Impact of Floods in the Kolyma River Delta on Navigation Conditions in the East Siberian Sea

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Abstract. Problem of improving the quality of medium- and long-term forecasting of changes in ice conditions in the Northern Sea Route, and in particular in the east Siberian sea, where one of the methods of selecting waterways is the passage of ships in areas of ice-covered polynya. The hypothesis is verified that during the summer months, such changes may be significantly influenced by the timing of the onset of high water in the Kolyma River delta. Data from the global reanalysis GLORYS12v1 supported by the European Copernicus Marine Service were used as factual material on the ice cover and levels of the East Siberian Sea in the months of May to October 1993-2019. The analysis is based on mathematical models of the NEMO family verified by satellite altimetry data. Using the developed methodology, the dates of abrupt changes in level and sea ice extent on the Kolyma River estuarine seashore have been estimated for selected periods of the year. The study uses statistical methods to confirm the validity of the stated hypothesis for a number of areas of the East Siberian Sea, through which the shipping routes of the Northern Sea Route pass. It has been established that the greatest influence of flood timing on ice conditions and navigation conditions in such areas takes place in July. It is shown that early floods in the Kolyma delta generally lead to improvement of ice conditions, while late floods lead to complication of ice conditions. The identified relationships are recommended for use in forecasting changes in ice conditions. It has been suggested that with further climate warming and shifting of flood dates to earlier dates, the complication of ice conditions due to freezing of the formed polynya is not excluded.

1 Introduction

Sections of the Northern Sea Route (hereinafter NSR) passing through the East Siberian Sea (hereinafter ESS) are extremely difficult for navigation and are not used most of the

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year. It is caused by heavy ice conditions in winter-spring navigation, and also the problems connected with absence of forecast models of ice conditions and with their adequate estimation for navigation [1,2], both at independent navigation of vessels, and at use of icebreaker escort, that is especially actual for all eastern sector of NSR [3-5].

Availability and reliability of forecast information on ice conditions are important for shipping companies, which plan in advance the crossings of their vessels along the NSR [6, 7] and for preservation of ecological safety of the Arctic seas [8]. The quality of ice forecasts for units of weeks and months is largely determined by how fully they take into account the factors causing changes in ice conditions in the medium and long term. Such forecasts are currently insufficiently accurate [2]. In this connection, the development of methods and technologies for forecasting ice conditions remains an urgent problem of oceanography and hydrography in ensuring navigation safety.

A complex of factors influences the dynamics of ice situation development. For this reason, statistical methods are widely used in forecasting. The latter are most effective when there is a significant causal connection between predicted processes and predictors, which are tens of days to months ahead in time.

During summer months, navigation of vessels in ESS usually takes place in the floodplains, which are actively formed during flood periods in the estuaries of Siberian rivers. The Kolyma River is the most full-flowing river in the area. It discharges into the Kolyma Bay, forming a delta 110 km long, 75 km wide and 3 000 km2. The river flows into the sea through three main channels: the Kamennaya Kolyma (navigable), and the Pokhodskaya Kolyma and Chukochya Kolyma. The aforementioned channels are ice-covered for an average of 286 days per year and break up in late May/early June, leading to flooding in some years. For the organization of year-round navigation on the NSR, the forecast of drifting ice movement is also an important element [9].

During Kolyma floods, the level of Kolyma Bay rises significantly, which breaks the ice covering it and creates currents that carry its debris away from the coast. As a result, the ice cover of the areas near the mouth of the river decreases sharply and a polynya is formed. The further development of this polynya depends on the sign of the thermal balance of its surface waters. If the amount of solar radiation they absorb is greater than the amount of heat escaping into the atmosphere, the area of the polynya increases, otherwise it is re-covered in ice.

The free water surface absorbs solar radiation most intensively during the polar day. Therefore, the greater the polynya area in July and August, the larger it was on July 1. The shorter the time interval separating this date from the date of polynya formation, the smaller will be the average values of its area in July and August and the heavier will be the ice conditions in the region. The latter makes it possible to hypothesise that interannual changes in ice cover in some parts of the ESS water area can be significantly and positively correlated with variations in the dates of polynya formation in Kolyma Bay. Knowledge of the locations of such areas will allow a better understanding and prediction of ice conditions formation for the purpose of planning navigation routes in the region during the summer period.

The aim of this work is to test the hypothesis put forward.

2 Materials and methods

The study was conducted in two stages:

1) Assessment of flood onset dates in the Kolyma River delta for the period from 1993 to 2019 based on information on average daily values of mean water surface level and ice cover of its pre-mouth seashore sections;

2) Assessment of statistical significance of interannual changes in ice cover of different parts of ESS water area with variations of Kolyma flood onset dates.

The data of global reanalysis GLORYS12v1 supported by the European Copernicus Marine Service [10] were used as factual material on ice cover and ESS levels in the months from May to October of 1993-2019. The methodological basis of the global reanalysis for transport routes of ships in the NSR water area was proposed in [11, 12].

The analysis is based on mathematical models of the NEMO family, verified by satellite altimetry data [13, 14]. Estimates of mean daily values of mean sea ice extent and sea level are presented for all areas of the World Ocean with a discreteness of 5 arc minutes by latitude and longitude. Additional verification of reanalysis data in this study was performed selectively by comparing them with the maps taken from [15, 16]. The information on the actual start dates of floods in the Kolyma delta (and floods caused by them) for some years of the 2010-2019 period was also checked against data from the archive of the Ministry of Emergency Situations of the Russian Federation.

In solving the first task, it was taken into account that an informative sign of a detectable process in the Kolyma delta is a significant increase in the water surface level in its forebay, followed by a significant decrease in its ice cover. As an example to illustrate typical changes in the above-mentioned parameters during floods in the Kolyma delta, Fig. 1 shows the dependence of average daily values of the mean sea ice extent and mean level on the Kolyma seashore on the number of days elapsed from the conventional date of April 30 in 1994 and 2016.

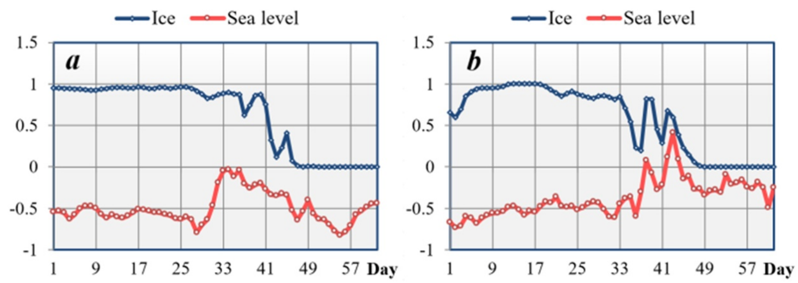

Fig. 1. Examples of changes in average values of ice cover and level of the Kolyma River forebay sections from May 1 to June 30 for the years: (a) 1994; (b) 2016.

Figure 1 confirms that in 1994 the level rise on the seashore began on 30 May (immediately on the date of the actual start of the flood), while the sharp decrease in ice cover was delayed by 7 days (6 June). In 2016, both processes started almost simultaneously. It follows from this that it is reasonable to consider the dates of the beginning of floods as the dates of significant level increases, provided that they are followed by a sharp decrease in the sea ice extent.

By analyzing similar information for other years, threshold levels of the aforementioned changes were determined, making it possible to estimate the dates of flood onset in the Kolyma delta for years for which no information on the actual dates of these events is available.

For the second objective, the method of correlation analysis and Student's test were applied. The threshold values of correlation coefficient have been estimated for the period from 1993 to 2019. If they are exceeded, the statistical significance of the considered association is proved to be not less than 0.9, 0.95 and 0.99 (they are 0.36, 0.4 and 0.53, respectively). Before the correlation analysis was carried out, linear trends in the compared series were compensated.

3 Research results and analysis

Using the described methodology, for each year of the period 1993-2019, the dates of abrupt changes in sea level and ice cover on the Kolyma River forebay have been estimated. The time dependencies of these dates are shown in Fig. 2.

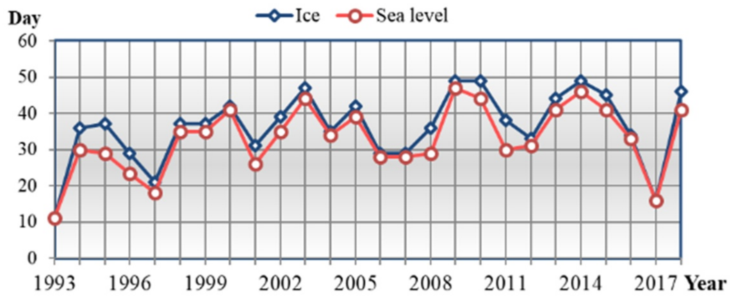

Fig. 2. Estimates of flood onset dates in the Kolyma River delta based on information on changes in mean ice cover and levels in sections of its forebay.

Fig. 2 shows that interannual changes in the date of the flood start in the Kolyma River delta are of an oscillating nature. The amplitudes of these fluctuations are so large that no significant trend of changes in these dates is revealed. The time dependencies of the estimates of the dates in question are practically similar.

When solving the second problem for months from July to October, the sections of ESS water area were identified, in which relations of interannual changes of their monthly average values of ice cover with changes in the dates of the beginning of floods were statistically significant. For example, Fig. 3 shows the locations of such sites in July and August.

It can be seen from Fig. 3, such sites are present in both July and August. Moreover, in July they are located in the Sannikov Strait and in open ESS areas located north of the Kolyma Bay directly on the high-latitude and coastal NSR routes. The reliability of the conclusions about the significance of the studied relationships for many of the sites is well above 0.99.

In August, the cumulative area of the study sites is smaller. They are located only on sections of the high-latitude NSR routes. In September they are even less, and in October they are not detected at all.

Consequently, the degree to which the timing of floods in the Kolyma delta and the formation of ice floes on its seashore influences ice cover and, consequently, navigation conditions in the ESS becomes weaker from July to October.

Thus, the results obtained confirm the validity of the hypothesis proposed.

4 Discussion of the results obtained

It follows from these results that changes in the timing of the formation of an ice floe in the Kolyma River forebay have a significant impact on its further development.

 https://doi.org/10.1051/e3sconf/202236301004

The earlier it is formed, the more extensive it becomes by July 1 (which is why the correlation of the studied processes is positive). This is because the earlier the formation of the polynya, the later the growth of its size occurs.

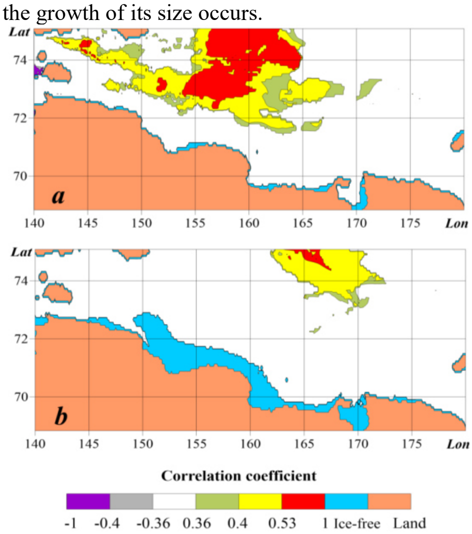

Fig. 3. Areas of the East Siberian Sea with significant correlation between interannual changes in monthly mean ice cover and flood onset dates in the Kolyma River delta for the months: (a) July; (b) August.

The timing of the start of flooding in the Kolyma delta is generally determined by the timing of flooding in the Kolyma delta recharge area. Due to the continuing warming of the local climate, a further shift of these dates to earlier dates can be predicted.

At the same time, if a polynya forms too early, when the sun is still low above the horizon, the amount of heat absorbed by it per day will not be great [17]. The amount of heat lost by the polynya waters during the first days of its existence is practically independent of the date of the event. Therefore, when an polynya is formed early, the daily value of its heat balance may decrease and even become negative. In the latter case, the water surface will be covered with ice.

Consequently, further climate warming in the feeding area of the Kolyma River, causing it to flood earlier, may lead to a lower rate of increase in its area, and in the more distant future even to a reduction in its area.

Considering the above, it seems likely that ESS ice cover cohesion will continue to decrease during the summer months in the coming years, but this trend may reverse in the future. As a result of the latter, in the more distant future, the ice cover cohesion of the NSR areas located in the ESS may start to increase.

The latter contradicts the conclusions [18, 19], nevertheless, such a scenario with further warming of the Siberian climate seems quite probable.

If it occurs, the conditions for independent navigation of vessels in the ESS water area will be favourable during the current decade. Nevertheless, it is possible that in the next decade, icebreaking of ships in the NSR areas located in the ESS will be required more often, as the conditions of navigation on it may become more complicated [20].

In view of the above, the strategy of the Russian Federation aimed at constructing and commissioning new nuclear-powered icebreakers, as well as increasing the fleet of high Arctic-class offshore vessels seems fully justified.

5 Conclusion

The study revealed that the timing of the occurrence of floods in the Kolyma delta during the summer months significantly affects the ice cover and navigation conditions on some sections of the NSR routes located in the East Siberian Sea. The most significant impact takes place in July.

Since the timing of the Kolyma River overflow in its delta and the formation of polynya can be predicted from the time of the beginning of the flood at the upstream sections of this river, as well as in its recharge area, this factor is advisable to take into account when making medium- and long-term forecasts of changes in ice conditions in such sections.

Earlier floods generally result in better ice conditions. However, with further climate warming, the timing of floods will shift to even earlier dates. Once these dates correspond to pre-polar day periods, the rate of inter-annual change in ice cover (towards its reduction) will slow down. Thereafter, there will probably be a phase of the process under study in which its development will take place in the opposite direction. In this case, the polynya will form in April or even earlier, due to which its surface will be ice-bound, and ice conditions in the ESS in late June-July will become more complicated.

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