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Melting ice, growing trade?

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Abstract

Large reductions in Arctic sea ice, most notably in summer, coupled with growing interest in Arctic shipping and resource exploitation have renewed interest in the economic potential of the Northern Sea Route (NSR). Two key constraints on the future viability of the NSR pertain to bathymetry and the future evolution of the sea ice cover. Climate model projections of future sea ice conditions throughout the rest of the century suggest that even under the most "aggressive" emission scenario, increases in international trade between Europe and Asia will be very low. The large inter-annual variability of weather and sea ice conditions in the route, the Russian toll imposed for transiting the NSR, together with high insurance costs and scarce loading/unloading opportunities, limit the use of the NSR. We show that even if these obstacles are removed, the duration of the opening of the NSR over the course of the century is not long enough to offer a consequent boost to international trade at the macroeconomic level.

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Introduction

An increasing body of scientific evidence (Lemke and Jacobi, 2012; Overland et al., 2014) details the extent of climate change in the Arctic region. The accelerating melting of the sea ice cover has received particular attention (Stroeve et al., 2014; Boé et al., 2009; Deser et al., 2010; Stroeve et al., 2012; Overland and Wang, 2013). Since 2008, the Arctic Ocean along the coast of Russia and Canada has been mostly free of ice in September (Stroeve et al., 2014). Some international shipping companies have used this opportunity, as well as the fact that Russia opened the region in the far north to non-Russian vessel maritime traffic, to transport goods between Northern Europe and the Far East. Nevertheless, the numbers remain substantially lower compared with maritime trade passing through the Suez Canal (41 against 17,799 in 2011[1]) and also in terms of traffic volumes (1.25 compared with 740 million metric tons). However, given that on average the NSR is 3000 km shorter than the Suez Route and would require 10 less days of navigation than via Suez Canal, some experts have predicted a large potential for development in the coming years (Koranyi, 2013). Russia is also adapting regulations to facilitate vessels taking advantage of this opportunity. In particular, the number of permits issued by the Russian Northern Sea Route Administration, the route's governing body, has grown from 4 in 2010 to 718[2] in 2013. China also recently set a record round trip time from Europe to north China through the NSR docking at Tianjin Port in October 2015 (China Daily, Monday, 26 October 2015 EDT, China mulls routine navigation through Arctic to Europe).

Yet despite high hopes expressed by Russian authorities to open the route to increased maritime traffic (Klimenko, 2014), enthusiasm regarding the trade potential of the NSR remains low (Klimenko, 2014; Vidal, 2014). Moreover, the increase in human activities in the far north will largely come from the development of extractive activities (Stephenson et al., 2014). Currently, a large number of commercial vessels (e.g., oil tankers and gas carriers with a gross tonnage of at least 10,000) are allowed to navigate the NSR without ice strengthening, yet they can do so only in very good weather conditions and under the assistance of icebreakers (Ministry of Transport of Russia, 2013). This assistance has costs in terms of fees paid to the Russian state to maintain the icebreaker service, and in terms of navigation time, which is increased under escort. Only

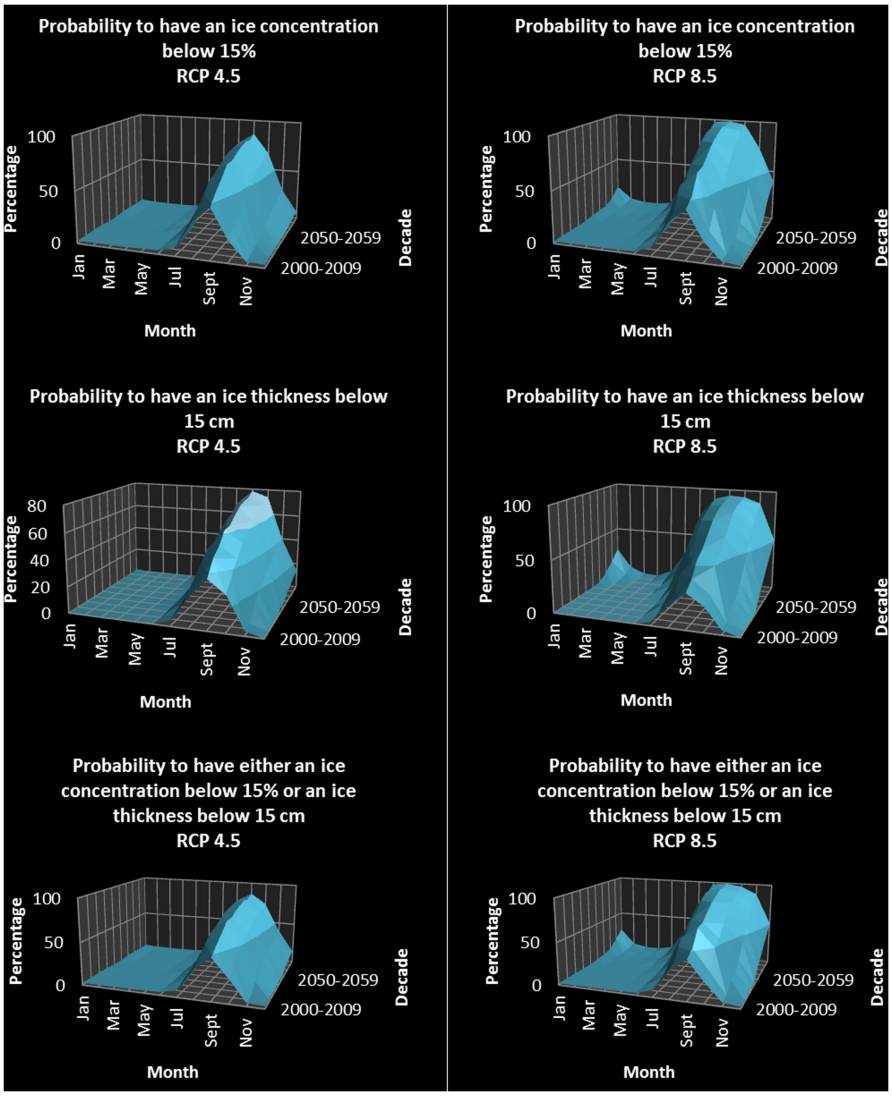

Figure 1

Probability of having ice on the Northern Sea Route.

Probabilities are provided as percentages by month and by decade for ice concentration < 15% (upper panels), ice thickness < 15 cm (middle panels), and either ice concentration < 15% or ice thickness < 15 cm (lower panels) for two future emission scenarios: representative concentration pathway (RCP) 4.5 (left panels) and RCP 8.5 (right panels).

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at the 2050 horizon may sea ice melt be significant enough to free the commercial ship from ice-breaker escort (Kupperman, 2014). In this paper we expand the forecast beyond 2050 to the end of this century, and evaluate whether the trade would increase between countries that could benefit from shorter trade distances using the NSR.

Discussion of approach and results

To answer this question, we combined future climate model projections of the sea ice cover from 33 climate models participating in the World Climate Research Programme Coupled Model Intercomparison Project Phase 5 (CMIP5) with economic expertise to assess the trade potential of the route over the 21st century. Our first task was to define the route (Text S1, Table S1, and Figure S1) and determine how many months of the year the route will be open for shipping in the coming decades considering two future emission scenarios, denoted by RCP 4.5 and RCP 8.5 (see Methods). Our focus was on the combined impact of climate change and distance reduction on trade; hence we have stated optimal conditions for the shipping industry. That is to say, when the route was considered navigable, the states bordering the route would be responsible for all the security-related expenses to keep the passage safe. In addition, commercial ships of any kind were assumed to navigate the route at normal commercial speeds. Our models show that even in these conditions, the trade growth resulting from the use of the NSR as a trans-Arctic route remains particularly low.

An important role of climate science in decision-making is to provide probabilistic predictions of potential outcomes; in this case, probabilistic predictions of navigable ice conditions in the NSR. Towards this end we assessed the number of months the route may be navigable on decadal time-scales from the multi-model ensemble mean probability of sea ice cover, sea ice thickness and a combination of both criteria within the

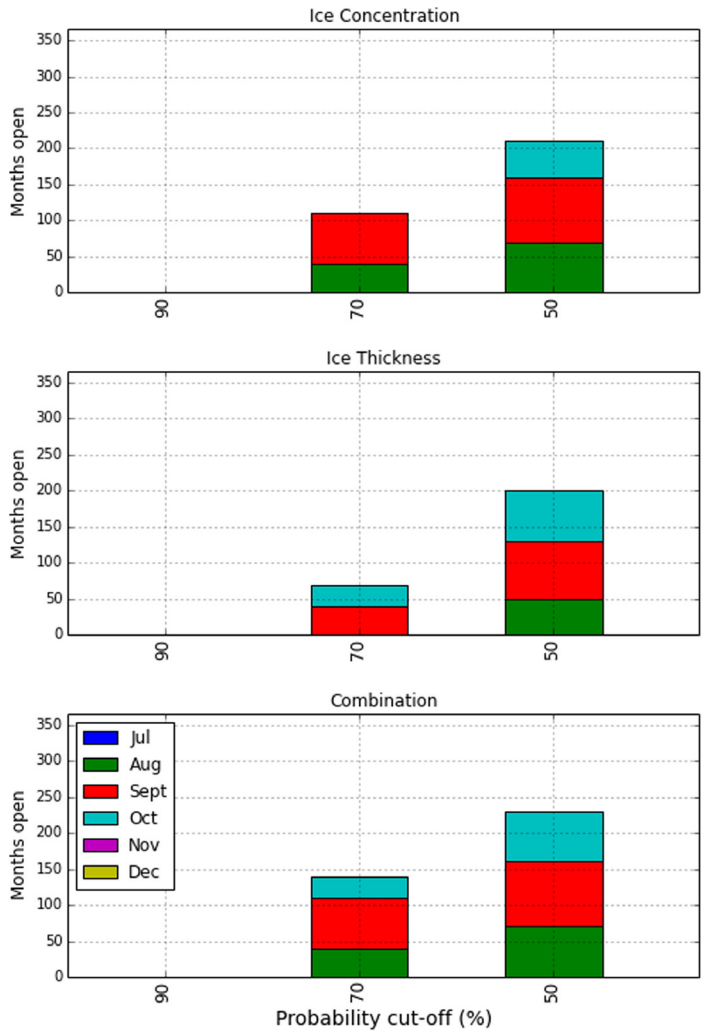

Figure 2

Projected number of months the Northern Sea Route would be opened to navigation according to RCP 4.5.

This projection is based on the future emission scenario representative concentration pathway (RCP) 4.5. Three ice probability thresholds are presented: 90, 70 and 50% chance that the Northern Sea Route (NSR) is covered by < 15% ice concentration (upper panels), by sea ice < 15 cm thick (middle panels), and by combination (< 15% ice concentration or < 15 cm ice thickness; lower panels).

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route. The use of an ensemble mean serves to average out internal variability, leaving behind the expected ice conditions from external forcing; in this case, from future atmospheric greenhouse gas concentrations. The probability of the NSR being navigable each month is shown in Figure 1 for the RCP 4.5 and 8.5 emission scenarios. We additionally present our results in terms of navigable months in Figure 2 (RCP 4.5) and Figure 3 (RCP 8.5)[3] for three different ice probability cut-offs: 1) when there is 90% chance the NSR is covered by less than 15% ice cover and/or the NSR is covered by sea ice less than 15 cm thick; 2) when there is 70% chance the NSR is covered by less than 15% ice cover and/or the NSR is covered by sea ice less than 15 cm thick; and finally 3) when there is 50% chance the NSR is covered by less than 15% ice cover and/or the NSR is covered by sea ice less than 15 cm thick. Under the RCP 4.5 emission scenario, the route is not navigable when we use a 90% ice probability cut-off. At best, if we consider the route open when there is more than a 50% chance of less than 15% ice concentration within the route or the ice thickness along the route is less than 15 cm thick, we find that the route will only be navigable during the month of September between 2010 to 2030 and up to 3 months (August, September, and October) between 2030 and 2100. In other words, from 2030 onwards, there are 3 months in summer that meet the 50% chance the route may have less than 15% ice concentration or consist of ice less than 15 cm thick. With this relaxed requirement, the states managing the NSR would need to have very reliable infrastructure and ice-breaker service to support commercial shipping as the probability of adverse sea ice conditions remains high: i.e., there is a 50% chance of encountering high ice concentrations or ice thicker than 15 cm.

Under the RCP 8.5 emission scenario the minimum number of months the route is navigable during this century is 50 months for the most restrictive cut-off (90%) using the calculation based on ice thickness. The maximum number of months the route is navigable is 330 months throughout the century for the most relaxed cut-off (50%) using either the ice thickness or ice concentration criterion. Under this scenario, only the month of September is ice-free for nine decades starting in 2010 (as in the RCP 4.5 emission scenario), whereas ice-free conditions expand to include the months of August through October for 8 decades starting

in 2020; the months of August through November for 4 decades starting in 2060, and the months of July through November for 3 decades starting in 2070. At the end of the century, a 6-month navigation period may be possible from July through December.

Armed with these future estimates of ice-free conditions within the NSR, we next determined the potential increase in international trade between Europe and Asia using a gravity model of trade (Tinbergen, 1962; Bergstrand, 1985; Martínez-Zarzoso, 2011). Gravity models have been widely used to investigate the role played by specific policy or geographical variables in bilateral trade flows and are currently a theoretically justified framework for modelling trade flows (Bergstrand, 1985; Anderson, 1979; Anderson and van Wincoop, 2003). Bilateral trade levels are usually related to the nominal incomes of the countries involved, to the bilateral trade cost (which includes transport cost and a number of trade impediments and trade-facilitation variables) and the country-specific multilateral resistance (Anderson and van Wincoop, 2003). Distance has been traditionally used as a proxy for transport costs and is an elementary component of the gravity model of trade since its origins (Tinbergen, 1962). Geographically, far-away pairs of countries trade less than proximate countries, with the question being how much less. Dummy variables, such as former colonies, common language, or a common border, are generally used as proxies for bilateral resistance or trade-facilitation factors.

Our results show that even under the most "aggressive" emission scenario (e.g., RCP 8.5), increases in international trade between Europe and Asia remain low despite 6 months of possible navigation during the last decade of this century. The increase in trade resulting from the reduction in distance was computed using the elasticity of trade-to-distance found in the gravity model of trade. This information, when combined with the number months open to navigation from the three ice cut-off scenarios allowed us to calculate the impact, in terms of trade, of the use of the NSR throughout the 21st century against a baseline scenario of trade as usual (Table 1). The longer the route is open, the more important the trade growth. However, even under the RCP 8.5 emission scenario, trade growth is only 7% at the end of the century. The corresponding annual trade growth rate would be only 0.072%.

These results suggest that use of the NSR is unlikely to significantly alter international trade patterns, and will not be a leading economic force in transforming the Arctic. That is not to say that the Arctic is not going through a period of rapid transformation. Instead, these changes are led by the growth of extractive industries, in particular offshore oil and gas (Brigham, 2011). The existence of important oil and gas resources under the seabed of the Kara Sea has been known since the late 1980s (CIA, 1988). In September 2014, the Russian company Rosneft announced the first successful drilling of a well in the Kara Sea with its partner Exxon (Rosneft, 2014). The continuation of exploration operations has been postponed because of sanctions targeting Russian Arctic oil projects following Russia's actions in Ukraine (Reuter, 2015). Nonetheless, this event reveals that political decisions so far have a greater potential to slow down activities than climatic environmental concerns have. In terms of traffic in the NSR, the oil and gas industry have already been important players. According to the Northern Sea Route Information Office, more than 50% of the vessels that used the NSR in 2014 were oil tankers (http://www.arctic-lio.com/nsr_transits). As the industry expands and new oil and gas fields are developed, an increasing number of vessels will be used to resupply offshore facilities from mainland Russia and to transport these commodities to their consumption markets.

Table 1. Percentage increase in trade over the 21st century according to NSR opening scenarios[a]

Navigability criteria	Total trade increase (%)			Equivalent annual increase (%)		
	Ice probability threshold			Ice probability threshold		
	90%	70%	50%	90%	70%	50%
Ice concentration						
RCP 4.5	0	2	5	0.000	0.024	0.046
RCP 8.5	2	4	7	0.020	0.042	0.063
Ice thickness						
RCP 4.5	0	2	5	0.000	0.016	0.045
RCP 8.5	1	3	5	0.012	0.033	0.050
Combination[b]						
RCP 4.5	0	3	5	0.000	0.031	0.051
RCP 8.5	2	5	7	0.022	0.046	0.072

[a]Based on ice concentration and ice thickness criteria, and a combination of ice concentration and thickness for RCP 4.5 and RCP 8.5 emission pathways.
[b]Combination criteria is based on < 15% ice concentration or <15 cm ice thickness.
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The Northern Route: A viable trade route?

There is significant distance savings between Europe and Asia offered by the NSR (Humpert, 2011), yet the lack of schedule reliability due to the difficulty in being able to predict the start and the end dates of summer ice conditions in the Arctic, combined with the lack of infrastructure in the hinterland could prevent the route from becoming popular with liner services. In contrast, for bulk dry carriers and wet carriers, the route may become an alternative to more traditional shipping routes in the near future. Indeed, transit statistics collected by the Northern Sea Route Information Office indicate that the number of voyages increased from 41 in 2011 (the first year transit statistics were made available) to 71 in 2013 (the year that recorded the highest number of transits between 2011 and 2014: see Table S2), out of which liquid and bulk carriers increased from 20 in 2011 to 34 in 2013. In terms of route direction, the number of vessels increased from 11 to 41 sailing from East to West while the number of vessels from West to East stayed the same at 30 vessels. However, 17 of the latter were empty vessels in 2013. Note that "transit" as used by the NSR Information Office is defined as every ship passing one of the Russian-defined boundaries of the NSR zone (see Text S1). In 2013 among these passages, 43 were passages of the East and West boundaries of the NSR and only 17 were truly trans-arctic passages; i.e., passages where the points of origin and destination were outside the arctic zone (http://www.arctic-lio.com/nsr_transits).

The economic potential, in terms of profits for ship owners, of using the NSR as an alternative route between Asia and Europe has been investigated as a function of navigable months of the NSR, Russian NSR fees, and bunker price (Lasserre and Pelletier, 2011). The conditions under which the NSR is competitive compared with the Suez Canal as a function of these variables has been evaluated under several scenarios. The profits under each combination of conditions are then calculated and compared for the case of non-ice container ships (4300 Twenty foot Equivalent Unit) using the Suez route and similar size ice-classed container ships (Class 1B) using either the NSR when open, and the Suez route otherwise. In this situation, the NSR is only competitive when the price of bunker fuel is low, the NSR is open for at least 3 months of the year, and the Russian NSR fees are reduced by 85% of the 2010 level. In the same way, the technical and economic feasibility of regular container transport along the NSR was evaluated (Liu and Kronbak, 2010). By taking the schedule between Shanghai and Hamburg, the relative costs of various axes in the Asia–Europe transport network were assessed, indicating that while shipping through the Suez Canal is still by far the least expensive option, the NSR and Trans-Siberian Railway appear to be roughly equivalent second-tier alternatives.

The impact of bathymetry was previously investigated and suggests that shipping companies might envision several trade routes in the Arctic to avoid the shallowest passages in the region (in particular, the Laptev and Sanikov Straits) (Stephenson et al., 2014). Nevertheless, in the coming decade ice-strengthened vessels (PC3 category) will still have the capacity to operate for a significantly longer period of time as sea ice continues to decline in the Arctic.

Most of the studies to date assessing the impact of climate change in the Arctic on economic activities have been interested in showing the impact of the decrease in sea ice extent on the shipping industry. This paper is one of the first to investigate the additional impact of distance reduction between some European and Asiatic countries due to melting sea ice in the Arctic on the flows of trade between these countries. There is only one other paper in the related literature (Bekker et al., 2015) that estimates the economic impact of melting sea ice. These authors used a general equilibrium model, requiring a number of strong assumptions concerning economic variables that could result in very uncertain predictions in the long term. Moreover, they assumed that by the year 2030 the NSR would be fully operational 12 months per year. Their economic model includes social effects and effects on pollution levels, and in this sense it is more comprehensive than ours. However, the gravity equation derived from the general equilibrium model was estimated using data for total bilateral trade for a single year (2011) in order to obtain transport cost elasticity. We have relied upon the results of the meta-analysis of Disdier and Head (2008), which was based on 103 different studies regarding this very significant element (see Methods). We also used monthly trade data for 11 years, and specifically used data on maritime trade, whereas the previous study used trade for all modes of transport (air, rail, road and maritime) to derive future trade variations. Their estimate was an average 10% increase in trade volume between countries in Northeast Asia and Northwest Europe (all-year navigability). This estimate is similar to our estimate of a 7% increase in the trade volume between Asia and Europe under RCP 8.5. However, our results derive from a build up over a century of incremental change in trade patterns resulting from the progressive melting of sea ice in the Arctic, whereas the results of Bekker et al. (2015) find their origin in a very dramatic setting, one in which the entire Arctic Ocean is free of ice from one year to the next.

Our results provide an upper limit of the potential increase in international trade. Indeed, we considered only the positive aspect of distance reduction on trade without tackling several emerging problems for shipping companies from using the NSR even in very good ice conditions (from the point of view of the transport industry). These problems include the lack of port of calls along the Russian coast and/or the shallowness of the route (Verny and Grigentin, 2009), both of which would dampen the positive impact of distance reduction on trade.

Supplemental Table S3 summarizes the loss or gain in terms of distance and days of navigation of the NSR between Europe and Asia for a number of selected ports. As indicated in Table S3 the NSR, which extends for about 3000 miles, depending on ice conditions, presents opportunities for international trade as a transit route between Europe and the Asia-Pacific region. More specifically, according to Table S3, Japan, South Korea and China are the three countries that benefit the most in terms of distance and time reductions. Russia, mainly concerned by the end point traffic, was not included in our study.

Methods

Sea ice projections

Key to understanding the potential of the Northern Sea Route is to know how long ice-free summer conditions or very thin ice conditions will last in the next several decades. An ice-free Arctic ocean is generally considered to be an Arctic Ocean with less than 1 million km^2 of ice cover (Stroeve et al., 2012). Nonetheless, we only need the NSR, as we have defined it, to be either ice-free or else covered by very thin ice. To estimate the probability of these conditions in the 21st century, we used simulations from models participating in the World Climate Research Programme Coupled Model Intercomparison Project Phase 5 (CMIP5) (See Table S4 for a listing of the models used) and systemically estimated ice conditions within the NSR for all decades to the end of the century.

To be considered ice-free, all pixels, corresponding to a 25 km^2 area, along the route must have had an ice concentration below 15%. This definition of an ice-free route is very close to the definition used by the World Meteorological Organization (WMO) for open water with an ice concentration below 10% (World Meteorological Organization, 1970). Note that regardless of the ice thickness of that remaining 15% sea ice concentration, we remain on very solid ground regarding navigability. We used the Transport Canada Ice Numeral (IN) calculation formula (Transport Canada, 1998):

$$IN = (C_a * IM_a) + (C_b * IM_b) + \ldots + (C_n * IM_n)$$

where C_a, C_b...C_n stand for the ice concentrations in tenths of ice type a, b...n, and IM_a, IM_b IM_n the Ice Multiplier of ice type a, b...n. The Ice Multiplier (IM) is an integer number from 2 to –4 associated with the danger presented for navigation by different types of ice, with –4 being the most dangerous, and pertains to a specific of class of ship. We calculated the Ice Numeral for a Type E ship (Class 1D and 1E in the Lloyd register or Class II in the Swedish-Finish ice classes). According to the Finnish Transport Safety Agency, ice Class II ships are defined as "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"; that is to say, most of the commercial open water fleet (Transport Safety Agency, 2010). In the worst case, where 15% of the area is covered by multiyear ice (IM = –4), and the rest is open water (IM = 2), the Ice Numeral for Type E ship is 11. A positive number means that the route is navigable.

In this work, ice thickness was defined as the average thickness of the pixel. According to Transport Canada (1998), conditions dominated by grey ice, defined by an ice thickness less than 15 cm, are fairly navigable for Type E ships. We considered the NSR navigable if all pixels along the route had an ice thickness less than 15 cm. Note that even if the entire area (100%) is covered by grey ice (IM = 1), the Ice Numeral for Type E ship is 10.

To assess future navigability, two future emission scenarios were considered: the representative concentration pathways (RCPs) 4.5 and 8.5. Total radiative forcing is stabilized at 4.5 W m^{-2} in the year 2100 for the RCP 4.5 and assumes a certain level of moderate greenhouse gas mitigation to curb the increase of the level of human greenhouse gas emission. RCP 8.5 stabilizes radiative forcing at 8.5 Wm^{-2} and assumes no greenhouse gas mitigation. We processed 92 ensembles from 32 climates models for the RCP 4.5 scenario and 61 ensembles from 28 climates models for the RCP 8.5 scenarios. For each model ensemble member, we calculated the frequency of ice-free conditions (defined here as sea ice concentration less than 15%) for each decade starting in 2000 and ending in 2100. Frequencies were calculated on the model native grids. Where models have multiple ensemble members, a model ensemble mean frequency was calculated. The resulting frequency grids were then regridded to a common 25 km EASE grid (Brodzik and Knowles, 2002) and a multi-model ensemble mean was calculated. The frequency of ice thickness was treated in a similar manner. The use of a multi-model ensemble mean in effect averages out natural variability (assuming the models sufficiently capture the amount of the observed variability), leaving the expected changes due to rising greenhouse gases.

Results are expressed as the probability (in percent) that the ice concentration for each pixel composing the route is less than 15% over decadal time periods, or that the ice thickness is less than 15 cm, or that either of the two criteria is fulfilled (Figure 1). Figure 2 summarizes the number of months that the route can be considered navigable (we used several ice probability cut-offs from more than a 90% chance that the route is ice-free to more than a 50% chance of ice-free conditions) in the coming decades under the RCP 4.5 and 8.5 emission scenarios.

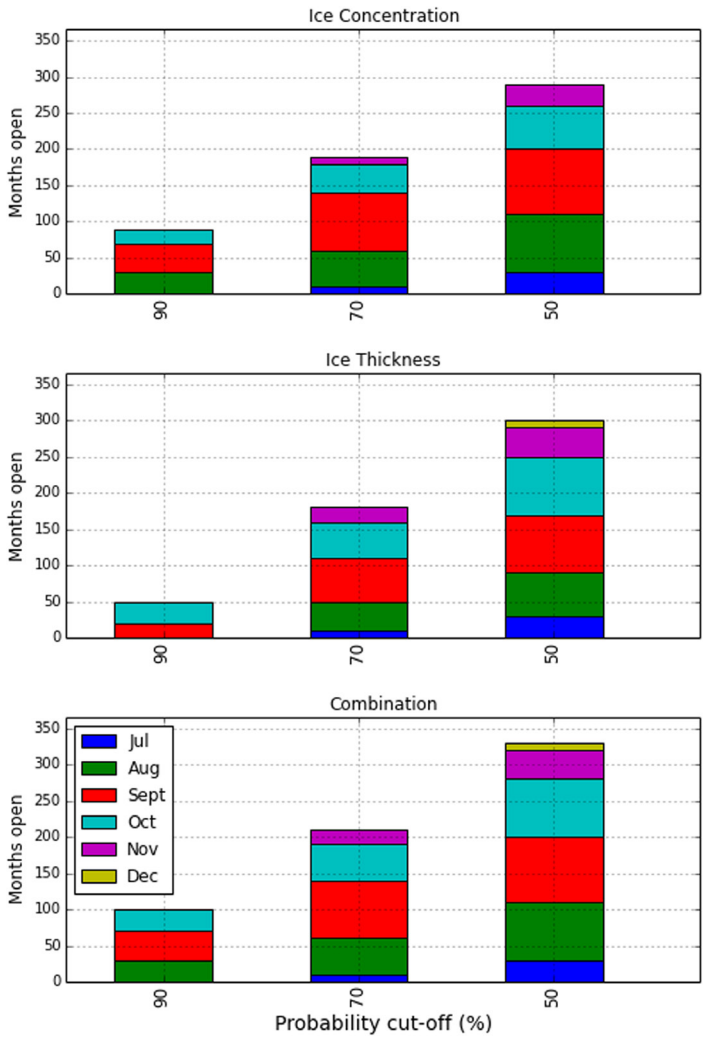

Figure 3

Projected number of months the Northern Sea Route would be opened to navigation according to RCP 8.5.

This projection is based on the future emission scenario representative concentration pathway (RCP) 8.5. Three ice probability thresholds are presented: 90, 70 and 50% chance that the Northern Sea Route (NSR) is covered by < 15% ice concentration (upper panels), by sea ice < 15 cm thick (middle panels), and by combination (< 15% ice concentration or < 15 cm ice thickness; lower panels).

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September is the month that witnesses the largest reduction of ice concentration and ice thickness over the century. The number of models with an ensemble mean September sea ice concentration greater than 15% in the NSR region is shown for three decades: 2000–2009 (Figure 4), 2040–2049 (Figure 5) and 2090–2099 (Figure 6).

The gravity model of trade

To estimate the elasticity to distance the gravity model is specified as:

$$Trade_{ijt} = \frac{Y_{it} Y_{jt}}{Y_{wt}} \left(\frac{\tau_{ijt}}{P_{it} P_{jt}} \right)^{1-\sigma} \tag{1}$$

where $Trade_{ijt}$ represents the exports or imports from country i to country j in period t; Y_{it} (Y_{jt}) indicates the GDP of the exporter i (importer j) in period t, Y_{wt} is the world nominal income, P_{it} and P_{jt} are country time-specific multilateral resistance terms, and σ is the elasticity of substitution between all goods.

The bilateral trade costs are represented by τ_{ijt}, which is assumed to be a log-linear function of observables trade costs z_{ijt} (cost directly related to transport but also to tariff, language, etc.) (Anderson and van Wincoop, 2004):

$$\tau_{ijt} = \Pi_{m=1}^{M} (z_{ijt}^{m})^{\gamma_m} \tag{2}$$

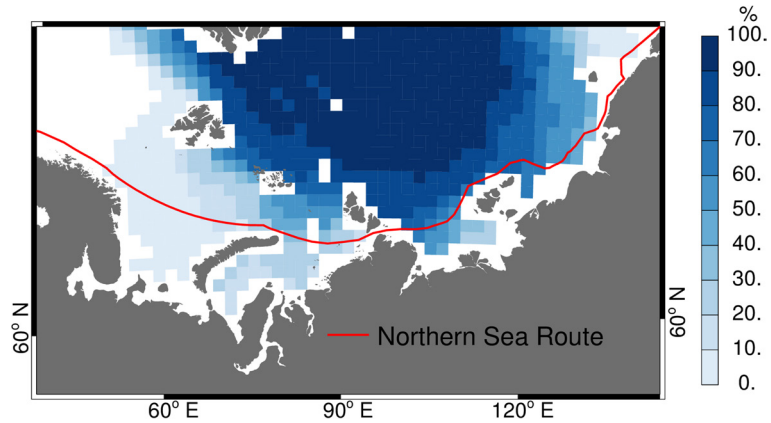

Figure 4

Percentage of models with ensemble mean September sea ice concentration greater than 15% for 2000–2009.

The red line shows the Northern Sea Route (NSR).

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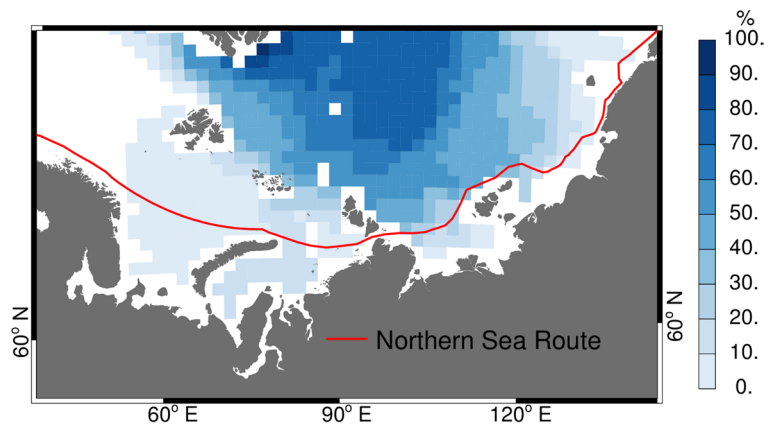

Figure 5

Percentage of models with ensemble mean September sea ice concentration greater than 15% for 2040–2049.

The red line shows the Northern Sea Route (NSR).

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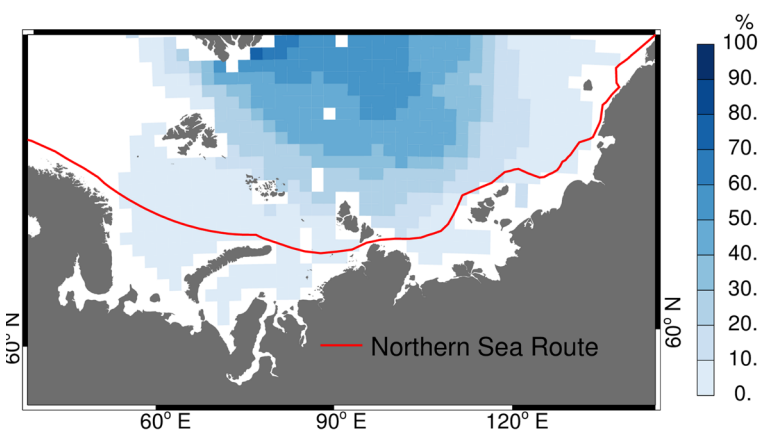

Figure 6

Percentage of models with ensemble mean September sea ice concentration greater than 15% for 2090–2099.

The red line shows the Northern Sea Route (NSR).

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where there are M different trade costs and γ is the weight of each trade cost in the total trade cost. In log-linear form the gravity model is:

$$\ln Trade_{ijt} = \ln Y_{it} + \ln Y_{jt} - \ln Y_{wt} + \Sigma_{m=1}^{M} (1-\sigma)\gamma_m \ln(z_{ijt}^{m}) - (1-\sigma)\ln P_{it} - (1-\sigma)\ln P_{jt} \quad (3)$$

Disdier and Head (2008) use the results obtained in 103 papers that estimate the elasticity of trade to distance ($(1-\sigma)\gamma_{m=distance}$) to perform a meta-analysis. According to the authors the average elasticity of trade to distance, is –0.9. Although the measure of distance used in these papers is far from homogeneous, namely great circle distances, road or maritime distance, the authors do not find any significant difference in the value of the coefficient across the different measures. In this study, we used this measure of trade elasticity to distance and considered all other factors held constant. We focused on the sole impact of distance savings of the NSR on international trade and ignored other impediments to trade, such as the current level of infrastructure along the route, tolls imposed by Russian authorities to use the route or additional insurance costs. These

elements would obviously reduce the positive impact of the distance reduction. Hence, we consider that if the shipping companies would have the choice between two trade routes, the Northern trade route and the Suez route, they would use the shortest.

The main source of data is Eurostat (http://ec.europa.eu/eurostat/data/database), where we obtained monthly bilateral maritime exports and imports in Euros for the first decade of the 21st century (2000–2010). We obtained port-to-port distance for the NSR and the Suez Route data from the Port World website (http://www.portworld.com/map). As we are interested in transit trade, we did not include Russia in our group of European countries. We also did not include European and Asiatic landlocked countries. Table S5 lists the European and Asian countries we selected, for which distance reduction is possible through the NSR and comprehensive monthly trade data available over our period of study. We used the average monthly total trade (Export + Import) calculated over the period 2000–2010 as our baseline for our estimations of the impact of the NSR. Having the elasticity of distance to trade, the "gain" in terms of distance of using the shortest route and the current value of bilateral trade, we were able to calculate the gain in terms of trade value of using the NSR for the months when the route would be opened, everything else held equal. We then multiplied these values by the number of months the route is opened under each scenario, and compared the value to a baseline scenario where trade flow is held constant over the coming 10 decades of this century (columns 2, 3 and 4 in Table 1)[4]. We finally calculated the equivalent annual increase (columns 5, 6 and 7 in Table 1)[5].

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Notes

1. The number for the NSR comes from the Northern Sea Route Information Office (http://www.arctic-lio.com/). The office is a joint initiative of the Norwegian Centre for High North Logistics (CHNL) and ROSATOM, the Russian state-run company in charge of Atomic Energy production and use. The number includes not only the ships transiting via the NSR but also all the voyages starting or ending on the NSR. There are only 22 transit voyages and 2 with a non-Russian starting or ending point. The number for the Suez Canal comes from the Suez Canal authority (http://www.suezcanal.gov.eg/).
2. This number comes from The Northern Sea Route Administration (http://www.nsra.ru), a branch of the Russian Ministry of Transport. It includes all kinds of ships applying to use whole or just parts of the NSR. Applying and receiving a permit carries no cost, so the number of applications is an indicator of the interest in the NSR from the shipping industry, not a precise indicator of the shipping activity on the NSR.
3. Only the months from July to December are presented, as our results show that for the rest of the year the route is not navigable during this century.
4. Elasticity of trade to distance, noted as β, where:

$$\beta = \frac{\frac{\partial Trade}{Trade}}{\frac{\partial Distance}{Distance}}, \partial trade = \frac{Distance}{trade} * \beta * \partial Distance, \text{and percentage change over the century}$$
$$= \frac{\sum_{2000}^{2099}[(100 - n_m) * trade_m + n_m * (1 + \partial_m) trade_m]}{trade_{2000,2010} * 10},$$

where n_m is the number of months a particular month is navigable over the century

5. Equivalent annual percentage increase i, where $i = \exp\left[\frac{\ln(1+i_{100})}{100}\right] - 1$ and i_{100} is the percentage increase over the century

Contributions

- Contributed to conception and design: SB, JS, IMZ, AB
- Contributed to acquisition of data: SB, JS, IMZ, AB
- Contributed to analysis and interpretation of data: SB, JS, IMZ, AB
- Drafted and/or revised the article: SB, JS, IMZ, AB
- Approved the submitted version for publication: SB, JS, IMZ, AB

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Competing interests

The authors have no competing interests to declare.

Supplemental material

- **Text S1. The Northern Trade Route (DOC)**
  doi: 10.12952/journal.elementa.000107.s001
- **Figure S1. Map and bathymetry of the NSR route as defined in this study (DOC)**
  doi: 10.12952/journal.elementa.000107.s002
- **Table S1. Vessels types that used the NSR in summer 2013 to link a European country to an Asiatic country (DOC)**
  doi: 10.12952/journal.elementa.000107.s003
- **Table S2. NSR transit data for the years 2011–2014 (DOC)**
  doi: 10.12952/journal.elementa.000107.s004
- **Table S3. Gains in terms of distance and estimated time related to the use of the NSR (DOC)**
  doi: 10.12952/journal.elementa.000107.s005
- **Table S4. Models (CMIP5) used in our simulation (DOC)**
  doi: 10.12952/journal.elementa.000107.s006
- **Table S5. List of countries considered in our study (DOC)**
  doi: 10.12952/journal.elementa.000107.s007

Data accessibility statement

The data about the characteristics of the vessels having the use the NSR in 2013 and their geo-localizations are available upon demand and subscription to the marinetraffic's website (http://www.marinetraffic.com/).