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Length of Navigation Season in Current Conditions of Climate Change on the Northern Sea Route

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ABSTRACT: The paper first analyzed ice maps for the years 2008-2022. Despite the general convergence of trends of opening and closing of navigable season for concentrations 18% and 81% the Eastern Part and Western Part of the NSR looks they are under different driving factors. Found some tendencies and cyclical changes, but not working for the whole studied period. The studied period of 15 navigation seasons from statistical point of view is too short period of time to forecast trends and cycles in the near future.
Next, ships traffic and ice conditions being on the NSR for the years 2012, 2013, 2015, 2017, 2018, 2020 and 2021 were examined. The navigable time windows of Arc4, arc5 and Arc7 class ships were determined. Found, the not navigable period of time for any class of merchant ships lasted 3 months.

1 INTRODUCTION

In the 21st century, the acceleration of global warming is noticeable. This results in a significant reduction of ice extent and ice thickness in the Arctic compared to the conditions prevailing in the 20th century. Lighter ice conditions result in increased ship traffic in the Arctic. However, despite the clear trend in reducing the amount of ice in the Arctic, there is considerable and unpredictable irregularity of inter-annual changes in ice extent [4, 9, 11].

In the literature on the problem of navigation in the Arctic, there is general confusion regarding the estimation of the number of days of availability for navigation in the Arctic. This is especially noticeable when determining forecast data regarding a significant time distance, e.g. for the mid and end of the 21st century [16, 9, 1, 7, 10] . The first reason is to consider forecasts for various climate change paths (the most frequently carried out studies are RCP 4.5 and RCP 8.5) [9, 16]. The authors of the publication confirm that the forecast results presented by individual climate change models are very divergent. Another case is, for example, taking it for granted that the navigable Arctic is „expected by midcentury or earlier", in this „in western Arctic for open water vessels starting in 2045 in addition to the central Arctic corridor over the North Pole" [10]. The work demonstrates the ability of ships with a steel hull, without ice reinforcements, to traverse the Arctic route. There are no restrictions on the number of days per year. It should therefore be understood that the possibility of year-round navigation has been assumed. Meanwhile, the above work [10] based the above statement on the publication [1], which use 2030 year as a benchmark year, for which assumed that the NSR will be fully operational all-year round. But not considered what ice class of ship will be used for transportation. In turn, the statement of Bekkers et al. [1] based on the publication [7]. But work [7] presented a map with predicted ranges for ice-free summer navigation seasons and not for the entire calendar year. Additionally, it does not consider ice classes of ships. It can be assumed that there has been a misunderstanding that misleads the reader.

It should be noted that the works consider "open water ships" [16, 2, 11] as having Type E ice class (Class 1D and 1E in the Lloyd register or Class II in the Swedish-Finish ice classes). There are ships that have a steel hull and that are structurally fit for navigation in the open sea and that, despite not being strengthened for navigation in ice, are capable of navigating in very light ice conditions with their own propulsion machinery. These very light ice conditions are grey ice of 0.15 m thickness [11] or ice conditions with acceptable Ice Numeral [15] for navigation [2], following another work [17]. The above work indicates that the definition of "ice-free" waters is very close to the definition of "open water" used by the World Meteorological Organization where ice concentration is below 10% [19].

Stephenson and Smith [16] searching optimal least-cost navigation routes using Arctic Ice Regime Shipping System [15]. Khon et al. [9] analyzed transit time window on the NSR, but accepted passage in ice-free conditions through 80% or 90% of the total NSR extent only. Assumed this passage will be easily realized with a minor icebreaker support. The above-mentioned discrepancies in research methods based on climate change models and forecasting shipping conditions in the distant future make direct comparison of their results difficult or even impossible.

The aim of this study is to investigate the number of days available for transit shipping through the Northern Sea Route (NSR). Ship traffic in subsequent navigation seasons will be analyzed. Several of the most common ice (Arctic) classes of ships transiting the NSR will be included, there are Arc4, Arc5 and Arc7. The intention is to find answers to the questions: What are the inter-annual changes in ice cover that limit navigation for open water, middle and high ice class ships and are there any relationships between ice conditions and the movement of these ships?; How long is the navigable season for particular ice classes of ships?; Is there a noticeable difference between individual ice classes, justifying higher costs of construction and subsequent operation in ice areas and outside these areas, when navigation on the NSR is not possible in the winter and spring season.

2 RESEARCH METHOD

The analysis was based on ship traffic on the Northern Sea Route in 2012, 2013, 2014, 2015, 2017, 2018, 2019, 2021 and 2022. Information on ship traffic on the NSR was obtained from official sources of the Northern Sea Route Administration (previously http://www.nsra.ru, now https://www.nsr.rosatom.ru) and Center of High North Logistic (http://www.arctic-lio.com). The following ice maps of the Arctic Ocean were used: the Arctic Marginal Ice Zone files in vector ESRI Shapefile format that contain two edge lines, for ice concentration 18% and 81%, published daily by US National Ice Center [18] (https://usicecenter.gov/Products/ArchiveSearchMulti?table=DailyArcticShapefiles&linkChange=arc-two); the Arctic regional (separate seas) maps in raster GIF format available during winter time with full Egg Code in Russian standard [5], published monthly by Arctic and Antarctic Research Institute AARI, „SEVER" Center, available till February 2022 (http://www.old.aari.ru/main.php?lg=0&id=17, Оперативные данные and Региональные ледовые карты Евразийской Арктики); the Arctic regional (separate seas) maps in raster GIF format available during summer time with ice concentration only with Egg Code in Russian standard [5], published monthly by Arctic and Antarctic Research Institute AARI, „SEVER" Center, available till February 2022 (http://www.old.aari.ru/main.php?lg=0&id=17, the tab Оперативные данные and Региональные ледовые карты Евразийской Арктики); the Arctic general maps of ice concentration or stage of development, in raster PNG format, published every 14 days by US National Ice Center (https://www.bsis-ice.de/IcePortal/ArcticBasin.html), and the Arctic general maps of ice concentration or stage of development in raster PNG format, with blended ice data from AARI, NOAA Alaska and US NIC, published weekly by AARI (https://www.bsis-ice.de/IcePortal/ArcticBasin.html). The Arctic regional maps of ice concentration and stage of development in raster PDF format, published every 14 days by US National Ice Center, since 2021 were not used for analysis (https://usicecenter.gov/Products/ArcticSynopsis). The reason was the short period of publication of the series of these maps.

In order to determine the difficulty of ice conditions in individual seas of the Northern Sea Route, the calculated equivalent ice thickness he (Equation1) was used for the period of time at the latest/earliest transit voyages of Arc7 class ships and at the latest one month later or earlier, so as to determine conditions more difficult than those prevailing during possible transit voyages. Ice conditions data were obtained from the most accurate ice maps for the winter period, including information for the so-called Egg Code. As these maps were no longer made available by the Russian Federation in March 2021, the missing data were taken from the general maps of the Arctic Ocean obtained, among others, based on Russian data. However, these data do not contain the wide range of Egg Code information.

$$h_e = \left(h_a \cdot C_a + h_b \cdot C_b + h_c \cdot C_c\right)/100 \quad (1)$$

where:
h_e – equivalent ice thickness in a given water area,
h_a – the greatest ice thickness in a given water area,
h_b – second in order, smaller ice thickness in a given water area,
h_c – the smallest ice thickness in a given water area,
C_a – percentage (partial coverage) of the thickest ice with a thickness of h_a in a given water area,
C_b – percentage (partial coverage) of ice with a thickness h_b in a given water area,
C_c – percentage (partial coverage) of the thinnest ice with a thickness h_c in a given water area.

Ship traffic was also examined, and more precisely, the dates of the beginning and end of the ship's voyage within the NSR (entering the area or leaving the area) regardless of the direction of passage. The ship's speed and the ice conditions were also analyzed. For some navigable seasons the number of ship voyage samples was very sparse or incomplete. The reason was the publication of statistical data in a different way for almost every year and the lack of a minimum set of data necessary to conduct the analysis. It happened, for example, that information was provided about the beginning of the voyage of an Arc7-class ship on day 347 Julian calendar, but there was no information when the ship completed its voyage and whether it successfully finished on the other side of the NSR. It is known from other sources that the ship did not sink. The following ice/arctic classes of ships were included: no ice reinforcements (No) based on ice maps and Arc4, Arc5 and Arc7 based on ship traffic statistics.

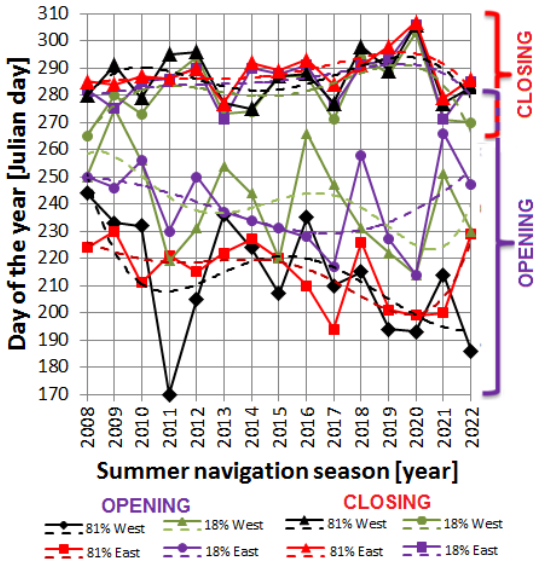

Figure 1. Opening and closing time for navigation for Eastern and Western parts of the NSR and for 18% and 81% ice concentration edges

3 THE LENGTH OF NAVIGABLE SEASON, DAYS OF OPENING AND DAYS OF CLOSING NAVIGATION ON THE NSR

3.1 *Beginning and end of navigable season based on Mariginal Ice Zone maps*

The US National Ice Center maps of Mariginal Ice Zone contain information about two ice edges – concentration 18% and concentration 81%. Geographical limitation of transit passage in ice assumed bathymetry depth 14 meters. Edges of ice concentration 18% and 81%, bathymetry isolines (isobaths) of 14 meters [8] and coastline [12] were presented on one screen with GIS software. It allowed easy review daily maps one by one and to find opening and closing days of a year (Julian calendar) for passable corridor for Western Part, Eastern Part and the whole NSR. An ice concentration of 18% corresponds to the term of "open water" [19, 16, 2, 11], similar to the term "ice-free water" [17, 7]. Meanwhile, the ice concentration of 81% corresponds to the limit of ice available for navigation by medium-class ice ships Arc4 and Arc5. The results presented on Figures 1-6. There is a large divergence in opening of the NSR for navigation and a very large convergence in closing of the NSR for navigation (Fig. 1). Rough data and trend lines give same conclusions. It suggests the closing day is easier to predict by about 2 times than opening day. Comparison of straight trend lines for the opening and closing dates of the NSR for transit shipping for 18% and 81% indicates an extension of the navigable season for Arc4 and Arc5 class ships. Approximation of trend lines with polynominal functions of 5th degree suggests quasi-cyclical reduction of navigable time window since navigation season 2020 (Fig. 1).

Shapes of opening lines of the Western Part of the NSR for 18% and 81% concentrations have convergent extremes (magenta arrow lines) presented on Figure 2. Shapes of opening lines of the Eastern Part of the NSR for concentrations 18% and 81% are similar only in recent years. i.e. since navigation season 2017 (yellow arrow lines) presented on Figure 3.

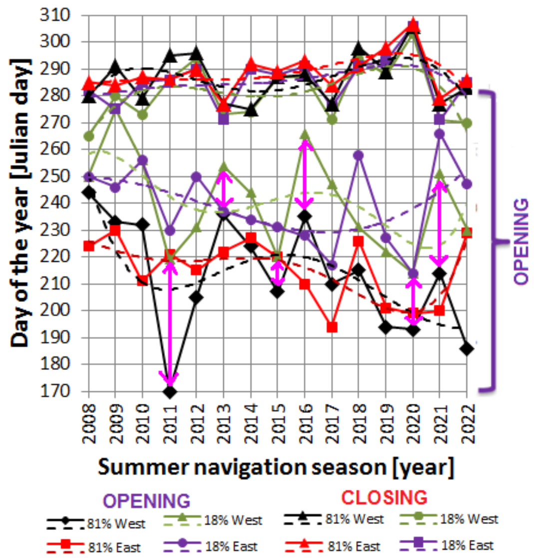

Figure 2. Convergent extremes for opening day of the Western Part of the NSR

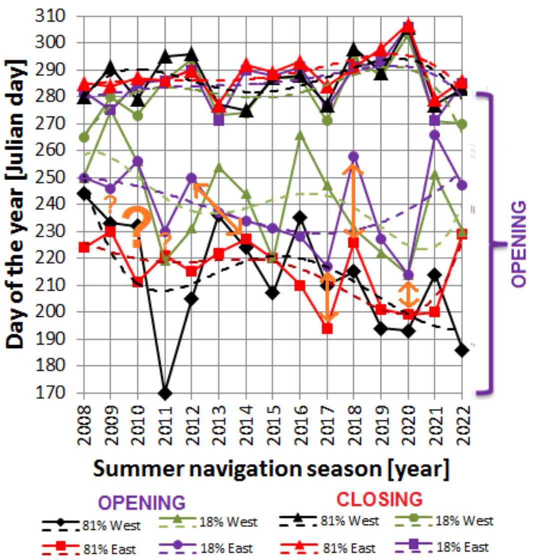

Figure 3. Extremes for opening day of the Eastern Part of the NSR

Same time the line shapes and extremes for closing the NSR for navigation are consistent, but separately - for the Western Part for 18% and 81% and separately for the Eastern Part of the NSR (Fig. 4).

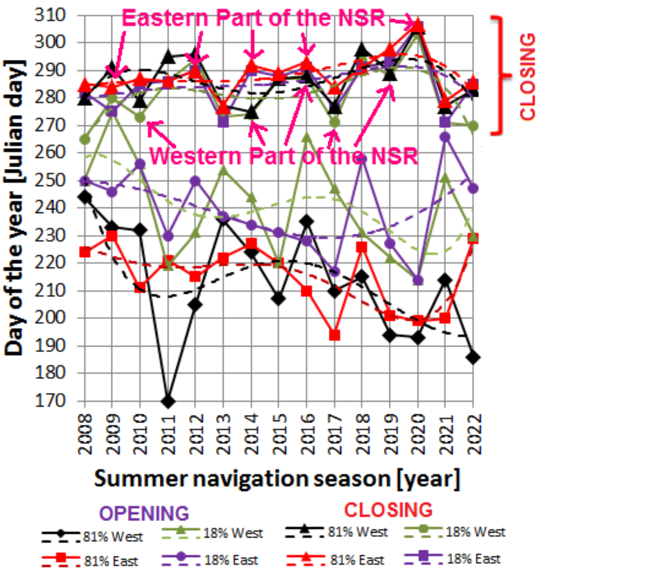

Figure 4. Extremes for closing day of the Eastern Part and Western Part of the NSR

Next, analysis of rough data for 81% concentration showed consistency in between length of navigable season (Fig. 5) at Western Part of the NSR and length of navigable season for entire NSR in 60% cases (black ellipses). Rough data for 81% concentration for Eastern Part of the NSR (magenta diamants) shows higher length of navigable season for about 40 days in relation to Western Part and the whole NSR. Lines of rough data for the Western Part of the NSR and the whole NSR are inconsistent every 3.5 years (2011-2012, 2015 and 2018-2019).

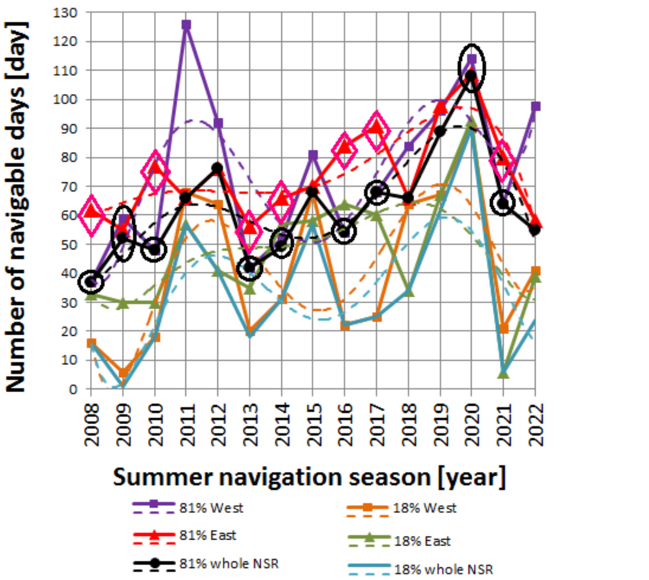

Figure 5. Consistency and inconsistency in between length of navigable season for various ice concentrations and parts of the NSR

Analyse of length of navigable season for both ice concentrations 18% and 81% (Fig. 6) found in 30% cases good consistency of extremes (black arrow lines) and in 15% cases clear inconsistency (magenta arrow lines). Cycle of ice phenomena was equal 4-5 years. It was related mainly to the Western Part of the NSR.

Based on the graphs, it is not possible to establish a clear cyclicality of the opening and closing phenomena of the NSR for transit navigation for 18% and 81% of ice concentration edges. It seems that the last few years provide the basis for more reliable predictions of the above phenomena than earlier data. The behavior of the phenomena is consistent separately for the Western and Eastern parts of the NSR. This suggests that each part of the NSR is modeled under the influence of different driving factors.

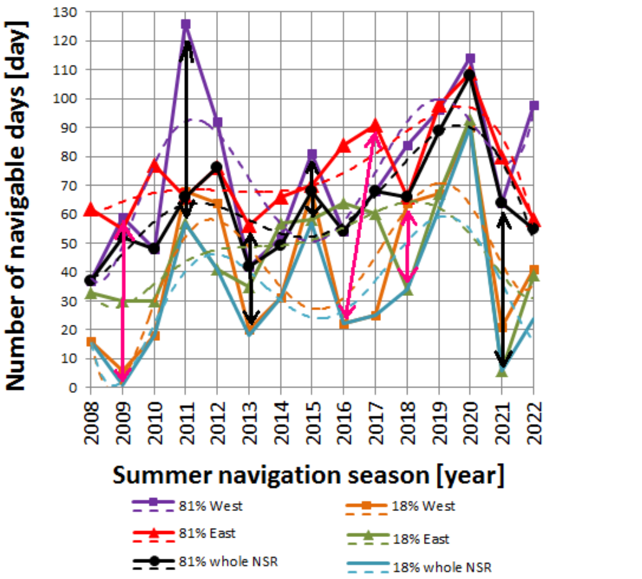

Figure 6. Seasonal consistency and inconsistency of length of navigable season

3.2 *Length of navigation season of Arc4 and Arc5 based on ships' traffic*

The length of navigable season for Arc4 and Arc5 class ships received from ships' traffic during summer navigation seasons 2012, 2013, 2015, 2017 and 2021. Only for these seasons satisfactory complete statistical information could be obtained. Statistical analysis of ships' traffic (CHNL 2023) showed that for 50% of Arc4-class ships voyages the length of navigation season was inside 46 days an average, from day 235 till day 280 Julian calendar. The maximal navigable time window lasted from day 193 till day 341 of Julian calendar.

The length of 50% of Arc5-class ships voyages was inside 71 days an average, from day 217 till day 289. The maximal navigable time window lasted from day 175 till 407 of Julian calendar (day 42 in new calendar year). It follows that the time window for ships of ice class Arc5 is 65% longer than the time window for ships of ice class Arc4.

For both ice classes Arc4 and Arc5 the rule was true: the lighter ice conditions (the greater number of days with light navigation conditions) in a given summer navigation season, the greater number of ships making transit voyages through the NSR. It suggests that ice conditions in a given navigation season were predictable in advance, allowing for operational and organizational preparation of Arc4 and Arc5 class ships with cargoes for them.

3.3 *Length of navigation season of Arc7 ships based on ships' traffic*

The length of navigation season for Arc7 class ships received from ships' traffic during summer navigation seasons 2012, 2013, 2015, 2017 and 2021. Only for these seasons satisfactory complete statistical information could be obtained. Statistical analysis of ships' traffic showed that the length of 50% of Arc7-class ships voyages was inside of 120 days an average [3], from day 248 till day 367 Julian calendar (2nd day in a new calendar year). The maximal navigable time window lasted from day 167 till day 439 (day 74 in a new calendar year).

It follows that navigable time window for ships of ice class Arc7 was 161% longer than time window for ships of ice class Arc4 and was 69% longer than time window for ships of ice class Arc5. Transit voyages of Arc7-class ships through the NSR were few only. These were mostly LNG carriers and ships for oversized and heavy loads.

Five nuclear-powered icebreakers were available to escort ships in difficult ice conditions. There were: Arktika, 50 let Pobedy, Sibir, Vaygach, Taimyr and Yamal. It was assumed that in the winter season one icebreaker can escort one ship of the Arc7, Arc5 or Arc4 ice class. The number of suitable icebreakers is therefore a factor limiting the capacity of the Northern Sea Route in the winter season. Next, the question was asked: If the voyage time depends on the speed of the ship navigating alone or with help of an icebreaker, what speed are Arc7 class ships capable of reaching? And what is the time of passage of Arc7 class ships through the whole NSR?

From the ships' traffic found Arc4-class ships' passage took an average of 12.1 days to transit NSR. In November, an average of 17.0 days from 9 to 27 days. In December, from 31 to 37 days.

The Arc5-class ships took an average of 13.6 days to transit the NSR. In November, an average of 15.6 days from 7 to 28 days.

The Arc7-class ships took an average of 14 days to transit the NSR. In November, an average of 16.5 days from 7 to 47 days. In January, an average of 33 days. Noted a sharp increase in passage time in winter period in relation to average passage time. This was in the period from November to January, respectively for individual ice classes. The above suggests that navigation in winter season is either impossible due to difficult ice conditions or is economically unjustified - regardless of the ice class of these ships. A surprise was significant number of voyages by Arc7-class ships made in the summer season, when ships with lower ice classes could be used.

3.4 *The speed limitation for ice class Arc7 ships*

Now we try to reply to the second question: What speed are Arc7 class ships capable of reaching navigating alone or with help of an icebreaker. Most appropriate were data form summer navigation season 2021. In first approach obtained the simplified 3-dimensional diagram of speed reached by Arc7 ships with R-square 0.28 (Fig. 7). Found the speed depends slightly on concentration of ice and depends greatly on average (equivalent) thickness of ice. The shortest assumption was that for ice thickness below 30 cm, speed of ship is 14 knots. With an increase in ice thickness to 50 cm, speed decreases to 10 knots and for an average ice thickness of 95-120 cm, speed decreases to 9 knots. Ice navigation conditions (independent voyage or with assistance of icebreaker) was not considered.

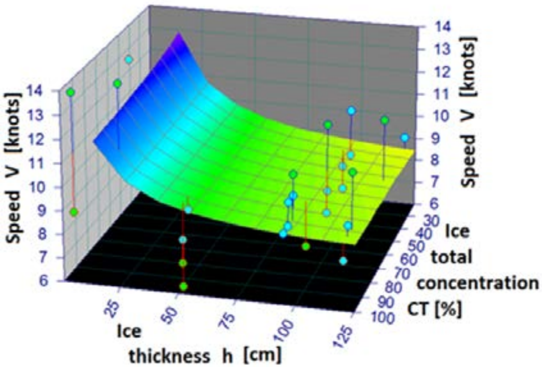

Figure 7. Simplified relationship of speed of Arc7 ships with total ice concentration and averaged ice thickness in area of ship operation.

The next, detailed 3-dimensional diagram of speed reached by Arc7 ships with R-square 0.28 was considered (Fig. 8). Same like for simplified analysis found the speed depends slightly on concentration of ice and depends greatly on average thickness of ice. Assumed for ice thickness below 30 cm, speed of ship is 14 knots. With an increase in ice thickness to 50 cm and at 100% ice concentration, speed decreases to 7 knots. For an average ice thickness of 95-120 cm, ships use icebreakers and their speed in convoy increases to 10 knots.

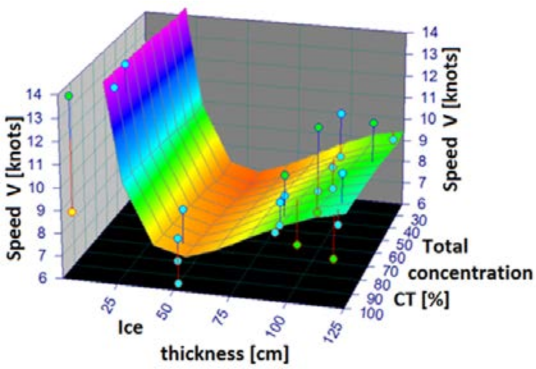

Figure 8. Detailed relationship of speed of Arc7 ships with total ice concentration and averaged ice thickness in area of ship operation.

Based on the diagrams, it can be assumed that during the period of economically unprofitable navigation, ice concentration is 100% or close to this value. The diagram in Figure 8 shows that Arc7 class ships are capable of passing ice with a concentration of 100% and a thickness of 170 cm. The result is consistent with the pre-2019 and post-2019 ship construction regulations of the Russian Register of Shipping [13, 14].

Another question that arises is during what period of time the ice thickness in the ice cover growth season (October) and in the winter and spring season (December-May) exceeds this value of 2.1 meters at 100% ice concentration. It was determined that this corresponds to an ice age younger than multi-year age. However, this is not a very precise definition of the ice thickness. In order to find the answer to the question, ice conditions maps (ice forms) were examined for the periods of ship transit voyages in the years 2013, 2015, 2017, 2018, 2020 and 2021.

The greatest ice thickness Sa was 120 cm (thick one-year-old ice), but with partial Ca coverage only 30%. The greatest partial coverage of the sea region with the thickest Ca ice was 90% with the Sa ice thickness of up to 95 cm (70-120 cm, i.e. average one-year ice). The most common limitation was the partial Ca coverage of the region of 80% with a Sa thickness of 95 cm (average one-year ice 70-120 cm).

4 EVALUATION OF THE RESULTS

4.1 *Changes to Russian regulations regarding ice navigation on the NSR*

Navigable ice conditions for ice classes of ships (IMO and other various regulations) are as follows: for Arc4 upper limit of ice concentration is 40-60% (open ice) and upper limit of ice thickness is 0.8 meter, for Arc5 (UL≈ L1 Super) upper limit of ice concentration is 40-60% (open ice) and upper limit of ice thickness is 1.0 meter and for Arc7 (ULA) upper limit of ice concentration is 70-80% (close ice) and upper limit of ice thickness is 1.7 meter.

Attention should be paid here to changes in the legal regulations of the Russian Federation regarding limitations on ship hull structures, including the Arc7 ice class. According to the shipbuilding regulations of the Russian Register of Shipping until 2018 [13], Arc7 Arctic class ships can navigate independently in the summer-autumn season (June-November) without restrictions. In the winter-spring season (December-May), these ships can navigate independently only in light ice navigation conditions. During this season they can navigate with icebreaker assistance without restrictions in light, medium and hard ice navigation conditions. In extremely difficult ice conditions, the operation of Arc7 class ships is subject to an increased risk of damage. Such conditions can therefore be compared to navigation in the yellow range, which may cause slight deformations of the hull plating, or even the red range, which may cause damage to the ship's hull structure indicated in the chart of permissible speeds and sailing conditions in the Ice Passport issued for Arc7 ice class ships. The author note that navigating within the yellow range on the permissible speed chart may cause slight deformations of the hull plating, and navigating within the red range on the permissible speed chart may cause damage to the ship's hull structure. For Arc7 class ships, independent year-round navigation is allowed only in the southwestern part of the Kara Sea during light to extremely hard types of ice navigation conditions. Need to mention, the older regulation [13] advise speed limitation and advise that RMRS regulation is not to follow by ship in service. Ship in service should follow recommendations of the Ice Navigation Ship Certificate. However, the author used the ice navigation limitations mentioned in these documents [6, 13, 14] as a base for analysis in this work.

Detailed regulations on navigation conditions allow Arc7 class ships to navigate in the winter-spring navigation season in first year ice up to 1.8 meters thick and in the summer-autumn navigation season in second-year ice without any ice thickness restrictions. On the other hand, navigation is allowed in the winter-spring navigation season in first-year close ice (concentration equal to 70-80%) up to 1.4 meters thick and in the summer-autumn navigation season in first-year close ice (concentration 70-80%) up to 1.7 meters thick at a permissible speed of 6-8 knots [13].

However, the ship construction regulations of the Russian Register of Shipping from 2019 inclusive [14] state that these ships can navigate in the Arctic during the summer-autumn navigation season (June-November) in all regions of the world ocean without restrictions. In the winter-spring navigation season (December-May), Arc7 class ships can navigate in the Arctic in close floating first-year ice up to 2.1 meters thick. It follows from the above that the new regulations of the Russian Ship Register allow navigation of Arc7 class ships in much more difficult ice navigation conditions, which may cause minor or major deformations, or even damage to the hull.

Responsibility for safe ship operations in ice covered areas (taking into account the navigating area, navigation season, current hydro-meteorological conditions, actual ice conditions, availability of icebreaker support) has been transferred to the ship operator (ship captain). The table specifying permissible navigation areas for individual ice classes of ships has been transferred from the documents of the Russian Maritime Register of Shipping [13] to local regulations related to navigation on the Northern Sea Route published by the Administration of the Northern Sea Route [6]. And there, the most severe ice navigation conditions considered concern hard ice conditions. Arc7 class ships can operate independently in hard ice conditions only from July 1 to November 30. Navigation with icebreaker support is unlimited in terms of season and ice conditions. The changes are summarized in the Tables 1 and 2.

Table 1. Changes in Russian regulations related to ice navigation in winter/spring period on the NSR for Arc7 class ships

Category	Till 2018, winter/spring	Since 2019, winter/spring
Ice concentration [%]	70-80 (close floating ice)	70-80 (close floating ice)
Ice type	First-year ice, but in other table thick first-year ice	First-year ice
Ice thickness in winter/spring navigation [m]	1.4, but in other table 1.8 (for thick first-year ice >1.2)	2.1
Permitted speed [knots]	6-8	No data
Table of ice navigation regime	Extreme navigation conditions included [13]	Extreme navigation conditions NOT included [6]
Regions under control	parts of the seas as regions [13]	detailed specific regions [6]

Table 2. Changes in Russian regulations related to ice navigation in summer/autumn period on the NSR for Arc7 class ships

Category	Till 2018, summer/autumn	Since 2019, summer/autumn
Ice concentration [%]	70-80 (close floating ice)	No limits [14], but no limits with icebreaker assistance and denied independent navigation in hard ice navigation conditions [6]
Ice type	First-year ice, but in other table second-year ice	No limits [14], but no limits with icebreaker assistance and denied independent navigation in hard ice navigation conditions [6]
Ice thickness in winter/spring navigation [m]	1.7 (for first year ice), but in other table second-year ice (no ice thickness limit)	No limits [14], but no limits with icebreaker assistance and denied independent navigation in hard ice navigation conditions [6]
Permitted speed [knots]	6-8	No data
Table of ice navigation regime	Extreme navigation conditions included [13]	No limits [14], extreme navigation conditions NOT included [6]
Regions under control	parts of the seas as regions [13]	detailed specific regions [6]

4.2 *Research results and Russian ice navigation regulations*

At the beginning, the question was asked why the limit of ice thickness established in the study is 120 cm, while navigation in first-year (average) ice with a thickness in the range of 70-120 cm is acceptable, i.e. an average thickness of 95 cm. At the same time, Russian regulations allow navigation in ice up to 210 cm thick. It should be assumed that the information on ice maps is the result of averaging observations using satellite remote sensing for a selected area. Statistical analysis of ice thickness measurements from March 12, 2003 using satellite remote sensing methods for two regions at latitudes 84.2° and 71.6° for 70 m x 70 m spatial resolution [20] showed identical results. The average value increased by one standard deviation was 147% of the average value, the average value increased by double standard deviation (accepted in maritime navigation) was 194% of the average value and the highest value was 261% of the average. The value reduced by one standard deviation was 53% of the average value and the smallest value was 12% of the average value. This shows that the ships navigated in first-year ice with a thickness of 70-120 cm, i.e. an average thickness of 95 cm. The value of 95cm + one standard deviation is 140cm, 95cm + double standard deviation is 184cm, i.e. the ice thickness does not exceed the value permitted by Russian regulations. However, the limit value of 120cm increased by double standard deviation is 233cm and this is more than the value permitted by the regulations of the Russian Federation. Therefore, it can be assumed that the results of statistical tests of navigable and non-navigable ice thickness are in accordance with the regulations of the Russian Maritime Register of Shipping [13, 14] and Rules for navigation in the waters of the Northern Sea Route [6].

4.3 *Limits of partial ice concentration fractions and thickness that allowed transit navigation of Arc7 class ships through the NSR*

Ice maps for the period of the analyzed transit voyages of Arc7 class ships in the 2013, 2015, 2017, 2018, 2020 and 2021 navigation seasons were analyzed and used to determine the partial fractions limiting navigation of these ships. The upper limit of the fraction of ice with a thickness smaller than the maximal (Sb and Sc) usually did not exceed 40% but could reach up to 75%. The lower limit of the partial fraction of Cb and Cc ice with a smaller Sb and Sc thickness than the maximal Sa usually reached values of 20% but could decrease even to 10%.

It should be assumed that the limit values of ice conditions come down to the average thickness of the thickest ice Sa, usually not exceeding 95 cm (average first-year ice) with the highest partial fraction of Ca amounting to 80% and in extreme cases even 90%. At maximum ice thicknesses Sa of 120 cm (thick first-year ice), the partial fraction of Ca did not exceed 30%.

The lower limit of the partial fraction of Cb and Cc ice with a smaller thickness than the maximal usually reached values of 20%, but could reach 10% only and usually was of an average thickness of Sb and Sc up to 45cm, but in extreme cases up to 56cm. This means that ice with a lower thickness Sb than the maximal can be young first-year ice with a thickness of 30-70 cm (thin first-year ice) and in extreme cases even ice with a thickness of 70-120 cm (medium first-year ice) with a partial fraction Cb of 10% only. The thinnest partial fraction of ice Sc could have a thickness of 5 - 30 cm, on average 17.5 cm (nilas and young ice) with a partial fraction Cc of most often 10% but sometimes only 5%.

4.4 *Variability of ice thickness limits that allowed transit navigation of Arc7 class ships in subsequent navigation seasons*

Based on the analysis of ice maps, it was determined that Arc7 class ships originally (i.e. until 2016) navigated in ice with an equivalent thickness of up to 31.5 cm (maximal 50 cm) and did not navigate in ice with a thickness of 45.3 cm or more (maximal 50cm). In 2017 and 2018, the Russian Federation changed the regulations of the Russian Maritime Register of Shipping [13, 14] and Rules for navigation in the waters of the Northern Sea Route [6]. The time of changing these regulations coincided with the export of LNG from the newly built terminal in the port of Sabetta. At the turn of 2018-2019, some ships navigated only in slightly thicker ice. Navigating in thicker ice than the ships' structures allowed could result in deformations or damage to the hulls, which were costly to repair. This probably led to the abandonment of the concept of navigating in much thicker ice. In the years 2018-2021 (December-December), ships sailed in ice with an equivalent thickness of up to 43.3 cm (maximal 50 cm) and did not sail in ice with a thickness of 46.3 cm (maximal 95 cm). These values are consistent with the period before the Sabetta port was put into operation. In February 2022, Arc7 class ships again navigated in ice with an equivalent thickness of up to 94.8 cm (maximal 120 cm) and did not navigate in ice with a thickness of 95 cm (maximal 120 cm).

From the above analysis it can be concluded that Arc7 class ships are able to meet the transport needs on the Northern Sea Route in winter in ice with an average thickness not exceeding 95 cm and a maximum thickness not exceeding 120 cm.

4.5 *Navigable time window for Arc7 class ships*

For comparison of navigable time window for ice concentration 18%, ice concentration 81%, Arc4, Arc5 and Arc7 class ships the median, first quartile, third quartile, minimum value and maximal value of Julian calendar days for transit passages of respective ships were calculated (Fig. 9). Found median of navigable time window for total ice concentration 81% equal median of navigable time window for Arc4 and Arc4 ships around the 260th day of Julian calendar.

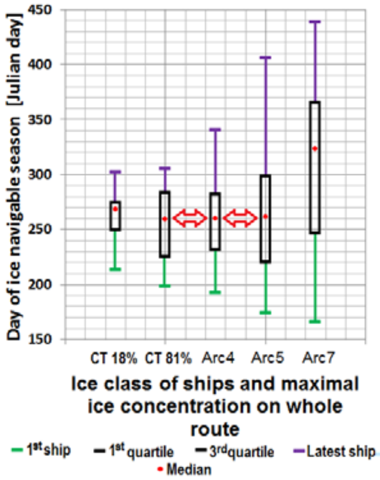

Figure 9. Ranges of navigable time window for various ice classes

First quartile of 50% of ships with ice class Arc4 transiting the NSR commenced passage in between first quartiles of navigable time related to ice concentration 18% and 81%. Same time third quartile of 50% of ships with ice class Arc4 transiting the NSR completed passage in between third quartiles of navigable time related to ice concentration 18% and 81% (Fig. 10).

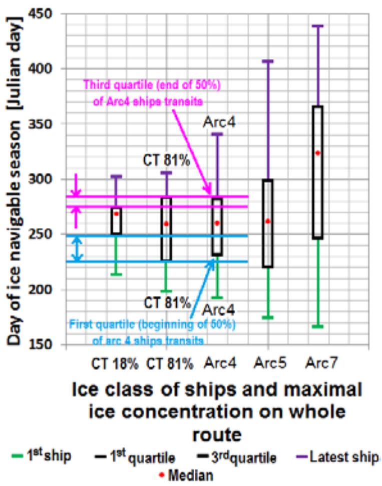

Figure 10. Ranges of navigable time window for Arc4 ships

First quartile of 50% of ships with ice class Arc5 transiting the NSR commenced passage slightly before first quartile of 50% of occurrence of the NSR open for navigation at 81% of ice concentration (Fig. 11). Third quartile of 50% of ships with ice class Arc5 transiting the NSR completed voyage slightly after third quartile of 50% of occurrence of the NSR open for navigation at 81% of ice concentration.

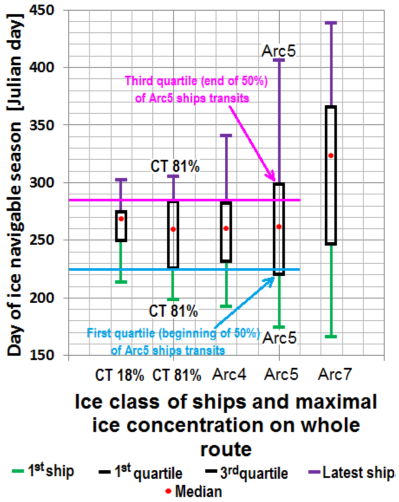

Figure 11. Ranges of navigable time window for Arc5 ships

First quartile of 50% of ships with ice class Arc7 transiting the NSR commenced passage at the first quartile of ice concentration equal to 18% and third quartile of 50% of ships ended passage at a New Year (Fig. 12). Maximal range of navigable time window of Arc5-class ships was close to maximal range of navigable time window of Arc7-class ships. Beginning of navigable time window of Arc4-ships was also very close to beginning of navigable time window of Arc7-class ships (Fig. 12). Maximal navigability time on the Northern Sea Route with the use of the most powerful Arc7-class ships did not exceed 273 days, i.e. 74.8% of a year.

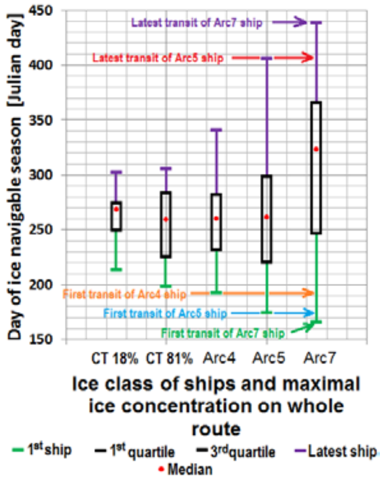

Figure 12. Ranges of navigable time window for Arc4, Arc5, Arc7 ships

5 CONCLUSIONS

Results of the work based on ships' traffic statistics and ice maps for navigation seasons 2012, 2013, 2015, 2017, 2018, 2020 and 2021. In order to determine beginning and end of navigable time window for 18% and 81% of ice concentration edges the ice maps of Marginal Ice Zone since 2008 till 2022 year were used.

Despite the general convergence of trends of rough data based on ice maps, there is a large divergence in opening of the NSR for navigation and a very large convergence in closing of the NSR for navigation. The end date of the navigation season can be determined with much greater probability than the start date of the season. Trends of opening of navigable season on the Eastern Part of the NSR for concentrations 18% and 81% are similar only in recent years. i.e. since navigation season 2017. Dates of closing the NSR for navigation are consistent, but separately - for the Western Part for 18% and 81% and separately for the Eastern Part of the NSR.

Ice edges for 81% concentration for Eastern Part of the NSR show higher length of navigable season for about 40 days in relation to Western Part and the whole NSR. For this 81% concentration exists consistency in between length of navigable season at Western Part of the NSR and length of navigable season for the entire NSR in 60% cases. No consistency found in between Eastern Part and Western Part of the NSR. No clear cyclicality of the opening, closing and length of navigable season for transit navigation phenomena was found for 18% and 81% of ice concentration edges. It seems that the relationships between opening and closing dates and the length of the navigable season have been more consistent over the last 6 years. However, from a statistical point of view, this is too short period of time to forecast these data even in the near future.

Ice free navigable time window for ships with no ice class transiting the Northern Sea Route was from 209 till 300 day of the Julian calendar, in a time window of 1 to 90 days, an average of 33 days. The maximal navigable time window of Arc4-class ships was from 209 till 300 day of the Julian calendar, in a time window of 16 to 86 days, an average of 75 days. The maximal navigable time window of Arc5-class ships was from 196 till 315 day of the Julian calendar in a time window of 95 to 120 days, with an average of 107 days. The maximal navigable time window using the most powerful Arc7-class cargo ships does not exceed 273 days, i.e. 74.8% of a year. Above results shows the Northern Sea Route navigability dates are inside the period from 16th of June till 26th of March. Under the current climate warming conditions, the NOT NAVIGABLE period of time lasts from 27th of March till 15th of June. It is 92 days ◎ 3 months.

ACRONYMS

AARI – Arctic and Antarctic Research Institute,
C_a – percentage (partial coverage) of the thickest ice with a thickness of h_a in a given water area,
C_b – percentage (partial coverage) of ice with a thickness h_b in a given water area,
C_c – percentage (partial coverage) of the thinnest ice with a thickness h_c in a given water area,
h_a – the greatest ice thickness in a given water area,
h_b – second in order, smaller ice thickness in a given water area,
h_c – the smallest ice thickness in a given water area,
h_e – equivalent ice thickness in a given water area,
NOAA - National Oceanic and Atmospheric Administration,
NSR – the Northern Sea Route,
RMRS – Russian Maritime Register of Ships.
S_a – stage of ice development occurring in fraction C_a (according to Egg Code),
S_b – stage of ice development occurring in fraction C_b (according to Egg Code),
S_c – stage of ice development occurring in fraction C_c (according to Egg Code),
US NIC - United States National Ice Center.

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