On the interaction of atmospheric dynamics Arctic and mid-latitudes under climate change

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Abstract. The article discusses some aspects of interaction between atmospheric dynamics processes in the Arctic and the mid-latitudes under conditions of global climate change and rapid warming in the Arctic in the lower layer of the troposphere (due to a mechanism of positive feedbacks, enhancement of atmospheric heat and moisture fluxes to the Arctic and heat transfer by currents in the ocean). This is a difficult task, given the fact that the observation of this phenomenon is relatively short. One of the plausible physical hypotheses of the effect of warming in the Arctic on the dynamics of the atmosphere in the mid- and high latitudes is that the reduction of sea ice and snow cover anomalies caused by this warming can lead to changes in the frequency and intensity of the extreme weather events and large-scale circulation in the mid-latitudes and in the Arctic region. Polar cyclones, stratospheric vortex, jet streams, North Atlantic oscillations - these objects of atmospheric dynamics are the subject of discussion in this article. The paper also presents the results of a study of the sensitivity of the Arctic Ocean and the sea ice to variability of atmospheric circulation, taking into account the dynamics of the NAO/AO. Special attention is paid to the circulation over the Norwegian and Greenland Seas, which are the area of formation of the initial trajectory of distribution of Atlantic waters in the Arctic Ocean.

1. Introduction

Relatively fast Arctic warming (FAW) in the recent decades [1-7] has a significant impact on the weather dynamics in the polar and mid latitudes of the Northern Hemisphere. One of the most important signs of this process is the dynamics of sea ice and snow cover. The Arctic Ocean is surrounded by North America, Greenland, and Eurasia. These vast territories of land occupy a large part of the sea ice, which annually grows during snowfalls and freezing and decreases during the process of sublimation and melting cyclically. A significant part of the old Arctic sea ice has disappeared during the last three decades. FAW has contributed to the rapid melting of sea ice and snow in spring at a greater rate than it is modeled in climate models. These changes in the Arctic system coincided with a period of more frequent extreme weather events throughout the Northern Hemisphere in the mid-latitudes [8-13]. It is possible to single out the following dynamic mechanisms connecting FAW with the weather dynamics in the high and middle latitudes: the dynamics of storm tracks; jet streams; planetary waves and the associated upward propagation of energy into the stratosphere and their interaction with the polar vortex, the leading modes of low-frequency oscillations,
NAO/AO [14-23]. With the change in these key features of atmospheric dynamics, it is physically justifiable to associate the mechanisms of interaction between the sea-ice dynamics with low-frequency variability of the circulation and weather in the high and middle latitudes. In particular, in recent years exceptionally cold winters in the mid latitudes of the northern hemisphere have been associated with a reduction of the Arctic sea ice and the anomalies of the snow cover on the continent in autumn [24 - 32]. Satellite observations of the polar oceans have revealed the presence of small intense vortices (mesoscale polar cyclones, MPCs, polar lows) [35] which often resemble hurricanes surrounded by convective clouds. The polar cyclone develops within a small baroclinic perturbation in a potentially unstable environment of the polar region; this can be explained qualitatively in terms of the Rossby radius deformation \( L_R = NH/f \). \( L_R \) indicates the minimum dynamically stable flow scale, the saturated adiabatic vertical gradient (small value of \( N \)), high-latitude location (large value of \( f \)), a very cold air mass (small scale of height \( H \)) lead to a much smaller value of \( L_R \) in the polar regions than in the region outside the tropical cyclones.

In the development of the Polar Cyclone, three phases can be distinguished: the initial stage of development, the mature phase, and the phase of destruction. At the initial phase of development, the baroclinicity and advection of the vortex at the upper levels and the potential vortex (PV) play an important role. At the mature phase of development, convection plays an active role. In most cases, the Polar Cyclone develops in the baroclinic zone of the Arctic air masses far from the polar front. This baroclinic zone can have a different origin, it can be the boundary between the air mass formed by the ice and the polar sea air (the Arctic front), with the remnants of occlusion. The amplification of the cloud cluster, which points to the baroclinic zone, is the result of advection of the vortex and advection of the warm air. This zone can be represented on maps by isolines of the equivalent potential temperature (\( \theta_e \)) at a surface of 850 hPa. The potential temperature of a wet thermometer (\( \theta_w \)) shows a similar picture. Very cold air covers the baroclinic zone leading to unstable stratification.

The Polar Cyclone (PC) usually develops inside the surface trough and in front of the upper trough inside the cold air mass, behind the vast depression or the cold front. Advection of a vortex (AV) plays an important role in twisting the low. The low at the upper levels of the troposphere is filled with a strip of strong cloudiness and causes the AV. Another mechanism is the advection of a potential vortex (PV). As a result of the unstable stratification of the atmosphere at the phase of development of the PC, deep convection arises. Convection is supported by latent and sensible heat fluxes caused by the difference in the air temperature and sea surface temperature and high wind speed. The release of latent heat in the process of convection and Ekman pumping, due to cyclonic circulation at the surface, leads to an intensification (deepening) of the PC. The mature phase of development of the PC is characterized by the formation of a warm core.

Large-scale low-frequency variability in the extratropical atmosphere is manifested in a shift of the storm tracks, and is associated with the variability of large-scale atmospheric modes [14, 37-43]. The main low-frequency atmospheric modes, which account for the largest percentage of atmospheric variability in the middle and high latitudes, including changes in the storm tracks, are the North Atlantic Oscillations/Arctic Oscillations (NAO/AOs). Changes in the storm tracks associated with NAO/AO have a profound effect on the surface temperature and precipitation variability in the North Atlantic sector. When the NAO/AO is in the positive phase, the storm tracks shift northward, and winter is characterized by mild weather over the northern part of Eurasia and the eastern United States but cold weather in the Arctic. In the negative phase of NAO/AO, the storm tracks are shifting towards the equator, and the winter becomes more severe throughout northern Eurasia and the eastern United States but relatively mild in the Arctic.

Recently, the observed temperature trends in winter on all continents of the Northern Hemisphere reflect a negative trend in the NAO/AO during the last two decades [20]. It is likely that the variability of sea ice and/or snow cover can affect the phase and amplitude of the NAO/AO and, therefore, the storm tracks. The structure of the temperature field associated with changes in the Eurasian snow cover correlates with the structure of the temperature field associated with the NAO/AO [44-48]. The difference in the temperature between the Arctic and the middle latitudes is a fundamental factor in the formation of the polar jet flow; a decrease in the temperature gradient between the pole and the mid-latitudes may lead to a weakening of the zonal jet and the appearance of meanders. The weak and meandering flow leads to the fact that the weather systems are shifted to the east more slowly, and warming in the Arctic can lead to long-lived weather systems. Extreme weather
conditions often occur when the atmospheric circulation system has a stable tendency to retain strong meridional wind components.

It should be noted that although warming in the Arctic has weakened the near-surface meridional temperature gradient, the temperature gradient between the tropics and mid-latitudes in the upper troposphere has increased [14], which leads to an intensification of the jet flow at this level. Large-scale Rossby waves over Eurasia are another possible dynamic link between FAW and the weather in the high and middle latitudes. The observed reductions in the Arctic sea ice in the autumn-winter period, especially in the Barents and Kara Seas, correlates with a strong anticyclonic circulation over the Arctic Ocean, which tend to cause the eastern flow and advection of the cold air over northern Europe [21]. This connection can be sensitive to the formation timing of sea ice anomalies.

Winter anomalies cause an immediate local atmospheric response caused by an increase in the turbulent heat fluxes over the Barents and Kara Seas, which, in turn, affects the baroclinicity and large-scale planetary Rossby waves in the atmosphere. While in autumn sea ice anomalies can influence with a delay, the atmospheric response due to the increase in the snow cover in Eurasia [44] or through the change in baroclinicity and high pressure over the Barents and Kara seas that generate upwardly spreading planetary waves into the stratosphere. The collapse of waves in the polar stratosphere weakens the stratospheric polar vortex and can cause stratospheric warming. Circulation anomalies associated with the stratospheric warming extend down to the surface in the following weeks, contributing to the maintenance of negative phases of the NAO/AO and cold conditions on the continent [44].

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. But the dynamic component is also very essential. In this paper we use the method of numerical modeling to evaluate the sensitivity of the ice cover variability to the atmospheric circulation variability. Special attention is given to the circulation over the Norwegian and Greenland seas; this is an area of formation of an initial trajectory of the Atlantic water currents in the Arctic Ocean.

2. Weather regimes and polar cyclones in the Arctic atmosphere

Rapid warming in the Arctic causes changes in the atmospheric conditions and, consequently, it can also significantly affect the intensity and frequency of formation of mesoscale cyclones. There are several prerequisites for mesoscale cyclogenesis [33]: 1) the movement of air from the ice surface to a relatively warm sea surface; 2) the temperature difference between the air and sea should be about 20°C; 3) the formation of a baroclinic zone along the ice edge or in a cold air stream; 4) the formation of increased convection in the cold air; 5) the formation, as a result of chilling of the cold air, of structured convection over the vast water areas in the sub-inversion layer; 6) the approach of a cold trough or a cold cyclonic core at a level of 500 hPa; 7) approximation of the jet flow; and 8) cyclonic vorticity of a large-scale flow. In different regions of the Arctic, the relative role of these factors is different. In this study, attention is focused on variation due to the global climatic changes in the atmospheric conditions favorable for the formation of PCs. At the preparatory stage the Northern Hemisphere (NH) was divided into 10 sectors [33-34], and the boundaries of the sectors of formation of the PC in the NH were identified and defined (Table 1).

| №  | area                                | Longitude       |
|----|------------------------------------|-----------------|
| I  | Greenland Sea, Norwegian Sea      | 15° W - 15° E   |
| II | Barents sea                        | 15° E - 60° E   |
| III| Kara Sea                           | 60° E - 105° E  |
| IV | Laptev Sea (no PC formation)       | 105° E - 150° E |
| Sector | Region Description                             | Longitude Range |
|--------|-----------------------------------------------|-----------------|
| V      | East-Siberian Sea                             | 150º E - 180º E |
| VI     | Chukchi Sea                                   | 165º W - 180º W |
| VII    | Alaska (no PC formation)                      | 150º W - 165º W |
| VIII   | Beaufort Sea                                  | 75º W - 150º W  |
| IX     | Davis Strait                                  | 45º W - 75º W   |
| X      | Danish Strait                                 | 15º W - 45º W   |

Figure 1. Average multiyear CAPE values for each month for a) 1971-2000 and (b) 2301-2330. Average long-term values of the turbulent latent heat flux for each month for c) 1971-2000 and (d) 2301-2330.

The simulation was made with RCP8.5 radiative forcing using a climate system model PlaSim [35], and the values of the available convective potential energy (\( CAPE = \int_{LFC}^{LNB} R_d (T_{vp} - T_{ve}) d\ln p \)) for each of the identified PC generation sectors were calculated, where LFC is the level of free convection, LNB is the level of neutral buoyancy, \( R_d \) is the gas constant for dry air, \( T_{vp} \) is virtual temperature of a certain volume, \( T_{ve} \) is the virtual atmosphere temperature, and \( p \) is the pressure. When moving from the surface of ice to a warm sea surface, cold and dry air is heated and saturated with moisture due to the latent heat flux, which can lead to the development of deep convection and the formation of an intense mesocyclone. For each selected sector the
turbulent latent heat flux \( Q_e = \rho L C_E (q_{sfc} - q) V \), where \( q_{sfc} - q \) is the difference between the specific surface moisture content and the lowest level atmosphere, \( L \) is the heat of evaporation, \( V \) is the wind speed, \( C_E \) is the Dalton number, and \( \rho \) is the density. Figure 1 shows the average multiyear CAPE values and the latent heat flux values calculated for each month for each period under consideration. A significant (4-fold) increase of the CAPE values was obtained for all isolated SP sectors, and an increase (~2-fold) for the turbulent latent heat flux was obtained in the case of climate warming.

These changes can contribute to the development of deeper convection and indicate that the atmospheric conditions with the growth of radiation forcing become more favorable for the development of polar mesocyclones (PMCs). However, with such an intensive growth of radiation forcing, there is a significant reduction in the area of ice in the Arctic, which, on the contrary, creates unfavorable conditions for the formation of PMCs.

Based on the simulation data, the number of cases was calculated where the relative vortex exceeded \( \xi_\theta = 10^{-4} c - 1 \) and the characteristic of the Rossby radius deformation for the vortex structures was estimated: \( L_R = NH/f \), the Rossby radius deformation is of the order of 200 km, which corresponds to the size of the polar mesocyclones. In the North Atlantic, the maximum cyclonic activity occurs between November and December. Compared to real data, the model region of cyclonic activity is shifted to the west. In the North Pacific, the cyclone frequency is approximately the same throughout the cold period.

Figure 2. Frequency of cold air outbreaks to the sea surface (upper: for 1971-2000 and lower: for 2301-2330).
In paper [49] it was noted that extreme weather conditions in the polar latitudes are most often associated with convective instability as a result of marine cold air outbreaks (MCAOs) to the marine surface. The criterion for this event was to consider the condition \( \theta_{700\text{hPa}} - \text{SST} < 2.9 \text{K} \). The number of MCAOs is shown in Figure 2. In the North Atlantic, the region with the maximum MCAO frequency is located somewhat to the south of the region with the maximum number of cyclones. How will the frequency and intensity of polar cyclones vary with climate change? This question remains open.

Theoretical and model estimates show a decrease in the cyclone frequency with an increase in the mean surface temperature, while reanalysis data give a statistically insignificant positive trend [13]. The frequency of cold air outbreaks was estimated for the data obtained with the help of the climate system model. Figure 2 shows the average multi-year frequency values for each period under consideration.

The MCAO frequency in the case of a higher surface temperature is lower everywhere except in the western Pacific. MCAO is often associated with weakening of the polar stratospheric vortex and the descending flow of cold air masses into the lower atmosphere.

3. Dynamic factor of atmosphere at changing state of the ice cover in the Arctic Ocean. Numerical model and Experiment 1 setting

The ice drift towards the pole and the Fram strait, strengthening periodically during the circulating mode changes, promotes an increase of the ice moving out of the Arctic Ocean [50, 51]. The intensity of the inflow of the Pacific and Atlantic waters which are one of the main sources of heat in the Arctic is an important factor for the ice cover state. During the last decades observations in the Fram strait have recorded warm signals coming to the Arctic Ocean with Atlantic water [52] in 1999, 2005-2006, and 2009. In spite of the fact that the layer of Atlantic water in the Arctic basin is at depths of 200-1000 m, the exchange of heat with the overlying layers can have an influence on the ice cover change [51, 53]. It was shown in [54] that the sea ice forcing on the atmosphere can be as significant as the atmospheric forcing on the sea ice in some seasons. Climate changes have occurred since the 1970s, including rapid loss of the Arctic sea ice and large-scale warming. Here we investigate the role of the North Atlantic Oscillation in these rapid changes through its influence on the Atlantic meridional overturning circulation and the ocean heat transport. For this study, a coupled numerical ocean-ice model SibCIOM developed at ICM&MG SB RAS was used. The oceanic part is described in detail in [55, 56]. The ice model CICE [http://oceans11.lanl.gov/trac/CICE] was used as the ice component.

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 that has a steady uptrend in the recent decades. Also, it is the variability of the atmosphere circulation which affects the large-scale ocean circulation. In this study, we have estimated the long-term influence of two atmospheric conditions on the Arctic ice cover. In order to do that, we used the NCEP/NCAR reanalysis data [http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html] of the atmosphere for 1960 and 1989. During 1960 the wind circulation over the Arctic Ocean was mostly anticyclonic (AC), and during 1989 it was cyclonic (CC). There are also differences in the atmospheric temperature between these two years, in 1989 the temperature throughout the year was higher than in 1960. Also, the NAO index, which is associated with the intensity of cyclonic water circulation in the Norwegian and Greenland Seas, for 1960 represented one of the lowest values, and for 1989, the highest value throughout the history of observations (1948-2014) [http://www.cpc.ncep.noaa.gov/ products/precip/CWlink/pna/ nao.shtml].

3.1. Results of Experiment 1

The analysis showed that qualitative differences were obtained in three regions of the Arctic Ocean: the most part of the Eurasian basin (EAB), the territory including all Canadian basin and Makarov's basin (CB), and the small territory to the North of Greenland including the Lincoln Sea (LS).

During the analysis of the experiment in the most part of the Arctic (EAB and CB), we observed a reduced ice volume under the atmospheric conditions CC (Figure 3). The 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 the CC circulation contributed to the reduction of the ice volume. As a possible reason of such distinction we can specify the geographical position of this territory, which is located near the trajectory of the transarctic drift carrying out the ice beyond the Arctic. As for the other parts of the Arctic, here the CC conditions in comparison to the AC conditions lead to a reduced ice volume. Note that in the CB region the difference increases constantly and in the EAB region the difference in distinctions does not always increase over time, after 5 years the plots begin to approach each other, and the rate of ice melting for the atmospheric conditions CC decreases. As a possible reason of such a distinction we can assume only the influence of the ocean in so far as the atmospheric conditions in this experiment throughout 10 model years did not vary.

To estimate the relations between the influence of the ocean and ice condition, we calculated the heat flux coming with oceanic waters to the Arctic through the Fram Strait and the Barents Sea (data is not shown). For the Barents Sea the heat flux calculated for conditions CC steadily exceeds the heat flux calculated for conditions AC. This is due to increased atmospheric circulation over the Norwegian and Greenland Seas for conditions CC. For the Fram Strait, the increased atmospheric circulation gave a response in increasing the income heat only in the first 4 years, and after that a decrease was observed. 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 strengthening circulation.

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

![Figure 3](image-url)  
**Figure 3.** Ice volume (km$^3$) in three regions in the Arctic obtained as a result of two experiments with different atmospheric conditions, cyclonic (CC) and anticyclonic (AC) ones. These regions are: most part of the Eurasian basin (EAB), the territory including all Canadian basin and Makarov's basin (CB), and the small territory to the North of Greenland including the Lincoln Sea (LS).
3.2. Experiment 2 setting

In order to separate the dynamic factor from the thermal factor of the influence of the atmosphere, in the next experiment we conducted a series of numerical model runs with identical reanalysis data differing only in the circulation over the Norwegian and Greenland Seas.

We performed a numerical experiment aimed at analysis of the sensitivity of the ocean-ice climatic system to long-term disturbances of small amplitude in the atmospheric circulation over the Norwegian and Greenland Seas. As the atmospheric conditions for the basic experiment, the atmospheric reanalysis data NCEP/NCAR 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 L, a radius of 1000 km and an amplitude of 4 mb.

- BASE: basic experiment, atmospheric data NCEP/NCAR
- GS_1: atmospheric data NCEP/NCAR + anticyclonic disturbance
- GS_2: atmospheric data NCEP/NCAR + cyclonic disturbance

The numerical experiments were conducted for 1970-2014. The climatic data set PHC [60] was used as an initial distribution of the hydrological characteristics.

3.3. Results of Experiment 2

The results of the numerical experiment simulate the variability of the sea water and sea ice state caused by the variability of atmospheric forcing. To analyze the sensitivity of the ice cover state to variations of the atmospheric dynamics of the region of the Norwegian and Greenland Seas, we calculated the variability of the ice volume obtained as a result of three experiments throughout the calculation period. In Fig. 4 plots of the ice volume for 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 Greenland Seas contributes to the ice cover reduction, and anti-cyclonic circulation, to the ice cover growing. The most sensitive to change in the wind circulation are two regions located at the beginning of the trajectory of the Atlantic water in the Arctic. These are region A, the Fram strait and the Eurasian shelf slope (Figure 4a) which correspond to the Fram branch of the Atlantic water, and region B, the Barents Sea (Figure 4b) where the Barents branch of the Atlantic water passes.

![Figure 4](image-url)

Figure 4. Ice volume distinctions from the BASE experiment, for two numerical experiments, GS_1 and GS_2, for 1970-2014 in the region (a) Fram strait and Eurasian shelf slope and (b) Barents Sea.
4. Conclusions

These modeling studies with the above climate system model have suggested that the changes of CAPE and latent heat fluxes can contribute to the development of deeper convection and indicate that atmospheric conditions of growth of radiation forcing become more favorable for the development of mesoscale polar cyclones (MPCs). However, there is a significant reduction in the area of ice in the Arctic, which, on the contrary, creates unfavorable conditions for the formation of MPCs. In addition, this is consistent with the fact that the MCAO frequency in the case of growth of radiation forcing is lower everywhere except for the Western Pacific Region. It is physically plausible to assume that this is due to the weakening of the polar vortex, since the interaction between the polar vortex and the tropospheric baroclinic zone likely plays an important role in the dynamics of the polar lows.

The results of the study conducted with a numerical ocean-ice model showed that the dynamical factor of the atmosphere plays an important role in the changing of the ice cover in the Arctic Ocean. It is related 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.

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