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New insights into projected Arctic sea road: operational risks, economic values, and policy implications

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Abstract

As Arctic sea ice continues to retreat, the seasonally navigable Arctic expected by mid-century or earlier is likely to facilitate the growth of polar maritime and coastal development. Here, we systematically explore the potentials for opening of trans-Arctic sea routes across a range of emissions futures and multi-model ensembles on daily timescales. We find a new Transpolar Sea Route in the western Arctic for open water vessels starting in 2045 in addition to the central Arctic corridor over the North Pole, with its frequency comparable to the latter during the 2070s under the worst-case scenario. The emergence of this new western route could be decisive for operational and strategic outcomes. Specifically, the route redistributes transits away from the Russian-administered Northern Sea Route, lowering the navigational and financial risks and the regulatory friction. Navigational risks arise from narrow straits that are often icy choke points. Financial risks arise from the substantial interannual sea ice variability and associated uncertainty. Regulatory friction arises from Russian requirements imposed under the Polar Code and Article 234 of the UN Convention on the Law of the Sea. These imposts are significantly reduced with shipping route regimes that enable open water transits wholly outside Russian territorial waters, and these regimes are revealed most accurately using daily ice information. The near-term navigability transition period (2025–2045) may offer an opportunity for maritime policy evaluation, revision, and action. Our user-inspired evaluation contributes towards achieving operational, economic and geopolitical objectives and serves the goal of planning a resilient, sustainable, and adaptive Arctic future.

Keywords Sea ice variability · Arctic maritime access · Model uncertainty · Scenario analysis · Navigation risk and cost · Geopolitics

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1 Introduction

As global temperatures rise, Arctic sea ice shrinks and thins rapidly (Kacimi and Kwok 2022). The emerging new Arctic state allows for a projected shift from a prevalent frozen regime to a seasonally navigable ocean expected by mid-century (Smith and Stephenson 2013) or earlier (Mudryk et al. 2021). Such a shift has potential to reshape global shipping corridors due to the economic benefits of the reduced distance, and with it reduced time and emissions: up to 40% between Asia and Europe when comparing Arctic routes to the Suez Canal route (Lynch et al. 2022). Consequently, it can alter the landscape of polar maritime development through the expansion of commercial activities for resource extraction (Bugnot et al. 2021), the promotion of a more sustainable international shipping industry (Frazão Santos et al. 2020), and the growth in port facilities and infrastructure assets to sustain maritime networks (Hanson and Nicholls 2020). There are stressors that can accelerate or decelerate the rate of shift or even cease operations. These include recent incidents such as the blockage of Suez Canal by a container ship in 2021 (Goldstein et al. 2022a), the unprecedented coronavirus disease (COVID-19) pandemic that restricts mobility and reduces global trade flows (March et al. 2021), and an array of economic sanctions imposed on Russia over Ukraine invasion (Goldstein et al. 2022c). While Arctic maritime access provides an important focus that connects the climate, economics, and law, its multifaceted implications are only beginning to be comprehensively explored under a range of possible futures.

Information from global climate system models is useful in understanding the physical response to dramatic Arctic transformations (Cooley et al. 2020; Stephenson et al. 2011), and holds promise for guiding decisions towards more effective mitigation, adaptation, and risk management actions (Pulkkinen et al. 2022). For example, by integrating knowledge of sea ice from general circulation models (GCMs) into a geospatial transportation modeling framework, assessments such as changing access to oceans (Stephenson and Smith 2015), ice risks to operational decision-making and strategic planning (Li et al. 2021b), and climatic response to future Arctic shipping (Stephenson et al. 2018) can be quantified. However, projections are subject to uncertainties arising from internal variability, model bias, and scenario uncertainty (Hawkins and Sutton 2009). An ensemble of climate simulations can provide a viable way forward by forming a probability space of system responses (Palmer and Räisänen 2002). Indeed, it has been hypothesized that multi-model ensemble (MME) mean outperforms individual simulations in weather and climate prediction (Gneiting and Raftery 2005; Meehl et al. 2014). However, nuanced information related to variability and extremes that are important for risk management and policy decisions (Kunreuther et al. 2013) can be missed when using only the MME mean. For example, a focus on central tendencies can undervalue risk assessment outcomes (Goldstein et al. 2022a) and hinder reliable interpretation of data for robust decision-making (Benestad et al. 2017). As a result, an approach that considers the full response space is more robust for policy development than one that considers only the MME mean.

In addition to the various sources of uncertainty associated with climate projections, challenges remain in appropriately translating climate science findings into user-relevant information. Instead of overwhelming users with an abundance and complexity of climate data, clarifying specific knowledge needs and contextualizing the variables of interest can deliver real benefits to support climate-sensitive decisions (Smith et al. 2014). For example, social planners might wish to be acquainted with temperature variability which implies increased economic cost of climate change (Calel et al. 2020). In another example, from a standpoint of stakeholders, questions of equity may be a larger concern than climate uncertainty when considering the impacts of methane policy (Errickson et al. 2021). Thus, a better-targeted delivery of relevant climate information will help bridge the gap between better data and better decisions (Findlater et al. 2021).

Here, we present a comprehensive evaluation of the possible ramifications of the opening Arctic sea routes through synthesizing insights from climate scenarios and risk assessment. This synthesis is essential to grasp the scope of future polar shipping activities, which can be both a reaction to and accelerator of Arctic amplification (Li et al. 2021a; Lynch et al. 2022). To navigate towards legitimate operator goals while assessing risks and benefits, a formal analysis of Arctic maritime accessibility ensembles in response to anthropogenic emissions (from very high- to low-emissions pathways) are created for open water vessels. These ensembles are produced by applying a multi-model multi-scenario approach that enables us to capture uncertainties stemming from model differences and scenario choices with the full distribution as opposed to central tendencies. This approach adds value to risk management and policy development under conditions of ambiguity. The methodological framework can be used as a generic tool to support the strategic decision-making processes in response to rapid and uncertain geophysical and socioeconomic change. In this application, we ask how the navigable regimes are likely to change across space and over time between 2015 and 2079 in ways that contribute to safe and cost-effective navigation. We also demonstrate an approach that tailors climate information to user-specific needs to better inform decisions in this domain.

2 Data and methods

2.1 CMIP6 climate models

The model intercomparison projects (MIPs) produce ensemble projections that quantify inter-model spread of past, present, and future climate states. The initiative promotes long-term efforts to develop and improve models and provides critical information to drive policy. These simulation outputs can be further used to drive impact models to explore how climate change will affect specific human sectors or natural processes (Tittensor et al. 2021). We use the Coupled Model Intercomparison Project phase 6 (CMIP6) across 14 GCMs (Table S1) that have their Arctic model performance rigorously evaluated (SIMIP Community 2020). For models when more than one realization is provided, we only use one ensemble member from each model for consistency. These CMIP6 simulations reasonably capture the Arctic sea ice volume and extent as compared to its precedent phase (Davy and Outten 2020). The output fields of daily sea ice concentration and thickness over the period of 2015–2079 are utilized to feed the Arctic maritime accessibility model. Using daily data provides a more nuanced picture of accessibility compared to previous applications of this approach (Stephenson and Smith 2015; Wei et al. 2020).

2.2 Scenario analysis

The Shared Socioeconomic Pathways (SSPs), which integrate dimensions reflecting global development across population, energy transitions, land use change, and air pollution emissions, represent a comprehensive assessment of future emissions pathways. Four illustrative emissions scenarios treated as Tier 1 experiments (O'Neill et al. 2016) are considered.

Descriptions of each scenario regarding the strength of major forcing agents are outlined in Table S2. Specifically, the four SSP scenarios are scenarios with high greenhouse gas (GHG) emissions (SSP5-8.5 and SSP3-7.0) in which CO_2 emissions are approximately doubled by 2050 and 2100, respectively. These scenarios represent the high end and the medium to high end of the range of future pathways; a scenario with intermediate GHG emissions (SSP2-4.5) in which the level of CO_2 emissions remain unchanged until 2050; and a scenario with low GHG emissions (SSP1-2.6) in which CO_2 emissions drop to net-zero after 2050. Notably, among the four scenarios, SSP3-7.0 represents a weak pollution control scenario, with high emissions of short-lived climate forcers (SLCFs) in particular, followed by SSP2-4.5 (moderate), and SSP5-8.5/SSP1-2.6 (strong). In the mid-century period (2041–2060), global warming of 2 °C relative to the historical level (1850–1900) is very likely to be exceeded under the very high emissions scenario (SSP5-8.5), likely to be exceeded under the high emissions scenario (SSP3-7.0), and more likely than not to be exceeded under the intermediate emissions scenario (SSP2-4.5). According to the recently released Intergovernmental Panel on Climate Change (IPCC) Six Assessment Report (AR6), the most likely emissions pathway lies between SSP3-7.0 and SSP2-4.5 (IPCC 2021).

2.3 Arctic maritime accessibility model

In order to investigate the maritime accessibility shaped by Arctic climate, we adopt the approach of Li et al. (2021b), which builds upon the Polar Operational Limit Assessment Risk Indexing System (POLARIS) (IMO 2016). Within the POLARIS framework, the viability of ship operation is quantified by Risk Index Outcome (RIO) values, defined as

$$RIO = \sum_{1}^{n} Conc_i RIV_i \tag{1}$$

where $Conc_{\mathrm{i}}$ and RIV_{i} refer to sea ice concentration and the corresponding Risk Index Value (RIV) of ice category i, respectively. The RIV can be inferred from ice type and vessel ice class, the former of which can be deduced from ice thickness range and the latter is assumed to be a common open water (OW) vessel class in this study. The derived RIV ranges from -8 to $+3$, with higher values yielding lower risks. A detailed look-up table of the RIV is provided in Table S3. By summing all ice categories together, the RIO suggests a "go or no-go" situation, with a range of -80 (worst-case conditions) to $+30$ (optimal conditions). A positive RIO is indicative of a normal operation of OW vessel class, under which condition the risk level is acceptable. The travel speed to safely navigate through the ice regime is determined by the relationship between RIO and International Maritime Organization (IMO)–recommended speed (IMO 2016). The resulting gridded travel speeds map is then used to identify the optimal least-cost routes with the implementation of Dijkstra's algorithm. The optimal route and its travel time are only recorded when the transit can be realized from the start location of Rotterdam, Netherlands, to the destination location of the Bering Strait. The Arctic maritime accessibility model is conducted independently for individual ensemble members and scenarios.

2.4 Season length, route forecasts, and risk quantification

For a given ice year from April 1 to March 31 of the following calendar year, the recorded navigable days are counted towards the season length calculation. The season length only considers continuously navigable days without gaps (that is, impassable days). Due to the high variability and concomitant uncertainty both at the opening (start day) and closing (end day) of the shipping season, 7 days and 5 days are used empirically to cut off the season shoulder to mirror operational decision timeframes (Kjerstad, personal communication, 2016). The MME mean is calculated by averaging the 14 CMIP6 models. The annual navigation probability is the fraction of models that have an operationally significant season length of a month or more.

The optimal shipping routes across the Arctic thus generated encompass but are not confined to those formally identified as the Northeast Passage (NEP) (including the Northern Sea Route (NSR)), Northwest Passage (NWP), and Central Arctic Route (CAR). To examine the interaction between the spatially and temporally variable retreat of Arctic sea ice and the particular risks presented by the NSR, we further select routes outside of Russian territorial waters—defined as 12 nautical miles (nm) from a nation's baseline under the United Nations Convention on the Law of the Sea (UNCLOS). Russian territorial waters—while comprehensively managed with ice breaker escort and experienced pilots—present a number of challenges for international shipping operators. Navigational risks arise from the narrow straits (e.g., Kara Strait, Vilkitsky Strait, Sannikov Strait). These straits enable ships to stay close to the coastline but are often ice choked. Such risks are quantified by a safe navigation index (SNI), measured as subtracting ratio of seemingly navigable days (but are in fact not) from 100% sure navigable (Li et al. 2021b). Financial risks, not unique to Russian waters, arise from the substantial interannual sea ice variability and associated uncertainty of accessibility from one season to the next. Such risks are quantified by an option pricing model, which assumes the Arctic shipping issue as a put option (Goldstein et al. 2022a; Sturm et al. 2017). Regulatory demands, asserted under Article 234 of the UNCLOS addressing ice covered waters, arise from mandatory insurance requirements, onerous authorization procedures, and the mandatory requirement for pilotage and ice breaker escort. These demands apply to all vessels, including foreign government vessels, despite the fact that this is not in accordance with key provisions of UNCLOS. Finally, there are uncertainties at the time of writing associated with the impacts of sanctions on Russia imposed in response to the invasion of Ukraine. To explore the impacts of ice retreat on accessibility free from these risks, we assess the trajectories of change in season length, start/end day of the season, and the likelihood of navigability outside of Russian territorial waters.

3 Temporal and geographical change of Arctic navigation

The shipping season is unconstrained by ice cover for the first time in the year 2024, 2040, 2041, and 2026 for the very high- to low-emissions trajectories respectively (Fig. 1a). The scenario trajectories start to diverge after mid-century associated with divergence in temperature responses by this time (see mid-term best estimate in Table S2). Over the next six decades, the projected trend for the MME mean season length is 1.94, 1.54, 1.28, and 0.73 days per year (at the 99% significance level) for the very high- to low-emissions trajectories, respectively. As expected, there is an overall high growth rate of season length under the very high emissions pathway (SSP5-8.5) and a low rate of increase under the low-end emissions pathway (SSP1-2.6). The rate of change is comparable under medium and high emissions trajectories (SSP2-4.5 and SSP3-7.0). Nonetheless, very large interannual

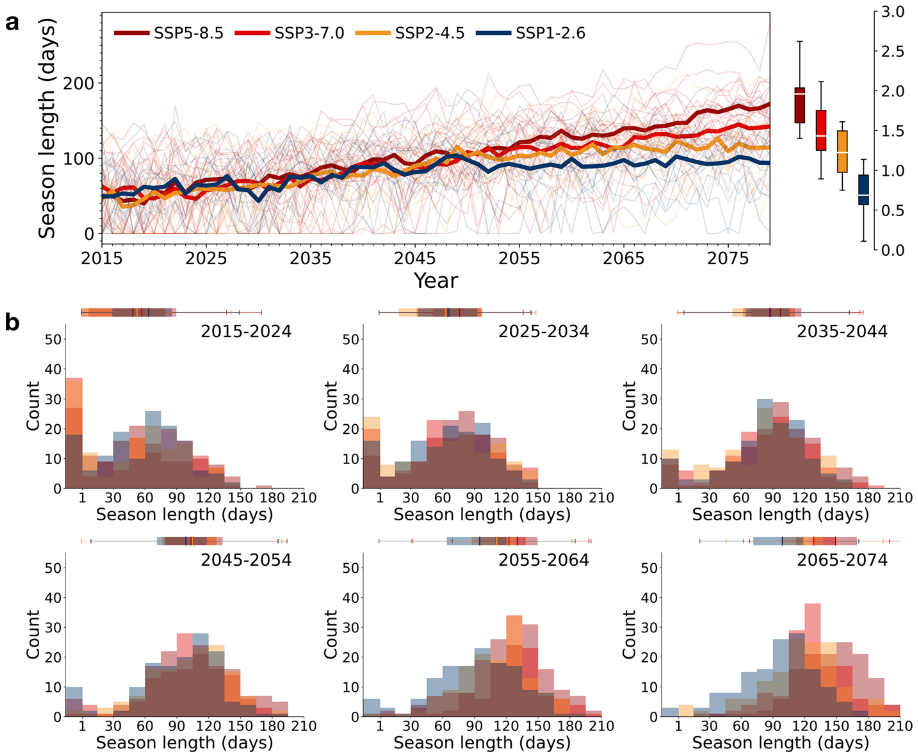

Fig. 1 Projected change in shipping season length under varying levels of anthropogenic emissions. **a** Interannual season length variability for 2015–2079. **b** Decadal season length distribution through time. The vertical boxplot in a shows the rate of annual change in season length and the associated uncertainty range for the corresponding level of emissions. The horizontal boxplot in panel b displays the interquartile and range of season length over the respective decade for 14 CMIP6 simulations. The boxplot is defined as line inside the box, median; colored box, interquartile range (IQR) from 25th percentile (Q1) to 75th percentile (Q3); upper and lower whiskers, bounds of Q3 + 1.5 × IQR and Q1 − 1.5 × IQR, respectively. Note that in panel b, the frequency of zero value is separated from the rest as a single bin in the leftmost of the histogram; and each emissions scenario is colored in the same way as that shown in a

variability is evident in all of the scenarios such that only the lowest emissions pathway can be considered to produce a significantly different growth rate.

To investigate in more detail how these outcomes change over time, the distribution of projected season lengths at the decadal scale is shown in Fig. 1b. There is a considerable number of completely non-navigable seasons at the beginning of the first two decades. The distribution of season length progresses towards a normal distribution from 2035, with fewer non-navigable seasons and a strong similarity in the evolving behavior of projected season length regardless of scenario. Importantly, the rate of season length growth in the low emissions scenario becomes stagnant after 2057 (at the 95% significance level). Reflected in this distribution, a tendency towards the low end of season length is observed under the SSP1-2.6 scenario during 2055–2064 and 2065–2074, in contrast to higher season lengths under the other emissions pathways; these evolve to left-skewed distributions.

Thus, different scenario pathways result in different rate and extent of regime shift for Arctic shipping (Figure S1). There is little difference in transit regime distribution in the first two decades, though with slight differences in the magnitude of navigable route density. During this period, the major shipping corridor is still centered on the NEP, while a few routes divert to the NWP, and to a lesser extent the CAR across the North Pole. The CAR gains in prominence in the 2040s in all scenarios. Moving to the mid-century and thereafter, a new Transpolar Sea Route shifted toward the western Arctic (hereinafter referred to as TSR to differentiate it from the CAR) emerges and is strongly pronounced in the highest emissions scenario (Figure S1, also labeled in Fig. 2). It is westward from the North Pole, close to Greenland and the Canadian coastline and does not impinge on

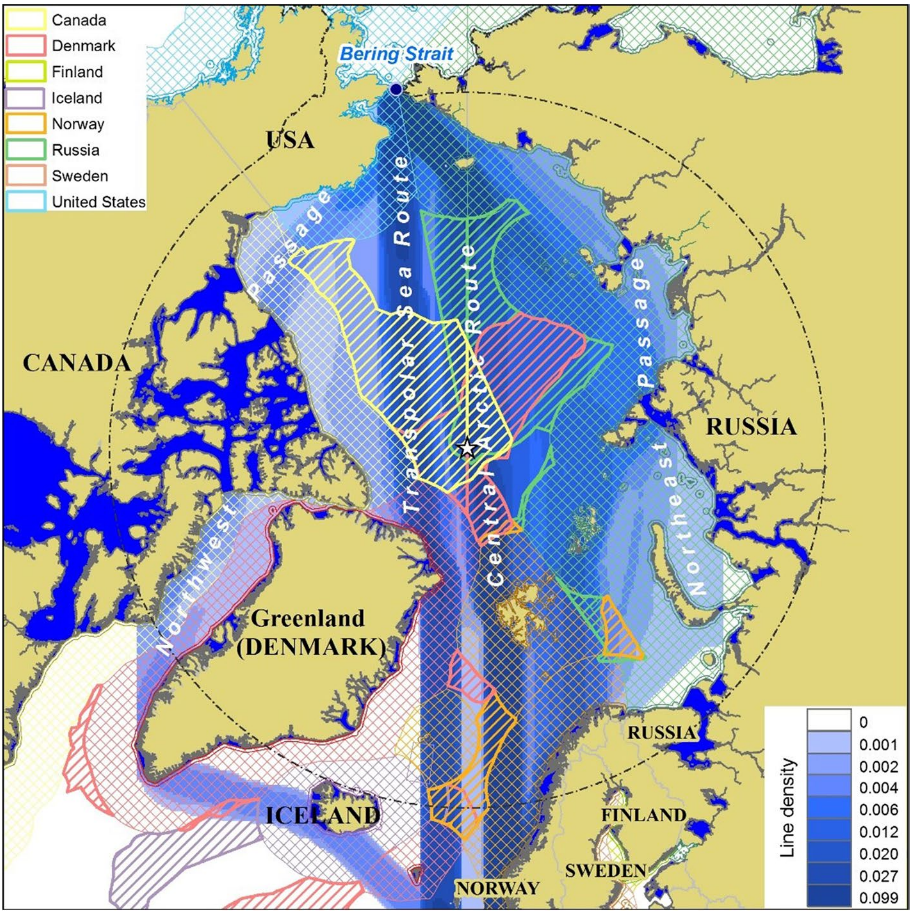

Fig. 2 Geographical distribution of projected trans-Arctic shipping routes under the SSP5-8.5 forcing scenario during 2065–2074. The navigation routes of Northeast Passage (NEP), Northwest Passage (NWP), Central Arctic Route (CAR), and Transpolar Sea Route (TSR) are labeled in white. The transit density is colored in blue shading and based on the proportion of total transits that falls within a certain radius (unit: km) over the decade. Each transit is attached to equal weight in line density calculation. The background Arctic map consists of North Pole (star symbol), land areas (brown), internal waters (dark blue), territorial seas (defined as 12 nautical miles (nm) from a nation's baseline; darker colored as per the inset legend), exclusive economic zones (EEZs; defined as 200 nm extending from a nation's baseline, thin crosshatched area), and claims to the extended continental shelf (thick hatched area) as of 23 May 2019. The March 2021 submissions for extensions of continental shelf made by Russia are not shown

the Russian exclusive economic zone (EEZ; defined as 200 nm extending from a nation's baseline) nor Russia's claimed extended continental shelf. Though the conceptualization of such TSR re-routing for geopolitical reasons can be traced in Bennett et al. (2020), their devised route is geographically southward and longer. The new TSR has not been explicitly revealed in previous studies (Stephenson and Smith 2015) largely due to the lack of daily resolution data and usage of an MME mean that smooths out inter-model variability. More importantly, the MME mean overestimates ice state (Shu et al. 2020) especially ice thickness (Wei et al. 2020) and tends to paint a conservative picture for polar shipping (Cao et al. 2022). The TSR is somewhat observed in Melia et al. (2016) using a calibration technique that accounts for both mean and variance bias in ice thickness (Melia et al. 2015). Nevertheless, it is questionable whether the established observational constraints used in this calibration hold true for future climate (Allen and Ingram 2002). Thus, this is the first rigorous scenario-driven identification of this route. The frequency of TSR systemically and gradually weakens under the SSP3-7.0 and SSP2-4.5 scenarios and is very faint under the best-case scenario (Figure S1).

The timing, magnitude, and duration of regime shift in maritime navigability will have multiple implications for Arctic navigation and economic and policy development. Currently, maritime activity in the western Arctic focuses primarily on research and tourism. Once reliably seasonally navigable, the TSR will allow for container shipping due to its deep bathymetry compared to the NSR/NEP and NWP. The emergence of the TSR, which is of comparable accessibility to the CAR and the NEP under the SSP5-8.5 scenario during 2065–2074 (Fig. 2), diminishes the need to traverse the NSR, raising the potential of diminished economic risks and regulatory friction (Lynch et al. 2022). Thus, the TSR is an attractive option for bulk cargo due to short distances (Humpert and Raspotnik 2012) but may also lead to additional opportunities for commercial fisheries and seabed mining. This presents, then, the critical concern of marine biodiversity (Stevenson et al. 2019) particularly with regard to areas beyond national jurisdiction (also known as the "high seas", Fig. 2). Economic exploitation along the TSR could have negative impacts on marine ecosystems (Hauser et al. 2018). To address the potential threat to marine diversity, on June 25, 2021, an agreement was reached to prohibit unregulated fishing in the Central Arctic Ocean. It takes effect until 2037, with a possible extension to 2042 when all parties agree (European Commission 2021). The existing legal framework pertaining to the Arctic Ocean has been characterized as fragmented and inadequate (Norchi 2018; Prip 2019) despite the fact that the need for comprehensive Arctic Ocean governance is rising (Young 2016).

4 Operational and financial risk assessment

Following Li et al. (2021b), we apply a safe navigation index (SNI) to quantify the operational risk posed by sea ice variability in the middle of a voyage. These risks primarily account for operations constrained to pass through narrow straits. As shown in Fig. 3a, highly varying amplitudes of monthly SNI are calculated in the coming three decades, and then the navigational risk is expected to reduce from 2045 onward for all the analyzed scenarios. Revealing large decadal variability, unstable ice conditions persist notably during June of 2035–2044, with concomitant high uncertainty under the very high- and low-emissions scenarios. Since the TSR and the CAR are non-coastal routes, a shift to these routes are one means to avoid the geographic barriers present in the NSR. As a result, the navigational risk of using these routes are low by this measure. However, other risks

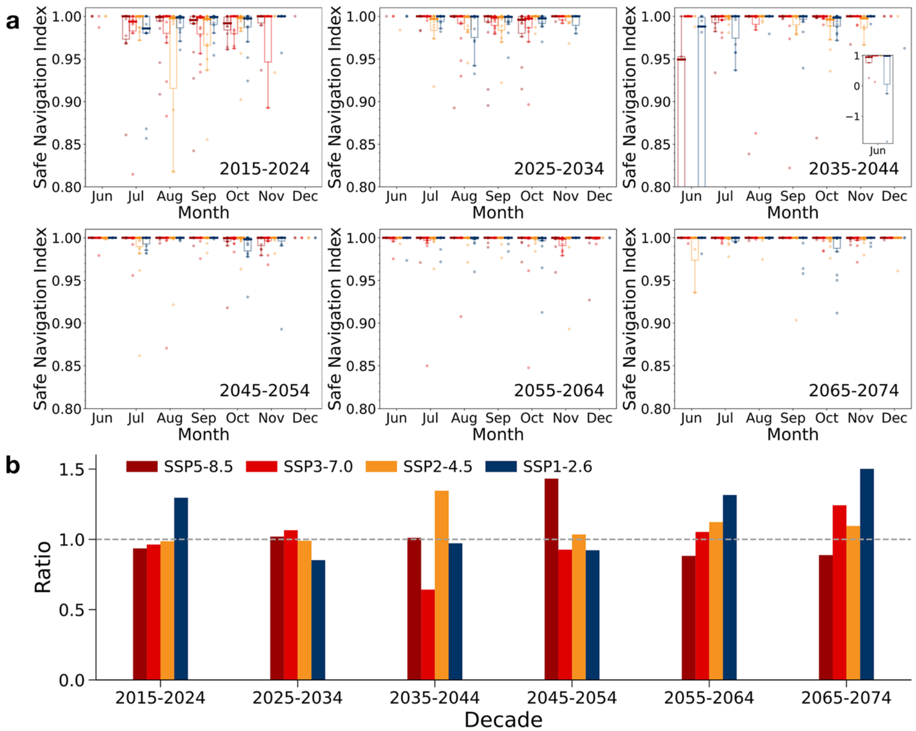

Fig. 3 Quantification of navigational and financial risks. **a** Monthly safe navigation index (SNI) across scenarios and decades. The monthly mean SNI values averaged for each model are displayed in dots. Boxplot is solely applied to months with no less than four models available. A SNI closes to 1 indicates low-risk navigation. For visualization, the SNI of June of 2035–2044 has the same bound limit as in other time periods, and a full view of it is shown in inset. **b** Risk of measuring additional cost of variance with multi-model ensemble (MME) mean. It is quantified by the ratio of additional variance cost estimated by applying MME mean to that resulting from model uncertainty across high- to low-emissions pathways. The dashed gray line indicates where the ratio is one. Above the dashed line, the cost of interannual variability is greater than that of model structural uncertainty and vice versa

related to ice dynamics not well represented in climate models (e.g., ice ridging, ice bergs from calving glaciers) and other weather related hazards (e.g., extreme wind, waves, poor visibility) have not been incorporated. For example, as the Arctic Ocean undergoes the transition towards a thinner, younger, and more migratory ice pack (Moore et al. 2021), high interannual variability in ridge occurrence (Babb et al. 2021) will create hazardous conditions to maritime operations not represented here. Emergencies requiring icebreaker escort or even search and rescue (Barber et al. 2018) will be more challenging in the TSR due to remoteness of the area (Lasserre et al. 2016). Finally, the corridor diminishes the benefits of the intermediate market and transshipment hubs (Goldstein et al. 2022d), which is important for the container shipping industry to realize loading/unloading opportunities at potential rotations.

Recognizing the navigational risks and opportunities in the decades ahead, it is important to understand the resulting economic impacts and how these evolve in the context of interannual sea ice variability, inter-model spread, and scenario uncertainty. Specifically, the cost of interannual variability arises from the internal climate modes pertaining to a single model; the cost of inter-model spread arises from the structural discrepancy between multi-models; the cost of scenario uncertainty arises from the unpredictability of which future pathway we are on. To address this, we make several assumptions to simplify the cost estimation. We assume that a fixed volume of international trade is shipped through the Arctic such that 90 days of accessibility is required. The relative percentage cost curve is not sensitive to this choice of the threshold but it serves for illustrative purposes (Goldstein et al. 2022a). When a sufficient navigable window is unavailable, it is assumed that the remainder of the required goods are delivered through the Suez Canal. Because the Suez Canal is longer, it incurs an additional cost (Goldstein et al. 2022a) as illustrated in Figure S2. The costs resulting from both interannual variability and inter-model spread significantly diminish over the course of six decades, especially for the SSP3-7.0 where high SLCF emissions are configured (Table S2). We apply a ratio to gauge the financial risk assessment of using MME mean in a relative sense (Fig. 3b). In general, model differences play a larger role in the near term whereas the interannual variability takes over in the long term. The third source of uncertainty, differences in emissions scenarios, is also apparent, and pronounced, after the mid-century.

5 Policy implications

Previous work has raised the issue of Russia's assertion of control over the NSR component of the NEP (Boylan and Elsberry 2019). More specifically, according to Article 234 of the United Nations Convention on the Law of the Sea (UNCLOS), coastal states of ice-covered waters enjoy additional competency in addressing environmental pollution from vessels (Lynch et al. 2022). However, the evolving scope of enforcement of laws and regulations by Arctic littoral states in the context of climate change remains obscure (Norchi and Lynch 2022). Specifically, while some segments of NSR run through the internal waters of Russia, Russia asserts sovereignty over the entire route (Vylegzhanin et al. 2020). In light of this prevailing practice, we evaluate the projected probabilities of navigation options that circumvent the NSR. Overall, there is no tendency for an earlier onset of an extra-NSR shipping season, although a prolonged shipping season is detected under the very high and high emissions scenarios (Figure S3). As a result, positive tendencies are observed for navigability as a function of time under the SSP5-8.5 and SSP3-7.0 scenarios (Fig. 4). Conversely, little change in probability of navigation is observed under the lower emissions scenarios. By the end of 2070s, it is likely that the ship can traverse outside the Russian territorial waters under the very high emissions scenario, as likely as not for the high to medium emissions scenarios, and the chance is low in the low-emissions case. These findings are in line with and extends the recent research of Lynch et al. (2022). As a result, it is extremely likely ($>95\%$) that the navigable seaway will not be bound by Russian administered waters from 2086 for the very high emissions scenario and post-2107 for the high emissions scenario (not shown). The likely ranges are limited for the medium- and low-emissions scenarios even into the next century. Notably, the rapid growth rate after 2045 is consistent with the opening timeframe of the TSR. This provides a range of probabilities that Arctic operators will be able to avoid the costs and risks of the current, dominant, NEP route. Furthermore, these results suggest the potential for avoidance of conflict associated with Russian assertions of regulatory administration over government, including military,

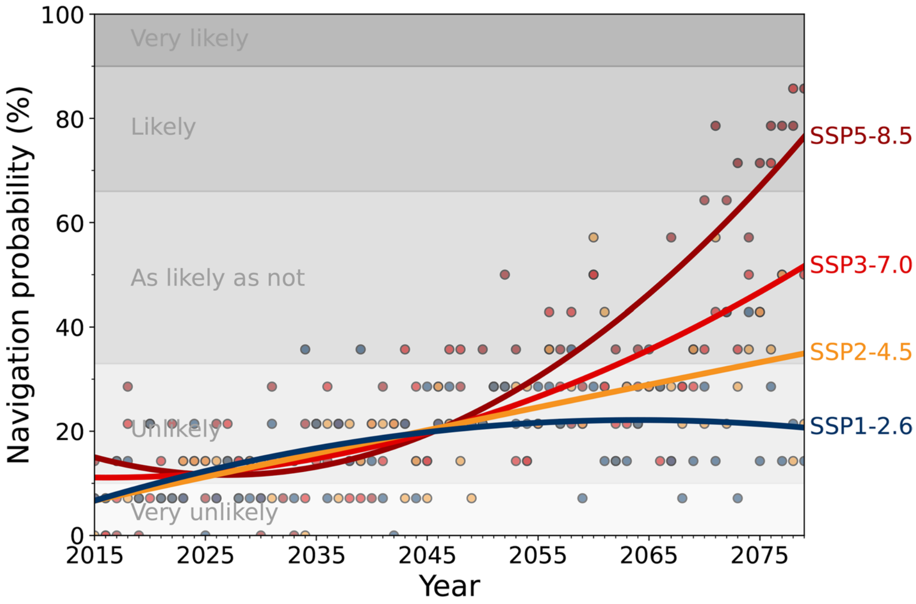

Fig. 4 Levels of Arctic navigability beyond the Russian territorial waters under the four SSPs scenarios over the period 2015–2079. Each dot represents the level of confidence in individual years. The color line indicates the change of confidence using a quadratic regression fitted to the navigation probability series, which explains 79%, 62%, 48%, and 20% of the variance in navigation probability from very high- to low-emissions scenarios. The level of confidence corresponds to the IPCC convention

vessels from all nations. In this context, the near-term transition period (2025–2045) may offer vital window for maritime policy evaluation.

6 Discussion

6.1 Uncertainty in Arctic routes

The development of measures of Arctic maritime accessibility provides a theoretical basis for examining impacts, costs, and risk assessments. It is important to note that the grounded operational, financial, and geopolitical insights must be viewed with caution as there are many sources of uncertainty associated with climate projections and assumptions in the maritime accessibility and risk quantification models. The current horizontal resolution of climate models is not optimal for informing Arctic navigation in detail, which requires spatial information of 300 m or finer, particular in the vicinity of complex coastlines (Veland et al. 2021). The underrepresentation of subgrid-scale processes including fundamental dynamics, ice ridging, and floe size distribution (Horvat and Tziperman 2015) may bias consequential outcomes. For example, when fueled with ocean waves and winds, sea ice floes can potentially be dangerous to safe navigation, especially during melting season when floes break up and fragments are drifting. In addition, some trajectories will emerge as unrealistic when compared with evolving observations. It is reported that the potential of trans-Arctic routes grows faster than model projections, which already reached around 3 months for open water vessels navigating along the NEP in the 2010s (Cao et al. 2022). Our future work will be focused on developing a more reliable envelope for the shipping season based on a Bayesian statistical model that takes advantage of prior knowledge (Fletcher et al. 2019). Regarding the Arctic maritime accessibility model, apart from ice dynamics and weather conditions that need to be accounted for when refining route algorithms, other aspects to consider include the shoulder season criteria that need to be informed by deeper consultation with shipping operators. In addition, the route calculation is limited to Rotterdam-Bering paired transits. Route alternatives may be identified elsewhere, and moreover even routes that are not the least-cost path can be preferable by other metrics. While we use Arctic maritime accessibility to posit viability of ship operations in ice-covered waters, ice state is not dispositive for any given voyage. The decision to use a transportation corridor for a particular destination depends on many factors, including operational uncertainties, risk tolerance, geopolitical and strategic factors, profit margins, and regulatory environment (Lee and Kim 2015). Indeed, the dramatic retreat of Arctic sea ice has not led to an upsurge in transit shipping. This contrast is partly explained by strategic and financial considerations (e.g., sanctions, global economics, natural resource markets; see, e.g., Goldstein et al. 2022b), implying that the melting of sea ice as an enabler, not a driver of the expansion of Arctic shipping (Lasserre 2019). Thus, it is important that these results be interpreted with appropriate caveats in the context of the assumptions and limitations detailed herein. With this perspective, multi-model climate projections, the Arctic maritime accessibility model, and the calculations of safe navigation and risk are useful tools to represent possible futures of trans-Arctic route evolution in the coming decades.

6.2 User-driven climate science

Demand-driven climate services have been highlighted particularly during the past decade but are difficult to achieve in practice. A key challenge is developing concrete linkages that connect science and domain-specific services. In this respect, our approach provides useful guidance for narrowing the gap between data and decisions and making climate information both usable and used (Lemos et al. 2012). By accounting for the different needs of active players in response to the opening of the Arctic to shipping under a variety of emissions futures, we suggest four possible context-specific information pathways. First, an ensemble of climate trajectories is recommended and generally characterized by the MME mean. But while the MME mean is a common way for researchers to relate climate simulations to observational records, the impact of averaging away the inter-model spread on decision processes can be substantial (Figure S2). Second, interannual variability as expressed across all of the ensemble members is a significant quantity. In this case, the interannual variability of sea ice leads to uncertainties in maritime accessibility and associated financial risk. Quantification of financial risk is needed to effectively enhance business resilience to climate change. Third, navigation in the Arctic can be jointly affected by model structural uncertainty and scenario uncertainty, further highlighting the importance of considering multi-scenario multi-model assessments for operational decision-making. Finally, to reduce the cognitive load of this breadth of information, probabilistic analyses of specific decision relevant variables, such as the likelihood of open water navigation outside of Russian-administered waters, pave the way to more informed decisions. Furthermore, this kind of targeted approach has the potential to better communicate how different mitigation options might influence geopolitical policy actions in the context of different drivers of uncertainty. In developing these approaches, it is important to recognize the dynamic interactions and trade-offs among operations, investments, and politics which can be highly complex (see, for example, Goldstein et al. (2022b)).

7 Conclusions

Few transformations are as dramatic as those occurring now in the Arctic. The implications of a seasonally navigable high North and its ramifications for polar maritime development demands an ongoing comprehensive exploration. A multidisciplinary approach incorporating climatic, geospatial and financial methods puts system change into perspective and can assist in translating climate information into consequences. In this study, we have demonstrated the importance of considering multiple emissions scenarios and multi-model ensembles on daily timescales that provide valuable climate information through assessment of variability and uncertainty. Our results reveal that pre-2045 maritime navigation is relatively risky when a high proportion of the trans-Arctic voyages utilize the Northern Sea Route where the narrow shallow straits are favorable for fast ice formation and sea ice ridging. The navigation risk is lowered with the emergence of a transpolar sea route we call the TSR that lies between the central Arctic (CAR) and the Northwest Passage (NWP). Furthermore, we find that the economic costs of using this route decreases with interannual sea ice variability over this century, although the rapidity of this transition varies with emissions pathways. By the end of the century, while scenarios of mitigation options for fossil-fueled development (SSP5-8.5) and regional rivalry (SSP3-7.0) are virtually certain ($>99\%$) and likely (83%), respectively, to detour around Russian territorial waters, middle-of-the-road (SSP2-4.5) and sustainability (SSP1-2.6) scenarios result in a more limited window of opportunity. This has consequences for the UNCLOS regime, and particularly the applicability of Article 234 on ice covered seas, that is explored in more detail in Norchi and Lynch (2022). In the near-term horizon, the coming transition period (2025–2045) presents an opportunity for policy design and appraisal.

The integrated perspective may be subject to uncertainties originating from various sources. However, when tuned to specific user needs, useful information can be gleaned even in the context of high levels of uncertainty arising from multiple sources. The quantity of interest can be different. Our work aims to stimulate a constructive dialogue among Arctic actors in the face of Arctic transformation to facilitate viable and robust decision pathways. In future work, we will further test the user customization approach based on the results of field surveys with our partners in shipping companies, decision makers, and other key stakeholders in the rapidly transforming Arctic. Through an iterative and collaborative process, we hope that sound science with all of its uncertainties and caveats can nevertheless be a pillar in directing toward a resilient, sustainable, and adaptive transition.

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Author contribution Xueke Li: Conceptualization, formal analysis, data curation, writing (original draft), visualization. Amanda H. Lynch: Conceptualization, methodology, writing (review and editing), supervision, funding acquisition. All authors read and approved the final manuscript.

Data availability The original datasets used in this study are publicly available. The daily ice fields of CMIP6 scenario analysis are available from the Earth System Grid Federation (https://esgf-node.llnl.gov/search/cmip6/). The produced Arctic maritime accessibility data under SSP5-8.5 is publicly available at https://doi.org/10.5281/zenodo.6539994.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

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Conflict of interest The authors declare no competing interests.

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