Probability assessment of possible ice encounters during the petroleum hydrocarbons transportation in the Sea of Okhotsk

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Abstract. The increase in freight traffic along the Northern Sea Route necessitates the study of the ice regime of the freezing seas of Russia, including the Far Eastern ones (Bering Sea, the Sea of Okhotsk and the Sea of Japan). This paper, on the basis of the analysis of the Sea of Okhotsk’s ice cover and the location of the edges of the Sea of Okhotsk’s ice massif, evaluates the probability of an encounter with ice for the ships in transit during cargo transportation on the Northern Sea Route through the Far Eastern seas along two basic routes from the southern tip of the Kamchatka Peninsula: 1) traverse Cape Lopatka–Sea of Okhotsk–La Perouse Strait; 2) traverse Cape Lopatka–Sangarsky Strait. It was shown that at the stage of ice cover maximum development in the Sea of Okhotsk (February–March), route No. 2 was the most adequate and the safest for ships of ice class Arc4 and below. The section of route No. 1 with a 70 % ice encounter probability was 421 km long in February and 382 km long in March. That section of the route was dominated by very cohesive first-year thin ice up to 70 cm thick with inclusions of first-year ice of average thickness (up to 120 cm).

1. Introduction

In view of the development of oil and gas resources of the continental shelf, as well as global tendency of increase in air temperature, which contributes to ice extent reduction of the freezing seas of Russia, much attention is currently paid to the development of the Northern Sea Route (NSR). In January 2021, Arctic tanker of Arc7 ice class "Christopher de Margerie", without icebreaker escort, successfully completed the passage from the port of Sabetta along the NSR in easterly direction. This event in practice showed the effectiveness of using this transport artery and the need for further development of its transit potential.

When transporting goods along the NSR to the countries of the Asia-Pacific region, after passing the Bering Strait, the vessel has two options on route to its destination: 1) through the Bering Sea, the Sea of Okhotsk and Sea of Japan (Far Eastern transport corridor) and 2) through the Bering Sea and the Pacific Ocean. It should be noted that in terms of the severity of ice conditions, the Sea of Okhotsk and Bering Sea are comparable to the seas of Russian sector of the Arctic. The maximum development of the ice extent in the Far Eastern seas is observed in February–March. Probability assessment of the encounter with predominant first-year ice, performed on the basis of regular ten-day aviation observations of the state of the ice extent in 1956–1991, was presented in [1]. Modern pentad (once every five days) satellite observation data enabled not only a more accurate probability assessment of encounters with ice of various ages, but also with ice of different concentrations. The objective of this paper was to assess the probability of ice encounter for the ships proceeding from the southern tip of
the Kamchatka Peninsula (Cape Lopatka) to the countries of the Asia-Pacific region through the Sea of Okhotsk and along the Pacific coast of the Kuril Islands at the phase of maximum development of the ice extent (February-March) for 1981–2010.

2. Material and Methods
The data of satellite microwave radiometers for variations in the ice extent area with pentad sampling rate from 1981 to 2010 (nominal spatial resolution up to 4 km) of the Japan Meteorological Agency [http://ds.data.jma.go.jp] were used as the initial data. The area of the ice extent was calculated using ICE software package [2] and original authoring software tools. Computational error of ice extent area does not exceed +/- 1–2 % [3]. Ice cover was calculated as the ratio of the area occupied by ice to the gross area of the sea, expressed as a percentage.

Statistical calculations were carried out for two navigation routes: 1) traverse Cape Lopatka–port of Korsakov–point 38°30'N, 134°00'E; 2) traverse Cape Lopatka–Sangarsky Strait–point 38°30'N, 134°00'E. Due to the ongoing active discussion about the creation of a multifunctional transport hub in the port of Korsakov, a call at the port of Korsakov, the largest port of Sakhalin region, was included in Route No. 1. The location of ice massif edge at the stage of its maximum development was refined based on the archive of daily data from the MASIE multispectral system for analysing daily satellite observations [http://nsidc.org/data/masie] for the period from 2006 to 2010 (nominal spatial resolution up to 1 km).

The probability of ice encounter (V) was calculated by the formula:

\[ V = \frac{N}{n} \times 100\% \]

where, N – number of ice encounters, n - number of observations.

When verifying and analysing the calculated data, the following tools were used: the archive of visible range satellite images of the ice extent (NOAA, Meteor, Kosmos, TERRA, AQUA, NPP spacecrafts), radar images (Sentinel-1, 2), atlases of ice and the boundaries of ice propagation [4–5], as well as the results of the analysis of complex hydro-meteorological studies carried out in different years in the Sea of Okhotsk [6].

All terminology and concepts of ice phenomena correspond to the "International Symbols for Nautical Ice Charts and the Nomenclature of Sea Ice" [7].

3. Trends in sea ice cover in the Sea of Okhotsk for the period 1882–2020
Analysis of the ice regime elements of the Sea of Okhotsk paid particular interest to the long-term fluctuations in the area of ice extent, which allowed assessing the intensity of ice processes and relating them to global climate changes occurring in the current period. [3, 8] developed the secular series of interannual variability of ice cover values in the Sea of Okhotsk, based on ship, aviation and satellite ice extent observations data and air temperature observation data at coastal hydro-meteorological stations. The analysis of the secular series allowed us to conclude that in recent decades there was intensive reduction in the area of ice extent.

Figure 1 shows the interseasonal variability of sea ice cover in the Sea of Okhotsk for the period 1882-2020. From 1882 to 1979, the magnitude of negative trend in ice cover was 0.3 % / 10 years. The decrease in ice cover from 1980 to 2020 was one order of magnitude more intense - 4.9 % / 10 years. Spectral analysis of the series under study made it possible to identify periods with fluctuations of 6, 9, and 17–18 years. The latest period of ice cover decrease (from 1980 to the present) coincided with the current period of warming and so far continued for 42 years.
4. Probability assessment of possible ice encounter

4.1. Route No. 1: traverse Cape Lopatka–port of Korsakov–point 38°30’N / 134°00’E

Route No. 1 total length was 2,457 km (1,327 nautical miles). Analysis of the calculated data for the southern region of the Sea of Okhotsk allowed us to conclude that in mid-February the zone with a high probability of ice encounter (more than 60%) was located along the eastern coast of Sakhalin at a distance of 120–250 km from the coast. South of 46°50’N latitude the width of the zone decreased to 60–100 km (figure 2). That ice mass was formed in the north-western region of the Sea of Okhotsk and drifted southward under the influence of winter monsoon [9]. In mid-February, the ice concentration was 9–10 points. The massif was dominated by thin first-year ice (up to 70 cm) with inclusions of first-year ice of average thickness (up to 120 cm).

Figure 2. Probability of ice encounter on Route No. 1 on February 15.
On Route No. 1, on the 85 km segment, the probability of ice encounter was 100%. On 336 km long section (from 144°25' to 143°30'E), the probability of ice encounter was 70–90%. A characteristic feature of ice conditions in this area was the decrease in the concentration of ice extent to 4–8 points. For the rest of the route, the ice extent was represented by open ice with a probability of encounter from 10 to 60%, which would not be a serious obstacle for ice class vessels. Thus, the overall length of the part of Route No. 1 with the probability of ice encounter of more than 1 % was 1 092 km. In the Aniva bay in mid-February, the probability of ice encounter was 70–80%. The ice massif of the bay was represented by ice of local generation, the thickness of which did not exceed 15–25 cm.

Figure 3 shows the map of probability of ice encounter at the stage of the maximum development of ice extent in the Sea of Okhotsk (March 10). The border of the zone with high probability of ice encounter (more than 60 %) was located 50–125 km east of its position as of February 15. The overall length of the part of Route No. 1 with probability of ice encounter of more than 1 % was 1 240 km.

Figure 3. Probability of ice encounter on Route No. 1 on March 10.

4.2. Route No. 2: traverse Cape Lopatka–Sangarsky Strait–point 38°30'N / 134°00'E

The total length of Route No. 2 – 2 378 km (1 284 nautical miles).

The islands that form the western, southern and eastern boundaries of the Sea of Okhotsk are a natural barrier, forming a "trap" for ice drifting from the northern part of the sea. At a certain stage of filling the natural trap, ice begins to squeeze out through the Izmena Strait, Catherine Strait, Frisa Strait and the First Kuril Strait into the Pacific Ocean. The overall length of the part of Route No. 2 with the probability of ice encounter above 1 % on February 15 was 502 km (figure 4). The maximum value of the frequency of ice encounter when a vessel passes along Route No. 2 in mid-February is 40 % (area of Shikotan Island). The ice massif in these areas was represented mainly by one-year thin ice. On March 10, the overall length of the part of Route No. 2 with the probability of ice encounter of more than 1 % increased to 580 km (figure 5).
Figure 4. Probability of ice encounter on Route No. 2 in February.

As in mid-February, the greatest probability of ice encounter in the first decade of March was in the area of the Lesser Kuril Ridge (maximum probability was 50%). Ice conditions during that time period were similar to those of mid-February. To exclude an ice encounter, the route could be laid further southeast, while its length would increase by ~ 70 to 100 km.

Figure 5. Probability of ice encounter on Route No. 2 on March 10.
5. Conclusion
1. The total length of Route No. 1 was 2 457 km, Route No. 2 – 2 378 km. When vessels take Route No. 1: traverse Cape Lopatka–port of Korsakov–point 38°30’N /134°00’E, the length of the section with the probability of ice encounter of more than 1 % was 1 092 km in mid-February and 1 240 km in the first decade of March. The length of the section of Route No. 1 with the frequency of ice encounters of 70–90 % in February and March was 336 and 265 km, respectively. The length of the route part with 100 % probability of ice encounter and the most difficult ice conditions (concentration of 9–10 points, ice thickness up to 120 cm and hummocking of 2–3 points) in March was 131 km, which was 31 km more than in mid-February.
2. On Route No. 2: traverse Cape Lopatka–Sangarsky Strait–point 38°30’N /134°00’E, the section with the highest probability (40–50 %) of ice encounter in mid-February and early March, was located to the southeast of the Lesser Kuril Ridge. The total length of that section was 200–250 km. Also, ice encounters were a possibility in the area of the First Kuril Strait and Catherine Strait. Those sections could be bypassed southeast, slightly increasing the length of the route.
3. In case of independent navigation of vessels of ice class Arc4 and below, from the point of view of the route length and ice encounter probability, the most favourable route was Route No. 2. With daily monitoring of ice conditions and adjustments of Route No. 2, the probability of ice encounter for ships could be completely eliminated.
4. For independent navigation of vessels during the period of maximum development of ice extent in the Sea of Okhotsk (February-March) along Route No. 1, the vessel should have a minimum ice class not lower than Arc5.

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