Icing of the Chukchi Sea in winter

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Abstract. The modern change trends for the navigation conditions in the Northern Sea Route, belonging to the Chukchi Sea in winter were investigated. In the context of ongoing climatic changes and reducing Arctic ice cover, shipowners are using this transport route. Trial voyages of merchant ships in the eastern part of the Northern Sea Route are being carried out in the winter-spring period; however, shipping has not yet become massive due to difficult ice conditions and insufficient knowledge of the navigation areas. This study was carried out on the basis of information on ice thickness obtained from the GLORYS12.v1 reanalysis databases, NASA ICESat, ICESat-2 and Ice Bridge missions and the Global Sea Ice Digital Data Bank for 1993–2018 for the period from November to March. The probabilities of solid ice posing a danger to navigation were assessed (using the example of “YamalMax” vessels). The distributions of these probabilities over the water area of the Chukchi Sea were presented in a map form. It was found that the navigation conditions improved in most areas of the Chukchi Sea; however, in the southern part of the sea they worsened. This effect was most pronounced in November; in the subsequent winter months, its intensity decreased. The revealed effect is presumably a consequence of the warming of the Arctic climate, leading to the melting of ice massifs of Greenland, the Canadian archipelago and Alaska. The latter causes an imbalance in the levels of the Chukchi and Bering Seas and a change in the directions of surface currents, capable of both delivering ice to the strait and carrying it to the north. The revealed trends suggest further complication of ice conditions in the southern part of the Chukchi Sea, as a result of which even vessels with a high ice class may require icebreaker assistance in November and December.

1. Introduction

The development of world shipping causes interest in new routes for merchant shipping. One of the promising sea routes that can reduce the duration of transitions between Europe and Southeast Asia is the Northern Sea Route (NSR). The relevance of its use increases with the reduction of the ice cover in the Arctic, caused by global climatic changes, and the development of the infrastructure of the Russian Arctic zone. Potential obstacles on the main trade route from Europe to Asia, passing through the Suez Canal, are also forcing shipowners to search for alternatives, as evidenced by the grounding of the container ship "Ever Given", which completely stopped the canal in March 2021. We should remember about geopolitical risks in the Middle East region. The interest of shipping companies in the
NSR is still cautious, since difficult ice conditions and insufficient hydrographic and hydrometeorological studies of a number of areas are obstacles for the sustainable navigation [1–3].

At present, year-round navigation is possible only in the Kara and Barents Seas. However, the construction of high ice-class large-capacity vessels and commissioning of new "Arctic" ice-breakers will expand the geography and time frames of navigation in the eastern sector of the NSR. Thus, the successful experience of the LNG carrier Christophe de Margerie (ice class Arc7), which made the transition to the east and back in January-February 2021, and the earlier voyages of similar vessels in May-June 2020 confirmed the feasibility of navigation in this area in the winter-spring period [4].

The most difficult for navigation are sections of the NSR routes passing through the East Siberian and Chukchi Seas (Fig. 1) [4–5]. In [6] on the variability of ice conditions of the Chukchi Sea, the lack of accumulated ice information for previous years and the need for a method of replenishing its gaps have been emphasized. The works on change trends for ice conditions in the Chukchi Sea in the winter months are few.

\[\text{Figure 1. Sections of the NSR located in the East Siberian and Chukchi Seas}^1\]

Thus, the assessment of probabilities of the occurrence of ice with characteristics exceeding the permissible ice class in the NSR, as well as trends in their change, are an urgent problem for both oceanographers and specialists in safety of navigation and maritime logistics.

The purpose of this work is to assess these probabilities for the Chukchi Sea (sections No. 25–28) using the example of YamalMax vessels in winter.

2. Materials and methods

Ice class Arc7 allows for the independent navigation in one-year solid ice up to 1.4 m thick. At the same time, YamalMax class vessels are capable of moving in continuous ice up to 2.1 m thick. Taking this fact and the fact that the actual material used in the work contains data on average values of ice thickness into account, ice with a thickness of more than 1.8 m is conventionally accepted as dangerous.

The goal was achieved in two stages. At the first stage, the values of probability of the occurrence of ice with a thickness of more than 1.8 m in the sections of the NSR No. 25–28 in the winter months, as well as in November and March, were estimated. From the results obtained for each month of 1993–2018, time series were created. At the second stage, the current trends in the change in these probabilities were revealed. The values of the angular coefficient of the linear trend of each series were used as a measure of the trend.

The work uses standard methods of mathematical statistics. To assess the probabilities of hazardous ice occurrence, each section of the NSR was divided into zones 1° long and 5’ wide. Trends were

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1 Navigation rules for the Northern Sea Route (approved by the Decree 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: 03/21/2021).
estimated based on the data for 1993–2018. The results obtained were displayed on maps using the Delaunay triangulation.

The results of the GLORYS12.v1 reanalysis obtained using the oceanic NEMO models [7] were used as factual material. Data on the thickness of the ice cover are available for the nodes of the coordinate grid with a step of 5 arc minutes starting from 01.01.1993. The reanalysis results were verified according to the satellite monitoring data within the NASA ICESat and ICESat-2 missions [8], whose main characteristics are presented in the table.

| Satellite characteristics | ICESat       | ICESat-2                  |
|---------------------------|--------------|---------------------------|
| Operation time            | 2003–2009    | 2018 – present            |
| Orbit                     | Low polar, 586/594 km | Low polar, 479/483 km   |
| Period of circulation     | 96.6 min     | 94.2 min                 |
| Track repetition period on Earth | 91 days       | 91 days                 |
| Altimeter type            | Laser single beam GLAS, 1064nm and 532nm | Laser six-beam ATLAS, 532 nm |

During its operation, the ICESat spacecraft was able to simultaneously probe a section of the water area in the form of a circle with a diameter of 70 m, which made it possible to measure the average thickness of its ice cover. The distances between the centers of the probed areas were 170 m, and the distances between the adjacent tracks were tens of kilometers depending on the latitude.

The six-beam lidar onboard the ICESat-2 satellite makes it possible to simultaneously measure the ice thickness in 6 areas of the water area, 3.3 km apart from each other. The sections of the satellite track differ by 2.5 km. The distances between the adjacent tracks above the NSR are tens of kilometers. As a result, the update interval for ice thickness data is at least one week.

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Until 2004 and from 2009 to 2018, gaps in satellite measurements of the ice thickness were filled by NASA's IceBridge mission. Aviation with laser altimeters installed on board took part in the measurements.

As can be seen, the data of satellite and aviation monitoring have a sufficiently large temporal discreteness, which does not allow for their use directly for assessing probabilities of exceeding the ice thickness. At the same time, such data are suitable for developing adequate mathematical models used for the reanalysis. At the points where the satellite measurement was made, its data coincide with the reanalysis data, which makes it possible to trust the simulation results for other points and points in time.

The adequacy of the reanalysis results for the Chukchi Sea water area was additionally checked by comparing them with information from the Global Sea Ice Digital Data Bank (GBCDML), formed within the World Meteorological Organization project. The basis of this archive is made up of ice maps of individual areas of the Arctic, presented by the national ice services of Russia (USSR), Denmark, Canada and the United States. The information has been available since 1933 with a time interval from 7 days to 1 month. Verification of the GLORYS12.v1 reanalysis data showed that its relative errors for the Chukchi Sea do not exceed 3%.

3. Results

For each year of 1993–2018 and each month from November to March, the probability of occurrence of ice more than 1.8 m thick in all zones of regions No. 25–28 of the NSR was estimated. For example, Fig. 2 shows their distributions for the winter season of 2018.
Figure 2. Distributions of probabilities of occurrence of ice with a thickness of more than 1.8 m in the southwestern part of the Chukchi Sea in 2018 by months: a – November; b – December; c – January; d – February; e – March

Fig. 2 shows that the most dangerous for shipping was November. In other months, the probability of ice occurrence decreased. In December it did not exceed 0.3, and in other winter months, ice more than 1.8 m thick was observed only along the coast in the form of fast ice and did not hinder the navigation.

This result turned out to be typical not only for 2018. Figure 3 shows the dynamics of trends in the probabilities from 1993 to 2018 by month.

It shows that in 1993–2018, in most areas of the NSR located in the Chukchi Sea, the probability of dangerous ice was decreasing, which is quite consistent with existing ideas about the consequences of the warming Arctic climate [9] and changes in the duration [10] of navigation along the NSR and the speed of ships in ice [11]. At the same time, in the eastern parts of these regions, as well as in the entire 28 NSR region, they were steadily increasing, and this process was fastest in November.

4. Discussion
The results require a deeper analysis. They indicate that in a number of areas of the Chukchi Sea (in contrast to other seas of the eastern sector of the Russian Arctic), the conditions became complicated not only in 2010–2018, but also over the entire observation period from 1993 to 2018. Similar results partially coincide with the data presented in [12, 13]. This process was revealed in the southern part of
the Chukchi Sea both according to the reanalysis data and satellite measurements. It was especially pronounced in November.

The ice cover in the Chukchi Sea forms at the end of October, and its thickness should gradually increase from November to March. The results obtained indicate the opposite, which can be due to surface currents, which are influenced by a seasonal factor. This may be the warming of the Arctic climate, leading to a significant increase in the volume of fresh water entering the Arctic Ocean and its seas. The latter are formed mainly as a result of the melting of the ice of Greenland, the Canadian archipelago and Alaska. In the Chukchi Sea, the upper quasi-homogeneous layer becomes desalinated. As a result, the average water density is decreasing faster than that of the Bering Sea. Consequently, at the same rate of warming of the waters of both seas, the level of the Chukchi Sea should rise faster than the level of the Bering Sea in late summer and early autumn. A change in the level difference at the northern and southern entrances to the Bering Strait affects the characteristics of the current, up to a change in its direction.

Figure 3. Probability change trends for ice with a thickness of more than 1.8 m in the southwestern part of the Chukchi Sea in 1993–2018 by month:
   a – November; b – December; c – January; d – February; e – March

The above effect was observed in August – October, when the difference between the levels of the Chukchi and Bering seas begins to increase. In October – November, this leads to a change in the direction of the current in the Bering Strait and in the southern part of the Chukchi Sea. The waters of
the latter collect drifting ice from a significant part of the Chukchi Sea water area to the entrance to it, which, obviously, complicates ice conditions, including for port hydraulic structures [14]. In November, the flow of melt water into the Chukchi Sea stops, and in December its level decreases. This leads to the restoration of the current from the Bering Sea in the strait whose waters carry the drifting ice to the north and distribute them throughout the Chukchi Sea. In addition, the waters brought from the Bering Sea are relatively warm, which accelerates the melting process.

The significance of the mechanism described above is an assumption. Reasons for the complication of ice conditions in the southern part of the Chukchi Sea in November and December requires further study. The revealed fact, nevertheless, testifies to the deterioration of the navigation conditions in November.

5. Conclusion

Probabilities of occurrence of ice hazardous to navigation from 1993 to 2018 decreased in most areas of the Chukchi Sea, belonging to the sections of the Northern Sea Route No. 25–28. In the southern part of the sea, coinciding with the area of influence of the waters of the Bering Sea Current, they increased. This effect was most pronounced in November, and in the subsequent winter months its intensity decreased.

The revealed effect may be a consequence of the warming of the Arctic climate. With its further development in the southern part of the Chukchi Sea, complications of ice conditions are likely; as a result, vessels, even those with a high ice class, may require icebreaker assistance.

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