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## **EVALUATION CRITERIA AND APPROACH TO VOYAGE PLANNING IN ICE. VERIFICATION ON THE EXAMPLE OF GERMAN SHIP ACTIVITY DURING THE SECOND WORLD WAR**

### **ABSTRACT**

Vessels designed for navigation in ice can perform voyage with the assistance of icebreaker in the navigation season in case an ice cover area is less than 20%. Whereas the same vessels could carry out successfully completed voyage through the NSR with intensive icebreaker help at the ice-covered area lower than 42%. Navigation of the same vessel at ice covered area above 80% is possible with intensive icebreaker help, but it threatens to damage the hull, rudder or propeller.

Excessive generalization of data analyzed may cause to wrong, even opposite conclusions. Using only basic statistical information in the form of average values and standard deviation may be not sufficient for the purpose of vessel's voyage planning in areas covered with ice. Much more opportunities for the assessment of navigation in ice covered regions provides cumulative distribution, which should be related to the time and geographical space distribution. It allows to determine the duration of time window for given area covered with ice in a particular region and predetermined probability of its occurrence. It is thus possible to plan approximate date of departure and duration of voyage for assumed safety criteria. Also, it is possible to plan a number of consecutive voyages in a navigation season.

Mathematical approach to voyage planning in ice based on a cumulative distribution is presented in the paper. It allows creation of an advisory computer application to support decision-making by the commander of a vessel. It will reduce the human factor in data processing and reduce possibility of making a mistake. By this way, can be enhanced the safety of maritime transport. Novell approach is verified on the example of historical data about the German Navy ship activity during the Second World War.

### **Keywords:**

Northern Sea Route, ice navigation, voyage planning.

## INTRODUCTION

Shipping routes along the Arctic coast of Russia were recognized systematically during the movement of the local population living on the coast of the Arctic Ocean. They led to the discovery of the O. Yu. Dezhnev the possibility of transition from Europe to the Far East in 1648 [14]. The first map of passage from west to east through the Arctic Ocean was made in the years 1691-1692.

Voyage of vessel "Vega" guided by Nils Nordenskjold was the first known case of travel by the Northern Sea Route (NSR) from west to east. The voyage lasted two navigational seasons 1878 and 1879. In 1920, attention was drawn to a very intense warming in the Arctic [5] lasting at least since 1890. In 1932 Soviet icebreaker "Sibiryakov" passed the first NSR during a single navigation season [14]. At the beginning, movement of transport vessels related mostly the passages from the east to the Kolyma river and the passages from the west to the Lena river [2]. Up to 10 vessels per annum called in to ports on the rivers Ob and Yenisei in the years 1920-1928 and up to 46 vessels in the years 1929-1939. Trend of vessel traffic was clearly growing.

The period of the Second World War disrupted the natural development of merchant shipping in this region. At the same time it forced to increase the number of cargo ships' voyages by 80% compared to the period before the war. There was a strong pressure to perform voyages back and forth in a single navigation season without loss of ships, and in addition, regardless of the prevailing ice conditions.

The main goal of this work was to draw a general conclusions that facilitate ship's voyage planning by the NSR and meet certain safety criteria. For this the identification of the prevailing ice conditions at the time of navigation seasons during the Second World War, which transport vessels were able to overcome has been executed. The second partial aim of the study was to determine the objective criterion of difficulty of ice conditions and the application of this criterion in ships' voyage planning.

The partial goals were:

- to determine an objective criterion for assessing difficulties of ice conditions on particular sections and on the entire NSR,
- to determine the effects of generalization of information about the state of the ice cover on the deviation of the mean statistical ice conditions by conditions in a particular space of time and geographical location,
- to determine the probability of more difficult conditions than average ones that can be encountered in any place and at any time during the performance of voyage on the NSR.

It was hypothesized that it is possible to determine the time window of ice conditions that are appropriate for implementation of passages on the NSR.

For this purpose, shall be determined ice conditions occurring in the specified time and geographical space to carry out a ship's voyage. Then the time needed for the voyage back and forth should be determined. On this basis the most difficult ice conditions, which ships should be able to overcome on their routes should be determined. Knowing the most difficult ice conditions, which ships were able to overcome it should be possible to determine the time window favorable for the implementation of the voyage back and forth in one navigation season.

### **SHIPPING ON THE NSR DURING SECOND WORLD WAR**

Movement of vessels on the NSR during the Second World War is not well known. A number of German warships operated in the waters of the Barents Sea, Kara Sea and Pechora Sea, especially in summer. In the winter of the 1941 to 1942 operated from 13 to 25 submarines in the Arctic [3]. The Germans knew that many Soviet navy ships sought refuge in the Kara Sea due to favourable occurrence of ice floes for almost 10 months a year. For this reason, as part of Operation "Wunderland" ships of the German Navy entered there in a convenient for navigation summer season. Germans even been reached on force a temporary suspension of the supply of military equipment by the NSR from Europe to the Soviet Union and complete resignation of them in the Arctic summer months till the end of 1942 years. In August and September 1942 in the Kara Sea operated one German heavy cruiser. In the area of Novaya Zemlya straits and at the entrance to the White Sea operated the next 5 German warships.

The activities of the German Navy had to destroy the transports of cargo on board ships from the United States to the Soviet Union by the NSR. However, these shipments get through the Gulf Provideniya, ports of Pevek and Ambarchik, estuaries of Yana and Indigirka rivers, the port of Tiksi, estuaries of Olenek, Anabar, Khatanga and Yenisey rivers as well as the port of Arkhangelsk. In the years 1943-1945 on this route were transported an average annual 131,400 metric tons of cargo [2]. The statistical information provided by [2] are given in Table 1. It's known that one vessel made two return voyages from Murmansk to Dudinka. Other vessel made two return voyages. First one was performed from west to Tiksi and next voyage was performed to Dudinka.

During the period of 1940 - 1945 the tonnage carried annually increased by 80%. From 23 to 34 vessels passed this Arctic Route each year. Large number of successful voyages were apparently made. The voyages were performed with very small loss of these vessels. They passed from United States ports on Pacific Ocean through Bering Strait bound for the ports east of Cape Cheluskin. Most frequently mentioned are Tiksi, Bukhta Provideniya, Ambarchik and Pevek. Only two vessels entered the NSR from west. Need to mention that normal transport activity by vessels in Kara Sea was performed during World War II same like before.

Table 1. Numbers of voyages from USA to different ports via NSR in 1942-1945.

Port \ Year	1942	1943	1944	1945
Arkhangelsk	—	1	—	—
Ports of Yenisey	2	4	4	3
Mouth of Khatanga	3	3	5	5
Mouth of Anabar	3	2	2	1
Mouth of Olenek	1	1	—	—
Tiksi	11	14	15	14
Mouth of Indigirka	1	3	2	3
Mouth of Yana	4	4	5	4
Ambarchik	9	7	6	6
Pevek	5	6	6	8
Bukhta Provideniya	1	9	14	11
Number of voyages made	33	32	34	31

Compiled by the Author based on [2].

The special place in this activity places voyage of German raider Komet in 1940 from east to west which was performed in the total time 21.5 days (steaming time 14 days only) and this information is used later in the paper.

Table 2. Statistics of shipping from USA to Soviet Arctic ports via NSR in 1941-1945.

Month \ Year	1942	1943	1944	1945
May		4		
June	6	5	9	7
July	16	16	15	20
August	1	7	9	4
September			1	
Total number of vessels	23	32	34	31

Compiled by the Author based on <http://www.o5m6.de/Routes.html>

## STATISTICAL ANALYSIS OF ICE CONDITIONS OCCURRING ON THE NSR DURING SECOND WORLD WAR

Distribution of ice covering individual regions of the NSR in the navigation seasons in years 1940-1945 (Figure 1) indicates that average statistical parameters do not reflect maximum possible coverage of regions by ice. The level may be higher than twice the standard deviation error of average ice cover area. Real minimal ice cover area exceeding statistical average minus standard deviation can be found on all the NSR seas. Also real maximal value of ice cover area exceeding statistical average plus standard deviation can happen in reality on particular seas.

The maximum ice coverage at the level of 100% can be expected on the East Siberian Sea, Laptev Sea and the north-eastern part of the Kara Sea. There must expect the most difficult ice conditions. These relationships can be used for vessel's voyage plan well in advance. It seems that it can fulfill needs of general forecasting of ice conditions ahead of time from three months up to three years. It was assumed that due to rapid regression in extent of ice cover due to climate change [5], statistical data should cover the last 5 years. Longer averaging period of ice extent could lead in too large deviations of average ice conditions.

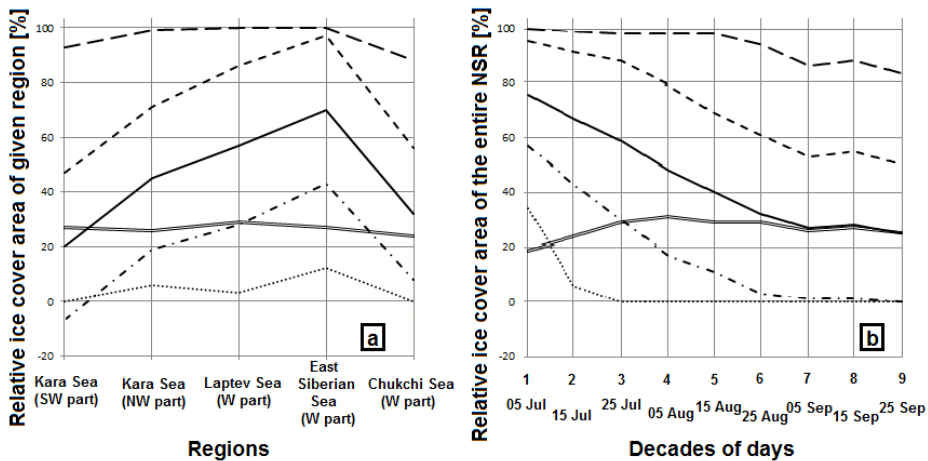


Figure 1. Statistical (based average and standard deviation) and real (based maximal and minimal) areas of ice cover on the NSR in the navigation seasons of the years 1940-1945: a - distribution of ice coverage of the NSR regions in all analyzed navigation seasons, b - distribution of ice coverage of the whole NSR during consecutive decades of navigation season. — — — maximal, - - - average +  $\sigma$ , — average, - • - average -  $\sigma$ , • • • minimal, = = = standard deviation  $\sigma$ . Compiled by the Author based on [13].

In subsequent decades of navigation season (ten-day intervals) ice conditions are systematically improved. The maximum ice cover exists till fifth decade inclusive (Figure 1b). The reduction of the ice cover has been declining since the first decade of navigation season. This is due to decrease in ice coverage of external seas of the NSR - Chukchi Sea and the south-western part of the Kara Sea.

The state of the ice cover tends to change on the all the seas from the seventh decade inclusive. At that time maximum possible ice coverage area of the seas does not exceed 90%. A top-secret US intelligence report [6] pointed out that in 1940 were exceptionally favorable navigation conditions. Graph on Figure 1b confirms this statement. It is generally confirmed in the 1940s, the Arctic experienced a warming period [7]. Need to mention one express actual climate warming and fast ice surface reduction same like in 1920s [5]. Taking into consideration actual knowledge in this matter [9] the word "fast" is relative and actual climate warming and ice surface reduction is much more accelerating with periodical oscillations [7].

The use of average relationships can lead to erroneous conclusions and further lead to wrong decisions. The minimum, average and maximum distributions of possible statistical area of ice cover on the NSR in the years 1940-1945 show significant differences (Figure 2). The actual state of ice covered area can therefore be much higher than expected and finally can be not possible to overcome by a vessel, even if she is assisted by icebreaker.

Wrong conclusions may be caused by excessive generalization of analyzed data. For example, the average of ice covered area of regions in different navigation seasons is in the range from 30 to 57% [13]. The smallest coverage area of ice which causes the highest difficulties in navigation season is in the range from 31 to 83%. The average coverage of regions by ice including a standard deviation in different navigation seasons is in the range from 56 to 89%. In certain navigation seasons the average coverage area of the NSR including standard deviation is always higher than the smallest ice coverage in a particular area which creates the largest difficulty in this navigation season. It could therefore be concluded that the adoption of the average ice coverage including standard deviation for voyage planning purposes puts the planner on the safer side. This value should indicate the more difficult navigation conditions in the lightest period of navigation season.

Whereas for a period of 1940 - 1945 the average ice coverage area of particular season was equal 45%, the lightest ice coverage of part of the sea that imposed the highest difficulties in the particular season was equal 83% and statistical average plus standard deviation was equal 77%. In case planner has used these more generalized information (average values for longer period of time), have drawn opposite conclusions. It can therefore be assumed that the use of only basic statistical

information in the form of average values and standard deviation may be not sufficient for the purpose of planning ship's voyage in ice covered regions.

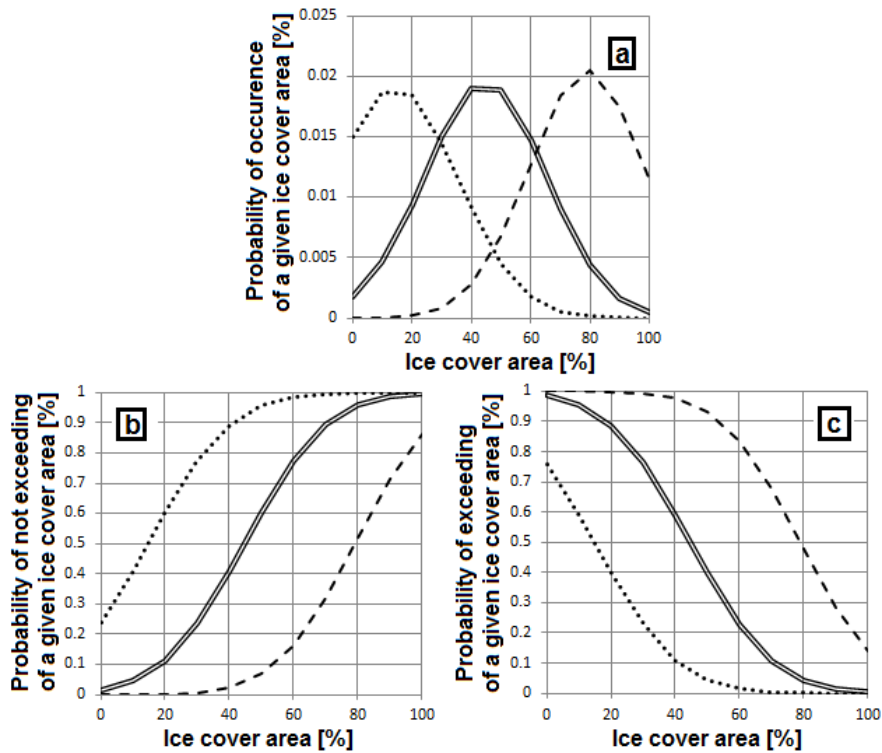


Figure 2. Average ice conditions on the entire NSR in the six navigation seasons in the years 1940-1945. a - normal probability density function, b - cumulative distribution for value less than or equal to the argument of the function, c - cumulative distribution for value more than or equal to the argument of the function. ••• minimal values — average values, — — — maximal values. Compiled by the Author based on [13]

The lightest ice conditions occur in the south-western part of the Kara Sea and on the south-western part of the Chukchi Sea (Fig. 3b). Relatively higher ice coverage occurs in the north-eastern part of the Kara Sea. The maximum ice coverage at the level of 100% can be expected on the East Siberian Sea, Laptev Sea and the north-eastern part of the Kara Sea. There should expect the most difficult ice conditions. In the western part of the Laptev Sea and in particular in the western part of the East Siberian Sea the ice cover area is highest and there is no complete release of the area from ice.

The highest probability of ice cover occurrence on particular sea is equal respectively: the south-western part of the Kara Sea - 20%, the south-western part

of the Chukchi Sea - 35%, the north-eastern part of the Kara Sea - 45%, the western part of the Laptev Sea - 58% and the western part of the East Siberian Sea - 70% (Fig 3a). The data on Figures 3a and 3b are comparable for specific cases. If the evaluation criterion is 50% probability of not exceeding an ice cover area,

the geographical distribution is as follows: the western part of the East Siberian Sea - 70%, the western part of the Laptev Sea - 58%, the north-eastern part of the Kara Sea - 45%, Southeast western part of the Chukchi Sea - 35% and the south-western part of the Kara Sea - 20% of ice cover area (Figure 3b). There is very easy on cumulative distribution diagram to read ice cover area on particular sea for other than 50% probability of not exceeding required value of ice cover area.

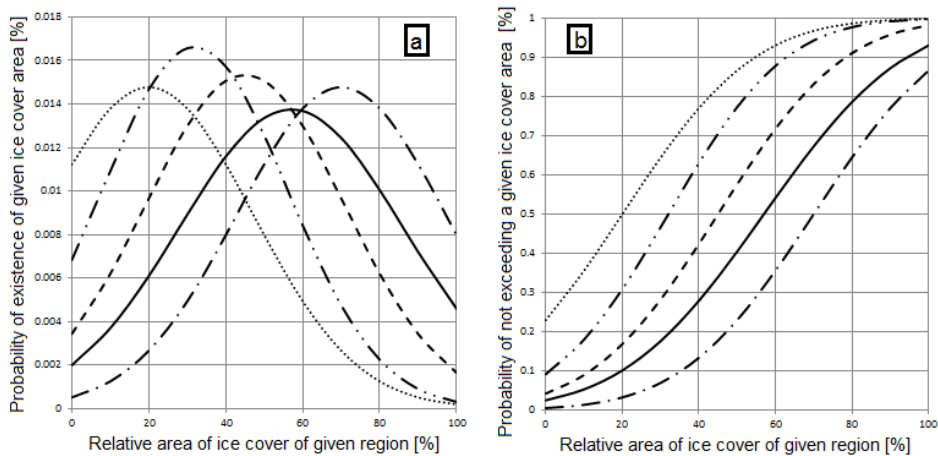


Figure 3. Average ice conditions on various regions of the NSR for the years 1940-1945. a – normal probability density function, b - cumulative distribution. ••• Kara Sea (SW part), – – Kara Sea (NE part), — Laptev Sea (W part), – • – East Siberian Sea (W part), – •• – Chukchi Sea (W part). Compiled by the Author based on [13].

The largest area is covered by ice in the winter season. Over time, the closer to the summer season, the area covered by ice decreases. The smallest ice cover occurs in the last decade analyzed navigation seasons. The highest probability of ice cover occurrence on particular decades of days is equal respectively: decade 1 - 25%, decade 2 - 27%, decade 3 - 28%, decade 4 - 32%, decade 5 - 42%, decade 6 - 48%, decade 7 - 58%, decade 8 - 67% and decade 9 - 77% (Figure 4a). Density curves are significantly narrower at the beginning and at the end of the navigation season. It is associated with the occurrence of a fairly consistent conditions in various NSR seas in a given decade - high area of ice cover in winter-spring season and low area



of ice cover in summer. The data on Figures 4a and 4b are comparable for specific cases. If the evaluation criterion is 50% probability of not exceeding an ice cover area, the time distribution is as follows: decade 1 - 25%, decade 2 - 27%, decade 3 - 28%, decade 4 - 32%, decade 5 - 42%, decade 6 - 48%, decade 7 - 58%, decade 8 - 67% and decade 9 - 77% (Fig. 4b). There is very easy on cumulative distribution diagram to read ice cover area on particular decade of days for other than 50% probability of not exceeding required value of ice cover area.

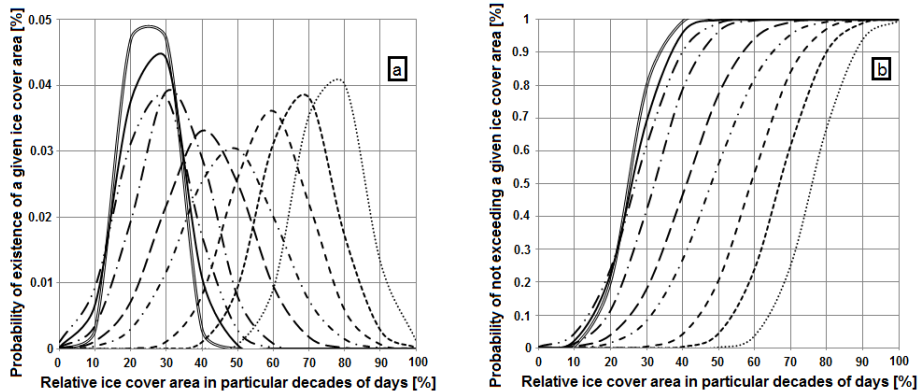


Figure 4. Average ice conditions in particular decades of navigation season in the years 1940-1945: a – normal probability density function, b - cumulative distribution. Decades of days:  $\equiv$  1 (05 Jul),  $\text{—}$  2 (15 Jul),  $\text{—} \cdot \cdot \text{—}$  3 (25 Jul),  $\text{—} \cdot \text{—}$  4 (05 Aug),  $\text{—}$  5 (15 Aug),  $\text{-} \cdot \text{-}$  6 (25 Aug),  $\text{—} \text{—} \text{—}$  7 (05 Sep),  $\text{-} \text{-} \text{-}$  8 (15 Sep),  $\cdot \cdot \cdot$  9 (25 Sep). Compiled by the Author based on [13].

Application of cumulative distribution function as a probabilistic method in evaluation of possibility of a vessel to overcome ice covered regions seem to be more flexible, more synthetic application and preserving continuity of matched indices than the method of average value of ice cover with discrete standard deviation of a fixed increment. To be able to apply it, one must determine the value of an average coverage of area by ice, where ships were able to reach a destination, or sail to the port of destination. In the work the experimental method was applied. The size of the area covered with ice in a time and geographical space, at which ships voyages has been completed successfully were determined. First, used for this purpose information on cargo ships, which successfully performed two consecutive voyages in one navigation season commencing voyages at the eastern side of the NSR. Then, information on the quantities of months and realized voyages of lend-lease ships, which commenced at the eastern side of the NSR. In the absence of detailed data it was assumed that each ship made only one voyage in the navigation season

(Table 1 and 2). It was assumed that all of the analyzed voyages took place with the assistance of icebreakers.

The information contained in the tables were derived from official manifests. It was not specified whether they relate to the date of departure or expected date of cargo discharge. Assumed that this is the date of departure of a vessel. Also assumed that ships performed their voyage and left the NSR area at the last moment before the freezing period, which would force ships to wintering in the area of the NSR. In order to determine ice conditions, which encountered lend-lease ships in the years 1942-1945 it was assumed that passage time back and forth along with the time spent for unloading of cargo lasted at least 2 months. Therefore, for purposes of the analysis the most unfavorable ice covered area of the NSR regions for the last two months of navigation season (August and September) was adopted for analysis. It was assumed that ships which began their voyage from the east of the NSR, first encountered in the first seas they sailed, more favorable ice conditions. The results are summarized in Table 3.

Table 3. Relative sea ice cover [in %] on the NSR for the month of August and September in 1942-1945.

Year	SW Kara Sea	NE Kara Sea	W Laptev Sea	W East Siberian Sea	SW Chukchi Sea	Adopted time of voyage
1940	13	67	<b>81</b>	45	6	2 months
1941	0	20	50	<b>80</b>	33	2 months
1942	0	51	35	<b>92</b>	67	2 months
1943	0	43	25	43	11	2 months
1944	0	49	<b>94</b>	60	18	2 months
1945	0	8	18	43	46	2 months

Compiled by the Author based on [13].

Statistical information is not very detailed. The number of vessels, landing ports, months in which realized voyages are known. But no information which ice class were the particular vessels or to which port the voyage was performed in a given month. With probability of 66% one may expect extremely high relative ice coverage of 80-94% on one of Laptev Sea or East Siberian Sea (Table 3). High level of relative ice coverage over 60% may be expected on NE Kara Sea, East Siberian Sea or Chukchi Sea. These conditions look be hard to pass also with assistance of icebreaker.

In order to verify statistical results and determine whether these conditions allow cargo vessels to realize their voyage, decided to perform experiment. The only described in detail a transit voyage has been used. It concerned the passage of the German auxiliary cruiser in 1940 from west to east. First, the travel details

and ice covered areas of the seas were determined, which corresponded to the time space and geographical space of the ship's voyage. It is known that the voyage took place with the assistance of the strongest Soviet icebreakers. It is also known that the ice conditions were hard. The ship was not able to perform her voyage independently without icebreaker assistance, twice stuck in ice and damaged the rudder so it required repairs after leaving the NSR region. It can therefore be assumed that conditions were extreme for the ship assisted by icebreakers.

## **EXPERIMENT TO VERIFY VALIDITY OF THE METHOD**

In order to validate correctness of the method of forecasting possibility to overcome the NSR and forecasting length of time window by using cumulative distribution was decided to carry out an experiment. For this purpose were used the data of successful transit voyage of the auxiliary cruiser *Komet* in 1940. It was first known successful commercial transit voyage performed through the NSR in one navigation season. For this purpose, collected all possible information about the ship and her transit voyage essential for the reconstruction of the navigation data and ice conditions present at the time of voyage.

### **Information about the ship**

After a long period of negotiations between the Germany and the USSR, the Soviet Union agreed to provide the Germans the Northern Sea Route, by which Germany could move their Navy forces between the Atlantic and the Pacific. Initially, the two countries agreed on the transit of 26 ships, but in a later stage the plan has been reduced to one vessel "*Komet*" [8].

Auxiliary cruiser "*Komet*" was built on the basis a merchant ship. The ship had a length of 115.5 meters, draft 6.5 meters, navigation range (autonomy) 35,100 NM, and reached a speed of 16 knots. Before dispatch for the Northern Sea Route, "*Komet*" was equipped with a specially strengthened hull and bow, and propeller blades suitable to navigate in ice.

### **Voyage schedule of the ship at time-geographical data spatial distribution**

The HSK7 ship sailed on a voyage from Gdynia (Gotenhafen) on 3 July 1940. The ship disguised as a Russian vessel Semyon Dezhnev sailed along the coast of Norway to Teriberka. There, in July and August 1940 was waiting for a suitable

moment to commence the passage. With the assistance of the Soviet icebreaker *Lenin*, he commenced passage in August 1940 to pass the Bering Strait at the beginning of September. In the final stage of her passage the ship was assisted by Soviet icebreaker *Joseph Stalin* and icebreaker *Kaganovitsch* [11].

Between July 15 and August 13 of 1940 *Komet* remained in the icy waters of the Barents Sea, mainly in drift occasionally at anchor [8]. During the second week of August the raider received reports of favorable conditions for a passage through the pack-ice and proceeded eastwards with maximum speed. Leaving her anchorage on August 13, and heading into the entrance to the Matochkin Shar Strait. The following day, August 14, the *Komet* arrived at the rendezvous point and took on two Russian pilots. Proceeding over 160 miles into the Kara Sea, but with no ice-breaker yet available to assist her, the raider was forced to return to the Matochkin Shar Strait the following day, August 15, and remain at anchor there till August 19. On August 19, he received his orders to proceed along a very precise course. The *Komet* forced her way through the melting ice-field, and reached open water on August 22.

On August 23, she was finally joined by the ice-breaker *Lenin* and proceeded to follow her through the Vilkitsky Strait. By midnight on August 26 the two ships had passed Cape Chelyuskin, and later that day were joined by the ice-breaker *Stalin*. On August 27, the raider resumed her voyage. The *Lenin* turned back on August 27 to resume her duties in the Kara Sea.

The *Stalin* led the *Komet* through the thick pack-ice and dense fog into open waters on August 28. Then the icebreaker *Stalin* left raider. The *Komet* should contact the ice-breaker *Kaganovitch*. Experiencing little difficulty with ice over the next two days the *Komet* was joined by the *Kaganovitch* on August 30, and was instructed to follow closely in her wake as heavy ice was expected ahead. After a difficult 24-hour period, during which the raider twice became trapped in ice and had to be freed under searchlights, and even sustained damage to her rudder, the two ships dropped anchor on September 1.

Relieved that the worst of the ice was that time behind ship, at a distance of 400 miles from the ice-free Bering Strait only, due to political reasons the *Komet* sailed on alone, and on the morning of September 5 reached the Bering Strait. Commander of the *Komet* acknowledged that he could not have achieved the goal of passage without assistance of icebreakers. At Anadyr Bay the *Komet* carried out necessary repairs to her ice-damaged rudder and proceeded southward down the coast. The route of the ship on the NSR is shown on Figure 5.

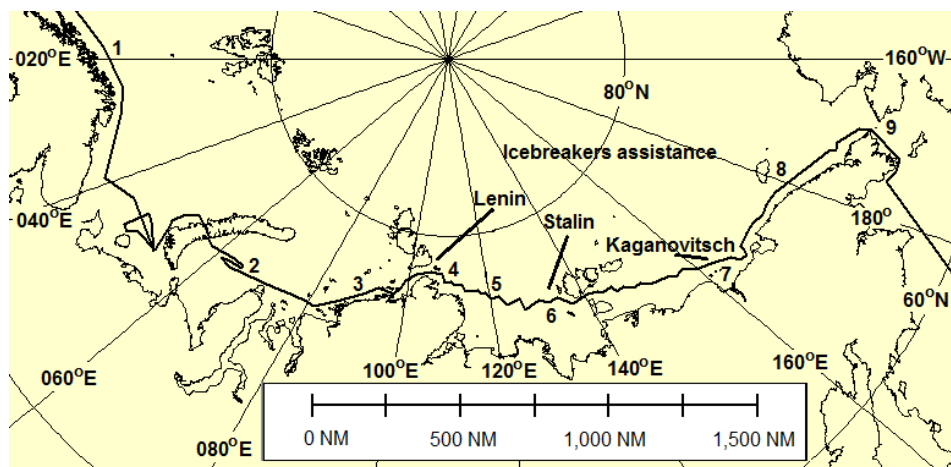


Figure 5. Track chart of the ship *Komet* through the NSR.

Solid line – performed route, 1 – 12.07.1940, 2 – 20.08.1940, 3 – 22-25.08.1940, 4 – 26.08.1940, 5 – 27.08.1940, 6 – 28.08.1940, 7 – 30.08.1949, 8 – 01.09.1940, 9 – 05.09.1940. Compiled by author based on [8], [4] and [10]. Made with Natural Earth - Free vector and raster map data @ naturalearthdata.com.

### STATISTICAL DATA OF ICE CONDITIONS DURING NAVIGATION SEASON IN 1940

Ice conditions occurring on the route of ship *Komet* given by [13] are shown in the table 4. They result from the statistical calculations of these data and the ice conditions recorded by the crew of the ship (total concentration of ice floe CT). It was also determined when she had the assistance of Soviet icebreakers. Icebreakers performed their service in places of concentration of ice floe, which prevented independent navigation of ships. It should be noted that the *Komet* was scheduled to pass in the fourth convoy [8]. The data show that ships have the ability to overcome the ice with a total concentration of ice CT from a zero to 70%. Icebreakers have assisted and led ships in convoys with a very high concentration of ice floes above 70%. Average ice coverage on the voyage in 1940 is highly compatible with an average ice coverage resulting from the statistical calculations for the years 1940-1945 (see Table 3). Only in the western part of the Laptev Sea ice coverage was almost twice higher than the statistical average for the period 1940-1945. It can therefore be assumed that the statistical average value well illustrates the average annual ice conditions in respect of the individual ten-day periods of time (decade's days). Reliability is at 80%. Optimistic statistical results, which is the lowest value

of ice coverage of particular regions provided by AARI for the year 1940 [13], are consistent with the value of the statistical average for six years reduced by standard deviation. Pessimistic statistical results, it means the highest values of the ice cover for particular regions provided by AARI for the year 1940 [13] are consistent with the value of statistical averages for six years increased by standard deviation. The annual values, however, have a greater deviation from the average value in relation to the value of „Average  $\pm\sigma$ ”. Values of total concentration of ice floe observed on board ship are less consistent in relation to statistical data resulted from AARI data.

Ice conditions recorded on board ship presented in Table 4 are those shown by the crew as higher concentration encountered. First question is a little discrepancy in between data. The AARI data are average coverage of sea area by ice irrespective of its concentration. The data recorded by the crew are total concentration of ice floe encountered along the route of the ship. The data could be comparable in case ice conditions along the route would be recorded by the ship's crew and then averaged for same area and period of time as made by AARI. But it was not available [8]. We may assume that recorded data are related to patches of ice floe of higher concentration. In between these patches were located areas of low ice floe concentration or free of ice at all. In this case average ice conditions of data recorded by ship's crew should be comparable with AARI data. Average AARI data show lighter conditions for Kara Sea and Chukchi Sea, quite same for Laptev Sea and East Siberian Sea. Only data for Sannikov Strait are not comparable. It looks due to very small area of the strait in relation to a half of the East Siberian Sea. The ship continued voyage on Chukchi Sea without icebreaker assistance. It means she encountered lack of information about ice conditions in front of the ship. Previously these data were available through icebreaker and Soviet ice pilots. Assumed the *Komet* was navigating straight ahead and encountered on her route harder conditions than existed maybe in close vicinity.

In general, one should take into account, as higher range of data averaged, as extremal values are less extending from average value. Average statistical multi-year data do not present exact possible ice conditions to be encountered along route passage. Pessimistic approach to the statistical data (Average $+\sigma$  and Maximal values) indicate possible conditions to encounter at short period of time or in the limited part of specific region. But this may lead vessel to stop and wait for icebreaker help or wait until ice conditions make them acceptable to continue voyage without icebreaker assistance. Realistic (Average statistical data) and pessimistic (Average $+\sigma$  and Maximal values) approach should be taken into consideration during general (6-12 months ahead) and initial voyage planning (15-30 days ahead).

Table 4. Comparison of ice conditions on the route during the Komet passage through the NSR in 1940.

Date Place	Statistical conditions based on climatological data						Conditions recorded on board ship
	Minimal (optimistic)	Average- $\sigma$	Average (1940)	Average (realistic)	Average+ $\sigma$	Maximal (pessimistic)	
20.08.1940 Matochkin Strait (Kara Sea)	0	-1	19	12	25	26	CT = 3-6
26.08.1940 Laptev Sea at Vilkitsky Strait	25	16	81	49	82	94	CT – 1-8 (Icebreaker <i>Lenin</i> , then <i>Sta- lin</i> )
28.08.1940 East Siberian Sea (Sannikov Strait)	34	36	45	59	82	92	Ice free
30.08.1940 East Siberian Sea (East of Medvezhy Islands)	34	36	45	59	82	92	CT = 6-7
31.08.1940 01.09.1940 (70°09'N 161°26'E)	36	29	43	53	76	87	CT = 9 (Icebreaker <i>Kaganovitch</i> )
03.09.1940 Cap Schmidt	2	5	6	20	34	41	CT = 9

Compiled by Author based on [1] and [7]

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**COMPARISON OF THE TIME-GEOGRAPHICAL DATA  
SPATIAL DISTRIBUTION DURING THE SHIP'S VOYAGE  
IN RELATION TO STATISTICAL DATA AND CUMULATIVE  
DISTRIBUTION OF ICE CONDITION**

Figure 6 shows different ice conditions on particular seas during voyage of the ship *Komet*. To illustrate the changes in relative coverage of ice marked points at appropriate moments by marking them with consecutive numbers and joining with dotted line. One can see in western part of the Laptev Sea, a much larger area covered by ice than in other seas. From graph it can be concluded that the NSR Administration was waiting to commence transit voyage until a significant reduction in ice-covered area of south-western and north-eastern part of the Kara Sea up to the level of 20% happened (waypoint 1 and 2). These ice conditions did not allow the ship to continue her voyage alone without icebreakers assistance and forced to wait for improvement of ice conditions. The ship with adapted hull and propeller for navigation in ice passed with assistance of icebreakers the Laptev Sea covered with ice in about 82 percent (waypoint 3) and the East Siberian Sea covered with ice in an average of 42 percent (waypoint 4). From description of the voyage made by the ship's crew concluded that the ice conditions on the East Siberian Sea were similar to those on the Laptev Sea (80% of the area covered by ice). The last 400 NM of voyage to the Bering Strait the ship performed independently without assistance of icebreakers at 12% of the area covered by ice (waypoint 5 on Figure 6). The commander of the ship confirmed that without icebreakers assistance the vessel could not reach the destination.

Several conclusions come from description of this voyage. First of all, in between 12 and 20% of the ice coverage of the sea appears be limit of the ability of independent voyage of the ship with ice reinforcements without icebreaker assistance. Secondly, from 42% of the average ice coverage of the sea the ship may get stuck and would not free up alone without assistance of an icebreaker. It is advisable continuous assistance by icebreaker. Despite the assistance of an icebreaker it is probable to experience damage to the hull, rudder and propeller. Third, at 80% of the sea covered by ice the ship has difficulty in overcoming the ice, even with the assistance of an icebreaker. Particular difficulties resulted from the state of ice cover in the western part of the Laptev Sea suggests that the ship has encountered more difficult conditions than average. This corresponds to the situation shown in Figure 2b when with the probability of 50% in average statistical conditions of 40% ice coverage may occur also local extremely difficult ice conditions of 80% ice coverage.



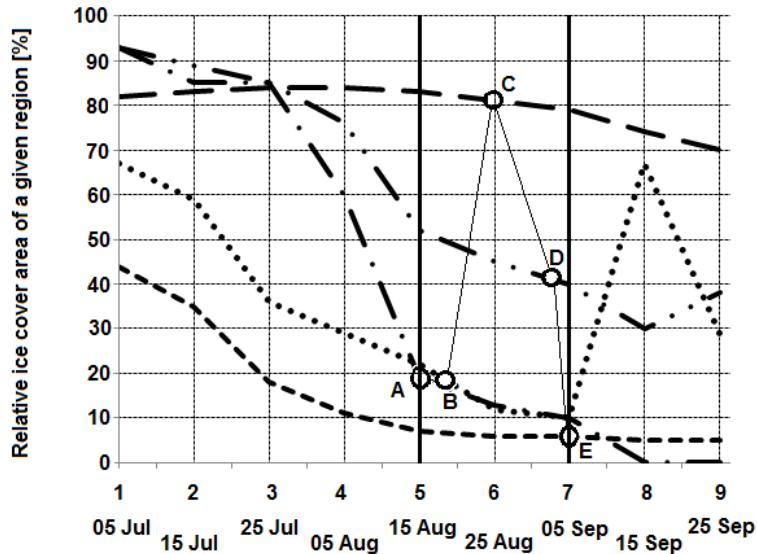


Figure 6. The relative area covered by ice on the NSR navigation season in 1940 during the NSR passage by the ship Komet. Regions: — • — Kara Sea (SW part), • • • Kara Sea (NE part), — — — Laptev Sea (W part), — • • — East Siberian Sea (W part), — — — Chukchi Sea (W part), — sequence of transit through the particular seas (A, B, C, D, E) performed by the Komet. Compiled by the Author based on [13] and [8].

Maps of ice floe concentration made by AARI for 1940 [1] do not contain information about state of ice cover on the east of the Severnaya Zemlya archipelago. It can be assumed that the ship was guided by an icebreaker without a thorough aircraft ice reconnaissance. Therefore she sailed without ice reconnaissance in 80% of ice covered area. It is possible that in the vicinity of implemented route there were areas with more favorable conditions similar to average ice coverage of 40%.

Based on this figure arising another question. Whether on the basis of the cumulative distribution function of statistical ice coverage, which includes a couple of years, one can determine more accurately probable ice conditions, than by simple statistical parameters which are the average value and standard deviation. In analyzed currently topic of decision-making is taking the risk of not achieving the success. It means not reaching the destination by a ship. If the aim of the decision maker is a 100 percent guarantee of success, in case of ice conditions occurring in the 1940-1945 period of time, the goal would not be achieved. The time window for the implementation of voyage in ice-free conditions is equal zero. It guide to conclusion that the decision maker should take a certain level of risk. The biggest limitation of possibility to overcome the NSR was the Laptev Sea. In order to decide

on the implementation of voyage by a cargo ship with icebreaker assistance is necessary to take a risk not less than 7.2% probability of failure (Figure 7). Then the time window is near to zero. For comparison, the probability to face worse conditions (higher ice coverage) encountered by the ship *Komet* on her route was on average 12.3% in the range of 7.2 to 15.9% (Figure 7). The average value of real conditions of ice cover is thus comparable with the statistical values. If take the value of 9% to make decisions, it should be considered that the most unfavorable upper value 15.9% in the East Siberian Sea can cause a ship not able to overcome existing in the area ice conditions.

In statistical practice is typically accepted probability value 0.99, 0.95 or 0.90, depending on the parameter analyzed. The limitation to reach the destination in 1940 were ice conditions on the Laptev Sea. The easier ice conditions that were continuously changing during navigation season were on the East Siberian Sea. The relationship of the time period favorable for navigation (time window) on the Laptev Sea and East Siberian Sea in function of ice covered area of the region is shown on Figure 8. The statistics cover only the period of time until the lightest ice conditions prevailing during the ninth decade of navigation season in 1940-1945, including beginning of the growth of the area covered with ice. A beginning of growth of ice cover is ending a navigation season. The smallest ice cover area on the heaviest NSR regions in 1940-1945 occurred on average in the first decade of September (Figure 8). The ninth decade is the limit of time window from the side of end of the navigation season. If one accepts the risk (failure of reaching goal of a voyage) of 50%, the corresponding ice cover area at the Laptev Sea is 48% and on the East Siberian Sea is 58% (Figure 7). This in turn determines time window limited by ice coverage on the Laptev Sea equal null due to out of range (Figure 8a) and time window limited by ice coverage on the East Siberian Sea equal 44 days from 12.08.1940 until 25.09.1940 (Figure 8b). It should be taken into account that this time period is counted from the statistic middle day of a ten day period. For this reason, the result of evaluating the number of navigation days is approximated only.

For the area covered with ice on the Laptev Sea of 12-20, 42, 80% the time window was equal respectively null, null (out of range), 24 days (Figure 8a). In the same way on the East Siberian Sea there were easier ice conditions. For the area covered with ice of 12-20, 42, 80% the time window was equal respectively null, 24 days and 75 (Figure 8b). This means that it was not possible that ships designed for ice navigation were able to pass the NSR without icebreaker assistance in 1940. Following this study several utilitarian conclusions were received for the purposes of general and initial voyage planning of cargo ships adapted for navigation in ice. Vessels suitable for navigation in ice could perform voyage with icebreaker assistance

in at least 24 days (ice conditions same to those in 1940), in case area of ice cover is less than 20%, in particular places, even 12%.

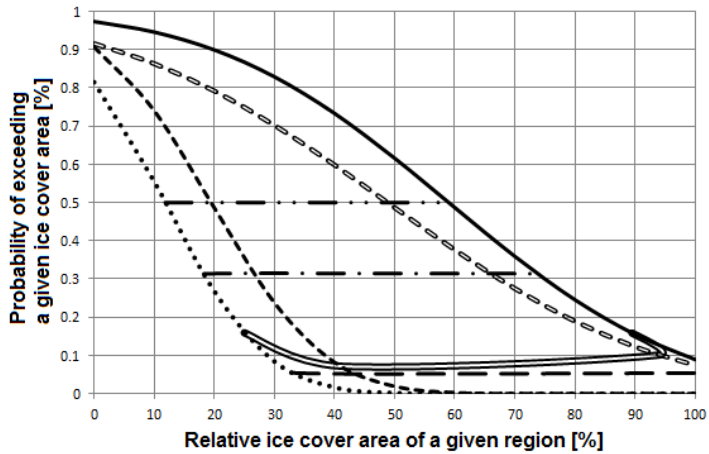


Figure 7. Cumulative distribution of exceeding a given ice cover area for specific regions and periods of time (decades of days) during the NSR passage by the ship Komet in 1940. Regions: ••• Kara Sea (SW part), = = = Laptev Sea (W part), — East Siberian Sea (W part), - - - Chukchi Sea (W part). Probabilities: — • • — 50%, — • — 31.4%, — — — 5.4%, ===== ice cover areas encountered by the ship Komet in her transit. Compiled by the Author based on [13].

Whereas the same ships could carry out successfully completed voyage through the NSR with intensive icebreaker help in 24-75 days at the ice covered area below 42%. Navigation of the same ships at an ice covered area above 80% is possible with intensive icebreaker help, but it threatens to damage the hull, rudder or propeller.

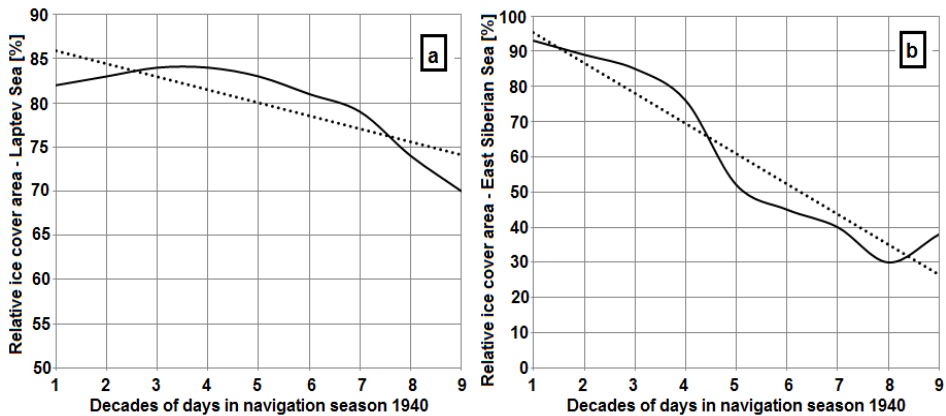


Figure 8. Area of ice coverage of the Laptev Sea (a) and East Siberian Sea (b) in 1940. Compiled by the Author based on [13].

## CONCLUSIONS

Statistical data on ice cover area on the NSR provided by AARI was confirmed by top secret information from the Central Intelligence agency (CIA) in 1959, that in 1940 prevailed on the NSR extremely light ice conditions. The smallest area covered by ice in regions of the NSR during the Second World War occurred on average in the first decade of September.

Ships suitable for navigation in ice were able to pass the route with the assistance of icebreaker where ice coverage of the region was equal 12-20%. The same ships were able pass successfully the region covered by ice in 42% with intensive help of icebreaker. If the region was covered by ice above 80% it was possible to overcome the ice with intensive help of icebreaker also. However, there was a risk of damage to the hull, rudder or propeller. With such determined criteria for planned voyage for ice covered areas on the Laptev Sea (which formed in 1940 the biggest difficulty for ice navigation) equal 12-20, 42, 80%, the duration of time window amounted respectively a null, null and 24 days. This means it was not possible that vessels designed for ice navigation were able to pass alone the NSR in 1940 without icebreaker assistance. This finding is confirmed by the opinion of the ship's commander, who at that time passed the NSR successfully.

It was noted that excessive generalization of data analyzed could lead to wrong conclusions. For example, the average ice cover area on the NSR including the standard deviation in different navigation seasons is always greater than the smallest ice cover in a particular area which creates the greatest difficulty in navigation season. It can therefore be concluded that the adoption of average ice coverage along with the standard deviation for the purpose of voyage planning puts a planner on the safer side. This value will give more difficult navigation conditions in the lightest period of navigation season. Meanwhile, the more generalized values for the averaged period of six years between 1940 and 1945 lead to opposite conclusions. It was also assumed that the use of only basic statistical information in the form of average values and standard deviation may be not sufficient for the purpose of ship's voyage planning in areas covered with ice.

Cumulative distribution of individual decades of days on the NSR regions can determine the duration of time window for a given ice cover area with a given probability of occurrence. It is thus possible to plan the date of departure at the assumed probability of occurrence of ice conditions that assumed are satisfactory to reach the destination. It is also possible to plan the number of consecutive voyages.

Mathematical approach based on the cumulative distribution of the normal distribution allows the creation of an advisory application to support decision-making

by the commander of the vessel. In this way it will be reduced the human factor in data processing and the possibility of making a mistake. In this way, can be enhanced the safety of maritime transport.

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### **STRESZCZENIE**

W 1940 Roku na Północnej Drodze Morskiej (PDM) panowały ekstremalnie lekkie warunki lodowe w stosunku do kilku lat wcześniejszych i późniejszych. Najniższa powierzchnia pokrywy lodowej w regionach PDM w latach 1940-1945 występowała średnio w pierwszej dekadzie września. Statki przeznaczone do żeglugi w lodach mogą realizować podróże ze wsparciem lodołamaczy w sezonie nawigacyjnym

w przypadku, gdy powierzchnia pokrycia poszczególnych mórz lodem jest mniejsza niż 20%. Nawigacja tego samego statku w rejonach PDM pokrytych lodem powyżej 80% jest możliwa przy intensywnej pomocy lodołamacza, ale grozi uszkodzeniem kadłuba, steru lub śruby napędowej.

Do błędnych a nawet przeciwnych wniosków może prowadzić nadmierne uogólnienie analizowanych danych. Wykorzystanie jedynie podstawowych informacji statystycznych w postaci wartości średnich i odchyleń standardowych może być niewystarczające do celów planowania podróży statku na akwenach pokrytych lodem. Znacznie więcej możliwości dla oceny warunków żeglugi w regionach pokrytych

lodem zapewnia rozkład skumulowany, który powinien być związany z rozkładem czasowym i rozkładem geograficznym. Rozkład skumulowany pozwala określić czas trwania okienka czasowego występowania określonych warunków żeglugi lodowej statków dla określonej powierzchni pokrycia danego regionu lodem i założonego prawdopodobieństwa o wystąpienia takich warunków. W ten sposób można zaplanować przybliżoną datę początku podróży i czas trwania podróży dla przyjętych kryteriów bezpieczeństwa. Możliwe jest również zaplanowanie szeregu kolejnych podróży w jednym sezonie nawigacyjnym.

Przedstawione matematyczne podejście do planowania podróży w lodzie oparte na rozkładzie skumulowanym pozwala na stworzenie doradczej aplikacji komputerowej wspierającej proces decyzyjny osoby dowodzącej statkiem. Zmniejszy to udział czynnika ludzkiego w przetwarzaniu danych i ograniczy możliwość popełnienia błędu. W ten sposób będzie można zwiększyć bezpieczeństwo transportu morskiego.