Investigating the relationship between inter-annual closeness of ice coating and ice thickness in the Chukchi sea and water level variations

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Abstract. The hypothesis is tested that there is a significant relationship between changes in water surface level in some areas of the Chukchi Sea and variations in average ice cover thickness and cohesion in them, which can be used to refine short- and long-term forecasts of ice conditions. The results of the GLORYS12v1 global reanalysis and standard methods of mathematical statistics were used for verification. Changes in average ice cohesion were found to be correlated with changes in sea level in some areas from November to June. The correlation between sea level and average ice thickness is traceable only in December. The areas where this correlation is found include numerous sections of the coastal routes of the Northern Sea Route. It is noted that making medium- and long-term forecasts of the development of ice conditions in these areas can be significantly improved by taking into account the current changes in sea level. The identified regularities are important for ensuring safe and sustainable navigation along the Northern Sea Route during the internavigation period for independent navigation of vessels with high ice class and during the winter period when escorted by nuclear-powered icebreakers.

1 Introduction

Developing shipping along the Northern Sea Route (hereinafter referred to as the NSR) is a priority of the Russian Federation's transport strategy in the Arctic. By 2030, NSR cargo turnover should grow to 120 million tonnes, so ensuring sustainable navigation in the eastern seas of the Russian Arctic (the Laptev, East Siberian and Chukchi seas) is becoming a key task. It cannot be solved without improving the quality of hydrometeorological support of navigation on the NSR in any season. For shipping companies and crews it is

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extremely important to have reliable forecast information about changes in ice conditions in order to plan safe maritime routes in advance.

The most important ice condition parameters directly affecting navigation safety are medium ice thickness (MIT) and mean closeness of ice cover (CIC). Therefore, studying possibilities for their improvement is an urgent problem of oceanography, hydrography and navigation safety.

The present work considers the Chukchi Sea. Parts of its water area are characterized by rather intensive ship traffic. At the same time actual monitoring of ice conditions is poorly developed and forecast information on MIT and CIC changes is insufficiently accurate.

The dynamics of changes in ice conditions in the Chukchi Sea over the last 30 years can be assessed from reanalysis data. The most precise reanalysis for this region is GLORYS12v1 [1], which presents MIT and CIC estimates obtained on the basis of NEMO family models [2]. The latter is verified using the results of satellite measurements of the mentioned indicators, covering the period starting from January 1, 1993.

The CIC measurements are taken using passive radiometric method [3, 4], which is implemented on DMSP (Defense Meteorological Satellite Program) series satellites [4]. The coordinates of these satellites relative to the centre of the Earth in the course of measurements are determined using global positioning system GPS.

The instruments deployed on these satellites scan the Earth's surface within a bandwidth of up to 2000 km. This makes it possible to measure CIC in all parts of the study area several times a day, which is sufficient for reliable verification of the models. Errors of such measurements are caused by the influence of clouds as well as fogs. In coastal areas of the seas, they are also caused by differences in the thermophysical characteristics of the sea and land, affecting their surface temperatures.

MIT is measured using the active method, which is lidar sensing of the area of the Earth's surface over which the satellite is currently located. Between 2004 and 2011, MIT was monitored using the ICESat-1 lidar sensor. At each sounding, the values of the mentioned indicator were measured for a section of water area 70 m in diameter [5]. For this reason, the probed areas of the surface of the World Ocean did not cover its entire water area. As a result, the verification of NEMO models describing MIT changes was in fact carried out using incomplete information, and the accuracy of the estimates of this indicator obtained with their help did not always meet the needs of practice. This problem was partly solved by the commissioning on 15.09.2018 of the ATLAS topographic laser altimeter on the ICESat-2 satellite. This instrument provides simultaneous measurement of the thickness of the ice coating layer by 6 beams. Adjacent areas of ice cover that are probed simultaneously have the same diameters and are separated by 3.3 km. As a result, the total area of the World Ocean area where MIT measurements are taken has increased by a factor of 6, resulting in improved modelling accuracy [6]. At the same time, the time series of the results of reanalysis of the indicated index lost homogeneity, which significantly complicated their application in forecasting tasks. The homogeneity of these series requires correction of their terms corresponding to the period prior to 15.09.2018, which is possible only with the use of more advanced mathematical models of the process in question. The use of such models would seem to improve the accuracy of the estimates and the CIC.

One of the ways to achieve this result is to use the results of measurements of other oceanographic characteristics in calculating the MIT and CIC estimates for the sea areas in question. The latter is in principle possible for those areas for which changes in such characteristics are statistically significantly associated with MIT variations.

According to the existing understanding of the reasons determining both the state of ice cover and the topography of their water surface, the dynamics of their waters are among the significant ones [7]. This suggests that there are areas in the Chukchi Sea where in some months interannual variations in mean monthly CIC or MIT values are statistically significantly related to changes in their level.

The validity of such an assumption is not obvious, since changes in MIT and CIC are multifactorial processes, so their links with variations in the levels of the corresponding water areas may not be significant.

Global satellite monitoring of sea levels in different parts of the World Ocean above the geoid surface is carried out since 01.01.1993 by the TOPEX/Poseidon, Jason-1, 2, 3 and other satellites [8, 9]. Radar altimeters equipped with the mentioned satellites, provide measurement of the above index with an accuracy of 1.7 cm for water surface areas with a diameter of 700 m, located along their tracks. The period between subsequent soundings of each such area is 9.9 days [10]. The results of global satellite monitoring of sea level are also used to verify the corresponding models of the NEMO family.

The GLORYS12v1 reanalysis estimates of the CIC, MIT and sea level for all sectors of the Chukchi Sea correspond to each day starting from 01.01.1993. Nevertheless, such a check has not been carried out before and the results of level monitoring of the Chukchi Sea in CIC and MIT assessments of any parts of its water area are not taken into account at present.

2 Methods and materials

The objective of this study is to test the hypothesis and to identify areas of the Chukchi Sea for which interannual changes in mean monthly values of MIT and CIC for any month are statistically significantly associated with changes in sea levels in these areas.

To achieve the objective indicated, estimates of mean daily sea level values, CIC and MIT corresponding to grid nodes of the GLORYS12v1 reanalysis referring to the Chukchi Sea water area for the period 1.01.1993-31.12.2019 were used as a factual material [1]. The meridians 180o W and 159.5o W as well as the parallels 72o N and 65o N were considered as boundaries of the region under study.

Maps showing the distribution of actually measured CIC and MIT values over the area of the Chukchi Sea were used to verify the factual material [11]. Testing has confirmed the adequacy of CIC and level estimates presented in [1] for any months. At the same time, MIT estimates qualitatively correspond to the actual values of this indicator only for open sea areas and for months from November to March.

The research methodology is based on the application of correlation analysis method as well as Student's criterion [12]. Time series of mean monthly values of sea level, MIT and CIC, containing 27 terms each, were formed from the indicated factual material for each month and each area of the Chukchi Sea water area under consideration. In each of these series the linear trends present in them were compensated.

For each site and month, the reliability of the statistical inference that the relationships between the corresponding sea level time series and the CIC or MIT series are statistically significant has been assessed. Taking into account the number of degrees of freedom of the series being compared, the threshold values of the module of their correlation coefficient have been determined, above which the reliability of the indicated statistical conclusion is at least 0.9, 0.95, and 0.99. The mentioned threshold values are 0.36, 0.40 and 0.53, respectively.

The values of the coefficient of pairwise correlation of the sea level time series and CIC are calculated for all months and all considered nodes of the reanalysis grid. The results obtained are shown on contour maps of the Chukchi Sea, where the areas within which the reliability of the considered statistical inference exceeds one or other threshold level are shown.

As it follows from the reviewed methodology and the factual material, their application does not eliminate many of the uncertainties that exist in solving the problem in question. Nevertheless, it allows answering the most important question - whether there are sea areas in the Chukchi Sea where the studied processes in any months are significantly related to variations in their level.

3 Results

In accordance with the above technique, for each month, maps showing the distribution over the Chukchi Sea water area of the correlation coefficient of interannual changes in its mean monthly levels with the values of MIT and CIC were constructed. As an example, Fig. 1 shows the maps showing the areas of the Chukchi Sea for which the reliability of the conclusion about the significance of the relationship between its level variations and CIC exceeds a certain threshold.

It follows from Fig. 1, that areas of the Chukchi Sea, for which the conclusion about significance of the considered statistical relationships is characterized by reliability not less than 0.9, exist in any considered months. The area of the sea for which the correlation of the studied processes is significant and negative in any months from November to March is Kotzeboo Bay, where the same occurs near its southern shore.

Fig. 1a shows that for November the areas where the correlation between CIC and levels is positive are only found in the western part of the sea (near the southern coast of Long Strait and near the eastern coast of Wrangel Island). The maximum confidence values of the conclusion about the significance of the relationship between these processes exceed 0.95. For the same month, there are many more sea areas where the significant correlation of the same processes is negative. They are located off the coast of the Alaska Peninsula. For some of these sites the reliability of the considered conclusion is much higher than 0.99 (the modulus of the correlation coefficient exceeds 0.751).

Fig. 1b shows that for December, the location of areas of the Chukchi Sea water area for which the significant correlation of their levels and CIC is positive or negative is largely similar to their location for November. Areas with a significant positive correlation are located only in the western part of the sea (their total area increased), while the areas where it is significant and negative are located only in its eastern part (their total area decreased). An important feature of the distribution over the sea area of areas of significant positive correlation of their levels and CIC is the passage through them of the Coastal route of the Northern Sea Route.

Fig. 1c and 1d show that for January and December, the location of areas of significant positive and significant negative correlation of the studied processes in the Chukchi Sea water area is almost symmetric with their location identified for December. The former are identified in the eastern part of the sea (near the northern coast of the Alaska Peninsula). The latter are located both in its eastern part (off the northern coast of the Seward Peninsula) and in the western part (off the southern coast of Wrangel Island and to the east of it). In February, the largest area of significant negative correlation is in the central part of the sea, north of the Bering Strait. The reasons for such changes need to be further investigated.

As shown in Figure 1e, the locations of the areas under consideration in March are similar to their locations in January and February. At the same time, the total area of significant positive correlation of the studied processes increased significantly, as well as the reliability of the conclusion about the significance of the relationship between them. For coastal areas of the northern part of Kotzebue Bay the reliability of this conclusion significantly exceeds 0.99 (correlation coefficient values in this case exceed 0.75). The regions of negative correlation of the same processes are located near the northern shores of

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the same bay, as well as to the east of Wrangel Island and in the southern part of Long Strait.

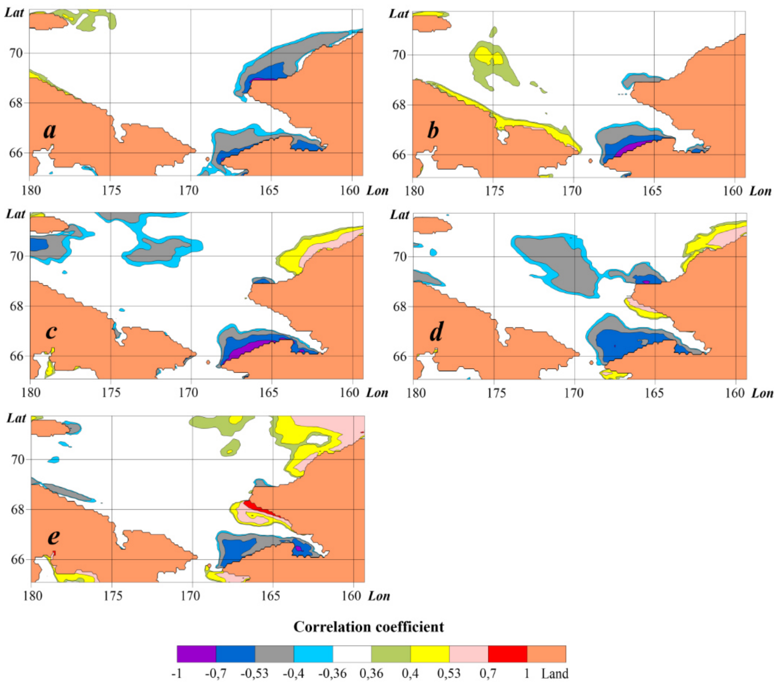

Fig. 1. Plots of significant correlation between monthly averages of closeness of ice coating and sea level in 1993-2019 for months: (a) November; (b) December; (c) January; (d) February; (e) March.

Similarly, the hypothesis is found to hold for all months from November to June. For the months of April through June, the locations of areas of significant positive and significant negative correlation are similar to their locations shown in Figure 1e. For the months July through October, the areas of the Chukchi Sea water area for which the relationships of their level variations and CIC are significant were not identified.

The study of statistical relationships of interannual variations of mean monthly levels and MIT of different areas of the Chukchi Sea water area showed that they are significant only for December. The location of such sites is shown in Fig. 2.

Fig. 2 shows that for the indicated month, a significant negative correlation between interannual changes in 1993-2019 in mean monthly MIT values and sea levels is detected for all coastal sea areas, which are located off the northern shores of Eurasia and Wrangel Island. The reliability of the statistical conclusion about the significance of the identified relationships for many of the indicated sites significantly exceeds 0.99. The coastal route of NSR passes through the identified sites, hence the obtained result shows the expediency of taking into account the results of satellite monitoring of their levels, as well as CIC, when assessing their MIT values. Consequently, the hypothesis is also valid for the mentioned indicator.

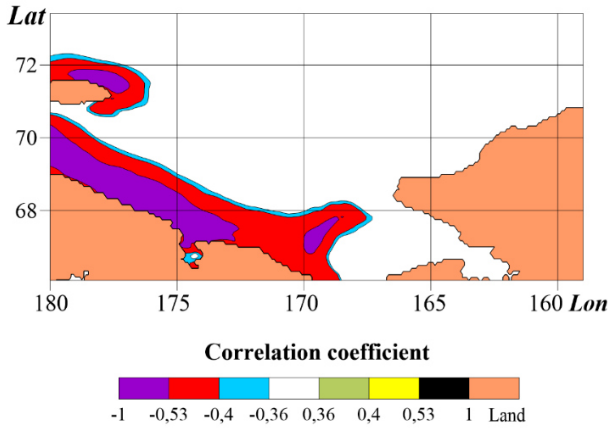

Fig. 2. Plots of significant correlation between monthly mean ice thickness and sea level for the December period 1993-2019.

4 Discussion

As is evident from Figs. 1 and 2, its main surface currents pass through the identified areas of the Chukchi Sea, delivering to it the cold waters of the East Siberian Sea, the Beaufort Sea and the Arctic Basin, as well as the warm waters of the Bering Sea. This result corresponds to the ideas [7, 13-16] on the role of water dynamics of the seas in changes of their water surface topography.

It follows from the obtained results that there is a correspondence between the locations of the areas of the Chukchi Sea, for which the correlation between the time series of their levels and CIC is significant and positive, and the locations where the correlation between the time series of their levels and MIT is significant and negative.

Similar studies carried out for other Arctic seas have shown that the mentioned correspondence is characteristic only for the Chukchi Sea. The reasons for its absence in other seas may be the differences in the factors determining the spatial and temporal variability of MIT and CIC that are characteristic of them [13-20].

The CIC increase of some area of the Arctic seas is facilitated by the prolonged dominance over it of an anticyclone with strong frosts and weak winds. At the same time, the arrival of cyclones, as a rule, causes destruction of the ice cover, which is accompanied by the formation of not only hummocks, but also ice openings. Therefore, not only warming of the Arctic climate (21-23), but also changes in atmospheric circulation characteristics are among the significant factors in CIC changes (24).

Ice drifting from areas with increased or decreased MIT in the Arctic seas can have a significant effect on changes in MIT.

Elevated MIT values in any month are characteristic of areas of the Arctic basin of the Arctic Ocean, and its lowest values correspond to areas where any warm ocean currents come in. Therefore, variations in the meridional components of ice drift velocity, the intensity of which for the Chukchi Sea is maximal precisely in December, are among the significant factors of MIT variability in the Arctic seas [25].

Other studies of navigation in the eastern sector of the Arctic [26, 27] and their connection with global trends in ice thickness, ice cohesion and actual water levels [28, 29] generally confirm the results obtained and the possibility of their interpretation for the Chukchi Sea.

Atmospheric circulation is one of the factors of sea ice drift. However, a much more powerful factor is surface ocean currents, the characteristics of which also depend on other processes [13]. Therefore, the correspondence revealed for the Chukchi Sea between the locations of areas where interannual variations in levels significantly affect changes in their CIC and MIT is not the rule but the exception. Nevertheless, the high reliability of the conclusion about the significance of relationships between the studied processes indicates the advisability of taking them into account when modeling changes in both CIC and MIT, for the benefit of hydrometeorological support of navigation.

5 Conclusion

The study found that changes in water surface levels in many areas of the Chukchi Sea have a significant effect on changes in medium closeness of ice coating and ice thickness. The correlation between the sea level and ice thickness is evident from November to June. The correlation between sea level and mean ice thickness is only significant in December. The reliability of the detected correlation for the areas through which the NSR coastal route passes exceeds 0.95 (0.99 in some areas).

When making medium- and long-term forecasts of changes in ice conditions along the NSR routes in order to ensure navigation in the Chukchi Sea, it is advisable to take into account the sea level changes occurring in this sea. As water surface levels can now be measured with centimeter accuracy, the accuracy of forecasting characteristics of ice conditions in some areas of the Chukchi Sea can also be significantly improved due to this.

The prospects for further research in this direction will be determined by the dynamics of shipping development on the NSR, as well as general trends in global climate change.

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