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A study of the timing and duration of icebreaks on shipping routes in the Laptev Sea

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Abstract. The dynamics of the development of the Lena polynya forming in the Laptev Sea and its impact on navigation conditions in the Arctic, in the Laptev Sea, is investigated. The hypothesis is tested that the timing of polynya may have a significant impact on its average growth rate. The results of the GLORYS12v1 global reanalysis and standard methods of mathematical statistics were used in this test. The validity of the hypothesis was confirmed by the example of the section of the polynya located at the mouth of the major navigable channel of the Lena delta Bykovskaya. Stable tendencies of changing the dates of the polynya formation towards earlier dates in the modern period have been revealed. A high probability of improvement of navigation conditions is observed in this region in 2020-2040. However, with further warming of the Siberian climate, the opposite process is possible - the freezing of the polynya that formed too early, which will lead to a colder climate in the region and deterioration of navigation conditions. The selection of general routes for ships in the areas where the polynya is spreading will contribute to more intensive and safer navigation. For this purpose, accurate forecasts of its size and position are required. The relevance of research results for ship traffic forecasting and plans for the use of icebreaker escorts for vessels is noted.

1 Introduction

Among the seas of the Arctic Ocean, the Laptev Sea, along with the East Siberian Sea, is the most difficult to navigate throughout the year. The difficult ice conditions there for most of the year pose a problem for ships with even the highest ice class. At the same time, the development of Arctic shipping implies the expansion of year-round navigation, including in the eastern Arctic seas. The latter is possible with a significant improvement in the quality of hydrometeorological support for shipping and the availability of more accurate forecasts of ice conditions, allowing the safest routes to be chosen.

The most efficient and safe type of navigation in the freezing Arctic seas is the polynya navigation. In this regard, it is crucial for navigators to have accurate forecasts of their condition and development. Improvement of methods for forecasting their average growth

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rate (hereinafter referred to as AGR) is an urgent problem of hydrography, oceanography and navigation safety.

In winter and spring, the Great Siberian polynya is formed in the Laptev Sea, which is located near the landfast ice border [1-3] and creates opportunities for winter navigation in the NSR. [4-6]

Polynya is also formed in the summer, on rivers near the mouths of seashores. The largest of these ice floes is situated on the Lena River, directly on the route of vessels travelling to the port of Tiksi. It is also crossed by a section of the NSR coastal route.

Navigation in this area of the Laptev Sea has so far taken place mainly during the summer-autumn months. Development of the existing ideas about the growth patterns of the Lena Pole would make it possible to improve the efficiency of ship traffic management on the mentioned routes.

Identification of the regularities, which manifest themselves in changes in the characteristics of the Laptev Sea ice cover during the summer months, has been devoted to the works of many authors [3, 7-10]. It has been established that the Lena ice floe develops mainly under the influence of two processes. The first one is the absorption of total solar and thermal radiation (hereinafter referred to as STR) by its waters, and the second one is their heat loss during evaporation from the surface as well as heat exchange with the surrounding aquatic environment and the atmosphere.

The formation of the Lena polynya starts on the estuarial seashores of the Lena delta during the high-water periods. The main role is played by the floods formed in the navigable channels of the delta - Bykovskaya, Trofimovskaya and Olenekskaya. The deepest and widest of them is Bykovskaya channel, which is the shortest route for ships traveling from the Lena River to Tiksi port.

During high waters the level of the water surface increases at the mouth of each of these channels. As a result the fast ice that has formed here is broken up and runoff currents are generated, sweeping ice debris away from the shores. On the estuarial seashores of the aforementioned channels, polynyas are formed, which subsequently merge into a single Lena polynya.

The albedo of the free water surface is considerably less than the albedo of sea ice. Therefore, the formed section of the polynya begins to absorb STR more intensively. The intensity of its heat loss also increases, as the flow of evaporated moisture from the free water surface, other things being equal, is much greater than that from the ice surface. As the polynya water heats up when absorbing STR, the intensity of its heat exchange with the atmosphere and the surrounding sea water increases. The greater the value of the difference between the heat fluxes generated in and lost by the polynya waters, the faster the melting of the ice surrounding the polynya and its further growth.

Flooding in the Lena delta occurs during the polar day period (in June and July). Obviously, the later it starts, the less STR will be absorbed by the polynya and the smaller will be the difference between the fluxes of heat generated in it and the heat lost. Consequently, its growth will also be slower.

The aforementioned regularities allow us to hypothesize that the earlier the Lena Pole is formed, the higher its average growth rate will be, and the connection between these processes may be statistically significant.

This hypothesis is not trivial as the Lena Pillow formation is a multifactorial process. Significant factors of its AGR may include snow reserves accumulated by the beginning of the flood in the Lena River feeding area, intensity of forest fires in Siberia and other processes. Consequently, although there is undoubtedly a causal relationship between the processes studied, this relationship may not be significant.

The timing of floods in the Lena delta depends on the timing of floods in the corresponding areas of the basin. The meteorological stations of Roshydromet located in the Lena basin monitor changes in the temperature regime in the Lena basin, directly determining these timing [11]. Thus, if the tested hypothesis proves to be true, information from these stations can be used in forecasting both the AGR and the size that the Lena river polynya may reach by a certain date, which in turn will allow to make more informed decisions about the timing of the opening of navigation. Verification of such a hypothesis has not been carried out before.

2 Methods and materials

The purpose of this study is to test the hypothesis and to identify the areas of the Laptev Sea for which changes in the dates of Lena polynya have a significant impact on interannual changes in the average monthly density of their ice cover.

To achieve the above objective, the following tasks were solved:

1) evaluation of the dates of the polynya formation in the area of the mouth of the Bykovskaya channel and the area of the Laptev Sea to the north, through which the NSR coastal route passes;

2) evaluation of significance of statistical relationship between interannual changes in AGR of the ice-hole in question and variations in dates of its formation;

3) determination of the Laptev Sea water areas, for which statistical relations between variations of the above dates and interannual changes in the sea ice concentration (SIC) were significant.

When solving the indicated objectives, the estimates of mean daily values of SIC of the World Ocean presented in the GLORYS12v1 reanalysis [12] were used as factual material. The above reanalysis was developed using mathematical models of the NEMO family [13], verified by the results of SIC satellite monitoring.

In the mentioned monitoring, SIC measurements were carried out using the passive method of satellite radiometry [14, 15], which is implemented in SSM/I (Special Sensor Microwave/Imager) and SSMI/S (Special Sensor Microwave Imager/Sounder) instruments operating on DMSP (Defense Meteorological Satellite Program) artificial satellites [15].

In the GLORYS12v1 reanalysis, the SIC estimates are presented for each day of the period 1.01.1993-31.12.2019 for all areas of the study area corresponding to the nodes of its coordinate grid in steps of 5 angular minutes.

When testing these estimates, they were compared with the information on the SIC distributions over the Laptev Sea water area presented in [16]. The test confirmed their adequacy.

It is known [8] that polynya is commonly referred to an area of ice cover of a water body where the ice is thin or young. Nevertheless, when developing the methodology for solving the first problem, a simplifying assumption was made that on the date of polynya formation in the ice cover of some sea area, the average daily SIC values for all its areas decrease to zero for the first time during the season. Therefore when determining the dates of polynya formation their estimates from above were actually found.

The above estimates D1(t) and D2(t) were determined for each year t of the period 1993-2019 for two areas. The first district is located in the immediate vicinity of the mouth of the Bykovskaya channel. It is bounded by meridians 130o E and 132o E and parallels 72o N and 72.08333o N. The second area is located between the same meridians, but to the north, directly on the NSR coastal route between parallels 73oN and 73.08333oN.

To the south-west of the second area there is the mouth of another navigable, but usually less full-flowing channel of the Lena delta - Trofimovskaya. The differences in lengths (106 km and 142 km respectively) and the invariability of many hydrological characteristics of the Bykovskaya and Trofimovskaya channels [17] mean that the dates of their flooding in different years are almost constant. It was assumed that the impact of the flood occurring at Trofimovskaya channel on the ice cover of Area 2 in comparison with the flood at Bykovskaya channel is small.

When solving the second problem, the AGR value was estimated as the average speed of advance of the northern edge of the ice cap formed during the flood on the Bykovskaya channel from Area 1 to Area 2. The indicated value was calculated as

$$AGR(t) = 111/(D2(t) - D1(t)).$$

Correlation analysis and Student's t-test [18] were used to assess the significance of the relationship between time series reflecting changes in D1(t) and AGR(t) in 1993-2019. The linear trends present in the compared time series were preliminarily compensated for. The value of the correlation coefficient for the obtained series has been compared with the threshold levels corresponding to one or another confidence level of the conclusion about the significance of the connection between them.

In the third task, the same approach was applied to identify areas of the Laptev Sea, where interannual changes in D1(t) were significantly related to variations in their SIC between 1993 and 2019. Areas were identified for which the conclusion of the significance of such relationships was characterized by reliability of at least 0.90, 0.95 and 0.99. For this purpose, the values of the correlation coefficient for these processes were calculated for all districts and compared with the corresponding threshold levels. The latter are determined taking into account the number of degrees of freedom of the considered time series and make up 0.36, 0.40, and 0.53. The results of the correlation analysis are shown on the district maps, where the areas with certain values of the correlation coefficient are highlighted.

The method considered does not take into account the multifactorial nature of the processes under study and is based on a simplifying assumption which is not always valid. In addition, the criterion used in determining the date of polynya formation in a particular area - the complete disappearance of its ice cover - is overly rigid. Nevertheless, the methodology used is quite suitable for identifying qualitative regularities and achieving the aim of this work.

3 Results

In solving the first problem for each year of the period 1993-2019, changes in the average daily values of their SIC averaged over the studied areas of the Laptev Sea were studied. As an example, Fig. 1 compares the changes in the above indicators occurring from May 1 to August 31 in Area 1 for two time intervals: 1994-1999 and 2015-2019.

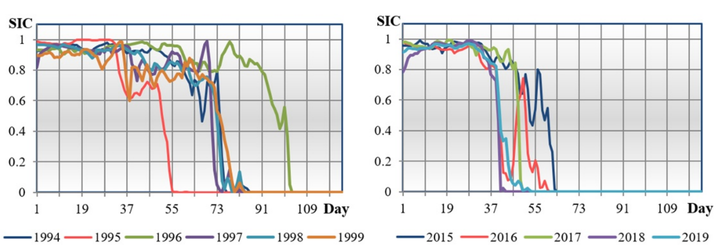

Fig. 1. Dependencies of the SIC for the Laptev Sea area, east of Tiksi Bay at 72o N, on the date from 1 May for the periods: (a) 1994-1999 (b) 2015-2019.

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Figure 1 shows that the timing of polynya formation in the area of the mouth of the Bykovskaya channel has changed over the period 1993-2019. As it can be seen from Figure 1a, in 1994-1999 in this area the complete disappearance of its ice cover occurred between 55 and 104 days, but more often it occurred on 79-81 days. Figure 1b shows that during 2015-019, an ice cap in the area formed on 41-63 days (i.e., on average 15 days earlier). Both the average value of the dates of its formation and the spread of the earliest and latest dates decreased.

Since the polar day in the area in question begins on 9-10 May, each square metre of the surface of the polynya in question absorbed much more STR during the summer months in 2015-2019 than during the period 1994-1999. More heat was also released into the atmosphere, which contributed to the warming of the climate of this region of the Arctic.

Similar estimates were made for the second region, which made it possible to generate the time series D1(t) and D2(t) for each of them and calculate the corresponding AGR values.

Fig. 2 shows the time dependences of the values obtained in this way (D2(t) – D1(t))/ (D2(t) – D1(t))max and D1(t))/D1max (here (D2(t) – D1(t))max = 14, and D1max= 102).

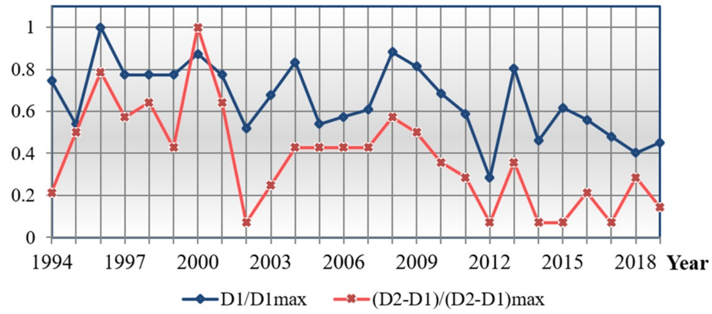

Fig. 2. Changes in (D2(t) – D1(t))/ (D2(t) – D1(t))max and D1(t))/D1max for the period 1994–2019.

The dependencies in question are similar, as can be seen. Both have decreasing trends.

The presence of the decreasing trend in the lag of the polynya formation date in region 2 in relation to the date of the similar event in region 1 confirms the validity of the accepted assumption that the flooding at Trofimovskaya channel has little influence on the SIC of the Laptev Sea area under consideration.

It is clear from Fig. 2 that the locations of the extremums of the plots presented on it practically coincide. As a consequence, the correlation coefficient for the corresponding time series is 0.61. Hence, it follows that the conclusion about the significance of the statistical relationship between them is characterized by the reliability of at least 0.99 (the corresponding threshold value of their correlation coefficient is 0.53). Thus, the result obtained confirms the validity of the hypothesis.

It has been established that the interannual changes in the AGR of the Lena Pillow River represent a complex oscillation, in which there is an increasing trend. In 2004, 2012, 2014, 2015 and 2017, the corresponding minimum D1 values of AGR estimates were 111 km/day. The latter indicates a significant influence on the process of polynya development of the dynamic factor - the runoff current caused by a sharp rise in the level at the mouth of the Bykovskaya channel (which exceeded 0.4 m in the days preceding D1 in the specified years).

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When solving the third problem, locations of Laptev Sea water areas were determined for which relations of interannual changes in their SIC and D1(t) were statistically significant. The greatest number of such areas was identified in June (Fig. 3). In July they are less, and in other months they are practically absent.

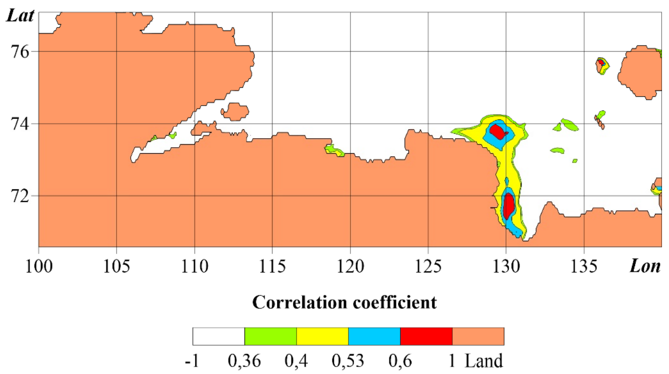

Fig. 3. Plots of significant correlation of interannual changes in SIC in June with dates of polynya formation in the Lena delta.

As follows from Fig. 3, the areas of the study area for which relationships of interannual changes in their SIC in June with D1(t) variations are statistically significant occupy the western part of Buor-Khaya Bay and adjacent areas of the Laptev Sea.

The identified areas are crossed by the coastal route of the NSR and the approach routes to the port of Tiksi, which allows us to estimate changes in their SIC using the obtained dependencies D1(t) and AGR (t).

4 Discussion

The results obtained indicate that a significant cause of the current climate warming in the Arctic region under study may be the formation of polynyas in it on earlier dates, which fall on the polar day period.

When comparing the results obtained with the work [19-21], which deals with the construction of general vessel routes under different ice conditions, it is possible to identify a trend that the actual routes during independent navigation pass along the formed polynyas, regardless of the physical principle of their formation. For the eastern sector of the Arctic, similar results have also been reported (22, 23), and they may be associated with changes in the water level of the Laptev Sea and the East Siberian Sea, as well as with elements of global warming and the flow of Siberian rivers.

If the current climate warming trends in the Lena basin persist in the future, the timing of the onset of Lena Pole formation will shift towards earlier dates. Nevertheless, it follows from Fig. 1 that in the next twenty years this process will, as now, occur during the polar day period (which begins here on May 9-10). Consequently, the ice conditions in the Laptev Sea area under consideration will become even more favorable for navigation in early summer and its climate warming will continue. Since the Lena is the most full-flowing river in the Laptev Sea basin, it follows from the results that the average STR flux converted by the underlying surface of this sea into heat warming the atmosphere above it will increase in 2021-2040. Therefore, the conclusion about climate warming is valid for at least the entire southeastern part of the sea in question. The latter is consistent with existing projections of climate and ice changes in the Arctic seas [3-10]. At the same time, with further climate warming in the Lena basin, the polynya in question will begin to form even before the onset of polar day. As a consequence, the STR flux absorbed by the polynya waters on the date of its formation will begin to decrease, in contrast to the heat flux lost by them. As a result, climate warming in the study region of the Arctic will slow down and may be replaced by cooling.

5 Conclusion

As a result of the study, it was found that the average growth rate of Lena polynya in the summer months is greater the earlier it is formed. The identified trends of changes in the dates of polynya formation confirm the validity of existing forecasts of further Arctic climate warming for the period 2021-2040. In these years, changes in the state of the ice cover of its seas during the summer months will be favourable for the development of shipping on the Northern Sea Route and the development of their natural resources. With further warming of Siberia's climate, the rate of climate warming in the Arctic region in question might, on the contrary, begin to decrease, which in turn might even cause cooling. Considering this, Russia's ongoing programme for the development of its icebreaker fleet seems very timely and extremely necessary to ensure the livelihood of the population of all its Arctic regions, as well as the sustainable functioning of their economies.

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