Variation in the sea level, ice concentration and ice drift speed near northern land archipelago in the autumn-winter period

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Abstract. Complicated ice conditions, which are typical of many areas of the Northern Sea Route, limit the possibilities for navigation and development of hydrocarbon deposits. Therefore, the development of ideas about the influence of natural factors on their changes is an urgent problem of oceanography, hydrography and water transport. The solution of this problem is of greatest interest for the highest latitude regions of this route, located near the Norther Land archipelago for the period from October to December. One of the reasons for the change in the ice cover is ice drift caused by surface currents, which also affect the topography of the water surface. Taking this into account, the study confirmed the hypothesis according to which in these areas a significant effect on changes in the ice cover in October-December can be exerted by variations in the topography of the water surface. The study used the standard methods of mathematical statistics. The significance of statistical relationships of interannual changes, average monthly levels and concentration of the ice cover in different parts of the water area with variations in the zonal components of ice drift speed were assessed. The results of GLORYS12.v1 and ICDC reanalyses were used as a data source. It was found that this influence is clearly manifested in the Vilkitsky Strait and the western part of the Laptev Sea. The revealed change trends for ice drift speed allow for the prediction of further improvement in navigation conditions in October and November. Key words: Northern Sea Route, Severnaya Zemlya archipelago, sea level, ice concentration, ice drift, climate warming, correlation.

1. Introduction

The global warming contributes to the expansion of the navigation period along the Northern Sea Route (NSR) [1–5]. At the same time, the possibilities of navigation and development of hydrocarbon deposits are limited by complex ice conditions. Therefore, an urgent problem of oceanography, hydrography and water transport is the development of ideas about the influence of natural factors on their changes.

The solution is of greatest interest for the most high-latitude regions of the NSR, where difficult ice conditions occur most often. One of them is the areas located near the Northern Land archipelago where navigation is carried out mainly through the Vilkitsky and Shokalsky straits, covered with ice. There are also promising oil and gas licensed areas (Severo-Karsky and Pritaymyrsky) whose
development is one of the priority directions for the development of the fuel and energy complex of Russia.

Ice conditions in any areas of the Arctic are created by the processes of melting and ice formation and ice drift, which is caused by the surface currents. The variability of characteristics of surface currents in many areas also determines the topography of their water surface. The latter suggests that changes in the topography of the water surface can significantly affect the variation in the characteristics of their ice cover.

The assumption would contribute to the improvement of the models used to predict changes in ice conditions. Its verification seems to be the most appropriate for the autumn-winter months, in terms of the prospects for expanding the time frame of the main navigation period (from August to October).

Changes in the navigation conditions have been studied in [6, 7]; however, the relationship between changes in their levels and variations in the ice cover has been understudied. The purpose of this work is to test the validity of the hypothesis put forward.

2. Methods and materials

One of the most important characteristics of the ice cover in the Arctic seas, which determines the safety of navigation is its concentration. Therefore, in order to achieve this goal, the relationships between the interannual changes in the average monthly levels of the seas adjacent to the Northern Land archipelago, with variations in the drift speed and concentration were studied. The research was conducted for October, November and December.

The water areas adjacent to the Northern Land archipelago include areas No. 8–14 of the NSR\textsuperscript{1}, which are shown in Figure 1.

![Figure 1. Scheme of the NSR areas near the Northern Land archipelago](image)

\textsuperscript{1} Navigation rules in the water area of the Northern Sea Route (approved by the Resolution of the Government of the Russian Federation dated September 18, 2020 No. 1487). [Electronic resource]. Access mode: http://www.nsra.ru/ru/ofitsialnaya_informatsiya/pravila_plavaniya.html (date accessed: 04/21/2021).
Figure 1 shows that communication between areas 8–10 located in the Kara Sea and areas 12–14 located in the Laptev Sea is possible either through the Vilkitsky and Shokalsky straits, or through area 11 (skirting the archipelago from the north).

When studying the relationship between changes in the sea levels and variations in drift speed and concentration, the method of correlation analysis and Student's test were used. The decision on the existence of a significant relationship was made if the reliability of this statistical conclusion, assessed by the Student's criterion, was at least 0.95. The corresponding threshold value of the correlation coefficient was determined taking into account the number of degrees of freedom of the time series. Before conducting the correlation analysis, linear trends were identified and compensated for in the supplied series. The values of their angular coefficients were estimated by the least squares method. Areas where significant connections were found between the processes were displayed on the map.

The ICDC reanalysis (supported by the Integrated Climate Data Center) [8] and GLORYS12.v1 (supported by the service Copernicus) were used [9]. The ICDC database provides information on the average values of the indicators in various parts of the World Ocean with dimensions of 13x13 km for 1979–2018. The GLORYS12.v1 reanalysis based on the oceanic NEMO models [10] contains data for each day of the period 1.01.1993–13.12.2018 and all nodes of the cylindrical coordinate grid with a step of 5 arc minutes. In [11, 12], the parameters of ice concentration and depths (bottom topography) are considered as the main factors influencing the duration of navigation in the Eastern sector of the Northern Sea Route.

The models used to conduct both reanalyses were verified by the same results of satellite monitoring of the parameters. At the same time, the models differ significantly; as a result, the corresponding modeling errors are also different. The latter allows for the conclusions obtained using one reanalysis to check the validity of the conclusions based on another reanalysis. Taking this into account, the above studies were carried out using both reanalyses, and their results were compared with each other.

3. Results
It was found that the threshold level of the correlation coefficient of the compared time series, corresponding to the confidence level of 0.95, is equal to 0.4. Taking this into account, at the first stage, for all points of the region, an analysis of the relationships between interannual changes for 1993–2018 was carried out for October, November and December. Both reanalyses revealed that the relationships are significant only for the zonal components of the drift speed. Figure 2 shows distributions of the correlation coefficient values obtained from the ICDC reanalysis data.

Figure 2 shows that significant connections are present in all months in the parts of the water area located along the coast of the Taimyr Peninsula, in the areas of the Northern Sea Route No. 9, 10, 12, 13, including in the southern part of the Vilkitsky Strait. For December and November, the total area of the sites where significant connections were revealed is higher than in October, and values of the correlation coefficients exceed 0.85 in some places. Similar results were obtained using the GLORYS12.v1 data.

At the second stage, the relationships between changes in the ice drift speed and the dynamics of changes in the concentration were studied. Figure 3 shows distributions of the values of the correlation coefficient in the area of the Vilkitsky Strait and approaches to it, obtained from the GLORYS12.v1 data (at the first stage, in these areas, the maximum correlation was revealed between changes in the sea level and ice drift speed).

Fig. 3a shows that in October, there areas of significant positive correlation of interannual variations in the concentration with changes in average monthly ice drift speeds in the Vilkitsky Strait near the western coasts of the islands of the Norther Land archipelago.

Figures 3b and 3c show that in November and December, there are areas where the correlation of the same processes is significant and negative. All of them are located in the Laptev Sea, Vilkitsky and Shokalsky straits. The values of the correlation coefficients of these processes in some areas are 0.96. The same results were obtained using the ICDC reanalysis.
At the third stage, the current trends of changes in the ice drift speeds were evaluated. To this end, for the period from 1993 to 2018, for all parts of the water area, the angular linear trend coefficients (ALTC) of interannual changes were determined. Their significance was assessed by the Fisher criterion. The conclusion about the significance of the ALTC is characterized by a reliability of 0.95 at their values exceeding 1 mm / (s per year) in absolute values. The distributions obtained are shown in Fig. 4.
Fig. 4 shows that the fastest increase in the ice drift speed in the Vilkitsky Strait was observed in November.

4. Discussion
The results obtained confirm the existence of significant relationships between the sea level, the ice drift speed and the ice concentration in the NSR areas 12, 13 and 14 in November and December, which determines the navigation and hydrographic support [13] for the navigation of large-tonnage vessels in the Arctic. The increase in the ice drift speed in November in the Vilkitsky Strait gives grounds to predict a decrease in the ice concentration in the western part of the Laptev Sea. This assumption is consistent with the concept of Arctic climate warming. At the same time, the conditions for navigation will improve. This is also evidenced by the revealed trend towards an increase in the water surface level in the Vilkitsky Strait near the coast of the Taimyr Peninsula.

5. Conclusion
Changes in the sea level are due to variations in the ice drift speed and which can cause changes in the ice concentration. This influence is clearly manifested in the Vilkitsky Strait and the western part of the Laptev Sea. The revealed changes in the ice drift speed in the autumn months give grounds to predict a further improvement in navigation conditions in October and November. The presence of significant statistical links between the variations in the ice concentration and changes in the topography of the water surface indicates the feasibility of taking them into account when modeling and forecasting ice conditions in other regions.

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