Current trends in the ice thickness and concentration on the waterways of the arctic

A V Kholoptsev\textsuperscript{1,2}, S A Podporin\textsuperscript{1} and V V Karetnikov\textsuperscript{3}

\textsuperscript{1} Sevastopol State University, Sevastopol, Russia
\textsuperscript{2} Sevastopol Branch, State Oceanographic Institute named after N.N. Zubov, Sevastopol, Russia
\textsuperscript{3} Admiral Makarov State University of Maritime and Inland Shipping, St. Petersburg, Russia

E-mail: sapodporin@sevsu.ru

Abstract. The current trends in the change in the ice cover thickness and concentration along the Arctic waterways are investigated. For the vessels following these routes, the dynamics of changes in the probabilities of occurrence of ice exceeding the maximum ice class characteristics in different seasons was determined using the example of the most difficult sections of the Northern Sea Route – the Sannikov and Vilkitsky straits. As the initial data on the ice cover, the results of GLORYS12.v1 reanalysis, previously verified using satellite monitoring data and archived information from polar stations were used. The application of reanalysis is substantiated by the fact that the methods of monitoring of changes in the ice conditions have limitations in terms of discreteness of observation of a specific section of the water area. Validation of the reanalysis results for the Vilkitsky and Sannikov straits confirmed their compliance with the actual observations. Therefore, this reanalysis is used as a source of factual material on the average daily values of concentration and thickness of the ice cover in various parts of the water areas of the straits. Data processing and trend detection were carried out using the traditional statistical methods. It was found that for the period from 1993 to 2018, in both straits, there was a monotonous decrease in the probability of occurrence of ice cover with characteristics exceeding the permissible ice class limits. Similar trends were identified in other Arctic waters, which confirms the possibility of expansion of the navigation period on the Arctic routes. However, starting from 2009–2012, in the summer months, an increase in the ice thickness and concentration was observed due to deterioration in navigation conditions. Reasons for the phenomenon are suggested. Despite the general improvement in the navigation conditions in the Arctic, the appearance of opposite trends confirms the relevance of further development of the icebreaker fleet.

1. Introduction
The development of sustainable shipping in the Arctic is one of the priorities of the transport strategy of the Russian Federation. To this end, a wide range of measures aimed at putting into operation a new icebreaker fleet, stimulating transit shipping, developing the infrastructure of Arctic ports, and improving the navigation and hydrographic support of the Northern Sea Route (NSR) routes are being taken. At the same time, difficult ice conditions remain the main obstacle to the uninterrupted navigation.
The issues of assessing the trends and prospects of Arctic shipping are widely covered in literature. Thus, in the context of ongoing climatic changes, authors predict the opening of high-latitude (including transpolar) routes by the middle of the 21st century [1–3]. In [3], a significant uncertainty of such estimates is due to the complexity of a full accounting of all climatic factors.

The current state of the NSR routes is being monitored; generalized conclusions are being published [4]. At the same time, the identification of medium-term and long-term trends in the variability of ice conditions remains a non-trivial task whose solution is of considerable interest for climatologists, and experts in hydrography and navigation safety.

The solution of this problem is of the greatest importance for the sections of the NSR that are traditionally difficult for navigation, among which are the Vilkitsky and Sannikov straits. The first is the highest latitude section of the NSR, and in the second one, due to its geographic features and proximity to ice masses, has especially difficult ice conditions [5].

In the long and medium-term planning of ships’ voyages along the NSR, it is important to have information on the trends in the formation of ice cover with characteristics exceeding those permissible for the ice class of the ship. This information can be used to develop the laws of distribution of ice characteristics and assess the probability of occurrence of ice of unacceptable thickness and/or concentration.

The most complete data on the concentration and thickness of the ice cover can be obtained using satellite radiometry and remote sensing. In this case, radiometers and lidars installed on specialized artificial earth satellites are used [6–8]. These methods allow for creating maps of ice conditions and assessing short-term trends in their development. At the same time, satellite monitoring has a number of methodological errors. In addition, the trajectories of the satellites do not allow for continuous monitoring of certain areas (discreteness of measurements for a single point can reach several days or weeks, depending on the satellite used).

The only way to obtain continuous information about the ice cover at each point in the Arctic is mathematical modeling. Among the most accurate models are the NEMO models verified by the satellite monitoring [9]. To reduce errors, the low-order Kalman filter is used. The modelling results for all nodes of the coordinate grid with a step of 5 arc minutes, covering the period from 01.01.1993, are presented in the GLORYS12.v1 reanalysis. Previously, they were not used to assess the trends in the formation of ice hazardous to navigation.

The purpose of this work is to assess the current trends in the change in the probabilities of occurrence of ice cover, which poses a danger to ships in the Vilkitsky and Sannikov straits.

To achieve this goal, the following tasks were set:

1. Task 1 – checking the results of GLORYS12.v1 reanalysis for the Vilkitsky and Sannikov straits;
2. Task 2 – estimation of the probability distributions for the ice cover for different sections of the straits in different months;
3. Task 3 – identification of the current trends in the probability of occurrence of the ice cover whose concentration or thickness exceeds certain levels.

2. Methods and Materials

The research methodology is based on the methods of mathematical statistics. To verify the adequacy of the GLORYS12.v1 reanalysis results, measurements of ice thickness and concentration obtained at the polar stations Sannikova Strait and Cape Chelyuskin were used. Information on the concentration and thickness of the ice cover in the Vil’kitsky and Sannikov straits derived from the WMO archive “Global Sea Ice Digital Data Bank” (GBCDML) was used.

The GLORYS12.v1 reanalysis results were checked in two stages. At the first stage, the concentration and thickness of the ice cover obtained from the reanalysis were interpolated to the points where the Sannikov Strait (77°42′N; 138°54′E) and Cape Chelyuskin (77°43′N; 104°18′E) stations are located. The estimates of the ice cover characteristics were also interpolated to the points of their water areas, for which the actual results of remote sensing are presented in the HBCDML archive. The interpolation used a cubic spline.
At the second stage, the interpolation results were compared with the actual results of ground-based or satellite measurements of the concentration or thickness of the ice cover in the straits. Values of the relative errors of the reanalysis results were estimated, and the reliability of the statistical conclusion about their correspondence to the results of actual measurements was determined. When assessing the reliability of statistical conclusions, the method of correlation analysis and Student's criterion were used.

To solve the second task, the waters of each strait were divided into 6 zones with a latitude step of 5 arc minutes. In the Sannikov Strait (55 km wide), each zone included 24 nodes, and in the Vilkitsky Strait (56 km wide) – 16. In each zone, the nodes of the GLORYS12v.1 reanalysis grid located along the corresponding parallel were considered. For each zone, histograms of density distributions of the probabilities of ice concentration and thickness were constructed. At the same time, data from the corresponding time series of the daily average values of these indicators obtained from the reanalysis for each month were used.

The total number of estimates for all nodes of each zone was as follows: for the Sannikov Strait for February – 672, for other months – 720 or 744; for the Vilkitsky Strait for February – 448, and for other months – 480 or 496. For each histogram, the average values and variances of the corresponding indicator, as well as the probability of exceedance of some levels, were estimated. For the ice concentration, the levels were considered from 0.3 to 0.9 with a step of 0.1, and for ice thickness – from 0.1 m to 3 m with a step of 0.1 m. When solving the third task, the dependences of estimates of each indicator on time and latitude of the corresponding zone and month were considered. For each strait, values of the ALTC were estimated. The latter were considered as a measure of the trend. The ALTC values were estimated for periods during which changes in the indicators prevailed. When solving the second and third tasks, information on the ice concentration and thickness obtained from the GLORYS12v.1 reanalysis was used.

3. Results

When solving the first task, it was found that the relative errors of the reanalysis data on the ice concentration in the Sannikov Strait do not exceed 10 %; for the Vilkitsky Strait, it is 14 %. The relative errors in the estimates of the ice cover thickness for the Sannikov Strait do not exceed 18 %, and for the Vilkitsky Strait – 22 %. For the regions of both straits, the significance of the statistical conclusion about the adequacy of the reanalysis results in the summer and autumn months is no less than 0.9, and in the winter and spring months, it is no less than 0.95. The results obtained confirmed the possibility of using GLORYS12v.1 reanalysis for further research.

When solving the second task, it was revealed that the probability distribution densities obey the normal law (which confirms the application of the Pearson criterion). It was found that from September to April, in all zones of the Sannikov Strait, the average values of ice concentration and thickness, as well as their variances, were decreasing functions. A decrease was also observed for the probabilities of occurrence of the ice cover of a certain thickness and concentration.

The table presents average rates of the interannual changes in the probabilities of occurrence of the ice cover of a certain concentration in July in different latitudinal zones of this strait.

Table 1. The rates of interannual changes in the probabilities of occurrence of ice cover of a certain concentration in July in the Sannikov Strait in 1993–2018

| Latitude | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
|----------|-----|-----|-----|-----|-----|-----|-----|
| 76.66    | -0.0112 | -0.0101 | -0.0086 | -0.0073 | -0.0058 | -0.0049 | -0.0031 |
| 76.58    | -0.0124 | -0.0126 | -0.0125 | -0.0129 | -0.0115 | -0.0080 | -0.0020 |
| 76.49    | -0.0119 | -0.0118 | -0.0128 | -0.0145 | -0.0148 | -0.0092 | -0.0002 |
| 76.41    | -0.0124 | -0.0128 | -0.0135 | -0.0144 | -0.0152 | -0.0071 | -0.0003 |
| 76.33    | -0.0136 | -0.0138 | -0.0138 | -0.0139 | -0.0139 | -0.0069 | 0.0014  |
| 76.25    | -0.0124 | -0.0124 | -0.0123 | -0.0127 | -0.0116 | -0.0072 | 0.0021  |
From May to August of 1993–2018, in the northern part of the Sannikov Strait, a decrease in the indicators was also observed. At the same time, in the zone located south of the parallel of 74.5° N, the similar trend was recorded only in 1993–2011. Since 2011, the thickness and concentration of the ice cover in the southern part of the Sannikov Strait have shown increasing trends. Figure 1 shows the time dependences of the probabilities of occurrence of ice with a concentration of more than 0.6 in different zones of this strait.

![Figure 1. Probabilities of ice concentration of more than 0.6 in different zones of the Sannikov Strait](image)

A different situation was observed in the Vilkitsky Strait. In the summer months, the average values of the probabilities of occurrence of the ice cover with characteristics above a certain level, as well as their variances, decreased only in 1995–2008. From 1993 to 1995 and from 2009 to 2018, their increase was recorded. Fig. 2 shows the time dependences of the probabilities of occurrence of drifting ice with a concentration of more than 0.6 in July in different zones of the strait.

![Figure 2. Long-term changes in the average probabilities of occurrence of ice cover with a concentration of more than 0.6 in the southern part of the Vilkitsky Strait](image)

### 4. Discussion

The results obtained indicate that for the period from 1993 to 2018, for any (including summer) months in both straits there was a monotonous decrease in the probability of occurrence of the ice cover with characteristics exceeding the permissible limits. These trends correspond to the generally accepted ideas about the ongoing climate changes [10], and consequences of the Arctic climate warming.
At the same time, changes in the probabilities of ice occurrence in summer contradict these ideas. Increasing thickness and concentration of drifting ice in the Vilkitsky Strait have been observed since 2009, and in the Sannikov Strait – since 2012. This anomaly can be traced in the results of reanalysis based on the mathematical models and in satellite data.

Similar studies were carried out for the entire water area of the Arctic Ocean and its seas [11–12] (including the areas of the NSR routes [13]). Their results confirmed that for 1993–2018, the average values of ice concentration and thickness decreased in all months. At the same time, the revealed effect is almost universal. An increase in the concentration and thickness of the ice cover is observed since 2009–2012 (the volume of Arctic ice is decreasing). The probability of occurrence of ice is increasing. The additional ice does not significantly affect the safety of navigation. However, the question remains whether this trend will be observed in the future. To answer it, it is necessary to establish causes of the phenomenon.

One of the possible reasons may be a significant increase in the consumption of fresh water generated in the summer as a result of global warming, which accelerates melting of both sea ice and glaciers of Greenland. This phenomenon causes a decrease in the salinity of the surface waters of the Arctic in the area of the Beaufort Gyre and other areas of the Arctic Basin. It also reduces the flow of warm and salty Atlantic waters entering the Arctic. These processes can contribute to both the formation and destruction of the Arctic ice cover and can cause the identified effects. However, the significance of this effect has not yet been confirmed and remains a subject of discussion.

5. Conclusion
The GLORYS12.v1 reanalysis based on the NEMO mathematical model appears to be a fairly reliable source of continuous data on the ice cover in the Arctic waters. Its results can be used for medium- and long-term assessments of trends in ice conditions and analysis of potential ice risks for ships of different ice classes.

Over the past three decades, there has been a steady trend towards a decrease in the concentration and thickness of the Arctic ice cover, which is especially pronounced in the autumn, winter and spring months. It confirms the feasibility and validity of plans to further extend the time frame of the navigation period by shifting the time to the winter months.

The opposite trend towards an increase in the average thickness and concentration of ice is observed in most regions of the Arctic in summer. Despite the lack of current threats to the safety of navigation, it requires further study when planning the development of the Arctic transport system. The effect is another confirmation of the relevance of further modernization and expansion of the Russian icebreaker fleet.

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