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Trends of Opening and Closing date for Navigation on the Northern Sea Route in the Light of Changes in Ice Cover on the Seas of the Siberian Shelf in the Years 2008-2022

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ABSTRACT: The Northern Sea Route (NSR) is a seasonal route. Its use by merchant ships that are not structurally adapted to navigation in heavy ice makes sense when it is free of ice along its entire length and can be used without the costly assistance of icebreakers. In the paper, ice cover maps were analyzed. The number of the Julian day of the year was determined on the first day on which the transit shipping season began, on the last day of the year after which this season ended, and the length of the ice-free period along the whole NSR was calculated. The analysis was carried out for the eastern and western parts of the NSR. Despite the high inter-year variability of the opening and closing times of the transit shipping season, it is possible, 2-3 months in advance, to obtain approximate information about the conditions of "ice-free" navigation on this route. For this purpose, average monthly sea ice extent of the Kara Sea in May of a given year should be used.

1 INTRODUCTION

The Northern Sea Route (North East Passage; hereinafter referred to as the NSR) is becoming an increasingly important shipping route. Currently, its shipping traffic is not impressive. In last summer navigation seasons commercial ships encountered severe ice conditions that reminded about the environmental uncertainties accompanying voyages on the Northern Sea Route [4, 14]. Despite this, cargo transport in the years after 2000 has been systematically increasing. Currently, the increase in transport applies to both destination shipping and transit shipping but destination shipping was increasing faster in the years 2017-2019 [9]. Also, more and more ships with a flag other than Russian used this route, treating it primarily as a transit route for voyages between Far Eastern countries and Europe and vice versa.

In 2021 alone, as many as four ships used the direct transit route from China to Poland via the Northern Sea Route [6]. Trips to the NSR took place in the summer and autumn from August 18 to October 16. Average speed on the NSR did not depended on the month of voyage and was from 9.8 knots till 14.4 knots. The time necessary to pass the NSR was equal from 9.6 days till 6.3 days respectively.

The NSR is a seasonal route. Its use by merchant ships that are not designed to navigate in heavy ice makes sense when its entire length - from the Barents Sea to the Bering Strait - is ice-free and can be navigated through without the costly assistance of an icebreaker. Due to the bathymetry and the occurrence of navigational obstacles, for ships with a larger draft, for example the PANAMAX type, the most favorable route is to pass the NSR on the route north of Novaya Zemlya (Mys Zhelaniya), north of the Severnaya Zemlya (Schmidt Island and Komsomolets Island) and north from the New Siberian Islands and Wrangel

Island (Fig. 1). This route is also the shortest. However, its use is only possible when the ice extent in a given navigation season moves exceptionally far north, leaving the entire Laptev Sea and the East Siberian Sea free of compacted ice cover.

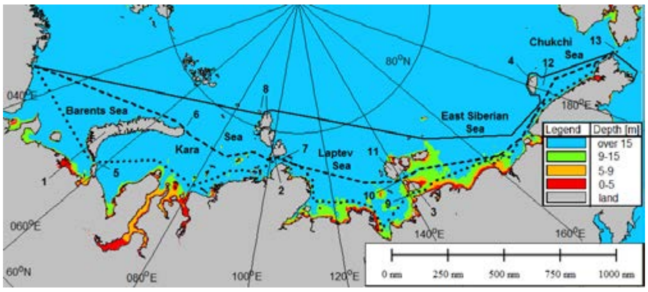

Figure 1. Distribution of shipping routes on the Northern Sea Route; ———— route northernmost of archipelagos and islands, - - - - - intermediate route, • • • • • coastal route; 1 - Novaya Zemlya archipelago, 2- Severnaya Zemlya archipelago, 3 - New Siberian Islands archipelago, 4 - Wrangel Island, 5 - Kara Gate Strait, 6 - Cape Zhelaniya, 7 - Sannikov Strait, 8 - Smidt and Komsomolets Islands, 9 - Dmitry Laptev Strait, 10 - Sannikov Strait, 11 - Kotelny Island, 12 - De Long Strait, 13 - Bering Strait.

The Severnaya Zemlya Archipelago is the northernmost point of the route. If the ice reaches the northern edge of the Severnaya Zemlya, and the deep water (minimum depth of 34 m) of the Vilkitsky Strait is free from ice, it is possible to continue the voyage through this strait. However, the consequence will be an increase in the length of the route. Due to the small depths in the Sannikov Strait (minimum depth 14 m) and even smaller depths in the Dmitry Laptev Strait (minimum depth 8 m), separating the New Siberian Islands archipelago from the continent, if ice conditions allow it, the route should lead north of the New Siberian Islands archipelago [15]. If the ice cover reaches the islands of the New Siberian Islands archipelago and if the Sannikov Strait is also blocked by ice, the route through the Dmitry Laptev Strait cannot be used. Its depths are too shallow for a PANAMAX or larger ship to use them when passing the NSR.

Therefore, we can talk about the full "opening" of the Northern Sea Route for navigation when, at the same time (at the same moment), the water areas between Mys Zhelaniya and the water areas north of the Schmidt and Komsomolets islands or between Mys Zhelaniya and the Vilkitsky Strait, as well as the water areas north of the New Siberian Islands (or the Sannikov Strait) and the area north or south of Wrangel Island are free from ice cover (De Long Strait; minimum depth 36 m). The "transit navigation" season on the NSR may be considered the time that elapses in a given year between the first day on which ice-free conditions occur along the entire route and the last day of the year when such conditions occur. In recent years, there have been major changes in the length of the transit navigation season on the NSR. It should be emphasized that due to the variability of the location of large areas of compacted ice that are difficult to overcome, routes should sometimes be plotted with a significant extension of length of the route. This occurs when, for example, in the western part of the NSR the route runs close to the continental coast and in the eastern part of the NSR - closer to the North Pole and vice versa [21, 22]. The most common southern extremes of such a designated route may occur in the eastern part of the Kara Sea, in the western or eastern part of the Laptev Sea and in the western or eastern part of the East Siberian Sea. The most common northern extremes may occur north of the Severnaya Zemlya archipelago, the New Siberian Islands archipelago or Wrangel Island.

In recent years, there has been numerous information in the media pointing to the "incredible" improvement in ice conditions on the NSR. There is also frequent information that as a result of the increase in global air temperature, the ice cover on the NSR will soon disappear and transit navigation on this route will be possible throughout the warm half of the year, and will even be year-round or so on [7, 8, 12, 17, 23]. More realistic are results of novel approach for calculation beginning and end dates, and also duration of navigation season along the NSR based on CMIP5 data [13].

The aim of this work is to examine the trends in changes in the beginning and end of "transit navigation" and the length of this season on the NSR, which occurred in the years 2008-2022. Further, when the term "navigation season" is used, it means the summer season for ships without ice reinforcements, expressed in the number of days on which transit navigation is possible along the entire length of the NSR.

2 DATA SOURCES AND METHOD DESCRIPTION

The basic material for determining the length of the "transit navigation" season was the analysis of daily maps of the Mariginal Ice Zone issued by USNIC in ESRI Shape file format [24] and after that, gridded maps of NCEP GFS with ice concentration forecast files in GRIB2 format, published four Times a day [18], maps of ice cover based gridded 3125m x 3125m data from AMSR-E (2002-2011) and AMSR (2012-2023) swath published daily by Bremen University [2] and later [3], and regional maps of the Arctic in raster GIF format published by Arctic and Antarctic Research Institute AARI „SEVER" Center every 3-4 days [19] and later [22]. All these maps assume the boundaries between ice-covered and ice-free areas related to the degree of ice coverage of the water surface, regardless of its stage of development and thickness, within 10-18%. Waters with an ice concentration of less than 10-18% were treated as ice-free waters.

Additionally, time series of sea ice extent within the boundaries of individual Arctic seas and their parts covering the NSR route provided by AARI were used [1]. According to definitione, sice extent is a surface of sea covered by ice of concentration from 15 till 100%.

Based on the analysis of the indicated maps, the number of the first day of Julian calendar on which the transit shipping season began (BNS) and the last day of Julian calendar after which the season ended (ENS) in the year were determined. This approach allows for simple and clear calculations. Length of navigation season LNS was then calculated as (ENS -

BNS) + 1. Standard statistical methods were used to analyze these data.

The analysis was carried out for two parts of the NSR - eastern and western, and for the entire potential NSR route. The western part covers the area from the western border of the Kara Sea to the eastern border of the Laptev Sea within their limits as defined by the IHO [10, 11]. Eastern part - from the southern border of the Chukchi Sea (Bering Strait) to the western border of the East Siberian Sea (Fig. 1). The ice cover being on the Barents and Bering seas in the considered period 2008-2022 does not play any role in regulating the opening and closing times for NSR transit navigation, because by the time the NSR opens and closes, they are already or still ice-free.

The compiled data for individual transit navigation seasons in 2008-2022 are presented in Table 1. The length of the time series (15 years) does not allow drawing more firm conclusions, but it reveals trends in changes in the behavior of the beginning and end of the navigation season and their duration. It also allows to indicate a predictor that can be used to roughly predict the ice conditions that will occur in the current navigation season already at the beginning of summer.

3 CHANGE TRENDS OF THE "TRANSIT NAVIGATION SEASON" ON THE NSR

The data presented in Table 1 indicate the occurrence of significant inter-annual variability in the beginning, end and length of the navigation season on the NSR. The length of the period during which "ice-free conditions" prevail along the entire NSR ranges from 1 day (2009) to 90 days in 2020. On average, the duration of the "transit shipping" season in 2008-2022 is 33 ± 6 days, which, with a standard deviation of 24.0 days, indicates a very high variability of this parameter.

Table 1. The number of the day of the Julian calendar year of the beginning (BNS) of the "transit shipping" season on the Northern Sea Route, the last day of the "transit shipping" season (ENS) and the number of days of the "transit navigation" season (LNS) on the western part of the NSR, the eastern part of the NSR and the entire NSR route from Mys Zhelaniya to the Bering Strait

Year	Western part of the NSR			Eastern part of the NSR			The whole NSR		
	BNS	ENS	LNS	BNS	ENS	LNS	BNS	ENS	LNS
2008	250	265	16	250	282	33	250	265	16
2009	275	280	6	246	275	30	275	275	1
2010	256	273	18	256	285	30	256	273	18
2011	219	286	68	230	286	57	230	286	57
2012	231	294	64	250	290	41	250	290	41
2013	254	273	20	237	271	35	254	271	18
2014	244	274	31	234	290	57	244	274	31
2015	220	287	68	231	288	58	231	287	57
2016	266	287	22	228	291	64	266	287	22
2017	247	271	25	217	276	60	247	271	25
2018	231	294	64	258	291	34	258	291	34
2019	222	288	67	227	293	67	227	288	62
2020	214	303	90	214	306	90	214	303	90
2021	251	271	21	266	271	6	266	271	6
2022	230	270	41	247	285	39	247	270	24

In the course of navigation time in ice-free conditions along the entire NSR route, there is a statistically insignificant positive trend (Fig. 2), indicating a relatively small extension of the transit navigation season. The trend is +1.61 ± 1.42 days per year and is statistically insignificant (p = 0.28). A very large error in estimating the intercept and the regression coefficient in the equation in Fig. 2 (in the box) makes it impossible to reject the null hypothesis, i.e. to state that the given trend value is different from zero.

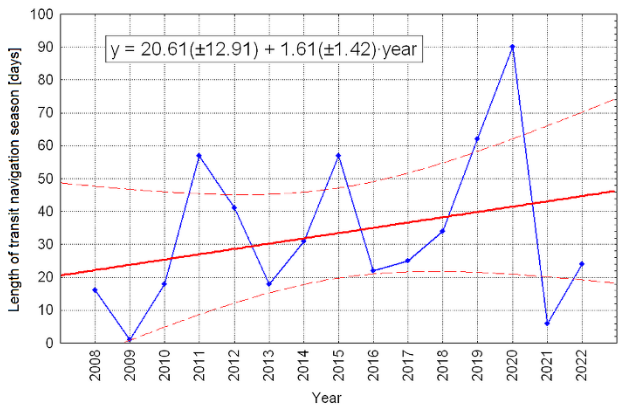

Figure 2. The length of the shipping season in "ice-free" conditions (LDO; number of days) along the entire length of the Northern Sea Route from Mys Zhelaniya to the Bering Strait in the years 2008-2020. Red solid line - fitting of a linear function (trend), dashed lines - marking the limits of the 95% confidence interval (p = 0.05)

Based on the trend values calculated from short time series, no conclusions can be drawn about the further pace of changes. Analyzing the course of variability of the length of the navigation season throughout the PDM, in a shorter series from 2008-2020 (13 years), a statistically significant positive trend is detected (3.96 ± 1.46, p = 0.02), indicating that the navigation season on the NSR is extended on average by almost 4 days each year. Observations from 2021 and 2022, when there was a significant delay in the beginning and earlier end of the navigation season, completely changed this picture.

An important issue from the point of view of shipping is the cost of which processes result in the extension of the transit navigation season. The analysis of the moments of occurrence of the first and last day of the transit navigation season (Fig. 3) apparently shows that the extension of the transit navigation time occurs as a result of the simultaneous acceleration of the beginning of the navigation season and delaying its end. While the acceleration of the beginning of the transit navigation season is on average faster (-0.95±0.99 days per year), its very large fluctuations from year to year make the trend statistically insignificant. This does not allow us to draw a conclusion that, in a statistical sense, there was an acceleration of the beginning of the navigation season. Similarly, slightly slower (+0.66 ± 0.64 days per year). But the timing of the end of the transit shipping season also changes irregularly. The trend of delaying the end of the transit navigation season is statistically insignificant (p = 0.322).

The correlation between the beginning of the transit navigation season (NRP) and the moment of its end (NRK) is weak (r = -0.53) but statistically significant (p = 0.043). This indicates that on the NSR there is a general, very weak tendency to extend the duration of the "ice-free" navigation season with its earlier beginning. However, this relationship is only statistical and cannot be applied to every single case. The length of the shipping season cannot be legitimately inferred based on its beginning date.

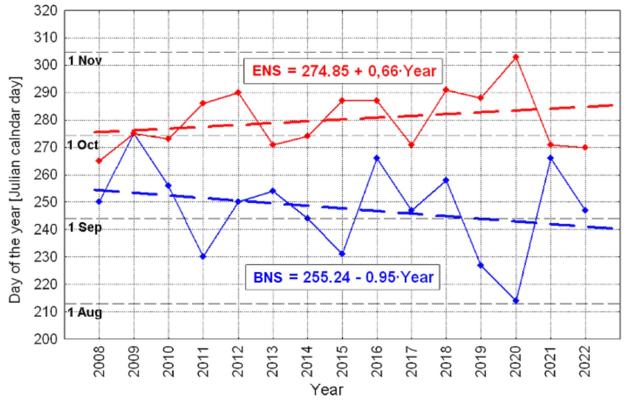

Figure 3. The course of the "opening" (NRP) and "closing" (NRK; numbered consecutive days of the Julian calendar year) moments of the transit navigation season on the NSR in 2008-2022. Labeled linear fits to empirical points (trend lines). Horizontal dashed lines mark the beginning of subsequent months (1 Aug, 1 Sep, 1 Oct, 1 Nov)

The analysis of the relationship between the average monthly ice area (extent) and the opening and closing moments of the shipping season in the PDM confirms the previously known regularity [15, 16] that the opening and closing moments are determined by the ice conditions in the Laptev and East Siberian seas, i.e. the border seas between the western and eastern part of the NSR. In the period under consideration, the opening of the NSR occurred only three times simultaneously in both these seas (2008, 2010 and 2020), while the variability of ice conditions in each of these seas with the same frequency (6 cases each) delayed the moment (Table 1) of the opening of the NSR. The timing of the closure of the transit navigation season on the NSR is much more influenced by the variability of ice conditions in the Laptev Sea than in the East Siberian Sea. During the years 2008-2022, ice conditions in the Laptev Sea resulted in the closing of the shipping season nine times, and only four times (2009, 2012, 2013 and 2018) in the East Siberian. In two years (2011 and 2021), ice conditions in both seas simultaneously led to the closure of the shipping season.

4 APPROXIMATE FORECAST OF CHANGES IN THE LENGTH OF THE NAVIGATION SEASON ON THE NSR

There are quite complicated, but statistically highly significant relationships between the processes of ice cover loss and the processes of its re-growth in individual Arctic seas. The analysis of these relationships shows that a kind of predictor, providing approximate information about the number of the day of the Julian calendar year on which the PDM opens and closes, and the length of the PDM navigation season, is the area of ice extent in the Kara Sea in May (KS_{E05}). The Kara Sea, with an area of less than 1 million sq. km (926,000 sq. km), is a shallow sea (average depth ~131 m) with small heat resources in the waters. For this reason, its ice cover responds very strongly to changes in meteorological processes taking place over the Arctic, as well as to changes in the complex of hydrological processes in the Arctic Ocean basin.

The rate of melting of ice in the Kara Sea in May of a given year is an indicator of the acceleration of the disappearance of the ice cover in the following months in this sea and in the Laptev and East Siberian seas. The behavior of the ice extent in the Kara Sea in May (KSE05) is relatively strongly correlated with the ice cover area in the Laptev and East Siberian Seas in July (r = 0.69, p < 0.001; 1979-2020). In turn, the intensity of further ice melting in July depends on the size of the "clean water" (ice-free surface) in these seas, which determines both the beginning and the end of the transit navigation season. As a result, there are relatively strong relationships between the area of ice cover in the Kara Sea in May and the number of the first day of the "transit navigation" season on the NSR (BNS), the number of the last day of this season (ENS) and the number of days of the "transit navigation" season on the NSR (LNS) (Tab. 2, Fig. 4).

Table 2. The values of the correlation coefficient (r) and the level of their statistical significance (p) between the average monthly sea ice area (extent) in the entire Kara Sea in May and the number of the day of the year, the first day of the transit shipping season on PDM (BNS), the last day of the transit shipping season (ENS) and the number days of the transit shipping season (LNS). The results or correlation period 2008-2022. r^2 - percentage of the explained variance of a given variable by the average monthly ice surface (extent) of the Kara Sea in May

Parameter	BNS	ENS	LNS
r	0.70	-0.80	-0.84
p	0.004	<< 0.001	<< 0.001
r^2	49%	64%	70%

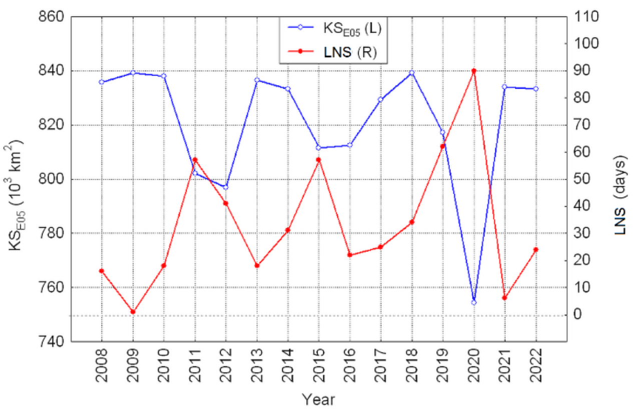

Figure 4. The course of the average monthly ice area (extent) in the Kara Sea in May (KS_{E05}; thousand sq. km) and the length of the "transit navigation" season on the NSR (LNS LDO; days).

On Figure 4, there is a visible sharp shortening of the season in 2021 and 2022, related to an equally sharp increase in the area of ice in the Kara Sea in May in these years. Table 2 shows that the beginning of the navigation season is least related to the May ice surface (extent) in the Kara Sea, and the strongest – to the length of this season (LNS). Significant linear correlations presented in Table 2 allow the creation of regression equations in which the BNS, ENS and LNS values constitute a linear function of KS_{E05}, i.e. the area of ice (extent) in the Kara Sea in May. Table 3 shows the values of these variables calculated from the regression equations for KS_{E05} varying in the range from 700 to 860 thousand sq. km.

Table 3. The values of the BNS, ENS and LNS (days) in a given year as a function of the variable average monthly sea ice area (extent) in the Kara Sea in May of a given year (KS_{E05}; thousand sq. km)

KS_{E05}	860	840	820	800	780	760	740	720	700
BNS	268.1	258.1	248.1	238.1	228.1	218.1	208.1	198.1	188.1
ENS	268.5	275.9	283.3	290.7	298.1	305.5	312.9	320.3	327.7
LNS	1.5	18.9	36.3	53.7	71.1	88.5	105.9	123.3	140.7

Note: Standard errors of estimation of the BNS, ENS and LNS are equal tp ±12.2 days, ±6.7 days and ±13.5 days respectively.

The occurrence in May of a given year of the average monthly iced area in the Kara Sea equal to or less than 800,000 sq. km indicates that in the upcoming "summer" ice season the length of the transit shipping season will most likely be longer than 54 ± 13.5 days, that is, its real length should be expected to be between 41 days (minimum) and 67 days (maximum), and the beginning of the season will take place no later than in the second decade of August - the first decade of September (August 25 ± 14 days).

5 CONCLUSIONS

The analysis of a short, only fifteen-year series of data informing about the beginning, end and length of the transit shipping season on the Northern Sea Route indicates the occurrence of very high variability of these parameters in this period. This variability is so significant that it does not allow reliable conclusions about the further development of changes in the length of the "transit shipping" season based on previously estimated trends.. Despite the undoubted lengthening of the shipping season since 1979 [5], and the acceleration of its beginning and delaying its end, the course of this process is so unstable that it is not possible to rely on emerging long-term trends in possible planning of the NSR transits. To an even greater extent, decisions about sending a ship to the NSR crossing cannot be made based on the opinions expressed by various "ecological" and "climate" organizations and politicians disseminated by the mass media.

Since so far the earliest opening of the NSR took place in the first decade of August (2020), and on average it occurs in the last decade of August - the first decade of September, it is possible, 2-3 months in advance, to obtain approximate information about the conditions of "ice-free" navigation on this route. For this purpose, data on the average monthly sea ice extent of the Kara Sea in May should be used (the set in file karamonthly.all.extent.csv, available from AARI website [1]. Data on the ice area for May in this set are usually completed between June 5 and 10, which allows, using these data and the contents of the Table 3, get an idea of the probable ice conditions on the NSR in mid-June.

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