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Study of the influence of Atlantic water on the ice cover state in the Eurasian basin of the Arctic Ocean using numerical simulation*

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Abstract. A numerical simulation of the water and sea ice dynamics of the Arctic Ocean was carried out to identify the physical mechanisms that determine the variability of the state of the ice cover. For the research, we used the coupled ocean-ice regional numerical model of the North Atlantic and the Arctic SibCIOM, developed at the ICMMG SB RAS. In the coarse of this study, heat fluxes on the ice boundary from the ocean and the atmosphere were analyzed, and the correlation coefficients of these fluxes with the volume of ice in the region in question were calculated. The results obtained indicate to a significant effect on the Arctic ice of the heat coming from the ocean along the trajectory of the warm Atlantic water.

Keywords: Arctic Ocean, sea ice, climate variability, numerical modeling.

1. Introduction

Among many physical processes that indicate that significant changes have occurred in the Earth's climate system over the past two decades, the most significant is a sharp reduction in the area of the Arctic sea ice in the summer period, which began in the early 2000s. In the last few decades, there has been a gradual reduction in the volume of perennial ice, the transition to the dominance of the seasonal ice over the perennial ice [1].

According to the National Snow and Ice Data Center (NSIDC) in the USA, the absolute minimum ice area in the Arctic Ocean (3.41 million km^2) was recorded in September 2012, this value being 49 % lower the average for the period from 1979 to 2000 [2].

Currently, the trend of the ice reduction continues. The rate of reduction of the Arctic ice is 12.8 % per decade relative to the average state between 1981 and 2010. The defining role in the process of reduction of the Arctic sea ice is conventionally assigned to the atmosphere due to a recorded increase in the surface air temperature in the polar latitudes and a change in the circulation regime, which forms a steady ice removal outside the Arctic basin [3, 4].

Among probable reasons contributing to the establishment of the current state of the ice cover of the Arctic Ocean, an increase in the thermal effect of the Atlantic and Pacific waters entering the Arctic basin is also considered.

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Analytical models [5, 6] show that the heat fluxes coming from the ocean to the lower boundary of the ice cover and causing ice melting are due to the existence of a layer of warm waters of the Atlantic origin. The Atlantic waters enter the Arctic Ocean in the form of two branches. One of the branches passes through the Barents Sea giving most of the heat to the atmosphere. The second branch, the Fram branch, runs at depths of 100–900 m. The Fram branch is considered to be one of the main heat sources for the Arctic Ocean.

The recent studies have increasingly emphasized the importance of the influence of the Atlantic waters on the state of the ice cover. In [7], the rate of ice melting at the lower boundary is estimated as 1 m per month, and this indicator is directly or indirectly related to the role of the ocean in the state of ice. The paper [8] refers to the increasing influence of the ocean heat on a decrease in the ice cover area northeast of Svalbard. A recent study [9] based on an analysis of observational data has shown that in the eastern part of the Eurasian basin of the Arctic Ocean there was a 2–4-fold increase in winter upward the heat flux from the AB layer from 2007 to 2014–2015. Estimates of the ice melting rate caused by the flows from the AB layer have become comparable with similar estimates caused by the atmospheric thermodynamic effects.

One of the main mechanisms involved in the heat transfer from the AB layer to the ice surface is the winter convective mixing [10]. Persistent stratification of the Arctic Ocean waters usually inhibits intense winter convection. With a shortage of fresh water due to the lack of ice or the prevailing circulation, the stability of stratification may be impaired. For example, in the western part of the Nansen basin, in the absence of a cold halocline, the mixing reaches a depth of 100 m by connecting the AB [10]. It is also possible to enhance the dynamic effects on the surface as a result of a decrease in the ice cohesion. As a result, there is an increase in the vertical mixing in the surface layer and a deepening of the upper mixed layer, which in turn contributes to a more intense heat transfer from the layer AB to the surface.

According to the observations for 2013, in the Central Amundsen basin [9], the heat flux from January up to April from the AB to the mixed layer is estimated as about 3–4 $\mathrm{V/m^2}$. In [7], where estimates of the additional thermal energy 1 $\mathrm{V/m^2}$ required to explain the ice reduction over the past 50 years are given, it was shown that an energy of 1 $\mathrm{V/m^2}$ is sufficient to melt 10 cm of ice per year.

In this paper, we analyze, based on the numerical simulation, possible physical mechanisms that might affect the variability of the state of the sea ice in the Arctic Ocean. The main emphasis is on assessing the role of the Atlantic water.

2. Research method

For our research, we used the regional three-dimensional coupled ocean-ice numerical model for the North Atlantic and the Arctic SibCIOM, developed at the Institute of Computational Mathematics and Mathematical Geophysics, SB RAS. This model includes the oceanic part, the ice block in the form of the CICE 3.14 model [11] and the GOTM numerical program package, General Ocean Turbulence Model, [12]. The interaction with the atmosphere is organized by using re-analysis data. The oceanic block of the model is a z-level version of the numerical model of the ocean dynamics developed at the Institute of Computational Mathematics and Mathematical Geophysics SB RAS. The basic principles of the building model are described in [13, 14]. The numerical model was modified based on the inclusion of the level surface of the ocean according to the method described in [15].

A numerical experiment was carried out for the model area including the North and Equatorial Atlantic and the Arctic Ocean. The horizontal resolution of the numerical curvilinear grid varied from 1 degree (111 km at the equator) in the Atlantic Ocean to 37 km in the Arctic Ocean. Vertically, 38 horizons were considered with thickening in the surface layer up to 5 m.

When conducting the numerical analysis, the following NCEP/NCAR re-analysis data were used—surface wind speed and direction, potential and absolute temperature of the lower atmosphere, specific humidity, surface pressure and air density, total downward solar and infrared radiation, and precipitation rate, [16]. The winter distribution of the PHC climate data array was used as the initial state [17]. The PHC array is a combination of S. Levitus data and a number of oceanographic data collected as a result of sensory studies of the Arctic and surrounding areas, and represents a monthly three-dimensional distribution of temperature and salinity in a layer up to 1 km deep, as well as the seasonal (winter and summer) and the annual average for the entire depth range. The numerical experiment was carried out for the time period 1948–2016.

3. Numerical results

3.1. The heat flow calculation. In order to assess the role of the ocean in the reduction of the Arctic ice, heat fluxes at the ocean-ice and atmosphere-ice boundaries were estimated, and the contribution of both to the variability of the ice cover was calculated using the linear correlation coefficients. The heat flux at the lower boundary of the ice is proportional to a difference between the water temperature of the upper layer of the ocean and the temperature of its freezing point and can be approximated by the formula [18]:

$$F_{\text{ocean-ice}} = \rho c_\rho c_h u_* (T_{\text{freeze}} - T_{\text{ocean}}).$$

Here $c_\rho = 3.99 \cdot 103$ J/kg/K is the specific heat capacity of the sea water, c_h is the coefficient of heat transformation, u_* is the ocean-ice friction velocity, and ρ is the water density.

To calculate the heat flux acting on the ice from the atmosphere, the three components of the radiation balance were summed — the apparent heat flux F_1, the latent heat flux F_2, and the long-wave flux F_3:

$$F_{\text{atm-ice}} = F_1 + F_2 + F_3.$$

The relationship between temporary changes in the ocean-ice heat flux and a change in the ice volume can be traced by the graphs of these values averaged over each of 12 regions (Figure 1). Figures are presented only for regions with the strongest influence (Figure 2).

3.2. Correlation estimation. To determine the relationship between the heat flux and the volume of ice, the linear correlation coefficients were calculated (the table). The linear correlation coefficients were calculated for each of 12 regions from arrays of the average annual values of ocean-ice flows and the ice volume for the period of 1997–2015. The linear trend characteristic of the last couple of decades was removed from the series, so that the correlation coefficients characterize the relationship between the variability of heat fluxes and the state of ice.

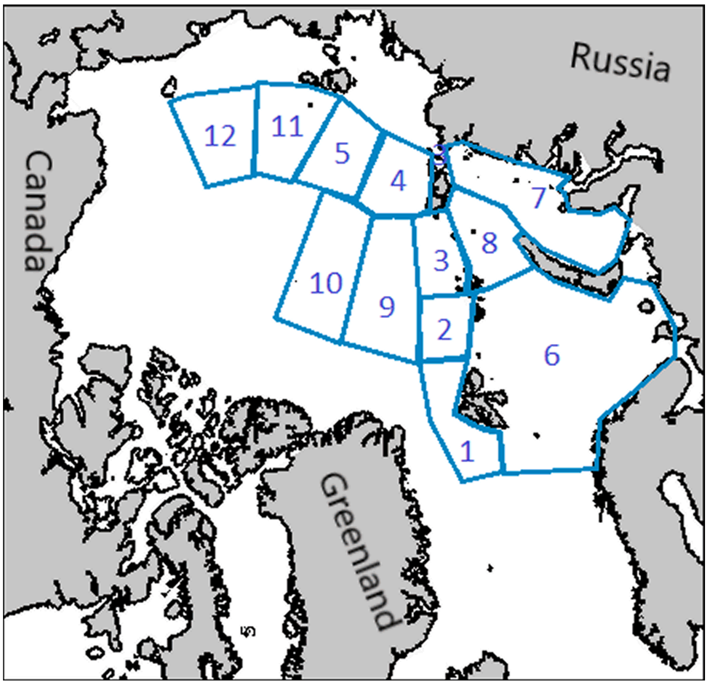

Figure 1. Regions in the Arctic Ocean under the study

Correlation coefficients between the ocean-ice and atmosphere-ice flows and ice volume on the regions of the Arctic Ocean (see Figure 1)

Region	Ocean-Ice	Atmosphere-Ice	Region	Ocean-Ice	Atmosphere-Ice
1	0.696	0.592	7	0.246	−0.102
2	0.691	0.275	8	0.768	0.323
3	0.763	0.218	9	0.727	0.314
4	0.704	−0.034	10	0.508	0.075
5	0.603	0.232	11	0.326	0.107
6	0.253	0.597	12	0.174	−0.016

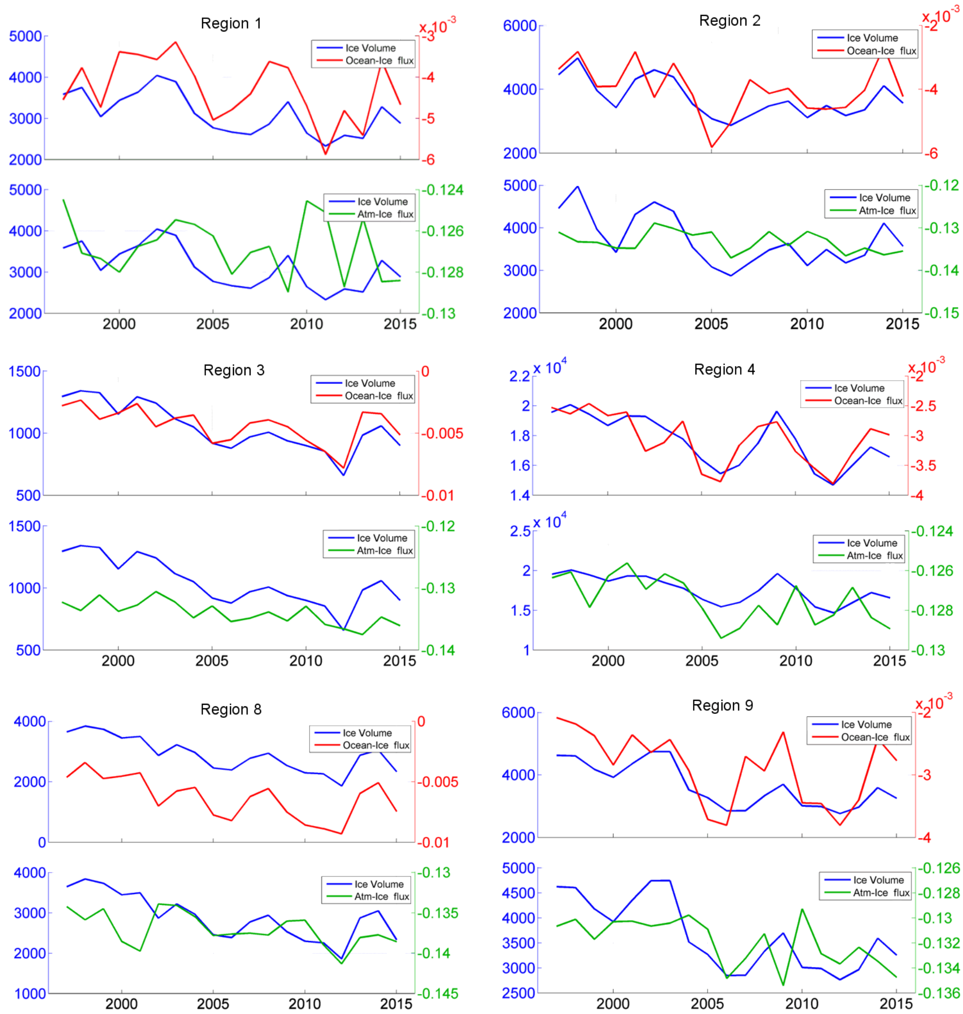

Figure 2. Graphs of ice volume, ocean-ice (upper) and atmosphere-ice (lower) flows obtained as a result of numerical simulation for the period 1997–2015

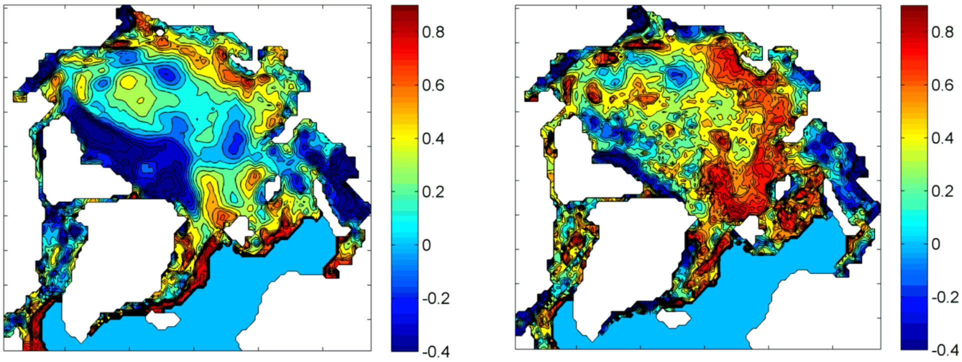

Figure 3. The distribution of the correlation coefficients between the volume of ice and heat fluxes from the atmosphere (left) and the ocean (right). The analysis was carried out according to the numerical modeling results for the period 1997–2015

The values in the table show that the correlation between the ice volume and the ocean-ice flow is highest in Regions 1–5. These regions are located along the trajectory of two branches of the Atlantic water entering the Arctic. Especially important is the influence of the ocean in Region 1, where the Atlantic water has a higher temperature.

The correlation of the ice volume with the atmosphere-ice flow in the Barents Sea (Region 1) and the Fram Strait (Region 6) is also high. Possibly, this is due to the mutual influence of flows from the atmosphere and the ocean in the regions with a low ice concentration. In these regions, there is a great correlation between the ocean and the atmosphere (0.645 in Region 1 and 0.783 in Region 6), which is natural for a large area of the year-round open water, so the direct ocean influence is more difficult to evaluate here.

The correlation patterns (Figure 3) allow us to get an idea of the spatial distribution of the correlation between the ice and the heat fluxes from the ocean and the atmosphere. In this figure, regions of the high ocean influence can be distinguished. They are located in the areas of the communication of the Arctic Ocean with the Atlantic and Pacific regions, and also cover a significant part of the distribution trajectory of the Atlantic waters within the Arctic Ocean. The atmosphere has the greatest impact only on the regions in the coastal part, which may be the result of longer periods of the open water.

3.3. The relationship of heat fluxes with a flow through the Fram Strait. The Atlantic waters entering the Arctic Ocean through two branches come with a non-uniform intensity and temperature. To observe the variability in the intensity of the passage of the Atlantic waters, the heat flux through the cross-section AB located in the Fram Strait and the cross-section CD located at the entrance to the Barents Sea (Figure 4) were calculated as follows:

$$\iint \rho c_\rho V \frac{\partial T}{\partial y}\, dx\, dz,$$

where ρ is the water density, c_ρ is the specific heat of water, V is the current velocity component normal to the cross-section, $\frac{\partial T}{\partial y}$ is derivative of temperature through the cross-section, x and z are the horizontal and vertical coordinates along the cross-section, respectively.

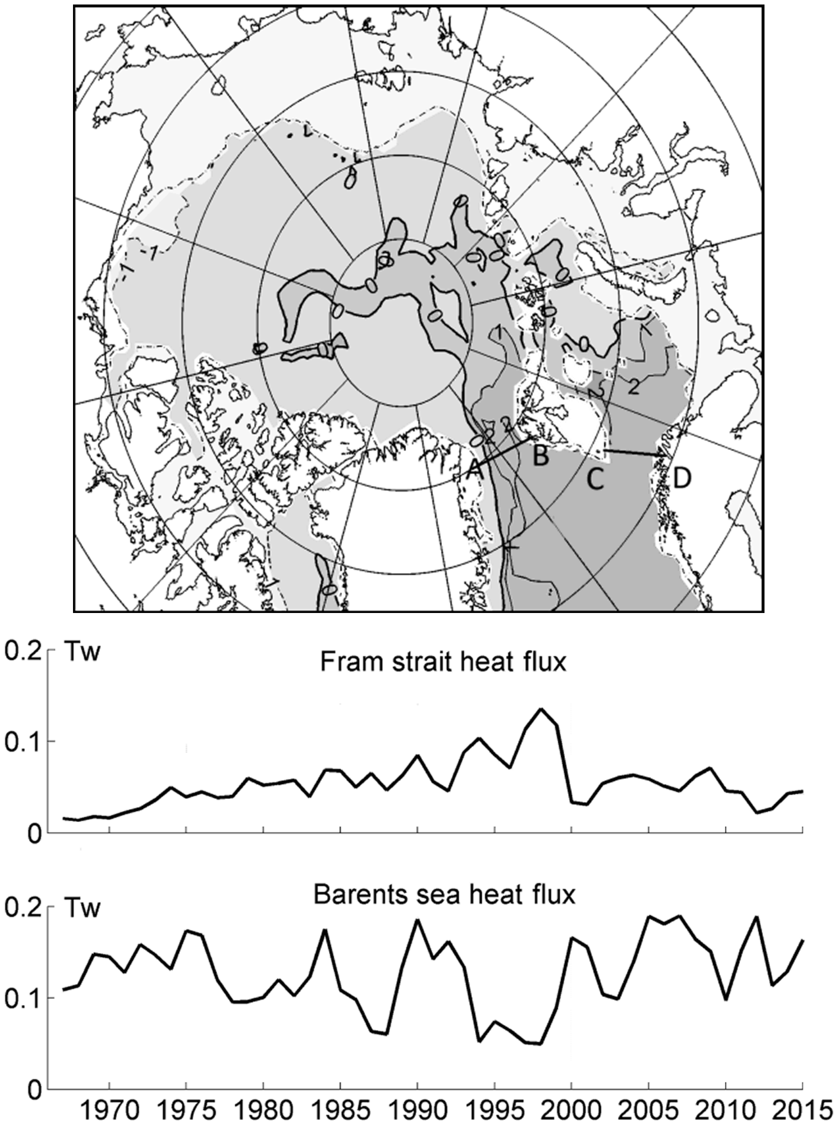

Figure 4. Cross-sections AB and CD and the heat flux through them

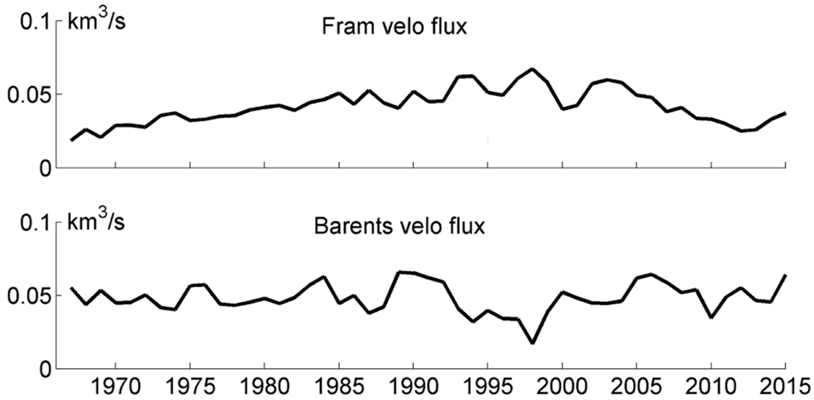

Figure 5. The water flow through cross-sections AB (upper) and CD (lower)

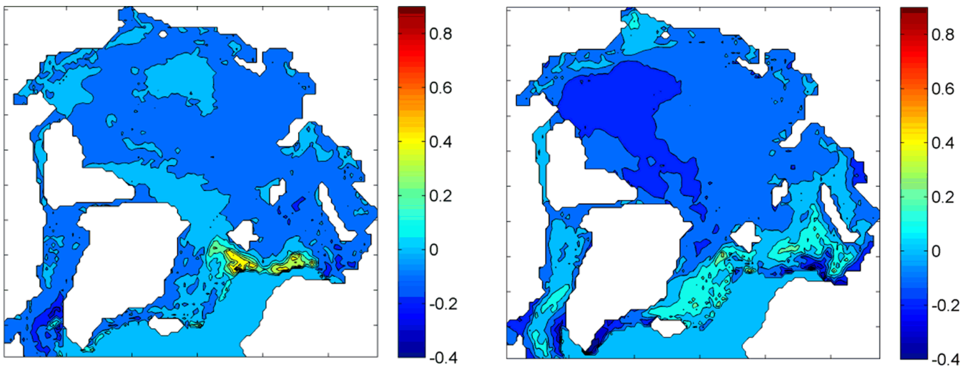

Figure 6. The distribution of the correlation coefficients between flows through the cross-sections AB (left) and CD(right) and ocean-ice heat fluxes

The graph of the flow through the Fram Strait shows a gradual increase in the flow, which ceased after 2000. Apparently, this was due to a decrease in the flow rate, which has the same variability in the graph (Figure 5), but not to a decrease in the water temperature, which was rather high after 2000. The flow through the Barents Sea, on the contrary, shows a weak growth after 2000.

The correlation of the flow through the Fram Strait with the ocean-ice flow (Figure 6, left) shows that the Fram Strait has the greatest connection with the regions nearby, as well as with the waters located north of Greenland and being on the path of the surface water through the Fram Strait. In these regions, either the AB return branch or the cold surface waters, which affect the temperature in the Fram Strait, can pass.

For the flow through the Barents Sea (Figure 6, right), the relationship is natural, capturing the trajectory of the Barents Sea branch, which includes the Barents and the Kara Seas, as well as the AB branch towards the Greenland Sea, the remaining regions of the Atlantic were not taken into account in the calculation, since they are free of ice.

In the correlation pictures, not all the regions are taken into account, since the time shift was ignored when calculating the correlation coefficient. In general, the consequences of the strongest signals passing through the cross-sections can be traced in the ocean-ice flow charts. In 1984–1985, enhanced heat flows through the Fram Strait and the Barents Sea were reflected in the ocean-ice heat flows in Regions 1, 2, 3, 7, 8. Following the intensified flow through the Fram Strait in 1994 and 1998, there were successive amplifications in the ice flows in Regions 1 (1994, 1999), 2, 3 (1995, 1999, 2000), and 9 (1996, 2000). A strong flow through the Fram Strait in 2004–2005 and through the Barents Sea in 2005–2007 entailed increased heat transfer to ice in Regions 1 (2004–2005), 2, 3, 6–9 (2005–2006). A strong flow in 2012 through the Barents Sea was reflected in an increased flow in Regions 7 and 8 in this year.

However, not all the periods of intensification of flows to ice have explanations in the form of an enhanced flow through the cross-sections AB and CD. In certain years, the flow was strong, although this was not preceded by the period of passage of a heat signal through the Fram Strait or the Barents Sea—e.g., in Regions 1 (2011, 2013) and 2 (2002, 2015). As a possible reason, either the atmospheric action or the increased heat transfer from warm intermediate waters to the surface under the influence of turbulent or convective mixing can still remain.

4. Conclusion

This study was carried out using the numerical simulation of the variability of the trajectory and intensity of the Atlantic waters flow into the Arctic Ocean during the period 1948–2016, as well as the impact of this variability on the variability of the state of the ice cover. The study is conducted using a numerical model SibCIOM.

From the calculated values of heat fluxes towards the ice, it was found that the connection between the ocean-ice flow and the volume of ice is highest in the regions adjacent to the Fram Strait, which may indicate to the influence of the heat of the Atlantic waters on the state of the ice cover in this region. The intensity of the heat flux entering the Atlantic waters through two branches is not the only factor affecting the ice cover from the ocean. The heat transfer from the AB to the ice through the mixing processes and the intensity of these processes have also a significant effect on the state of ice in the Arctic Ocean.

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