to obtain the whole picture the discharge of the above-mentioned rivers was increased 1.3 times, including those of the Atlantic basin. The rivers’ fresh water flux was calculated on the basis of an assumption that the river water has zero salinity. The specified mass transports at the open boundaries and river inflows are compensated by transports through the outflow boundary at 20° S.

3. Simulation

3.1. Variability of Siberian river runoff pathways in the Arctic Ocean
In our basic experiment (hereafter E1) we have simulated large-scale variability of the Arctic Ocean circulation and the sea ice state caused by the variability of the atmosphere from 1985 to 2014. We started our experiment using the ocean and sea ice state previously obtained in numerical experiments discussed in our published works [20, 29] and showed how the numerical model restores the variability of the thermohaline fields of the Arctic Ocean known from the observational data. In this paper we analyze possible paths of the river water distribution of the most full-flowing Siberian rivers: Ob, Yenisei, and Lena based on a consideration of the trajectories of tracers entering the shelf zone of the Siberian seas with the river waters.
Our simulation forced by the atmospheric reanalysis has shown that a significant part of the tracers arriving with the waters of the Ob, Yenisei, and Lena rivers in different periods of the atmospheric circulation remains within the shelf zone. Earlier in paper [30] we discussed the results of modeling the water circulation and the distribution of river waters on the shelf of the Laptev Sea. In the paper in question it was shown that the circulation pattern of the passive tracers injected from the Lena River mouth is fairly complicated, being subject to the wind forcing and the ice edge position. The river tracers changed their direction several times per year and, eventually, a lot of the tracers remained within the eastern part of the Laptev Sea shelf longer than one year.

Having reached the mainland slope, the river tracers are involved in the large-scale circulation system of the Arctic basin. Two main modes of the surface circulation of the Arctic Ocean, cyclonic and anticyclonic, determined by the atmospheric dynamics, have been repeatedly discussed in the literature [31]. By analyzing the tracer propagation paths, we tried to identify these two periods. In Figures 1-3 the distribution of the river tracers outgoing from the three main Siberian rivers (Lena, Ob, and Yenisei) is presented. Figure 1 shows the distribution of tracers that arrived in 1989-1996. The Arctic Ocean Oscillation index (AOO) [32, 31] was defined on the basis of a wind-driven simulated sea surface height field across the Arctic and represents a measure of the intensity and sense (clockwise/anticyclonic or counterclockwise/cyclonic) of the Arctic Ocean wind-driven upper oceanic circulation. These years, 1989-1996, are characterized by an increased negative AOO index, which corresponds to the formation of a cyclonic mode of the surface water circulation. Figure 1 shows mainly the north-east distribution of the river tracers.

Figure 1. Distribution of the sum of all tracers released from largest Siberian rivers in 1989-1996.

The transition to the anticyclonic circulation mode in the subsequent years [31] is shown in Figure 2. A significantly smaller number of tracers released during these years have appeared in the central part of the basin. The figure shows that the tracers are distributed towards the Fram Strait. The percentage of tracers at various depths is also shown in the figure.

To complete the picture described, we have also presented the distribution of all tracers released between 1989 and 2006. Examination of Figures 1-3 shows that the part of the tracers moving to the central basin during the cyclonic circulation period (Figure 1) was redistributed according to the
changed water circulation system. Some of the tracers were involved in the anticyclonic cycle and moved towards the Canadian Straits. A significant number of the tracers were located in the Eurasian basin, and some tracers went beyond the Fram Strait and joined the subpolar cycle. A small number of the tracers (less than 5%) went down to the deep layers of the Canadian basin.

Figure 2. The same as Figure 1, but over 2000-2006.

Figure 3. Distribution of the sum of all tracers released from the largest Siberian rivers in 1989-2006.
3.2. Sensitivity study to an increase in the largest Siberian rivers discharge

Given the tendency of an increase in the runoff of Siberian rivers in the recent decades [3], we have carried out a numerical experiment to study the sensitivity of the model temperature and salinity distributions in different regions of the Arctic Ocean to an increase in the discharge of the rivers. Using the ocean and sea ice state obtained in the reference experiment E1 for 2000 as the initial one, we have increased the runoff of the Siberian rivers one and a half times and repeated the numerical experiment for the period from 2000 to 2014.

A discussion of our results will be based on an analysis of hydrological characteristics averaged over individual regions. As such characteristics we will consider the difference in the temperature and salinity obtained from the results of the present (E2) and reference (E1) experiments.

An analysis of the comparison of the calculated fields for the two experiments has shown that due to an increase in the flow of rivers into the Siberian seas the most significant decrease in the salinity was in the upper 25-meter layer. Regional averaging over 15 years of the model calculation of the salinity of the surface layer has shown a decrease of this value by 2.5 psu in the Laptev Sea, 1.75 psu in the East Siberian Sea, and 2 psu in the Kara Sea. In the Kara Sea, the most dramatic changes in the salinity are sharply limited to the upper 20-meter layer. Below the surface layer the Atlantic waters penetrating into the region make a significant contribution to the water stratification. In the East Siberian Sea anomalies of salinity penetrate deeper than in the Kara Sea and in the Laptev Sea (up to 60 m at the end of the experiment). This can be explained by remoteness of the region from the mouths of the most powerful rivers. The salinity reduction in the region occurs due to the fresh water transport from the Lena and Kolyma rivers along the coast of eastern Siberia.

An analysis of the temporal variability of the temperature averaged over the regions also makes it possible to highlight some features of its distribution in the Siberian seas caused by an increase in the river inflow. By analyzing the deviation field in the Laptev Sea and in the East Siberian Sea, we have detected positive temperature anomalies (up to 0.3 °C in the Laptev Sea and up to 1.15 °C in the East Siberian Sea). These anomalies regularly occur in the summer in the surface layer, propagate into deeper layers, and cause an increase in the bottom layer temperature. A similar character of the anomalies was obtained in numerical tests [30] when the thermal runoff of the Lena River was taken into account. The measurement data obtained from 1940 to 2011 confirm the process of increasing the bottom layer temperature of the Laptev Sea. The results obtained for the Kara Sea do not allow us to say anything definite about the temperature anomalies that occasionally appeared and were localized in the bottom layer.

According to our experiment, visible changes in the salinity field begin to appear over the continental slope of Eurasia after about 2 years (Figure 4b). The strongest anomalies were recorded in the Nansen basin region (1-3 psu), first at the continental slope of the Kara and the Laptev Seas (R4) and near the St. Anna trough (region R3), and then the salinity anomaly moved toward the Fram Strait (regions R2 and R1). The salinity anomalies in the eastern part of the continental slope are much weaker and do not exceed 1 psu at the sea surface. In the central part of the basin and along the American coast anomalies not exceeding 0.5 psu at the sea surface appear after 6-8 years.

It should be noted that in some cases, in areas adjacent to the Fram Strait, a decrease in the surface salinity is accompanied by an increase in the salinity and temperature in deeper layers (Figure 4c). Such a temperature anomaly has been detected in regions R1 and R2 in 2009 – 2011 (0.1-0.2°C) and in 2014 (0.55°C) in region R1. This means that the appearance of fresh water at the surface led to the suppression of the mixing processes and to a more prolonged conservation of the heat in the layer of Atlantic waters flowing through the Fram Strait. Positive temperature anomalies are observed in the layer of Atlantic waters in the regions located along the continental slope (in R4). An analysis of the simulation results shows that the depth of the upper mixed layer in this period is 10 m smaller than that in the reference experiment E1. A negative temperature anomaly in the region R3 over the past three years indicates that intense mixing has occurred. This fact underlines the ambiguity of the Arctic Ocean response to possible climate changes.
In the areas adjacent to the continental slope in the eastern part of the basin, small positive temperature anomalies were detected in the uppermost layer. Their values do not exceed 0.06°C. After 7 years of calculation, a positive temperature anomaly in the layer from 100 to 200 m is constantly present in the Canadian basin. This depth corresponds to the distribution of the Pacific waters layer in the Arctic basin. The magnitude of this anomaly (maximum: 0.04°C) is too small, but the fact of the appearance of this anomaly seemed of interest to us. It may mean a decrease in the Pacific water heat loss on the Chukchi Sea shelf due to more stable stratification.

**Figure 4.** Left panel: Regions of analyzing temperature and salinity anomalies, Upper-right panel: Salinity anomalies (psu) averaged over a certain region and in 25-meter layer. Lower-right panel: Temperature anomalies (°C) averaged over a certain region at a depth of 200 m. The line color corresponds to the region of averaging.

The response of the Arctic Ocean ice cover to a decrease in the surface layer salinity is ambiguous depending on certain regions and time periods. The largest ice volume reduction caused by an increase in the fresh water amount occasionally reaches 10% in the Nansen basin region. In most regions it does not exceed 1-2%. In the central part of the basin the numerical model shows a trend for an increase in the ice volume.

### 4. Summary

Our model results support the hypotheses that the atmospheric changes reflected in the AOO play an important role in the distribution of fresh water in the Arctic Ocean. We have simulated paths of tracers representing distributions of the Siberian river runoffs in different modes of the Arctic Ocean circulation. Analyses of the simulation results have shown that a lot of tracers injected from river mouths remain trapped near the shelves and tend to exit from the shelves after several years. In a cyclonic mode of the circulation (1989-1996) the tracers, crossing the shelves, moved north-eastward into the central Arctic, and part of them reached the northern part of the Canadian basin. In response to a change in the wind patterns associated with a trend toward positive values of the AOO in 2000-2006, the tracers shifted westward into the Eurasian basin and then moved to the Fram Strait. Some of the tracers exiting in 1989-1996 were involved into an anticyclonic circulation and reached the Canadian Straits. Only a small number of the tracers reached the Beaufort Sea in 2006.
To understand the consequences of an increase in the runoff of the Siberian rivers known from observational data, we carried out a numerical experiment in which we increased the runoff of the Lena, Yenisei, and Ob Siberian rivers by one and a half times. The experiment was performed for the period from 2000 to 2014. The results of our experiment have shown that different thermohaline characteristics of the Siberian seas respond differently to the input of additional fresh water. Their behavior in the Kara Sea is quite different from that in the Laptev Sea and the East Siberian Sea.

Outside the Arctic shelf, some regions of the Eurasian basin are most sensitive to the increased runoff of the Siberian Rivers. This is probably due to the fact that during this period there was a positive mode in the AO index. A predominantly anticyclonic circulation was established during this period, which contributed to the transfer of excessive fresh water to the Fram Strait. Temperature anomalies of various intensities were detected not only in the surface layer, but also in the layer of Atlantic waters entering the Arctic Ocean through the Fram Strait. These anomalies correspond to a decrease in the mixing depth of the upper layer.

Small positive temperature anomalies were found in the Pacific Water layer in the Canadian Basin. We believe that, despite the fact that these are small anomalies, this result deserves attention and should be verified with a higher-resolution model. Our arguments in favor of this conclusion are as follows: It is the contribution of the Lena River waters in the experiment that caused the appearance of these anomalies, since these waters can be transferred to the East Siberian Sea and then carried off the shelf of the Chukchi Sea, where they can affect the mixing processes.

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