

Studying the influence of the wind circulation above the Norwegian and the Greenland seas on the Arctic sea ice*

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Abstract. The numerical results obtained have shown that the dynamic atmosphere factor plays an important role in changing the state of the ice cover. A change in the Atlantic water pathway has an influence on the ice depth in the regions of the Barents Sea, the Fram Strait and the Eurasian shelf slope. The numerical results have shown the reduced ice depth in this region with strengthening the cyclonic wind circulation in the Norwegian and the Greenland seas, and increased ice depth with weakening the cyclonic wind circulation. However it is impossible to say that this dependence is direct, after five years the physical processes proceeding outside the Arctic begin their effect on state of the ice cover.

1. Introduction

The climatic changes, occurring on the planet in the last decades, are reflected most brightly in reduction of the area of the Arctic ice. Many factors affect the state of the ice cover in the composite climatic system of the Arctic. The most significant among them is the temperature trend in the atmosphere. However, the dynamic component is also very essential. The ice drift towards the Pole and the Fram strait, regularly strengthening during the circulation mode changes, promotes an increase of the ice moving out of the Arctic Ocean [1, 2]. The intensity of the Pacific and Atlantic waters inflow which is one of the main sources of heat in the Arctic appears an important factor for the state of the ice cover. During the last decades observational systems in the Fram strait have recorded warm signals incoming to the Arctic ocean with the Atlantic water [3] in 1999, 2005–2006, 2009. In spite of the fact that the layer of the Atlantic water in the Arctic basin is at depths of 200–1000 m, the exchange of heat with overlying layers can have influence on changes in the ice cover [2, 4].

In this paper we use the method of numerical modeling for evaluating the sensitivity of the variability of the ice cover to atmospheric circulation variability. A special attention is given to the circulation over the Norwegian and the Greenland seas as the field of forming an initial trajectory of the Atlantic waters in the Arctic Ocean.

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2. The numerical model and statement of the experiment setting

For this study we used a coupled numerical model “ocean-ice” developed in the ICMMG SB RAS. The oceanic part is described in detail in [5, 6]. The ice model CICE [7] was used as an ice component. The ocean model is based on the conservation laws for heat, salt and momentum and on conventional approximations: Boussinesque, hydrostatic and rigid lid. After the separation of the momentum equations into the external and internal modes the barotropic equations are expressed in terms of a stream function. The mixed layer parameterization as a vertical adjustment is based on the Richardson number. No-slip boundary conditions are used at the solid boundaries. The model domain includes the Arctic and the Atlantic Ocean north of 20°S. At 65°N, the North Atlantic spherical coordinate grid is merged with the displaced poles grid in the Arctic. The size of the horizontal grid in the Arctic varies from 10 to 25 km. The model version used here has 38 unevenly spaced vertical levels. A minimum depth of the shelf zone is taken to be 20 m.

The model used for the sea ice, known as the elastic viscous-plastic model, is a modification of the standard viscous-plastic model of the ice dynamics [8]. This model is well documented in [9]. The ice thickness is calculated based on the thermodynamic model [10] for each category of ice. The horizontal ice transfer is performed using the semi-lagrangian advection scheme [11].

3. Experiment 1. The sensitivity of the sea ice in the Arctic Ocean to the state of the atmosphere

Among the factors affecting the state of the ice cover in the Arctic Ocean the atmospheric processes occupy the most important place. First of all, it is the temperature of the atmosphere, which has a steady uptrend in the recent decades. Also, it is the variability of the circulation of the atmosphere, which affects the large-scale ocean circulation. These factors are not independent; the air temperature also rises because of an increase in the warm air masses entering to the Arctic from the North Atlantic during the periods of the positive NAO index [13].

The atmospheric circulation variability can affect the ice cover state in several ways. On the one hand, the trajectory of the transarctic drift, that carries the ice outward the Arctic, can change. On the other hand, changes in the direction of the water cycle in the Central Arctic can alter the trajectory of the Atlantic water, the positive temperature water, which is one of the sources of heat in the Arctic Ocean. The intensity of the circulation in the cyclonic atmosphere over the Norwegian and the Greenland Seas affects the

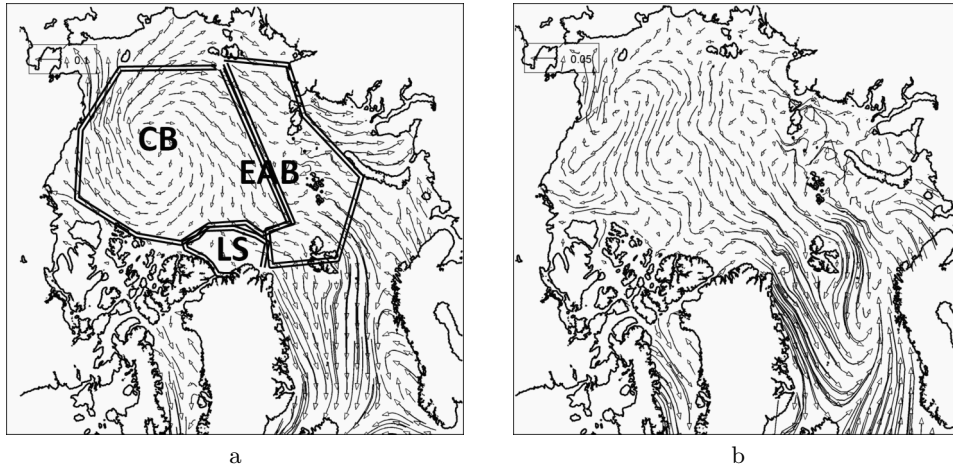
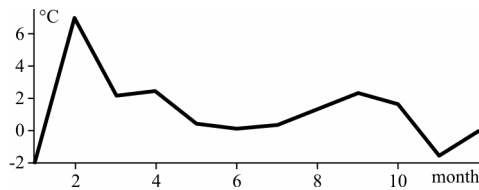


Figure 1. The mean annual atmospheric circulation over the Arctic Ocean for 1960 (a) and 1989 (b). In 1960, the circulation over the central Arctic is anti-cyclonic, in 1989 – cyclonic

Figure 2. Difference in the monthly average atmosphere temperature between the two reanalysis data NCEP/NCAR for 1989 and 1960 through the entire Arctic: $T_{1989} - T_{1960}$



intensity of the heat entering from the Atlantic to the Arctic Ocean with the air and water masses.

In this study, we have estimated the long-term influence of two atmospheric conditions on the Arctic ice cover. In order to do this, we used the NCEP/NCAR [12] reanalysis data of the atmosphere for 1960 and 1989. During 1960, the wind circulation over the Arctic Ocean was mostly anti-cyclonic (AC), during 1989 – cyclonic (CC) (Figure 1). Also, there are differences in the atmospheric temperature between these two years: in 1989 the temperature throughout the year was higher than in 1960 (Figure 2). Also, the NAO index, which is associated with the intensity of the cyclonic water circulation in the Norwegian and the Greenland Seas, represented one of the lowest values for 1960, and for 1989 – the highest value throughout the history of observations (1948–2014) [13].

At first, the model spin-up for 1948–1965 has been triggered with the use of the climatic data set PHC [14] as the initial distribution. Thereafter, two model runs for 10 years with two different atmospheric conditions CC and AC have been started. As an initial distribution, data sets obtained as

a result of spin-up of 1948–1965 were used. We assume that if the prevailing condition of the atmosphere affects the state of the ice cover, distinctions between the results of model runs with opposite atmospheric circulations will increase every year, and after 10 model years we will see an appreciable difference.

4. Results of Experiment 1

The analysis of the results obtained was aimed at evaluating the state of the ice cover on various regions of the Arctic Ocean, as the sensitivity to the atmospheric variability depends on the location of regions relative to the main atmospheric movements, ice drift, trajectories of warm currents, etc.

The analysis conducted has shown that the qualitative differences were obtained in three regions of the Arctic ocean: the greatest part of the Euroasian basin (EAB), the territory including the whole Canadian basin and the Makarov basin (CB), and a small territory to the North of the Greenland including the Lincoln sea (LS). These territories are depicted in Figure 1a. When analyzing the experiment, we observed the reduced ice volume under the atmospheric conditions CC in the most part of the Arctic (EAB and CB) (Figure 3).

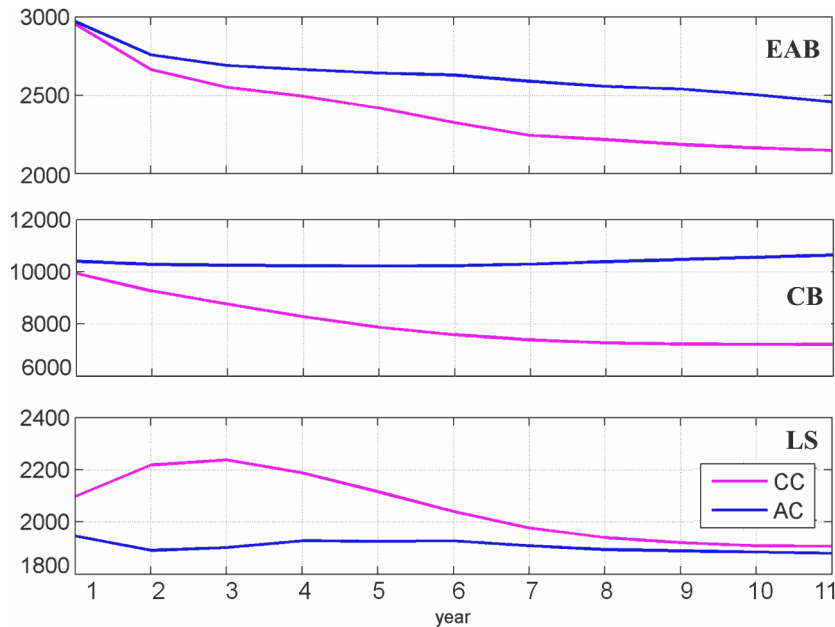


Figure 3. The ice volume (km^3) in the Arctic regions designated in Figure 1, obtained as a result of experiments with cyclonic (CC) and anticyclonic (AC) atmospheric conditions

Quite an opposite result was obtained for the LS region. The experimental results show a significant increase in the ice volume in this region under the atmospheric conditions CC, in contrast to the atmospheric conditions AC, whereas for the Canadian basin located near by the CC circulation has contributed to the reduction of the ice volume. As a possible reason of such a distinction, we can specify a geographical position of this territory, which is located near to the trajectory of the transarctic drift carrying the ice outside the Arctic. With the prevalence of the cyclonic circulation in the atmosphere above the Arctic, the trajectory of the transarctic drift shifts toward the Lincoln Sea, and the amount of ice in this region is increasing due to the ice brought by the winds from the Canadian basin (see Figure 3). Thus, the atmospheric circulation has a direct impact on the ice content in the LS region.

As for other parts of the Arctic, the CC conditions in comparison with the AC conditions lead to the reduced ice volume. Notably, in the CB region the difference regularly increases, and in the EAB region the difference in distinctions does not always increase with time: after 5 years the plots began approaching to each other, the ice melting rate for the atmospheric conditions CC decreases. As a possible reason of such a distinction we can assume only the influence of the ocean, since the atmospheric conditions in this experiment throughout 10 model years did not vary.

For the purpose of estimating the relations between the influence of the ocean and the ice state, there was calculated a heat flux coming with the oceanic waters to the Arctic through the Fram strait and the Barents Sea (Figure 4) For the Barents Sea the heat flux calculated for the conditions CC steadily exceeds the heat flux calculated for the conditions AC. This is due to the increased atmospheric circulation above the Norwegian and the Greenland Seas for the conditions CC.

For the Fram Strait, the increased atmospheric circulation has given the response in the increasing the income heat only during the first 4 years; after that a decrease was observed. The heat impulses of the Atlantic water coming to the Arctic are often associated with a high value of the NAO index, when the heat from the subarctic region comes to the Arctic Ocean with the circulation strengthening.

However, according to the results of the experiment, the long-term existence of the strengthened circulation in the subarctic region leads to the weakening of a heat flux, whereas, with the weak circulation, the heat flux steadily increases with time and after 6 model years exceeds the value of a comparable experiment for the conditions AC. And at the same time point a difference between the ice volumes for the conditions CC and AC in the Eurasian basin begins to be reduced (see Figure 3). Thus, the ice cover state in the greatest part of the Arctic is determined by the atmospheric conditions. However in the Eurasian basin the influence of the ocean has also been noticed.

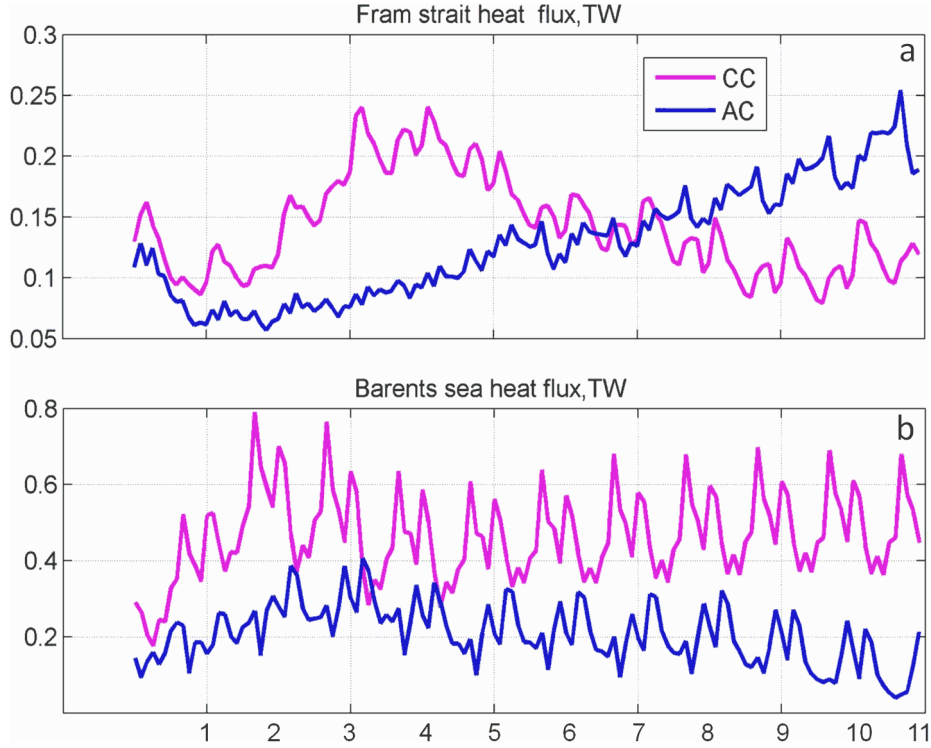


Figure 4. A heat flux entering the Arctic Ocean through the Fram Strait (a) and the Barents Sea (b)

The dynamic factor of the atmospheric influence is clearly expressed only on territories to the North of Greenland (LS). On other parts of the Arctic Ocean both the dynamic and thermal factors of the influence of the atmosphere are possible. The air temperature for the conditions CC throughout the year exceeds the air temperature for the conditions AC and along with atmospheric circulation could be the cause of reducing the Arctic ice thickness. In order to separate the dynamic factor from the thermal factor of the influence of the atmosphere in the next experiment, we have conducted a series of numerical model runs with the identical reanalysis data differing only in the circulation over the Norwegian and the Greenland seas.

5. Experiment 2. The influence of the atmospheric circulation in subarctic region on the state of the sea ice

We have carried out the numerical experiment aimed at the analysis of the sensitivity of the ocean-ice climatic system to the long-term disturbances of a small amplitude in the atmospheric circulation over the Norwegian and the Greenland seas. As the atmospheric conditions for the basic experiment,

the atmospheric reanalysis data NCEP/NCAR [12] were used. Two next experiments included additional cyclonic or anticyclonic disturbances in the atmospheric pressure field with the center at the point of 72.64°N , 2.93°E , 1000 km radius and the amplitude of 4 mb:

- BASE— the basic experiment, atmospheric data NCEP/ NCAR;
- GS₁— atmospheric data NCEP/ NCAR + anticyclonic disturbance;
- GS₂— atmospheric data NCEP/ NCAR + cyclonic disturbance.

The numerical experiments were conducted for the period of 1970–2014. The climatic data set PHC [14] was used as an initial distribution of hydrological characteristics. We assume that the intensity of the Atlantic water income into the Arctic through the Fram strait and the Barents sea depends on the intensity of the cyclonic circulation of the atmosphere over this region and therefore it affects the state of the ice cover.

6. The results of Experiment 2

The results of a numerical experiment simulate the variability of the sea water and the state of the sea ice caused by the atmospheric forcing variability. For the analysis of the sensitivity of the ice cover state to the atmospheric dynamics variations of the region of the Norwegian and the Greenland seas we have calculated the variability of the ice volume obtained as a result of the three experiments throughout the calculation period.

In Figure 5, the plots of the ice volume for the three experiments are shown. The main result of this comparison is the conclusion that the inclusion of an additional cyclonic circulation in the region of the Norwegian and the Greenland seas contributes to the ice cover reduction, while the anti-cyclonic circulation— to the ice cover grow.

The most sensitive to changes in the wind circulation are two regions located at the beginning of the trajectory of the Atlantic water in the Arctic: the region A— the Fram strait and the Eurasian shelf slope (see Figure 5a) which correspond to the Fram branch of the Atlantic water, and the region B— the Barents sea (see Figure 5b) in which there passes the Barents branch of the Atlantic water.

Except for our general conclusion about the influence of the anticyclonic and the cyclonic anomalies in the subarctic region on the state of the Arctic ice an additional specification can be made. From Figure 4 one can see that during the period of 1980–1990, deviations of GS₂ result from the BASE experiment are most essential. The strengthening of the cyclonic wind circulation in the subarctic region has gradually led to an increase in the intensity of the ocean circulation (Figure 6) and, also, has caused an increase in the warm Atlantic water inflow to the Arctic both through the

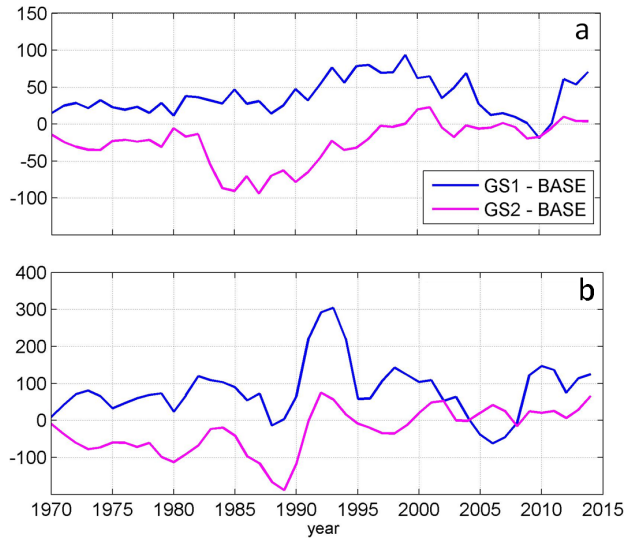


Figure 5. The plot of the ice volume distinctions from the BASE experiment, for the two numerical experiments GS_1 and GS_2 for the period of 1970–2014 in the region (a) the Fram Strait and the Eurasian shelf slope and (b) the Barents sea.

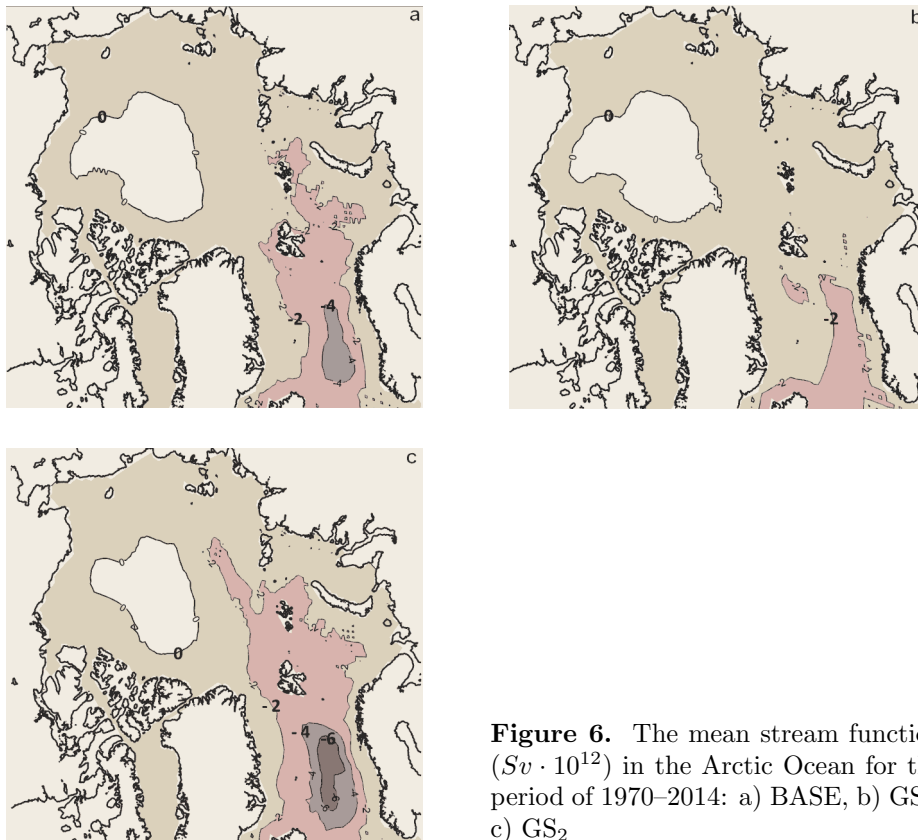


Figure 6. The mean stream function ($Sv \cdot 10^{12}$) in the Arctic Ocean for the period of 1970–2014: a) BASE, b) GS_1 , c) GS_2 .

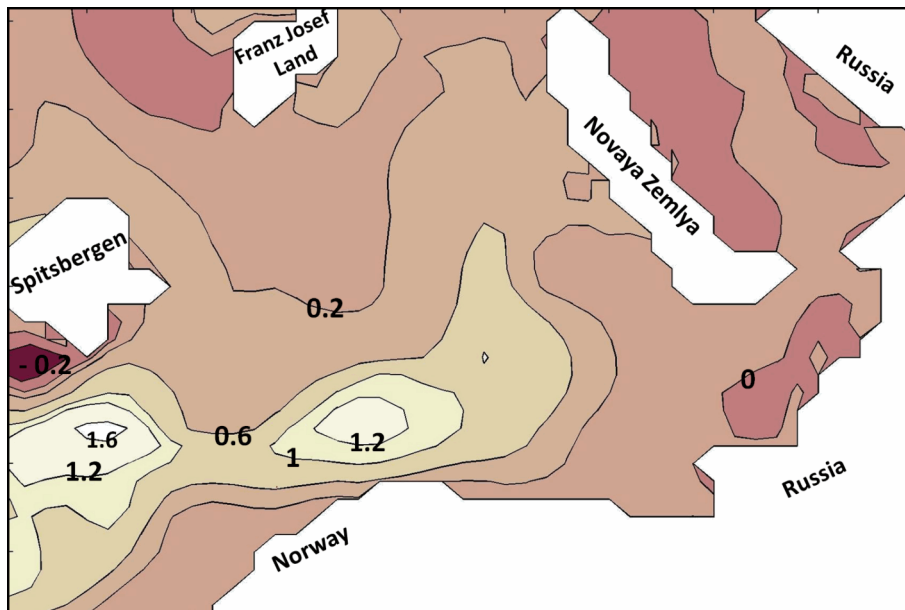


Figure 7. Differences in the sea ice depth between the results of the two numerical experiments: GS₁ minus BASE. The results are shown in the Barents Sea region for March, 1993

Fram strait and through the Barents sea, that has eventually resulted in essential reduction of the ice volume.

During certain periods (1990–2000, 2007–2012) the strongest distinction between the results of the BASE and the GS₁ experiments is observed. In this case, there are essentially no distinctions between the BASE and the GS₂. These distinctions are especially noticeable for the Barents Sea region that is also confirmed by the pictures of the ice thickness distribution for the BASE and the GS₁ experiments (Figure 7).

These results can be due to the strong basic cyclonic circulation in the above mentioned years, therefore its strengthening (GS₂) does not yield an additional warming in the region. On the other hand, its weakening, which leads using the GS₁ to, causes an increase in the ice thickness. not only because of the weakening of the Atlantic water inflow, but also because of carrying the ice through the Barents Sea.

7. Conclusion and discussion

The results of this study, obtained with the use of the numerical ocean-ice model have shown that the dynamic factor of the atmosphere plays an important role in changes in the ice cover state in the Arctic Ocean. This regards as to the wind impact on the ice drift on the ocean surfaces, and

to the wind influence in the subarctic region on the intensity of the warm Atlantic water inflow to the Arctic basin.

The numerical experiments on simulating the Arctic ice cover state have shown the reduced ice thickness at the atmospheric conditions with the prevailing cyclonic circulation over the Canadian basin and the central Arctic in comparison with conditions with the prevailing anti-cyclonic circulation. Though, it is not the only factor that has an impact on the ice cover, there are also differences in the atmosphere temperature for these two periods.

The dynamic factor is supported by the results that have shown an increase in the ice volume in the Lincoln Sea to the north of Greenland for the cyclonic circulation in the atmosphere while its reducing in the other part of the Arctic. So, with the cyclonic circulation in comparison with the anti-cyclonic there is a partial redistribution of the ice cover and strengthening of its carrying beyond the Arctic.

The atmospheric circulation in the subarctic region has also an impact on the of ice melting rate in the Arctic. The intensification of the cyclonic atmosphere circulation in this region causes the intensification of the Atlantic water inflow entering the Arctic and hence bringing about the ice thickness reduction.

However it is impossible to say that this dependence is direct, as in the prolonged period of the acting on the long-standing atmospheric conditions, the unambiguous influence on the ice cover lasts only the first 5 years of the experiment. Further nature of the variety of ice cover seems to be caused by the physical processes proceeding outside the Arctic Ocean.

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