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ARTICLE

A climate model-based long-term capacity forecast of the Northern Sea Route

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Abstract

This article estimates the future transit capacity of the Northern Sea Route (NSR) in consideration of the ice navigation capabilities of the world fleet and the escort capacity of the current and planned Russian icebreakers. The work employs two different storyline simulations from the Coupled Model Intercomparison Project Phase 6 (CMIP6) to account for the future development of sea ice extent and thickness between 2024 and 2050. In both simulations, the transit traffic is expected to remain seasonal and highly dependent on limited icebreaking capacity, affecting the potential of liner shipping in particular. In the analyzed simulations, the current and estimated maximum transit capacity of the NSR significantly exceeds currently realized transport volumes, confirming prior assumptions that volumes on the route are not a capacity issue but are instead mostly caused by a lack of time savings, poor economic viability, and navigational safety concerns.

Keywords Northern sea route · Europe–Asia transport · Climate change · Winter navigation

1 Introduction

For decades, the importance of Asia, and China in particular, to the world economy has been steadily growing. In line with the trend toward globalization, Asia has embraced its role as a production hub of consumer goods. Due to this, cargo transport volumes between Europe and Asia have increased steadily (UNCTAD 2023), making

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the Europe–Asia connection one of the main lanes of global trade, with trade volumes expected to increase (UNCTAD 2023).

There are three potential routes for freight between Europe and Asia. The overwhelming majority of traded goods are transported by sea on a route traditionally passing the Suez Canal (ITF 2022). Given the recent political unrest in the Middle East, as of 2024, these volumes are currently rerouted around Africa via the Cape of Good Hope, increasing the distance traveled by up to 30% (Notteboom et al. 2024). Even with these developments, other alternative routes are not gaining ground. Rail volumes across the Eurasian land bridge constitute just a fraction of the total volume due to capacity and cost concerns (Zeng et al. 2020).

The third alternative is the Northern Sea Route (NSR) in the Arctic Ocean, which runs from the Barents Sea in the west to the Bering Strait in the east through Russia's exclusive economic zone (EEZ). Depending on the origin and destination, the distance traveled through NSR is around 40% less than the Suez Canal route (Schøyen and Bråthen 2011; Vanhatalo et al. 2021) offering—at least theoretically—savings in time and fuel cost. Tightening environmental policies have sparked discussion regarding a shorter NSR that would increase competitiveness due to potential savings in emission charges (Ding et al. 2020).

This rationale applies only to open water conditions. Harsh winter conditions still prevail for most of the year. Currently, the route can be operated with Category C vessels according to IMO Polar Code for 2–3 months a year (August to October) and with Category B vessels for 4–5 months a year (July to December) (Aker Arctic 2023). Even during these windows, operating these vessels requires icebreaker assistance. For these reasons, NSR transport volumes have remained limited and are mostly destinational, meaning that either the origin or destination is within the Arctic (Gunnarsson 2021), as they are related to the utilization of Russia's natural resources in the Arctic.

The past few years have seen the rise of a growing stream of research analyzing the route's potential under different assumptions and configurations, including both liner and tramp shipping. However, extant research has not identified any significant indicators of the commercial shipping potential of the NSR, at least under current conditions (Theocharis et al. 2018; Cheaitou et al. 2020).

Climate change is a key factor in the discussion about the future potential of the NSR. Climate change causes temperatures to rise, especially in polar regions (Clem et al. 2020), gradually leading to diminishing ice cover (Årthun et al. 2021). The amount and cover of multi-year ice is already declining, and forecasts indicate that, in the coming decades, the Arctic could be entirely free of ice in the summer months (Clem et al. 2020). With the ice cover withdrawing and the open-water season lengthening, the NSR could potentially attract larger trade volumes than today.

Previous long-term estimates of potential cargo volumes in the NSR have been offered. For example, Kiiski et al. (2018) consider icebreaking capacity as a key variable in estimating the potential increase of cargo volumes. Chen et al. (2020), relied on simulation data from Coupled Model Intercomparison Project Phase 6 (CMIP6) to analyze the navigability of open water and polar classed vessels during the coming decades. Cao et al. (2022; on the other hand, approach the NSR volumes from the perspective of sailing days and assume that the open-water season will gradually lengthen due to climate change.

Much of the previous research attempting to forecast the navigability of NSR have maintained the analysis on a level of ice classes, combining the simulated ice concentration and thickness with the required ice-going capabilities of different ice classes. This research takes a step further by including vessel level data on ice going capability and cargo carrying capacity to estimate the potential throughput capacity of the route. This research considers the number of sailing days as a dynamic concept that depends on (i) the number and capacity of different ice class vessels; (ii) the availability of icebreaker escort capacity; and (iii) existing weather (ice) conditions, which, in turn, depend on the pace of climate change.

The methodology relies on climate models and predictions on the concentration and thickness of sea ice to estimate the potential capacity of the route, considering weather (winter) conditions, the size and technical characteristics of the global ice classed fleet, and the availability of icebreaking assistance. Two climate model simulations from the CMIP6 based on different sea ice storylines are included (see O'Neill et al. 2016) to answer questions about the potential volume and share of Europe–Asia trade that could be transported via NSR based on the current icebreaker capacity and known investments into these assets.

Section 2 discusses the key literature related to cargo transport in the NSR, including the primary characteristics of Arctic navigation and the economics of the NSR. Section 3 introduces the research methodology, including the datasets and data sources. The main results of the analysis are presented in Sect. 4, followed by conclusions and a discussion in Sect. 5.

2 Literature review

2.1 Arctic sea routes

Arctic sea routes are a set of shipping routes connecting the Atlantic Ocean and the Pacific Ocean, passing through the Arctic Ocean. They comprise (i) the Northwest Passage (NWP) along the northern coast of North America, (ii) the Northeast Passage (NEP) mostly within Russia's EEZ, (iii) the Northern Sea Route (NSR) along the Russian coastline and mainly within its territorial waters, and (iv) the Transpolar Route navigating across the north pole (Liu and Kronbak 2010; see also Fig. 1). Of the four, the Northwest Passage and Transpolar Route are currently not used for commercial purposes, whereas there has been growing commercial interest and relatively steady cargo volumes along the NSR.

There are two basic rationales for the use of the Arctic routes. The first is that the geographical distance through the Arctic Ocean is considerably shorter than through the Suez Canal route, which covers the vast majority of the transport volumes between Asia and Europe. Depending on the origin and destination, the difference in favor of

Fig. 1 The Northwest Passage, the Northeast Passage, the Northern Sea Route and the Transpolar Sea Route.
(adapted from Dyrcz 2017).

NSR could be as much as 30%, making it at least theoretically an attractive alternative for cargo transport. Even with this advantage, however, the transit volumes via the NSR have been, and still are, quite modest, with the bulk of the cargo volumes coming from destinational traffic (Gunnarsson 2021; NSRIO 2023).

The majority of destinational and overall NSR volumes come from the extraction of natural resources, particularly oil and gas fields such as the onshore gas fields in and around the Yamal Peninsula or the offshore Prirazlomnoye oilfield south of Novaya Zemlya (see Fig. 1). A small portion of destinational volumes serves communities in the Russian Arctic coastline.

2.2 Previous research on the potential of NSR

The development and potential of cargo volumes in the NSR have mainly been studied from two perspectives. One consists of studies that look at the past development, basing their analysis on realized vessel movement data. Cao et al. (2022) estimated the past development in the length of navigational season for different ice classes using realized ice thickness and extent data for years 1979–2019, concluding that the ice conditions have in fact changed, and thus the navigational season have become longer and potential for additional volumes increased. Based on this, Cao et al. (2022) assume similar development also for the future. Vliestra et al. (2023) focus on the accessibility of different ice classes with realized ice data for years 2021–2022. Hu et al. (2024) analyse the accessibility of different ice classes in the NSR using observed vessel movements. In addition to identifying which ice classes and to what extent operate in the NSR, they were also able to analyse the impact of ice thickness on sailing speed, and finding out that especially for the lower ice classes (in the arctic context) the speed is reduced to as low as 5 knots in deeper ice, most likely indicating escort or convoy service.

The other perspective is forward-looking, estimating the future accessibility based on climate and ice models, or other key variables. In these studies, the accessibility is usually been estimated based on the ice-going capability required from different ice classes. In 2014, Stephenson et al. (2014) simulated accessibility of polar classed and non-ice classed vessels utilizing daily CCSM4 data, identifying that there is strong uncertainty especially considering the accessibility of Kara, Laptev and East Siberian Seas and concluding that due to the highly variable access, maintaining a year-round or permanent service is likely to be challenging also in the future. Chen et al. (2020) estimated the navigability of open water vessels and PC6 classed vessels for both the NSR overall as well as for some the crucial straits (Vilkitstkiy, Laptev, Shokalskiy and Sannikov) until 2050, utilizing different CMIP6 models. Goldstein et al. (2022) to a bit different perspective, in which they utilized CMIP6 scenario data for the ice extent, but focused their analysis to estimate potential savings or losses for container traffic for a single year, comparing situations where the NSR would be utilized against the current status quo, where international traffic is limited due to the geopolitical situation and sanctions. Kiiski et al. (2018) did not include climate or ice model scenario data as such, but estimated the capacity and icebreaker need based on three alternative (melting, baseline and freezing) scenarios for the development of ice thickness and extent.

2.3 Factors impacting the traffic volumes in the Arctic routes

Even with the distance advantage, there are clearly factors preventing cargo from taking the relatively shorter Arctic route. The first and most obvious obstacle is harsh weather conditions. During winter (February to March), the ice thickness in the Arctic may exceed 4 m (Kwok 2018), meaning that only highly ice classed (PC5 or above) vessels are able to safely operate on the route (DNV 2017). Vessels built for this purpose must have their hulls reinforced and have sufficient engine power to navigate on ice. In addition, they also have to be winterized to bear harsh conditions, such as freezing. Material class selections should be made to prevent material failure in low temperatures, excess heating conditions, etc. (Tikka et al. 2008). Even under summer conditions, vessels traversing the Arctic are still required to have an ice class (Gleb and Jin 2021). Vessels must be able to survive and maneuver in the NSR under harsh conditions, which often lead to additional wear and tear and, subsequently, higher maintenance and insurance costs compared to vehicles traversing the Suez Canal route (Koçak and Yercan 2021).

A small part of highly ice classed vessels can operate independently in the NSR, whereas most ice class vessels still require escort capacity provided by a limited number of icebreakers (Kiiski et al. 2018). Icebreaking capacity, or lack thereof, is one of the key bottlenecks of the NSR, as existing icebreakers are able to escort only a limited number of vessels. In their analysis, Kiiski et al. (2018) assumed the number of escorted vessels to vary between 2.5 and 4, whereas Liu et al. (2022) assumed a slightly higher number of 5 vessels in a convoy. If the demand for escort services were to increase, it would lead to longer waiting times and therefore a reduction of distance advantage. The need to utilize icebreaker escorts constitutes an additional cost due to icebreaking fees (Xu and Yin 2021).

Both navigating independently in ice and navigating as part of a convoy escorted by icebreakers reduce the speed of trading vessels dramatically (Wang et al. 2021) while simultaneously increasing fuel consumption due to increased resistance (Solakivi et al. 2019; Cariou et al. 2021). For fuel efficiency, vessels usually attempt to maintain a constant engine load (according to Adland et al. 2020; usually 70–80%) while the speed of the vessel is reduced due to the increasing resistance of ice Nam et al. (2013). According to Goerlandt et al. (2017) in convoys the speed may be reduced to as low as 5 knots.

Navigating the Arctic for commercial purposes requires addressing many challenges in addition to harsh weather conditions. The bathymetry of the route has been identified in the literature as one of these challenges (see, e.g., Hermann et al. 2022). Currently, much of the traffic traveling along the coastal NSR, defined as within 120 miles from the shoreline, passes through islands in the Kara Sea, the Laptev Sea, and the Sannikov Straits. On this route, both the maximum draft and beam are restricted, restricting vessel size to smaller vessels relative to those on the Suez route, thus limiting economies of scale. Some of the traffic is able take the route around the New Siberian Islands, where similar size restrictions do not apply. However, their cost level and structure are considerably different from open water vessels (see for example Solakivi et al. 2018) impacting the competitiveness of the route.

In addition to the various limitations set by nature, man-made obstacles in the utilization of the NSR as a shipping route have emerged. The majority of trading volume is currently destinational to and from the oil and gas fields, whereas trading volume to Russian Arctic communities is minor. Thus, port- and shipping-related infrastructure along the route is limited and often insufficient for supporting efficient commercial transport (Kiiski et al. 2018).

At the same time, Russian and particularly Chinese authorities have expressed their desire to increase cargo throughput in the NSR. The NSR passes through the Russian EEZ and partly through its territorial waters. Thus, the route is mostly governed by Russian authorities, to whom it constitutes a potential source of income and provides control over volumes possibly traversing through its territories. In addition, Russia has recently reiterated its ambition for an extended continental shelf in the Arctic Ocean beyond the borders of the 200-mile EEZ (Maritime Executive 2023). China, on the other hand, has been actively seeking alternative transport routes for its trade, with the NSR viewed as such a potential pathway (see, for example, Huang 2016).

At the same time, rising geopolitical tensions have shaped the balance and competitiveness of the Asia–Europe transport corridors, at least in the short term. After the start of Russia's war in Ukraine, on March 7, 2022, the Joint War Committee of the Lloyds Market Association declared all Russian territorial waters as war-risk zones, which has substantially increased insurance costs for vessels plying these waters (Lloyds 2024). At the same time, many Western shipping companies have decided not to serve Russian ports for the time being.

However, the Suez Canal route has also suffered from the political unrest in the Middle East. In 2023, the Houthi Movement in Yemen started to attack commercial vessels transiting through the Red Sea, ultimately forcing most commercial traffic to reroute around the Cape of Good Hope and the entire African continent, thus increasing the distance of the Asia–Europe transport volumes as much as 30% (Notteboom et al. 2024).

3 Methodology and data

Two capacity models were created to assess cargo throughput potential along the NSR. The first model estimates the maximum transit capacity based on the cargo capacities and ice navigating capabilities of commercial fleets around the world. The second model factors in existing icebreakers of the Russian administration as well as the administration's known investments into additional icebreaking capacity. Both models are operated monthly, with a timescale extending to 2050. The methods and calculation parameters of the models are discussed in greater detail below.

The route analyzed in the model is the Rotterdam–Yokohama route via the NSR. A similar route has been used by Fuglestvedt et al. (2014) to analyze the climate effect of shifting part of Europe–Asia container traffic from Suez to Arctic routes. This route was chosen as the average route between European and Asian destinations based on historical data from actual voyages (NSRIO, 2022, 2023). Additionally, navigational distance, potential sea ice, and bathymetric conditions along the NSR were considered. The total length of the route is 6,920 nautical miles (Liu and Kronbak 2010).

The average sea ice thickness along the route was used as input for the model. The data stems from two different CMIP6 climate model simulations, CNRM-ESM2-1 (second generation Earth System Model by Centre National de Recherches Météorologiques) and NorESM2-MM (Norvegian Earth System Model version 2), both following an SSP370 (shared socioeconomic pathways) scenario, which is in the upper middle part of the anthropogenic radiative forcing and CO_2 emission scenarios (O'Neill et al., 2016). Figure 2 illustrates the sea areas of the NSR for which the ice thickness was averaged.

One limitation of using spatially averaged data on sea ice thickness on rather large sea areas is that, in reality, there are substantial variations in ice thickness. Therefore, even if the ice class of a ship complies with average sea ice thickness, there might be areas in which the ice is much thicker than usual. On the other hand, a southerly route could provide more favorable conditions than what the average suggests. For the model, the thickness and coverage of sea ice were estimated as monthly averages until 2050. As raw data from the CMIP6 models for sea ice thickness were used in this model, the biases of these models still prevail. According to Wei et al. (2020), many CMIP6 models have large biases before they are calibrated with historical data. The largest biases seem to be with NorESM2-MM, which overestimates sea ice thicknesses and volumes during the summer season (i.e., September and the surrounding months). According to Séférian et al. (2019), the CNRM-ESM2-1 simulation is able to provide reasonably accurate estimates of temperature and ice cover especially considering winter months.

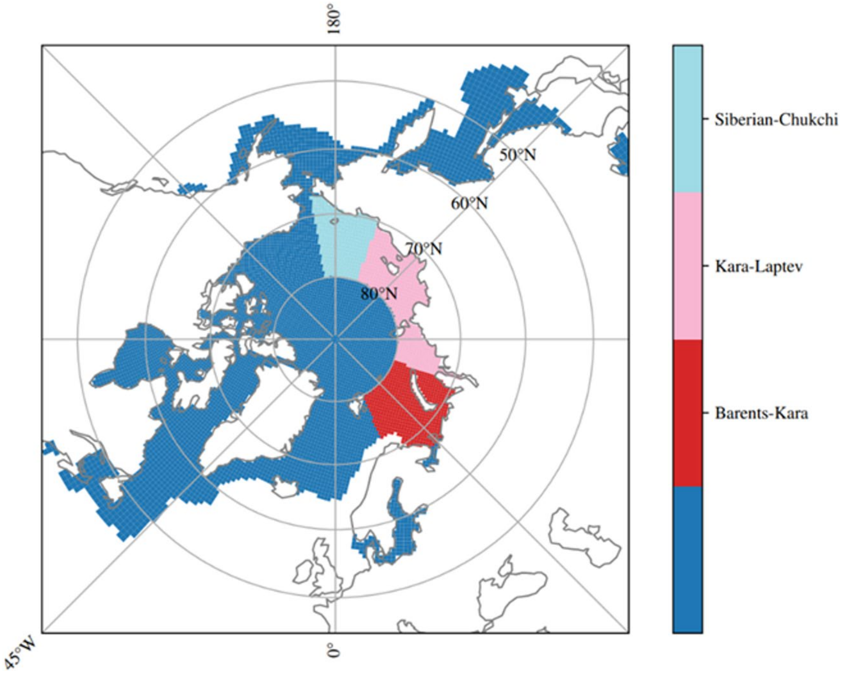

Fig. 2 Northern Sea Route sea areas used for calculating the spatially averaged sea ice thicknesses

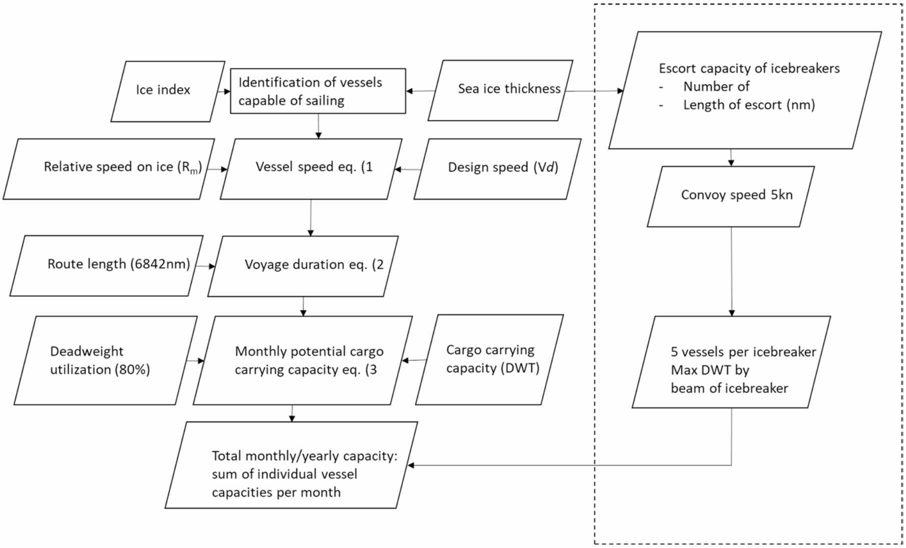

Fig. 3 The logic of the analysis for independent navigation and icebreaker escort capacity

The parameters used for the first part of the model are as follows: (i) ice index, (ii) vessel speed, (iii) sea ice thickness, (iv) route length, (v) deadweight tonnage (DWT), (vi) yearly operation time, (vii) utilization rate (DWT), (viii) cargo carried per DWT, and as derivatives of these, (ix) voyage duration, and (x) potential monthly cargo capacity. The logic of the analysis is illustrated in Fig. 3.

The analysis included all the commercial vessels with an ice class between "icebreaker" and ID of the Finnish-Swedish ice class regime. The details including the ice class, cargo carrying capacity in DWT and design speed were obtained from the World Fleet Register (Clarkson´s Research Services Ltd. 2024), for which the descriptive statistics are depicted in Appendix table 2.

The ice index describes a vessel's ability to traverse ice of a certain thickness. Ratings range from 1 (lowest) to 9 (highest) and are derived directly from the ice class of the ship. The relationships between ice class, ice index, and ice thickness are illustrated in Table 1. For the ice class ID, a maximum ice thickness of 0.2 m was extrapolated from the existing data.

Potential average vessel speeds were calculated based on the design speeds and average monthly relative speeds of the ships included in the model.

$$V_a = V_d * R_m \tag{1}$$

where V_a is the actual speed, V_d is the design speed, and R_m is the average monthly relative speed (relative to the design speeds). The relative speeds were calculated on a monthly basis for different sea areas based on actual daily vessel movement data including position, bearing and speed obtained from Northern Sea Route General Administration Rosatom (2025) The calculated relative speeds are presented in Appendix table 3 and numbers of observations per vessel type and ice class in Appendix table 4. Appendix table 5 presents the realized average speeds during different months per vessel type and sea area. The average relative speeds were not available for all months of all sea areas, so the blank points in the data were extrapolated based on the available data. Some months do not have any data as there was no traffic recorded during these periods due to adverse weather and sea ice conditions. Design speed was not available for some individual vessels. In these cases, the average design speed of similar vessels (type, ice class, and size) was used. Further, we

Table 1 Relationships between vessel ice class, model ice index, and actual ice thickness (Traficom 2021 for Finnish-Swedish ice class rules [FSICR]; Neftegaz 2015)

Ice Class	Ice index	Maximum Ice thickness (m)
ID	1	0.2
IC	2	0.4
IB	3	0.6
IA/Arc4	4	0.8
IA SUPER	5	1
Icebreaker6/LL4	6	1.5
Icebreaker7/LL3	7	2
Icebreaker8/LL2	8	3
Icebreaker9/LL1	9	4

analyzed the ratio between the design speed and actual speed of different vessel types with ANOVA. The only statistically significant difference was found between icebreakers and cargo vessels (Tankers and General cargo vessels). Therefore, we could conclude that the impact of sea ice conditions could be considered symmetrical for all the cargo vessel types.

The basis for the cargo capacity calculation was the deadweight tonnage (DWT) of the ships. For cargo carrying, a utilization rate of 80% was assumed based on historical vessel utilization data. Additionally, 95% of the DWT was assumed to be cargo (McKinsey & Company 2024).

Voyage duration was calculated based on route length and monthly actual vessel speeds. A total of 1.5 days were added to the total duration of the journey to account for average ship waiting and berthing times (Park and Suh 2019).

$$T_{Voyage} = S_{Voyage}/V_{Voyage}/24 + 1.5 \tag{2}$$

where T_{Voyage} is the duration of the voyage, S_{Voyage} the length of the route used, and V_{Voyage} the actual speed of the vessel. Finally, the potential monthly cargo carrying capacity is calculated as follows:

$$C_m = DWT * U_{DWT} * C_{DWT} * O_Y * (30/T_{Voyage}) \tag{3}$$

where C_{m} is the monthly cargo capacity, DWT is the deadweight tonnage of the ship, U_{DWT} is the utilization rate of DWT, C_{DWT} is the rate of cargo per DWT, O_{Y} is the yearly operation time of the vessel, and T_{Voyage} is the duration of the voyage. This equation calculates the monthly cargo capacity for one vessel, and the total capacity for the month is the result of adding the capacities of all vessels that are able to traverse for the month.

Finally, it is assumed that the vessels in the current fleet will be operational until 2050. This is a simplification of reality: many of the vessels will reach the end of their economic life during this period (see, e.g., Solakivi et al. 2021) and will ultimately be replaced. However, as shipping volumes are expected to remain and even increase (UNCTAD 2023), vessel capacity is expected to remain at least at the current level.

The second capacity model relies mostly on similar methodology and parameters, with one key difference: the capacity of the latter model is defined by the escort capabilities of existing icebreaking capacity and known investments. Several key defining factors and calculation parameters are considered.

First, it was assumed that the maximum size of the vessels that could be escorted was defined by the beam of the icebreakers, thus limiting the capacity to vessel sizes capable of being escorted. Second, following Liu et al. (2022) s, the size of the convoy was limited to five vessels per icebreaker.

Another key assumption was the speed of the vessels. In convoys, vessels are usually organized so that the slowest (i.e., the least ice-going-capable vessels) vessels are placed closest to the icebreaker for easy access to assistance, if necessary. Thus, the speed of the entire convoy is defined by the maximum speed all vessels can maintain in brash ice. Typically, the speed of the convoys can drop to as low as 5 knots when operating in heavy ice conditions (Goerlandt et al. 2017).

4 Results

The capacity estimates were calculated for two different simulations of which the NorESM2-MM can be considered harsher, and CNMR-ESM2-1 milder. Even though the capacity estimates were initially calculated on a monthly bases, the results are presented as annual sums of monthly estimates for clarity. Figure 4 presents the estimates of individual navigation capacity until 2050 and Fig. 5 the icebreaker assisted capacity, whereas Fig. 6 presents the sums of independent and assisted capacities in the two estimated simulations. For clarity of presentation, the estimated monthly transit capacities are aggregated into annual capacities and detailed in Figs. 4, 5 and 6. Depending on the simulation, there are large differences in the estimated annual capacities (Fig. 4). In case the development of ice thickness and coverage follows the harsher NorESM2-MM simulation, the independent navigation capacity remains very low all the way until 2050. If the development of ice coverage followed the CNMR-ESM2-1 simulation instead, NSR's annual transit capacity with independent navigation would mostly vary between 200 and 300 million tons throughout the analysis period, with no observable or statistically significant trend. In the annual forecasts of independent navigation, two clearly visible anomalies can be detected. As in all simulations, also here there is a certain possibility to extreme values, which can be seen as an unusually mild winter and high capacity in 2039 as well as an extremely harsh winter and low capacity in 2046.

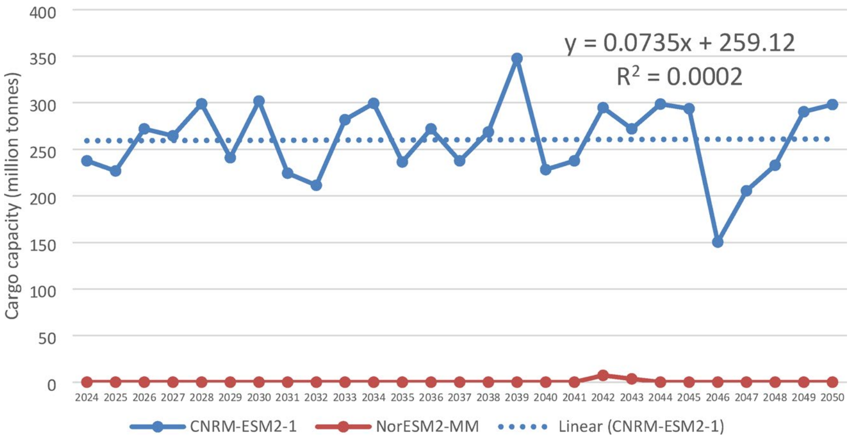

Fig. 4 Estimated Northern Sea Route transit capacity (ice class vessels, independent navigation) until 2050

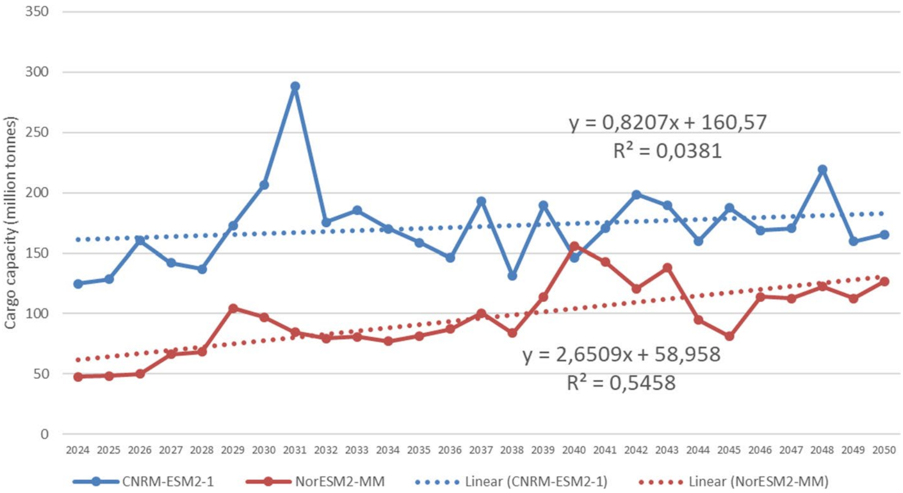

Fig. 5 Estimated NSR transit capacity with icebreaker assistance until 2050

Figure 5 presents the results of the capacity model estimating transit capacity with icebreaker assistance until 2050. Unsurprisingly, estimated capacity based on the CNMR-ESM2-1 simulation results in higher transit capacities than in the NorESM2-MM simulation. The annual transit capacity is expected to vary between roughly 120 million and 200 million tons, excluding the anomaly in 2031, where the estimated capacity is close to 300 million tons.

The estimated transit volumes of the NorESM2-MM simulation are lower, starting from 50 million tons p.a. in 2024, and reaching 125 million tons in 2050. Depending on the simulation, the annual increases in the estimated maximum capacity also differ. The linear regression analysis of the estimated capacity of the CNMR-ESM2-1 simulation revealed an annual capacity increase of 0.8 million tons of throughput for the entire period till 2050. However, the R^2 of the regression analysis was just 0.038, indicating major uncertainties in the estimated (linear) development. This is mostly due to the anomaly of year 2031. In case the year 2031 would be smoothed from the data, the coefficient would become statistically significant ($p<0.05$), indicating a modest annual increase of 1.1 million tons. The annual increase of the NorESM2 -MM simulation is expected to be higher at 2.6 million tons with a substantially higher R^2 (0.55).

Figure 6 presents the estimated total capacities of both simulations, including both icebreaker-assisted and independent navigation following the CNMR-ESM2-1 simulations. The annual maximum transit capacity of the NSR would initially be around 360 million tons in 2024 and increase gradually to 463 million tons by 2050. If the development were to follow the NorESM2-MM simulation, the estimated transit capacity of the route would be around 48 million tons in 2024, increasing to 127 million tons by 2050.

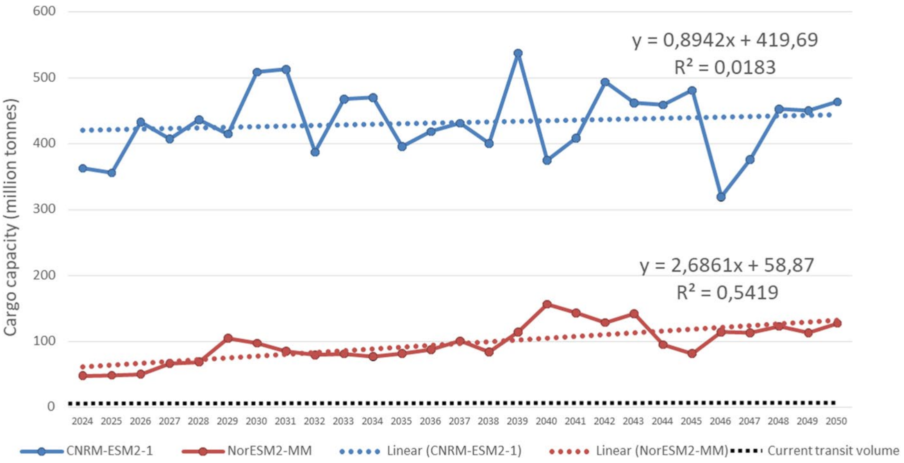

Fig. 6 Estimated total NSR transit capacity (icebreaker-assisted + independent navigation) until 2050

For comparison, Fig. 6 also presents the current transit volumes of the NSR. As identified by Gunnarsson (2021), these volumes are mainly destined to or originate from Russia's Arctic coast. Genuine transit volumes are just 0.4%–0.8% of annual volumes, or less than 250,000 tons p.a.

5 Conclusions and discussion

This research estimated the long-term throughput capacity of the Northern Sea Route by considering the capabilities of the ice class fleet and current and future icebreaking capacity under the control of the NSR administration. To consider the impact of climate change and the expected ice conditions, this research employed two climate simulations from the Coupled Model Intercomparison Project 6 (O'Neill et al. 2016) and predictions on the sea ice concentration and thickness in estimating the potential capacity of the route, considering the weather (winter) conditions until 2050. Both CNRM-ESM2-1 and NorESM2-MM follow the SSP370 (Shared socioeconomic pathways) scenario, which is in the upper middle part of the anthropogenic radiative forcing and CO_2 emission scenarios (O'Neill et al., 2016). Compared to the NorESM2-MM simulation, the CNRM-ESM2-1 simulation expects climate change to develop faster, consequently resulting in the faster withdrawal of ice cover.

The results indicate that the overall cargo throughput of the NSR would increase from 50 to 120 million tons p.a. in the slower ice melting simulation or from 350 to 460 million tons p.a. in the faster ice melting simulation. Based on these model simulations, the yearly fluctuations are substantial. For example, in the faster ice melting model simulation, annual throughput capacity fluctuates between 300 and 520 million tons.

The results of the analysis indicate higher throughput capacities than in some of the previous long-term forecasts (Kiiski et al., 218), although the estimates remain more conservative than other forecasts (Cao et al. 2022).

The results regarding the potential throughput capacity can be compared against the realized cargo volumes in the NSR. According to our analysis, the potential throughput capacity of the NSR is currently between 48 and 362 million tons, depending on the used model. With the assistance capacity of the current icebreaker fleet, the potential transit capacity is estimated at 47 and 124 million tons p.a., but the realized volumes are around 3 million tons p.a. (Gunnarsson 2021; Center for High North Logistics 2024). The destinational volumes are considerably higher, reaching 37,9 million tonnes in 2024, but are different from capacity perspective, as they do not travel then entire route, but are rather focused especially to the Yamal gas field, from which the majority of transports still travel westwards, being mostly outside the NSR.

This finding emphasizes that, at least currently, the utilization of the route is not a capacity issue but instead depends on other factors, such as economic viability and safety considerations. Even as the geographical distance through the NSR is shorter than the competing routes, the realized transit time, combined with other factors, is a major hindrance for economically viable shipping operations through the NSR. Transit through the NSR is, and according to the results will also be in the future highly dependent on the Russian icebreaking capacity. The availability and pricing of the icebreaking capacity is completely dependent on Russian political decision making.

Of the two simulations, NorESM2 assumes slower warming and therefore a slower decline of sea ice concentration and thickness. According to this simulation, the route would be operable mostly via icebreaker escort even in 2050, whereas independent operation would be minimal and practically impossible during most months of the year. This is expected to be a major hindrance especially for time-sensitive liner shipping, in particular in the coming decades, as previously predicted by Cariou et al. (2021).

The CNRM simulation, which assumes faster warming and decline of sea ice concentration and thickness, would allow for independent operations around the year, at least for cargo vessels with a high Polar Code class. In this case, year-round operations would become possible, which might enable the route's use even for liner shipping. Thus, investments must center around efficient use throughout the year (Hermann et al. 2022). Currently, vessels of high ice classes are quite expensive and are suboptimal in open-water conditions (Solakivi et al. 2019).

Efficient liner shipping networks require sufficient supporting infrastructure throughout the travel route. Currently, major container operators have 6–8 port calls along the Asia-Europe route to secure sufficient volumes and frequency for efficient operation (see, e.g., Maersk 2024). Such ports do not exist along the NSR, which also lacks navigational safety infrastructure and services. Although the construction of hubs for a container network along the Arctic Ocean coastline (see, e.g., Kovalenko 2024) has been proposed, there has been no interest in or concrete actions toward initiating such investments.

This research focuses on sea ice concentration and thickness in the Arctic Ocean and its potential impact on cargo flows through the NSR, considering the capacity and ice navigation capabilities of commercial fleets. The work's main finding is that the relatively low volumes in the NSR are not caused by capacity issues but are rather based on either direct or indirect economic factors. This relationship is likely to hold in the future as well.

Volumes in the NSR are also dependent on other factors. As noted previously, China, in particular, has been increasingly interested in finding alternative corridors around the chokepoints of the world seaborn trade for its imports and exports. Should China and Chinese companies consider plying the route to serve its goals, whether commercial and/or geopolitical, they have both the trading volume and resources to direct significant trade to the route. As the most recent example of the dynamics around the Arctic shipping volumes, on September 2 2025, Russia and China signed a memorandum of understanding on building so-called Power of Siberia 2 gas pipeline (Reuters 2025). When realized, the pipeline would be able to transport 50 billion cubic meters of gas per year, which would likely have a strong impact on the shipping volumes on the NSR as well.

At the same time, several (geo)political considerations must be factored in to understand the interest in direct cargo volumes to the route. After Russia's attack on Ukraine, the trade relations between European countries and Russia have deteriorated significantly. The countries have imposed a series of sanctions against each other and restricted trade and other commercial activities. It is unlikely that the situation will improve in the short or medium term; thus, European countries and companies are unlikely to risk subjecting significant volumes of their trade and transportation to Russian control. Ultimately, safety and security concerns in shipping along the NSR are tangible and corroborated by uncertainties with maritime insurance and the impact of sanctions.

The results of this research are subject to certain limitations. The analysis is based on the structure, size, and capabilities of the currently existing global fleet. It is evident that the explanatory power of our model—based on a fixed tonnage of ice-classed vessels and icebreakers—diminishes over time. As in any shipping market, vessel supply will naturally adjust to future changes in demand through fleet expansion or the phasing out of existing vessels. Despite this limitation, our framework offers a useful approximation of the balance between supply and demand in this specific market and serves as an indicator of emerging capacity requirements. Further, our analysis does not take into account the possibly political, regulatory or operational issues, but is technical in nature, and provides a theoretical capacity, whereas in reality regulatory requirements or operational decisions may reduce the realized capacity.

At the same time, several factors may impact the future composition of the world's fleet. As an example, the IMO's tightening of energy efficiency requirements may discourage shipping companies from building less energy-efficient, highly ice classed vessels. The estimated capacities are based on two simulations from the upper-middle part of anthropogenic radiative forcing and CO_2 emission scenarios. Should the realized development in emissions and climate change differ from the estimations, this would naturally have an impact on the results of this research as well.

Appendix

Table 2 DWT and speed of the world ice classed fleet by vessel type and ice class (Clarkson´s Research Services Ltd. (2024)

No.						
	Icebreaker	IAS	IA	IB	IC	ID
Bulk carrier	1	1	39	24	347	2
Tanker	15	42	550	225	297	7
General cargo		24	1025	261	415	18
LNG carrier		16	37	45	64	1
Container		17	350	12	46	12
RoRo/PCC		45	97	2	37	0
DWT						
Mean/*Std. Dev.*	Icebreaker	IAS	IA	IB	IC	ID
Bulk carrier			38,490/*37,463*	33,561/*30,418*	43,068/*20,761*	9830/*9941*
Tanker	26,522/*14,099*	46,580/*25,142*	33,304/*38,426*	36,321/*31,548*	28,401/*44,930*	5472/*907*
General cargo		12,175/*6254*	9031/*4955*	4935/*2063*	7635/*7413*	4611/*2800*
LNG carrier		91,338/*21,923*	51,033/*39,934*	9661/*7188*	30,950/*35,178*	
Container		13,455/*4494*	15,400/*11,714*	36,264/*15,446*	16,240/*11,342*	13,184/*6975*
RoRo/PCC		11,647/*5288*	8910/*4021*	3843/*1899*	11,261/*7066*	
Speed						
Mean/Std. Dev.	Icebreaker	IAS	IA	IB	IC	ID
Bulk carrier			12.8/*1.53*	13.4/*1.16*	13.9/*0.75*	13.5
Tanker	13.3/*0.44*	14.77/*1.01*	14.3/*1.2*	13.8/*1.37*	13.2/*1.48*	13.1/*1.05*
General cargo		15.5/*1.59*	13.9/*1.62*	12.0/*1.02*	12.27/*1.99*	13.4/*2.4*
LNG carrier		19.0/*1.41*	16.5/*2.68*	15.0/*1.24*	16.3/*2.36*	
Container		17.9/*2.0*	18.3/*1.41*	19.3/*2.93*	18.2/*2.54*	18.6/*1.79*
RoRo/PCC		19.4/*1.68*	17.6/*2.78*	17	18.7/*2.09*	

Table 3 Realized vessel speed as a percentage of design speed in the NSR 2013-2019. Monthly averages based on daily vessel movement data (NSR General Administration Rosatom (2025)) and technical details from Clarkson's Research Services Ltd (2024). See also Fig. 1

	Kara West	Kara East	Laptev West	Laptev East	East Siberian West	East Siberian East	Chuchi
January	54.9%	49.6%	*	*	*	*	*
February	48.1%	*	*	*	*	*	*
March	42.9%	45.5%	*	*	*	*	*
April	41.8%	52.8%	*	*	*	*	54.8%
May	46.5%	47.9%	63.8%	49.2%	*	*	27.3%
June	57.7%	55.8%	*	85.9%	86.2%	55.2%	73.3%
July	70.0%	61.2%	65.9%	76.0%	60.5%	60.4%	76.8%
August	74.0%	71.8%	71.9%	75.8%	74.6%	70.6%	78.0%
September	77.0%	75.7%	74.7%	77.1%	77.9%	74.8%	78.2%
October	73.5%	70.8%	71.8%	70.0%	68.2%	71.2%	71.9%
November	61.5%	54.9%	60.1%	44.6%	60.5%	62.2%	68.8%
December	54.8%	42.8%	68.6%	66.7%	55.0%	57.8%	63.9%

*No traffic

Table 4 Number of daily observations of vessel movements per vessel type and ice class used to calculate relative speeds

	Icebreaker	IAS+	IAS	IA	IB	IC	ID
Bulk Carrier			804	1072	24	32	
Tanker		2546	1256	4841	277	275	1221
General cargo		2235	4454	2771	242	1263	2220
LNG Carrier		950	129	168	50		
Container				50			
RoRo				4			

Non-cargo vessels and ships on anchor (speed=0) excluded

Table 5 Monthly average speed (nm/h) per vessel type and NSR sea area 2013-2019 (NSR General Administration Rosatom (2025)

Bulk carrier							
	Kara West	**Kara East**	**Laptev West**	**Laptev East**	**East Siberian West**	**East Siberian East**	**Chuchi**
January	7.9	4.9					
February	7.2	7.0					
March	4.5	1.3					
April	5.2	8.4					
May	5.1	8.3					
June	7.1						
July	9.8	5.5	6.8		4.3	6.3	
August	10.4	9.4	8.8	8.6	12.0	11.0	11.0
September	10.6	10.1	9.8	11.8	11.7	10.8	
October	10.1	9.6	10.1	11.0	8.5	10.6	9.7
November	7.8	5.9	7.0	7.2	6.7	8.1	8.9
December	5.0	8.3	10.0	12.1	10.1		5.4
General cargo							
	Kara West	**Kara East**	**Laptev West**	**Laptev East**	**East Siberian West**	**East Siberian East**	**Chuchi**
January	9.6	8.2					
February	8.3	8.5					
March	8.3	7.8					
April	7.4	8.7					8.5
May	8.7	8.8	11.0	8.8			4.2
June	10.1	10.1	13.5	14.0			10.7
July	10.5	10.5	9.3	9.4	10.8	9.7	10.5
August	10.1	10.1	8.9	9.1	9.6	9.0	10.6
September	9.9	10.7	9.8	9.5	9.7	9.2	10.4
October	10.0	10.2	9.5	9.1	9.3	9.5	10.1
November	9.5	9.5	8.6	6.1	8.7	9.4	10.2
December	9.9	9.1	10.2	9.5	7.1	10.3	10.8
LNG carrier							
	Kara West	**Kara East**	**Laptev West**	**Laptev East**	**East Siberian West**	**East Siberian East**	**Chuchi**
January	11.0	10.0	11.0	6.0	8.0		
February	9.0	1.3					
March	9.6	6.8	5.0				
April	15.9						
May	12.3						
June	10.7	10.0					
July	12.6	14.8	14.0	15.6	12.8	9.9	14.5
August	10.7	12.6	12.3	13.7	12.8	11.6	14.9
September	12.8	13.5	13.8	12.9	12.7	15.3	15.1
October	13.8	12.2	12.6	14.6	12.8	11.3	13.3
November	13.4	10.3	9.0	11.8	9.7	11.9	17.4
December	12.5	6.2	7.1	8.2	5.1	7.5	11.4
Tanker							

Table 5 (continued)

	Kara West	**Kara East**	**Laptev West**	**Laptev East**	**East Siberian West**	**East Siberian East**	**Chuchi**
January	8.8	9.3	9.4	6.0	7.2		
February	8.2	7.2					
March	7.8	8.7					
April	7.7	8.5					
May	8.4	8.7					
June	9.7	9.3		12.6	12.5	10.2	
July	11.0	8.9	9.3	9.3	7.9	7.6	10.2
August	10.8	9.5	9.8	8.6	8.8	9.1	10.9
September	10.6	10.1	9.4	8.9	8.8	9.4	10.4
October	10.5	9.4	9.8	8.9	8.7	9.9	9.6
November	10.1	9.3	9.7	6.5	10.0	8.0	8.8
December	9.6	8.2				11.3	9.3
<u>Container</u>							
	Kara West	**Kara East**	**Laptev West**	**Laptev East**	**East Siberian West**	**East Siberian East**	**Chuchi**
January							
February							
March							
April							
May							
June							
July							
August	11.7	11.0	12.2			12.6	12.8
September	13.5	11.5	13.2	11.2	12.3	11.9	13.2
October	14.9					13.8	11.4
November							
December							

Non-cargo vessels and ships on anchor (speed=0) excluded

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Data availability The data that support the findings of this study are available from WCRP and CRSL. Restrictions apply to the availability of these data, which were used under license for this study.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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