Article

Ships are projected to navigate whole year-round along the North Sea route by 2100

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In the context of global warming, the Arctic sea ice is rapidly receding, and the possibility of navigating the Arctic shipping route continues to increase. Here we combine climate and ship navigability data and use low and medium emission scenarios to analyze sea ice conditions and navigability from 2023 to 2100, focusing on Polar Class 7 and open water vessels. The results show that sea ice motion deteriorates the navigability. Polar Class 7 ships will be able to sail the Arctic passages throughout all seasons except for the spring of 2065, while there is a comparative advantage of the Northern Sea Route for open-water ships. The optimal shipping routes of Polar Class 7 ships from 2065 to 2100 are more distributed toward the Central Arctic. These could considerably reshape the patterns of global shipping networks and international trade among Asia, Europe, and America.

The Arctic is very sensitive to climate change[1], and the Arctic sea ice retreat continually accelerates because of global warming [2]. Specifically, the sea ice extent (SIE), sea ice thickness (SIT), and sea ice concentration (SIC) will be more sensitive to climate forcing and decrease sharply in summer and autumn[3–5]. Thus, an ice-free Arctic in September is foreseeable under all scenarios considered[6] but with much uncertainty in the timing[7]. This makes possible the opening of Arctic passages.

It is widely believed that the retreat of sea ice enhances the feasibility of Arctic maritime transport. The Arctic passages, compared with traditional shipping routes (such as the Suez Canal), could reduce maritime transport distance by 40% and transport time by 30% between Europe and north-western Asia[8,9]. It thus could not only reduce fuel consumption and carbon emissions from international maritime transport[10,11] but also enhance the efficiency of the global transportation network[12]. Given that trade volume between Europe and northwestern Asia occupies a large share of global trade, the opening of the Arctic passages would clearly change the international division of labor and industrial distribution[13] and affect global trade patterns[14].

There are some studies on the feasibility and navigability of maritime transport in the Arctic region. Most of the existing studies focus on the effects of the navigation environment on maritime transport. For example, some studies have examined the impacts of weather conditions[15,16]. Other studies, e.g., the Polar Operational Limit Assessment Risk Indexing System (POLARIS)[17] and the Canadian Arctic Ice Regime Shipping System (AIRSS)[18], focus on the influence of SIT and SIC. These studies have found that meteorological and hydrological risks, such as strong wind, low

visibility, low temperature, and shallow water, are also major obstacles to ship navigability[19–23]. Water depth is the key constraint to the Arctic shipping [24]. Other studies have concluded that sea surface temperature and sea ice motion (SIM) are key factors in the feasibility of maritime transport in the Arctic region[25–27]. SIM and sea ice drift may change the heading of ships for interaction with the hull, especially for large carrier ships[28].

In recent years, predicting the overall impacts of climate change on Arctic maritime transport has been attracting researchers' interest in the field[29–31]. These researchers try to build links between long-term climate change, the changes in sea ice conditions in the Arctic, and the navigability and optimal shipping routes of maritime transport across the Arctic region, mostly using non-strengthened open water (OW) ships and medium-strengthened Polar Class (PC) 6 ships as ship samples[32–34] without due consideration for the choice of PC6 and its practical impact on transportation and logistics. Undeniably, two research gaps still need to be filled in the field. One is that, when navigability is assessed, only SIT and SIC have been considered. The other is that the most widely used, thin-strengthened PC7[35] ships have seldom been evaluated.

This paper aims to fill these gaps by analyzing the temporal and spatial changes of sea ice and the navigability of maritime transport in the Arctic passages during the period 2023–2100. First, we compared the observed data with the simulated Coupled Model Intercomparison Project Phase 6 (CMIP6) data to reduce the uncertainty of projected data. Second, we examined PC 7 and OW ships, which are (respectively) predominantly and potentially used in the region. Finally, we performed temporal and spatial analysis of navigable days (ND), navigable period (NP), navigable area, and

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optimal navigable routes distribution with consideration of SIC, SIT, and sea ice dynamic factors.

Results

The impacts of climate change on sea ice conditions

We first verified the accuracy of four main climate change scenarios according to distance between indices of simulation and observation (DISO) (Fig. 1a). The SSP1-2.6 scenario performs the best with respect to SIT, followed by SSP2-4.5. SSP3-7.0 has the lowest DISO among SIC, and SSP2-4.5 comes in second place. SSP2-4.5 has the smallest difference with observed data in terms of SIM. Overall, the SSP2-4.5 scenario demonstrates the lowest DISO and best simulation performance. Thus, SSP2-4.5 was selected to project the navigability. Based on the trend of SIC and SIT variation shown in Fig. 1b, we divided the yearly data into three slices: 2023–2040, 2041–2064, and 2065–2100. Additionally, an overall decrease with fluctuation of both SIT and SIC from 2023 to 2100 could be seen. Monthly variation of SIC and SIT by year was analyzed (Fig. 1c, d). The results show that the maximum SIT lies in May and the minimum in October, revealing a time lag compared to SIC. In particular, SIC increases more sharply compared to SIT. Moreover, a gradual decrease in both SIC and SIT can be seen from 2023 to 2100. Again, we partitioned the monthly data into three segments—May to July, August to October, and November to December—excluding January to April for their high SIC and SIT.

The impacts of climate change on navigability

The SSP2-4.5 scenario was selected according to the validation and its smallest DISO. The risk index values (RIVs) of PC7 and OW ships, with SIM both considered and not considered, were calculated. The non-negative and navigable grid proportion is 70.33%, 41.51%, 13.20%, and 0.01%, respectively. Figure 2 shows that SIM matters, increasing the navigational risk and reducing the navigability. Overall, the RIV of PC7 ships is higher than that of OW ships. The navigable conditions with the consideration of SIM, including ND, NP, and OASR, were not analyzed because of their rather low navigable grid proportion.

A given area is considered navigable when the risk value is not negative. The spatial distribution results of PC7 ships are shown in Fig. 3: the green area is navigable, whereas the red one is not. The Greenland Sea and Barents Sea are year-round navigable in months from May to December. From 2023

to 2040, the NWP excluding Baffin Bay is navigable from May to July, and most parts of NSR are non-navigable. From August to October, the entire Arctic Ocean is navigable, except for the eastern part of the Central Arctic. The NWP and NSR are only navigable from November to December along the coasts of the Chukchi Sea, Beaufort Sea, Baffin Bay, and Kara Sea. From 2041 to 2064, the Arctic remains non-navigable from May to July. There is no notable difference in navigable areas between the period of August to October and November to December, and the coastal areas have no navigational risks. The western part of the Central Arctic remains non-navigable. During 2065–2100, the Arctic is non-navigable except for the Barents Sea from May to July. The entire Arctic Ocean is navigable from August to December.

Compared to PC7 ships, OW ships have a smaller navigable area, but the adjacent regions of the Greenland Sea and Barents Sea are navigable throughout the years (Fig. 4). However, more regions are navigable in the period of 2065–2100 from August to October, including the Kara Sea and most part of the Baffin Bay. For the duration of the studied period, the NWP is persistently risky, but the high-risk navigational area of the NWP gradually decreases from 2023 to 2100.

Additionally, the likelihood of navigability along the NWP appears to be lower compared to the NSR in the foreseeable future. The coastal areas fall within the critical range of safe navigation from −0.2 to 0, hinting that there is a high possibility of opening for navigation in these areas after 2100.

The NP of PC7 and OW ships from 2023 to 2100 was predicted from the daily average risk index outcome (RIO) by the POLARIS model (Fig. 5a, b). Scenarios of SSP1-2.4, SSP2-4.5, and SSP5-8.5 were all analyzed, with particular emphasis placed on SSP2-4.5. The difference in ND between 2023 and 2100 under SSP2-4.5 is moderate compared to the other two scenarios. For PC7 ships, the average annual ND is projected to increase from 199 days in 2023 to 301 days in 2100, representing an average annual increase of 1.31 days. Similarly, for OW ships, the ND is expected to rise from 195 days to 247 days, with an average annual increase of 0.67 days. The average ND for PC7 ships by 2100 is approximately 240 days under SSP1-2.6 and 283 days under SSP5-8.5. The average ND of OW ships under SSP1-2.6 and SSP5-8.5 is approximately 210 and 248 days, respectively.

The OASR for PC7 ships under the SSP2-4.5 scenario are plotted (Fig. 5c–g), focusing on the period of 2065–2100 for its best performance in the navigable area. Since the peak value of shipping route density occurs only
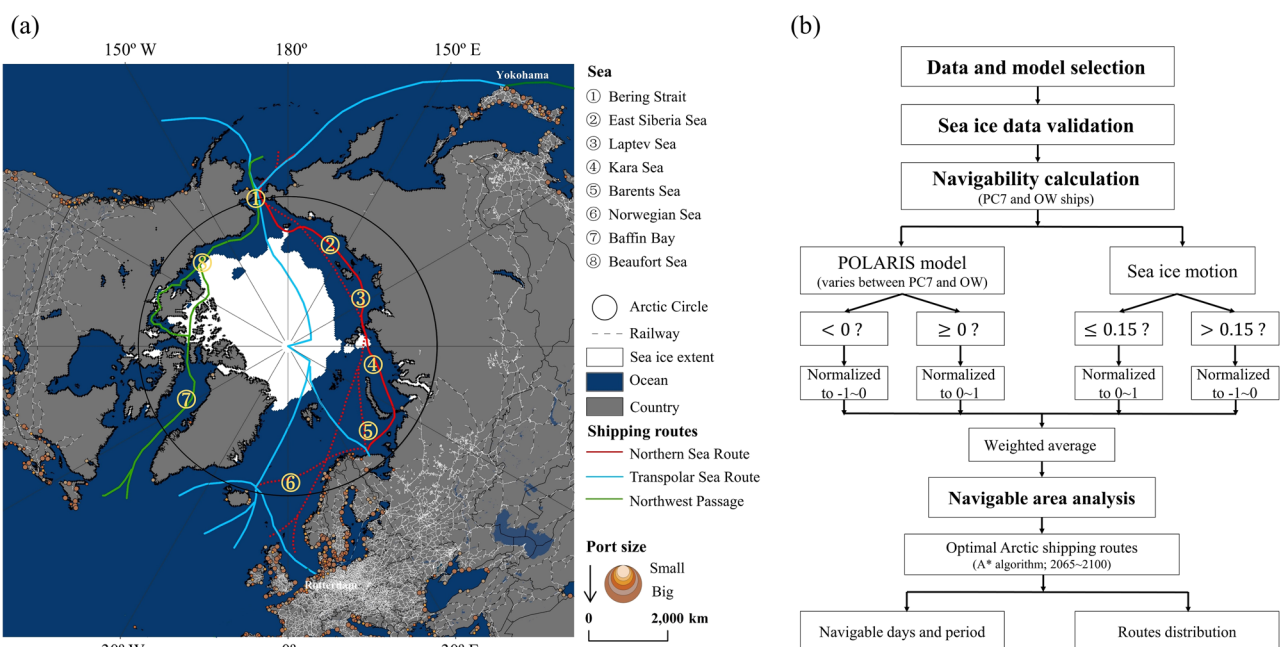

Fig. 1 | The study area and research framework. a Arctic shipping passages (the SIE is from NSIDC September 2021). **b** Methodological framework of this research.
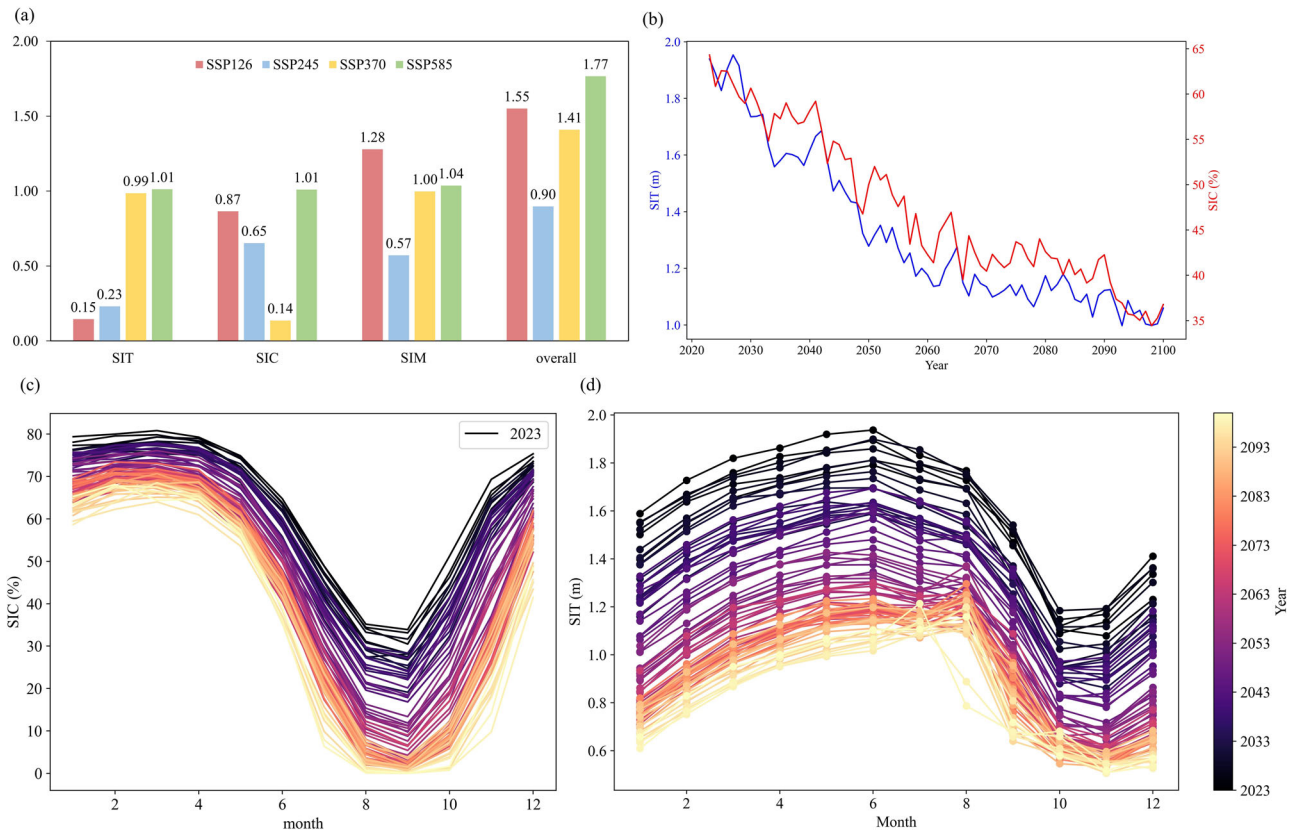
Fig. 2 | Evolution of sea ice conditions. a DISO of SIT, SIC, SIM, and overall situation. b The annual variation of simulated SIT and SIC from 2023 to 2100. c The monthly variation of SIC from 2023 to 2100 by year. d The monthly variation of SIT from 2023 to 2100 by year.
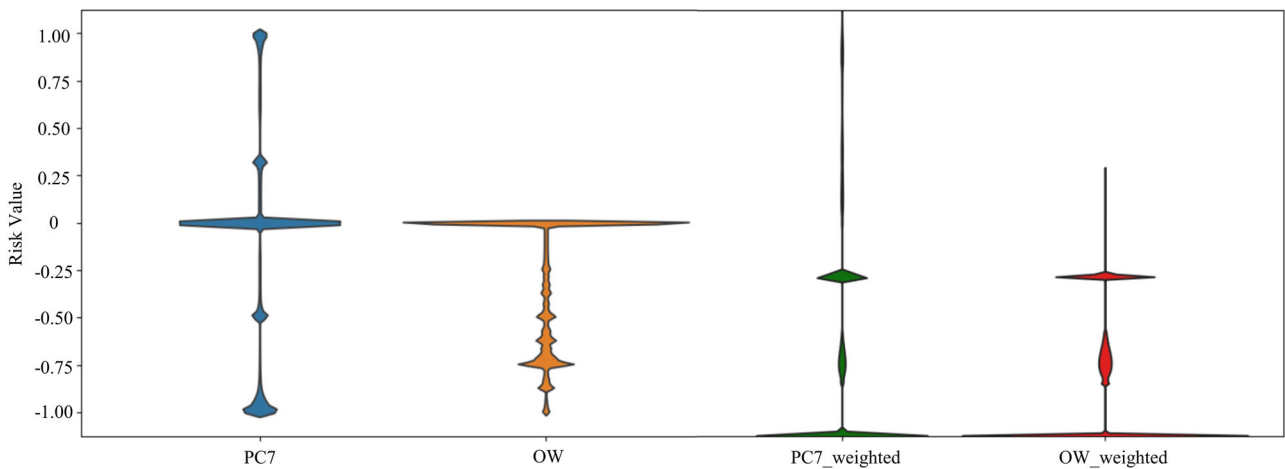

Fig. 3 | The risk index value distribution of PC7 and OW ships with SIM both considered and not considered. The blue means the risk index value distribution of PC7 ships, and the orange means the one of OW ships; The green and the risk index value distribution of PC7 ships with the consideration of SIM, and red means the one of OW ships with the consideration of SIM.

from July to November (Fig. 5h), the analysis of OASR density is limited to this period. The OASRs are consistently at 14 routes and primarily concentrated in the TSR during the months of August to October (Fig. 5d–f). In particular, the OASRs are more concentrated in the Central Arctic in September, with the smallest SIC (Fig. 5h), in which the road density and SIC show a high correlation of -0.95 (p-value < 0.01). Conversely, the OASRs are more distributed along the coastal areas in July and November. Regarding specific shipping routes, there exist OASRs from July to

November for NSR. However, the OASRs are only feasible in July and November for the NWP.

Discussion and conclusions

The Arctic region is sensitive to climate change. The impacts of climate change on Arctic maritime transport have become one of the key topics in climate change studies. The feasibility and navigation in the Arctic region may bring changes to trade routes among European, North American, and
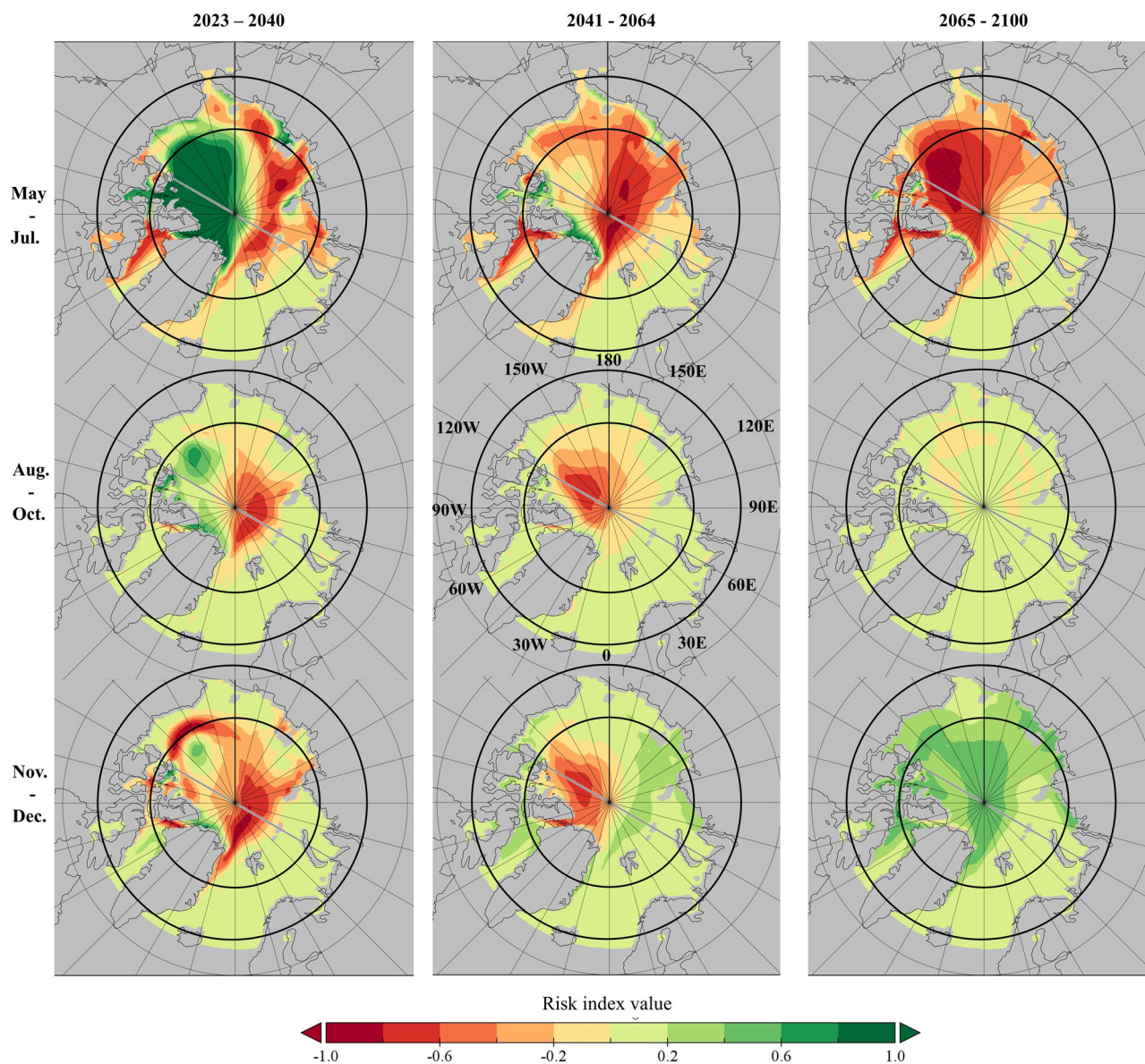
Fig. 4 | The spatial pattern of risk index of PC7 ships. The green from light to dark means the non-negative risk index, which is navigable area. The red from light orange to dark means the negative risk index and vice versa.

Asian countries; in particular, it will bring new opportunities to China's "Polar Silk Road" framework. This paper examined the effects of climate change on sea ice situations and navigability in the Arctic from 2023 to 2100. The PC7 and OW ships instead of the PC6 ships selected by most previous studies[36–39] were examined and the navigational feasibility with more factors considered was predicted, which is simultaneously a much higher temporal resolution than previous research[40]. SIM has an impact on navigability, heightening the navigational hazards. The results of the analysis show that under SSP2-4.5, PC7 ships will be able to achieve stable and safe navigation during the summer and autumn seasons, with the potential for year-round navigation from 2065 onward. By 2100, the average annual NDs for PC7 and OW ships are projected to be 301 days and 247 days, respectively, under the SSP2-4.5 scenario. The high-density OASRs for PC7 ships exist from July to November, predominantly along the coastal areas of the NSR. Moreover, the OASRs along the NWP only exist in July and November, which is a development opportunity for the NSR. This comparative advantage may affect the joint interest in implementing the SDGs among countries in the Arctic region[41].

In future research, the potential negative effects of Arctic maritime transport should be recognized and investigated. It is believed that the opening and utilization of the Arctic passages may yield negative effects on the Arctic ecosystem, including maritime-related pollutions and accidents, oil spills, and other harms to the region[42–46]. Oil tankers and cargo ships are prevalent in the Arctic passages[35]; and container ships, among which are ships with TEU below 2000[47], are seldom used[48]. Additionally, the design and cost of vessel types matter. First, the selection of suitable material and strengthening of the hull form can improve response to loads up to a certain extent[49]. Thus, the freight volume, breadth, etc. of ice-strengthened ships needs to be further discussed, as the increasing utilization of the Arctic passage relates not only to more ND but also to cargo capacity. Second, the cost and possibility of icebreaker escort, which is mainly decided by shipping companies[50], should be further discussed. Additionally, more uncertainties like the Russo–Ukrainian War should also be considered[51]. More international collaboration and balanced strategies are needed to coordinate the environmental protection and uncertainties of the Arctic region in the context of climate change.
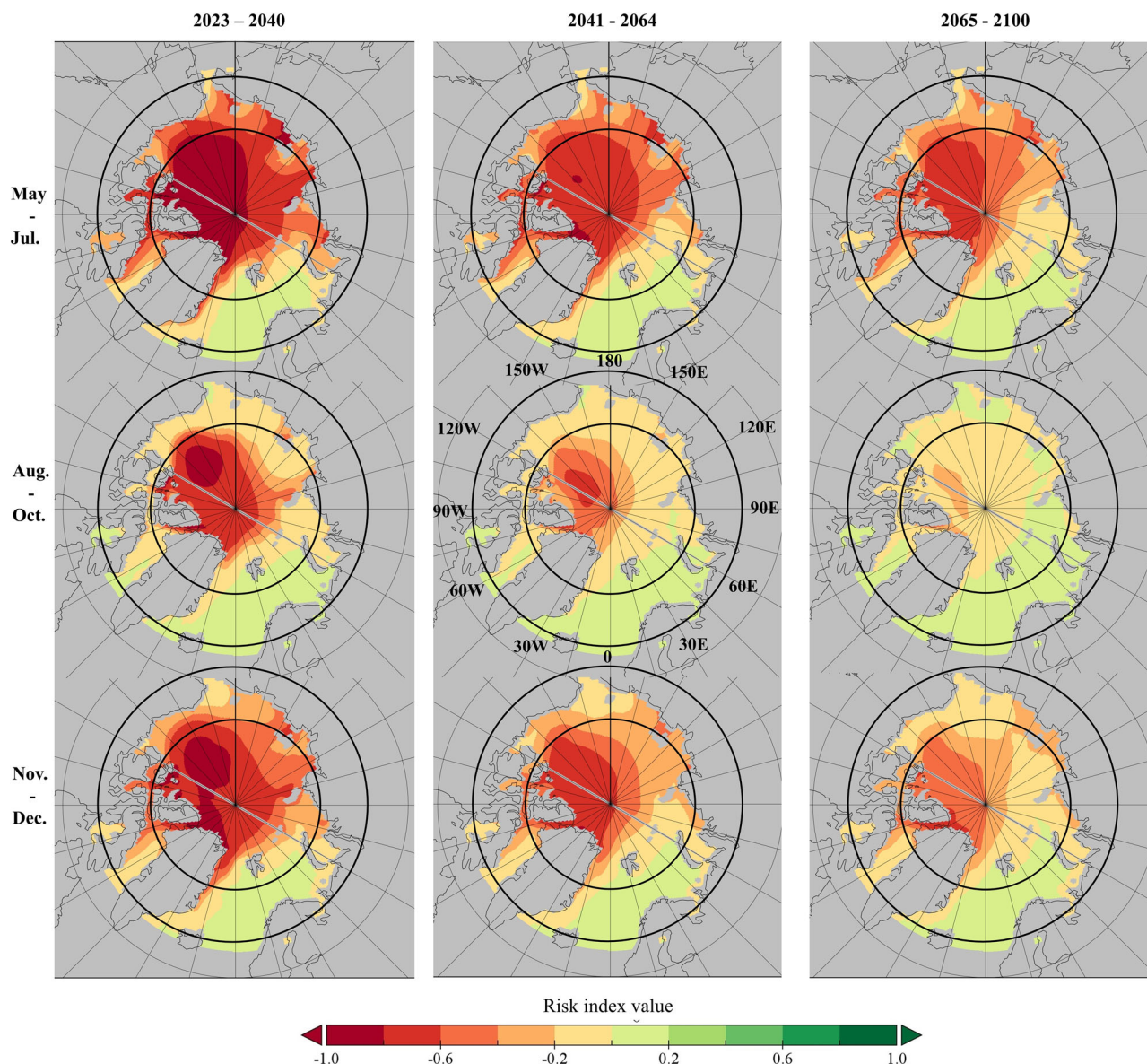
Fig. 5 | The spatial pattern of risk index of OW ships. The green from light to dark means the non-negative risk index, which is navigable area. The red from light orange to dark means the negative risk index and vice versa.

Methods

Study area and research framework

The internationally recognized Arctic passages include the Northern Sea Route (NSR), also known as the Northeast Passage; the Northwest Passage (NWP); and the transpolar sea route (TSR)[16]. The NSR is an international coastal route beginning in the Bering Strait, along the coasts of Russia and Norway (Fig. 6a). The NWP starts from the Bering Strait and goes eastward along the northern offshore waters of Alaska, but it is hindered by perennial ice and ice mounds. The TSR is the shortest sea route linking Asia and Europe near the North Pole, which is currently still covered by multi-year ice.

This study's methodological framework and main factors are presented in Fig. 6b. First, we selected proper data and models in terms of their accuracy and representativeness, based on other studies (Supplementary Notes 2). Second, we applied a validation of sea ice conditions to examine the consistency between the observed and simulated data. Third, we selected the navigation model. We chose to use the POLARIS model with more factors

considered (Supplementary Notes 1) to predict the navigation, as it is currently considered a widely acceptable methodology for the assessment of operational limitations in ice-infested waters by the International Maritime Organization. Finally, the temporal and spatial situations of navigability were predicted.

Method for navigability evaluation

CMIP6 models that offer available data and fit best, with high resolution (100 Km), were selected in this study. The simulated SIT, SIC, and SIM data were converted to 25×25 Km^2 using inverse distance weighting interpolation, facilitating model–data comparisons within the period from 2015 to 2023[52]. In this research, the DISO was constructed to quantify the comprehensive quality of CMIP models to select the model of the following evaluation. A lower DISO suggests a better performance[53]. In the DISO, we calculated the correlation coefficient (CC) and root-mean-square deviation (RMSE) as the metrics for both SIT and SIC. The metrics of RMSE and mean absolute error (MAE) were used for SIM speed and angle, respectively. The
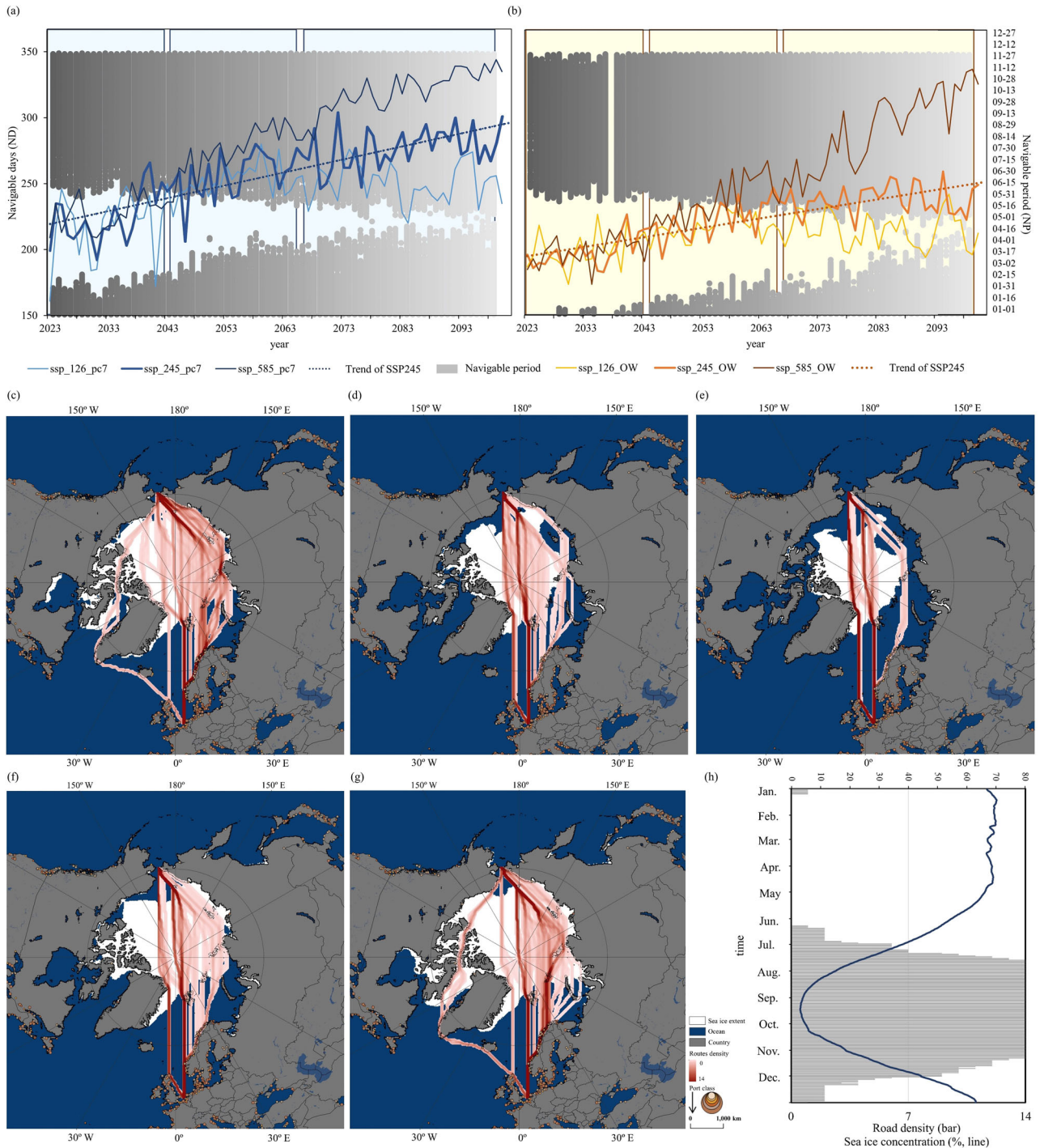
Fig. 6 | The navigable conditions of PC7 ships. a ND and NP of PC7 ships, with the blue line representing the variation of ND and the grey bar showing the variation of NP; **b** ND and NP of OW ships, with the orange line representing the variation of ND and the NP, the same as (**a**); **c** OASRs in July; **d** August; **e** September; **f** October; **g** November; and **h** time variation in routes density and SIC.

equations of DISO can be defined as:

$$
\begin{aligned}
DISO_{1i} &= \sqrt{\left(\text{nor}CC_{1i} - 1\right)^2 + \text{nor}RMSE_{2i}{}^2} \\
DISO_{2i} &= \sqrt{\text{nor}RMSE_{2i}{}^2 + \text{nor}MAE_{2i}{}^2} \\
DISO_{3i} &= \sqrt{DISO_{SIC}{}^2 + DISO_{SIT}{}^2 + DISO_{SIM}{}^2}
\end{aligned} \tag{1}
$$

where $i = 0, 1, \ldots, m$, and m is the total number of CMIP6 models. $DISO_{1i}$ denotes the DISO for both SIT and SIC, and $\text{nor}CC_{1i}$ and $\text{nor}RMSE_{1i}$ are the normalized CC and RMSE. $DISO_{2i}$ denotes the DISO for SIM, and

$\text{nor}RMSE_{2i}$ and $\text{nor}MAE_{2i}$ are the normalized RMSE and MAE. $DISO_{3i}$ indicates the model's overall situation of SIC, SIT, and SIM. The normalization equation can be expressed as

$$
\text{nor}M_i = \frac{M_i - \min(M)}{\max(M) - \min(M)} \tag{2}
$$

where M indicates the selected metric, such as CC, RMSE, and MAE. When $i = 0$, the metrics of CC, RMSE, and MAE between the observed data and itself are 1, 0, and 0, respectively.

The navigability is represented by the RIO value of POLARIS, which combines the ice class of the vessel. For each ice condition and corresponding SIT, there is an RIV determined by the vessel's ice class and without icebreaker escort[54,55]. The calculation method is shown in the following equations[35]:

$$RIV_{PC_7} = \begin{cases} 3, & SIT = 0 \\ 2, & 0 < SIT \le 0.30 \\ 1, & 0.30 < SIT \le 0.70 \\ 0, & 0.70 < SIT \le 0.95 \\ -1, & 0.95 < SIT \le 1.20 \\ -2, & 1.20 < SIT \le 2.0 \\ -3, & 2.0 < SIT \end{cases}$$

$$RIV_{OW} = \begin{cases} 3, & SIT = 0 \\ 1, & 0 < SIT \le 0.10 \\ 0, & 0.10 < SIT \le 0.15 \\ -1 & 0.15 < SIT \le 0.30 \\ -2 & 0.30 < SIT \le 0.50 \\ -3 & 0.50 < SIT \le 0.70 \\ -4 & 0.70 < SIT \le 0.95 \\ -5 & 0.95 < SIT \le 1.20 \\ -6 & 1.20 < SIT \le 2.00 \\ -7 & 2.00 < SIT \le 2.50 \\ -8 & 2.50 < SIT \end{cases}$$

$$RIO = (C_1 \times RIV_1) + (C_2 \times RIV_2) + \cdots + (C_n \times RIV_n) \quad (3)$$

Here, RIV_{PC_7} and RIV_{IB} are the RIV of PC7 and OW ship, respectively; SIT (m); C1…Cn is the SIC (in tenths) of ice types within the ice regime; and RIV1… RIVn are the corresponding RIVs for each ice condition.

In addition to SIT, there is a comprehensive calculation with SIM considered[56], the threshold of which is 0.15 m/s[14,57]. A normalized negative risk value from -1 to 0 will be assigned when the SIM exceeds the threshold, which does not differentiate between vessel types. The calculation is performed using the following equation[57,58]:

$$COMRIV = \begin{cases} w_1 x_1 + w_2 x_2, RIO \ge 0, SID \le 0.15 \\ w_1 \times (-1) + w_2 \times (-1), else \end{cases} \quad (4)$$

Here, COMRIV represents the comprehensive RIV, w_1, and w_2 are the weight of the risk index (equals 0.75 and 0.25, respectively)[57]; x_1 is the normalized value of the risk index, ranging from -1 to 1, with negative and positive holding the same before and after normalization; x_2 is the normalized SID (non-negative and ranging from 1 to 0 where SIM given beyond the threshold). The normalization is constructed with respective daily maximum and minimum values.

This study adopts the A* shortest path algorithm to investigate the optimal shipping routes. The COMRIV is measured between the nodes of Rotterdam port (starting point [51°5′ N, 4°30′ E]) and the Bering Strait (endpoint [65°38′36″ N, 169°11′42″ W])[57]. The algorithm searches for elements with a non-negative COMRIV and defines them as navigable[59,60,错误!未找到引用源]. Each grid was then treated as a network dataset in GIS with the least-cost path computed as the route accumulating the lowest travel time between origin and destination[11,61]. The ND and NP are calculated according to a combination of daily COMRIV and A* algorithm, a day that exists optimal shipping route is defined as an ND, and NP is a set of continuous NDs. Any day that the Optimal Arctic Shipping Routes (OASR) can be found by the A* algorithm is defined as an ND, and the NP thus consists of all continuous NDs[32].

Data availability

Code availability

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Author contributions
Pengjun Zhao led research plan forming, conceptualization of research questions, and manuscript writing. Yunlin Li acquired and processed data, created figures, interpreted results, and led manuscript writing. Pengjun Zhao and Yunlin Li contributed equally. Yu Zhang contributed to the CMIP6 model validation.

Competing interests
Pengjun Zhao, Yunlin Li, and Yu Zhang declare that they have no conflict of interest.

Additional information
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