Main modes of the Arctic Ocean circulation and a relationship between their trends and the Atlantic water heat content

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Abstract. A study is presented on integral variability in Arctic Ocean characteristics, such as the volume transport and the heat content of the Atlantic water (AW) layer, obtained as results of numerical simulations using a model, SibCIOM. On the basis of an EOF decomposition three non-degenerate modes are obtained for the integral stream function and three modes for the heat content of the AW layer in the Arctic. Considering the cross-correlations of the EOF principal components a 44-yr cycle is obtained. It relates the cyclonic circulation mode in the Arctic and the second mode of AW heat content, associated with the AW warming in the area of the Beaufort Gyre. The Atlantic Multi-decadal Oscillation (AMO) statistically can act as a source of such a cycle, however, the thus obtained correlation is at the limit of the admissible significance, and the period of AMO oscillations is 1.5-2 times longer. In our opinion, a relationship with fluctuations in the Atlantic Meridional Overturning Circulation (AMOC) seems to be more plausible. However, no understanding of the role of these two mid-latitude and polar processes in relation to what extent they act as a cause or a consequence has yet been established in this study.

1. Introduction

The variability of the structure of currents, heat content, and stratification of the upper layer of the Arctic Ocean is largely determined by atmospheric circulation, since it forms inhomogeneities in the movement of the upper layer and sea ice, and is also responsible for the transfer of heat, cloudiness and humidity by air flows, determining the balance of thermal flows on the surface of the ocean and ice [1, 2]. Feedback is determined by the presence of ice-free areas, changes in the albedo of the underlying surface, and changes in the temperature and humidity conditions of the surface air.

The dominant mode of atmospheric circulation in the Arctic and in the adjacent mid-latitudes is the Arctic Oscillation (AO) [3]. This has become even more evident since the 1990s. It was shown that the interannual variability of the winter northern stratospheric flow in 1964–1993 is closely related to large-scale circulation anomalies in the middle troposphere. Using the EOF method of decomposition (expansion in terms of empirical orthogonal functions) carried out for the difference in geopotential heights of 500 and 50 hPa, AO structures were obtained, including anomalies in eastern Siberia [4]. In [5], on the basis of numerical modeling, a relationship was established between the tropospheric and stratospheric circulations with the temperature of the
ocean surface.

A noticeable decrease in the volume and area of sea ice [6], on the one hand, was associated with the dynamic features of atmospheric circulation [7], and on the other, with the influence of warm air masses [8]. Thanks to [9, 10], the connection with the general structure of the atmospheric circulation, largely represented by the AO, has become more obvious.

In this paper, we present preliminary results of an analysis of the integral variability in the Arctic Ocean characteristics, such as the volume transport of the main currents, the heat content of the Atlantic water (AW) layer depending on the values of the main indexes of atmospheric circulation.

2. Methodology

To analyze the results of numerical experiments, we will use the method of expansion in empirical orthogonal functions (EOFs). The method allows one to reduce the dimension of the analyzed system, find a relatively small number of independent variables that contain the greatest information about the variability of the data, and assess the relative significance of each structure.

The EOF decomposition method, based on the identification of statistical regularities of the variability of hydrodynamic characteristics, has been used for a long time and is one of the tools for analyzing data and results of numerical modeling, allowing one to describe the nature of the variability of 2-3-dimensional fields using a limited set of eigenfunctions (modes) and their amplitudes (principal components). Using statistical methods and the EOF decomposition method in a number of works (for example, [11, 12, 13, 14]), a direct relationship was shown between the modes of atmospheric circulation and the nature of ice distribution in the Arctic and its dynamics. In [13], based on observations in 1953-1992, a mechanism of relationships between anomalies of ice concentration and pressure at sea level was proposed, providing a cyclical repetition every 10 years. According to [10], a growing trend of the North Atlantic Oscillation (NAO) caused a significant reduction in ice in the Arctic Ocean.

Here we are going to analyse the integral variability in the Arctic Ocean characteristics, such as the volume transport of the main currents, the heat content of the AW layer depending on the index values of the main atmospheric circulations.

To assess the characteristics of the dynamics and thermodynamics of the Arctic Ocean, we used the simulation results obtained using the coupled ice-ocean model of the Arctic and North Atlantic, SibCIOM. The model grid is built using a three-polar system and has 1/2 degree resolution in the North Atlantic and a resolution in the range of 10-26 km in polar region. The model has 38 levels vertically, with a surface resolution of 5 m at the surface, and the upper 1000 m layer contains 24 levels. The model is initialized using PHC data [15]. Sea ice is described using the CICE-3 model. The discharge of the main rivers in the region is taken from the RivDis-1.0 data [16] and annually repeats the averaged seasonal variation. The flow rate in the Bering Strait is set equal to 0.8 Sv. At the southern boundary (20S), a uniform flow rate is set to compensate for all external inflows.

The main part of the analyzed results was obtained in a numerical experiment to restore the dynamics of the ocean and sea ice in the period from January 1948 to December 2019. Atmospheric forcing was obtained from the results of NCEP/NCAR reanalysis [17] and includes the surface air temperature (at the level of \( \sigma=995 \text{ db} \)), air humidity, pressure at sea level, precipitation rate, downward long-wave and short-wave radiation, as well as surface wind velocity.
3. Results

3.1. EOF decomposition of integral stream function

Figure 1a-c shows the first three non-degenerate EOF modes of the expansion of the integral stream function: SF1, SF2, and SF3. The first mode represents unidirectional (cyclonic or anticyclonic, depending on the sign) circulation in the entire Arctic Ocean basin, with the exception of the marginal seas, where the opposite compensating circulation is formed.

The second and third modes show the dominant circulation in the Norwegian and Greenland Seas (NGS) opposed in the first case with the circulation in the Canadian basin (while the Amundsen basin has a weak tendency to support the NGS circulation) and in the second case with the circulation in the Amundsen Basin (while the Canadian basin has a weak tendency to support the NGS circulation). We should recall that we are talking about anomalous deviations from the average climatic distribution of currents. Note also that the enhancement of the second mode corresponds to the formation of the so-called anticyclonic phase of the Arctic Ocean Oscillation (AOO) [18], and its weakening corresponds to the formation of a cyclonic phase.

3.2. EOF decomposition of the AW heat content

The second field that we analyzed using the EOF decomposition is the heat content of the AW layer. The upper boundary of the layer $h_u$ was determined as the point of transition of the water temperature from negative values typical of the surface Arctic waters to positive ones, and the lower $h_l$ as the reverse transition from positive to negative temperatures of deep waters. Thus,
the heat content $HC$ is a function of geographic coordinates and time determined by

$$HC(x, y, t) = \int_{h_i}^{h_u} c_p \rho T(x, y, z, t) dz,$$  \hspace{1cm} (1)

where $T$ is the water temperature, $\rho$ is the density, $c_p$ is the constant pressure heat capacity, $x, y, z$ are the horizontal and vertical (positive is upward) coordinates, $t$ is time.

Figure 1d-f shows the result of the EOF decomposition of this function in three non-degenerate modes. To understand these modes, we will assume that their structure reflects a reaction to the inflow of abnormally warm waters through the Fram Strait. It means that the signs of the first two modes coincide with that shown in the figure, but the sign of the third one must be opposite.

The picture of the first mode gives a distribution when, simultaneously with the arrival of warm AW, it cools north of the islands of the Canadian Archipelago and warms in the Makarov Basin area. The second mode demonstrates the widespread cooling of AW, except for the Eurasian shelf slope. And, finally, the third mode practically does not affect most of the Arctic Ocean, but results in a significant cooling (taking into account the opposite sign) on the Eurasian slope.

3.3. Relationship between the Arctic Ocean circulation modes and the change in the AW heat content

When considering the obtained modes, the question of the correspondence between the Arctic Ocean circulation modes and the variability of the AW heat content is of great interest. Table 1 shows the values of the cross-correlation coefficients of the corresponding principal components.

| Q1   | 21  | 15  | -34 |
| Q2   | 10  | -52 | 2   |
| Q3   | 4   | -12 | 2   |

If we consider synchronous changes in the main components of the expansion of the stream function and the AW heat content, we can establish the following linear relationships:

- The first circulation mode (SF1, representing the overall Arctic cyclonic mode) is poorly synchronized with all modes of variability of the AW heat content. The most noticeable
effect with a coefficient of 21% is exerted on the first mode and associated with warming in the central regions of the Arctic and cooling off the Canadian Islands. However, it should be recognized that this correlation is not significant.

- The most remarkable relationship, constituting -52% of the correlation, is manifested between the second Arctic Ocean circulation mode and the second mode of the AW heat content variability. This relationship is expressed in a significant warming of the AW in the Canadian Basin during the formation of a cyclonic mode of circulation in the Arctic Ocean (corresponds to the positive phase of AOO).

- The third circulation mode is anti-synchronized with the first mode of variability of the AW heat content. A negative trend is especially noticeable on the Eurasian shelf slope, with the correlation of -34%. It is at the edge of the significance level.

- The rest of the cross-correlations are either weak or insignificant.

However, we cannot expect that the restructuring of the circulation should lead to an immediate change in the heat content in the AW layer, or vice versa, the second one will immediately cause the first one. Therefore, it is appropriate to consider cross-covariances taking into account the time lag. Table 1 also lists the maximum values of correlations and anticorrelations with the time lag at which such a correlation is achieved. As a positive lag value we will take the situation when the flow restructuring precedes the change in the heat content of the AW layer. Let us note the most significant relationships:

- A change in the first circulation mode of SF1 leads in six years to co-directional changes in the first mode of variability of the heat content of the AB layer. The corresponding correlation coefficient is significant and amounts to 60%.

- A more significant reaction to a change in SF1 occurs after 13 years. We can trace it in the amplification of the opposite phase of Q2. The correlation coefficient is -78%. On the contrary, a change in Q2 leads with a correlation of 73% to a co-directional change in SF1 after 9 years. Thus, within these two modes (SF1 and Q2), we can trace a 44-yr cycle: positive SF1 - negative Q2 after 13 years - negative SF1 after 9 years - positive Q2 after 13 years - again positive SF1 after 9 years ...

- The change in the second SF2 circulation mode in two years forms the opposite change in Q2 with a coefficient of 85%. After 14 years, with a coefficient of 67%, the opposite change in Q3 occurs.

- The reaction to a change in the SF3 circulation mode is similar to that in SF2, but opposite in sign and less reliable in correlation. For Q2 the correlation is 48% after 2 years, and for Q3 it is 37% after 15 years.

- With a correlation of 54%, the change in Q1 after 13 years is followed by the opposite changes in the SF3 circulation.

4. Discussion
The most interesting conclusion that follows from the correlation analysis of EOF decompositions is the formation of a 44-yr cycle for the first circulation mode SF1 and the second mode of the AW heat content in the Arctic. First of all, we are interested in whether, among the known climatic fluctuations, there is one similar in frequency and related to circulation in the North Atlantic and Arctic regions. Among those, two can be distinguished with similar abbreviations:

- AMO – Atlantic Multi-decadal Oscillation,
- AMOC – Atlantic Meridional Overturning Circulation.

Note also that on the basis of geographical observations of the high flow of inland water bodies and, in particular, Lake Chany (West Siberia) [19] and changes in the mountain glaciation in
Eurasia and North America [20], similar conclusions have already been made about the existence of a 35–45-year climatic cycle. It is possible that there is a connection between the periodicity discovered in these works and the oscillation we have identified.

To begin with, let us clarify how the periodicity we obtained is manifested. The intensification of the SF1 circulation mode results in the strengthening of the general cyclonic gyre in the Arctic (Fig. 1a). At the same time, the transport of AW coming from the North Atlantic increases. Most of this Atlantic anomaly enters through the Barents Sea opening, while the supply through the Fram Strait, on the contrary, weakens somewhat. Further movement of this anomaly consists in following along the St. Anna Trough and the shelf slope of the Laptev Sea down to the Lomonosov Ridge. Further, one part of the anomaly moves along the ridge towards the Fram Strait, while the other one penetrates into the Makarov basin. Following along the shelf slope of the East Siberian Sea, the flow divides again. One part of the anomaly moves along the Mendeleev Ridge, and the other one penetrates into the Beaufort Sea. Thus, following the trajectory represented by the stream function anomaly (Fig. 1a), we conclude that a significant part of the Atlantic waters reaches the Beaufort Sea area carrying warmer and saltier water into the local AW layer. According to the correlation (Table 1), this happens after 13 years. The temperature anomaly takes the form of the second mode Q2 taken with the opposite sign (Fig. 1e). 9 years after this, the negative phase SF1 sets in, which means that the general cyclonic direction motion of the surplus AW weakens, as a result of which the AW deficit is formed in all the indicated areas along the trajectory along with a negative anomaly of the AW heat content (positive Q2).

Both the AMO and AMOC can have an impact on the rate of the AW entry into the Arctic. However, according to [21, 22] the period of the characteristic AMO fluctuation is 1.5–2 times longer and is about 60–80 years. It is characterized by coherent changes in the sea surface temperature (SST) over the whole of the North Atlantic that are most pronounced in the extratropics. Figure 2 presents a comparison of the AMO index (downloaded from NOAA site [23]) and the principal component of SF1, both smoothed with a 5-year sliding average. Also, this figure presents a view of the principal component of SF1 when shifted 19 years backward in time and taken with opposite sign. This shift gives the best correlation equal to 35.6%, which is at the edge of statistical significance. Also, the figure shows that the time period of the SF1 principal component is visually shorter than that of the AMO index. Therefore, we can only with some doubt assume the relationship of these two processes.

The AMOC, defined as the integrated meridional transport in the Atlantic, plays an essential role in the maintenance of the Northern Hemisphere climate as it transports a substantial amount of warm and saline waters poleward [24]. The northward heat transport associated with the AMOC is up to 1.3 PW around 25N [25].

The interdecadal variability was estimated in some realistic climate models, for example:

- [26] suggested that North Atlantic fluctuations with a dominant time scale of approximately 50 yr appeared in the GFDL model. The irregular oscillation in the North Atlantic Ocean appears to be driven by density anomalies in the sinking region of the thermohaline circulation (approximately 52N to 72N) combined with much smaller density anomalies of opposite sign in the broad, rising region.
- [27] proposed a coupled mechanism to explain a 35-yr mode of North Atlantic variability in the ECHAM3-LSG model. If AMOC is anomalously strong, the ocean is covered by positive SST anomalies. The atmospheric response to these anomalies involves a strengthened NAO, which leads to anomalously weak evaporation and Ekman transport off Newfoundland and in the Greenland Sea, and the generation of negative surface salinity anomalies reducing the deep convection in the oceanic sinking regions and poleward heat transport. The formation of negative SST anomalies completes the phase reversal.
Figure 2. Comparison of AMO index (blue) and principal component of SF1 (red), both are smoothed with 5-yr sliding average. Dashed red line represents principal component of SF1 shifted 19 years backward in time and taken with opposite sign. This shift gives best correlation equal to 35.6%.

Both are claiming periodicity close to 44-yr and relate it to a density anomaly in a subpolar region of the North Atlantic.

To calculate the value corresponding to the magnitude of the AMOC, we consider the value \( W \) – the total northward transport at 25N according to

\[
W = \int_{-H}^{0} \int_{X_w}^{X_e} V^+ dx dz,
\]

where \( V^+ \) is the positive northward velocity component

\[
V^+ = \begin{cases} 
  v & \text{if } v > 0 \\
  0 & \text{if } v \leq 0 
\end{cases}
\]

\( v \) is the meridional velocity component at 25N, \( H \) is the depth, \( X_w \), and \( X_e \) are the west and east boundaries at 25N. Before a comparison of the SF1 principal component and the \( W \) timeseries, we made 5-yr sliding averaging to remove short-term variations, then we removed quadratic trends from both timeseries, and finally we normalized them, i.e. by means of scaling and offsetting made the average equal to zero and the standard deviation equal to unit. Figure 3a shows the correlation coefficient between the SF1 principal component and \( W \) depending on the time lag. As positive lag we considered the time shift when changes in the Atlantic overturning circulation precede changes in the Arctic SF1 mode.

Figure 3b presents a direct comparison of these two timeseries. If we consider a positive lag, then according to Fig. 3a we have two significant extrema in the correlation coefficient. The first one is negative and equal to -56.2%, it corresponds to a lag of 15.5 years and the second one is positive – 87.8% with a lag of 26.4 years. The whole picture could be presented as follows (let us consider the AMOC change as its strengthening): the AMOC increase first leads to a
Figure 3. Comparison of SF1 principal component and $W$ – total northward transport at 25N, both are smoothed with 5-yr sliding average, taken without quadratic trend and normalized: (a) correlation coefficient depending on time lag, (b) timeseries of $W$ (blue) against SF1 principal component (red), (c) timeseries of $W$ (blue) against two positive lags of SF1 principal component: 15.5 years backward in time and with opposite sign to give better negative correlation -56.2% (thin red), and 26.4 years shift backward in time to give better positive correlation, 87.8% (bold red), (d) timeseries of $W$ (blue) against two negative lags of SF1 principal component: 9.6 years forward in time to give better positive correlation, 52.7% (thin red), and 21.4 years shift forward in time and with opposite sign to give better negative correlation, -89.9% (bold red).

slowdown of the Arctic SF1 mode after 15.5 years, and then after another 11 years the SF1 reaches a maximum.

If we consider a negative lag, i.e. changes in the Arctic SF1 circulation precede changes in the AMOC, we again have two significant extrema in the correlation coefficient. The first one is positive and equal to 52.7%, it corresponds to a lag of 9.6 years and the second one is negative – 89.9% with a lag of 21.4 years. In this case the picture could be described as follows: the increase of the SF1 circulation mode first leads to a speedup of the AMOC after 9.6 years, and then after another 12 years the AMOC becomes weak.

Both scenarios seem plousible and need to be investigated in a future work. We are still to consider more sophisticated study on the raised issue providing an observational background. So far our study does not show whether these processes are linked and which physical mechanism could be responsible for this linkage, but it emphasizes the statistical possibility of interacting middle-latitude and polar ocean circulations.
5. Conclusions

In this paper, we analyzed integral variability in Arctic Ocean characteristics, such as the volume transport of main currents, and the heat content of the AW layer, obtained as results of numerical simulations using the SibCIOM model. To analyze these results, we used a statistical method based on an EOF decomposition of time-dependent two-dimensional fields. Three non-degenerate modes were obtained for the integral stream function and three modes for the heat content of the AW layer in the Arctic. Considering the cross-correlations of the EOF principal components of these modes, we have found that the most obvious relationships between these revealed modes manifest themselves when the possible time lag between timeseries is taken into account. The most interesting feature revealed by this analysis is the presence of a 44-yr cycle in the interaction of the cyclonic circulation mode in the Arctic and the second mode of heat content of the AW layer associated with AW warming in the area of the Beaufort Gyre. Considering possible reasons for the formation of such a cycle, we have identified two large-scale oscillations. The Atlantic Multi-decadal Oscillation (AMO) statistically can act as a source of such a cycle, however, the thus obtained correlation is at the limit of the admissible significance, and the period of AMO oscillations is 1.5-2 times longer. In our opinion, a relationship with fluctuations in the Atlantic Meridional Overturning Circulation (AMOC) seems to be more plausible. A number of model studies indicate the presence of near 44-yr periodicity of these oscillations, and an analysis of our own results indicates the presence of a strong (almost 90%) dependence of the characteristics of the meridional overturning circulation and the cyclonic circulation mode in the Arctic with a significant (up to 20 years) time lag. No understanding of the role of these two mid-latitude and polar processes in relation to what extent they act as a cause or a consequence has yet been established. This requires further research.

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