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Projected changes in sea ice and the navigability of the Arctic Passages under global warming of 2 °C and 3 °C

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ABSTRACT

Although a rapid decrease in sea ice due to global warming has improved the navigable potential of the Arctic passages, the extent to which this area will become viable for commercial shipping in the future remains unclear. This study investigated the accessibility of the Northern Sea Route and Northwest Passage under global warming of 2 °C and 3 °C. We applied the Polar Operational Limit Assessment Risk Indexing System to measure navigability by considering the impacts of sea ice and ice resistance of ships. Except for the Parry Channel, surface air temperature is positive in the Seas along two passages in September under 2 °C warming. With global warming of 3 °C, the warming area extends northward, and the concentration of sea ice drops below 20%. The thickness of the sea ice is still substantial in the eastern Beaufort Sea and the waters within the Canadian Arctic Archipelago and north of Greenland, both of which can restricting the opening of the Arctic passages. Temperature increases cause sea ice to be younger and are more pronounced in the seas on the European side of the Arctic. The results indicate that changes in sea ice improve the navigability of the Arctic passages. Ships in Polar Class 6 may be unimpeded along two Arctic passages in November from 2 °C warming onward, whereas ordinary ships may be capable of passing the Northern Sea Route with global warming of 3 °C, with maximum potential in September. This study provides an important reference for planning global shipping in the Arctic in the future, even with some uncertainty in the model projections.

1. Introduction

As one of three coldest regions in the Earth system, the Arctic is very sensitive to climate change (Koenigk et al., 2020). From 1971–2019, the annual average surface air temperature increased in the Arctic by 3.1 °C, three times faster than the global average (AMAP, 2021). The newest Coupled Model Intercomparison Project Phase 6 (CMIP6) showed that the annual mean Arctic surface air temperature will rise to 3.3–10 °C above the 1985–2014 average by the end of this century (AMAP, 2021). With rapid global warming and atmospheric pattern-induced warming, the Arctic sea ice extent, thickness, and concentration dramatically decrease in summer and autumn (Cai et al., 2021a). In contrast to the early 1980 s, at present, more than half of the sea ice disappears in summer (Stroeve and Dirk, 2018). Summer sea ice variability is impacted by major internal climate patterns, and the reduction in sea ice is enhanced by the positive ice/ocean albedo feedback loop, which is accelerated by Arctic amplification (Lei et al., 2016; Cai et al., 2021b).

With a continued decrease in sea ice coverage, both the area and the duration of open water have increased in the Arctic (Wang et al., 2018), thereby offering favorable conditions for navigating the Arctic. Arctic navigation passages are economically valuable and also help to ease the increased pressure on traditional shipping routes resulting from the growth of international shipping (Schøyen and Bråthen, 2011; Zhang et al., 2019). Compared with the traditional shipping routes passing through the Suez Canal and the Mediterranean Sea, for example, the Northern Sea Route can shorten the sailing distance, save shipping time and reduce shipping costs. This route has also been considered environmentally friendly since the 21st century; furthermore, such a route avoids economic and political risks in high-danger zones, such as the Malacca Strait and the waters off the coast of Somalia (Buixadé et al., 2014). The Northwest Passage can therefore bring greater benefits than the Panama Canal in terms of sailing distance, time, and cost (Haas and

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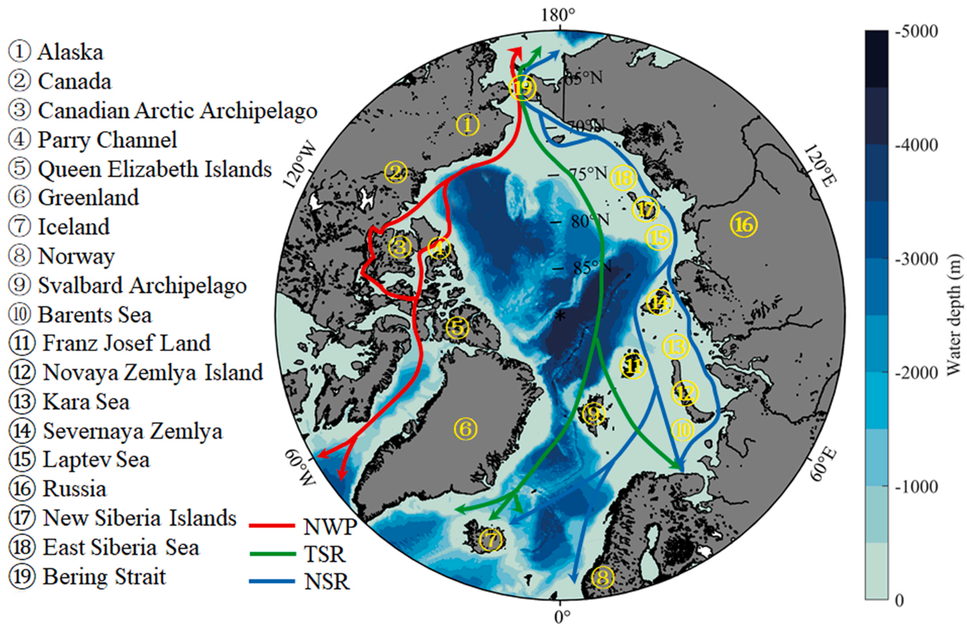

Fig. 1. The distribution of topography, geographical locations, and Arctic passages (the red line is the Northwest Passage (NWP), the green line is the Transpolar Sea Route (TSR), and the blue line is the Northern Sea Route (NSR)).

Table 1
Temperature increasing thresholds of 2 °C and 3 °C under SSPs in IPCC AR6.

Scenarios	SSP2 – 4.5	SSP3 – 7.0	SSP5 – 8.5
2 ℃	2043 – 2062	2037 – 2056	2032 – 2051
3 ℃	N	2066 – 2085	2055 – 2074

Table 2
Risk values (RVs) for OW ship and PC6 ship under different ice classes.

Ice Class	OW ship	PC6 ship
Ice free	3	3
New ice (0–10 cm)	1	2
Gray ice (10 cm – 15 cm)	0	2
Gray white ice (15 cm – 30 cm)	-1	2
Thin 1st year 1st stage (30 cm – 50 cm)	-2	2
Thin 1st year 2nd stage (50 cm – 70 cm)	-3	1
Medium 1st year 1st stage (70 cm – 95 cm)	-3	1
Medium 1st year 2nd stage (95 cm – 120 cm)	-3	0
Thick 1st year ice (120 cm – 200 cm)	-4	-1
Second year ice (200 cm – 250 cm)	-5	-2
Light multiyear ice (250 cm – 300 cm)	-6	-3
Heavy multiyear ice (more than 300 cm)	-6	-3

Howell, 2015). The spatially-averaged length of its open period increased to 114 days in the 2000 s and reached 146 days in 2012 (Lei et al., 2015). Observational evidence has also shown that the average navigable period of the Northern Sea Route for normal merchant ships was extended to October 24 from 2010 to 2017 (Chen et al., 2019). By analyzing changes in sea ice and shipping activity in the Canadian Arctic Archipelago from 1990 to 2015, Pizzolato et al. (2016) suggested that navigability was negatively correlated with sea ice concentration. Multiyear ice had a much greater impact on shipping than seasonal sea ice.

The majority of CMIP6 models projected that the first instance of a large sea ice-free Arctic in September will occur before 2050 under most emission scenarios (AMAP, 2021). The potential scale of the international marine shipping industry may be 2.4–12 times that of today by the middle of the 21st century (Sardain et al., 2019). The future navigational capacity of the Arctic passages has been investigated via atmospheric circulation models. The Polar Class (PC) 6 icebreaker will be able to navigate the Northern Sea Route from July to September, for example, and during these three months the Northwest Passage will be approximately 82% navigable by the middle of the 21st century (2045–2059) (Stephenson et al., 2011). The travel time of open water (OW) ships through the Northern Sea Route will be shortened by approximately 10 days compared with the traditional Suez Canal route (Melia et al., 2016). These ships will be able to pass through the Northwest Passage in September (Chen et al., 2021a, 2021b). By the late 21st century (2080–2099), the navigable area for PC3, PC6, and OW vessels will increase to 95%, 78%, and 49%, respectively (Stephenson et al., 2013). This increasing rate will be nearly or more than double that at the end of the 20th century. The sailing period of OW ships will increase to 4 and 6.5 months in the Northern Sea Route under representative concentration pathway (RCP) 4.5 and RCP8.5, respectively (Khon et al., 2017).

The scenarios described above were estimated from either a single or multiple models from CMIP5; the release of CMIP6 provides data to update these assessments of the changes in sea ice and navigability along Arctic passages. Such knowledge is meaningful for the analysis and planning of future passage routes in a rapidly changing area. In addition, global and Arctic warming are concerns of the Paris Agreement (Horowitz, 2016), and evaluating future navigational potential of Arctic shipping routes under different warming scenarios can improve the science needed to address these concerns.

This study therefore addressed the following research questions. First, how will sea surface temperature and sea ice conditions change under global warming of 2 °C and 3 °C above preindustrial levels? Second, how will such changes affect the navigability of different types of ships along the Arctic passages? The hypotheses guiding the research are as follows. First, the sea surface temperature is likely to rise overall in the Arctic, and sea ice may continue to retreat northward with global warming. The effects would be more significant at 3 ℃. Meanwhile, sea ice will be younger, and sea ice thickness and concentration will decrease in most areas. Second, navigability will improve in the Arctic under global warming of 2 °C and 3 °C above preindustrial levels, especially for vessels with high resistance to ice. The Northern Sea Route is likely to open first, followed by the Northwest Passage. In addition, navigation time will lengthen, and the navigation area will expand.

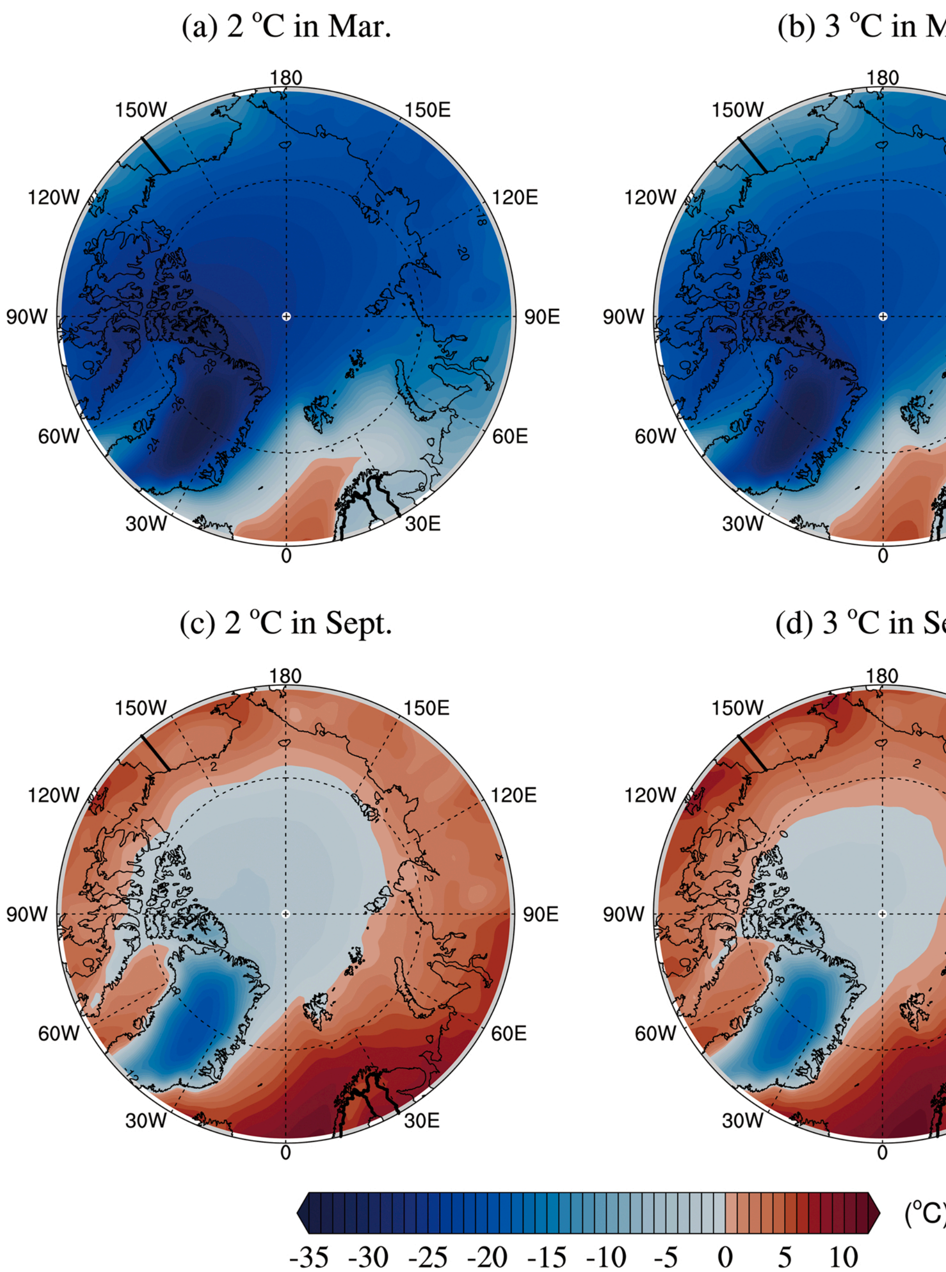

Fig. 2. The distributions of Arctic surface air temperature in March and September under global warming of 2 °C and 3 °C, respectively, as averages of SSP2–4.5, SSP3–7.0, and SSP5–8.5.

2. Methodology

2.1. General approach

To address the two research questions, the general approach involved calculating multi-model averages of three shared socioeconomic pathways. Such calculations would generate distributions of surface air temperature, sea ice concentration, sea ice thickness, and sea ice age. The percentage of navigable areas in each month would also provide insight into the potential navigability of OW ships and PC6 ships. The Polar Operational Limit Assessment Risk Indexing System (POLARIS) would further enable evaluation of the passage of OW ships and PC6 ships. This prospective study would therefore obtain further insight into the future changes in sea ice in the Arctic and the navigability of the Arctic.

2.2. Study area

The Arctic passages refer to the sea routes connecting the North Atlantic Ocean with the North Pacific Ocean through the Arctic Ocean basin. The Arctic passages include three routes (Fig. 1): the Northwest Passage, the Transpolar Sea Route, and the Northern Sea Route (also named the Northeast Passage). The Northwest Passage lies along the northern coast of Alaska, passes through the waters of the Canadian Arctic Archipelago, and reaches the city of St. John in the province of Newfoundland and Labrador in northern Canada (Howell et al., 2013). The complex geographical environment comprising multiyear ice, ice mounds, and numerous islands inhibits navigation of the Northwest Passage (Buixadé et al., 2014). The Northern Sea Route starts from the Bering Strait, runs along the coast of Norway and Russia, passes through the Bering Sea, East Siberian Sea, Laptev Sea, Kara Sea, and Barents Sea, and ends at Rotterdam in the Netherlands (Chen et al., 2020). Compared

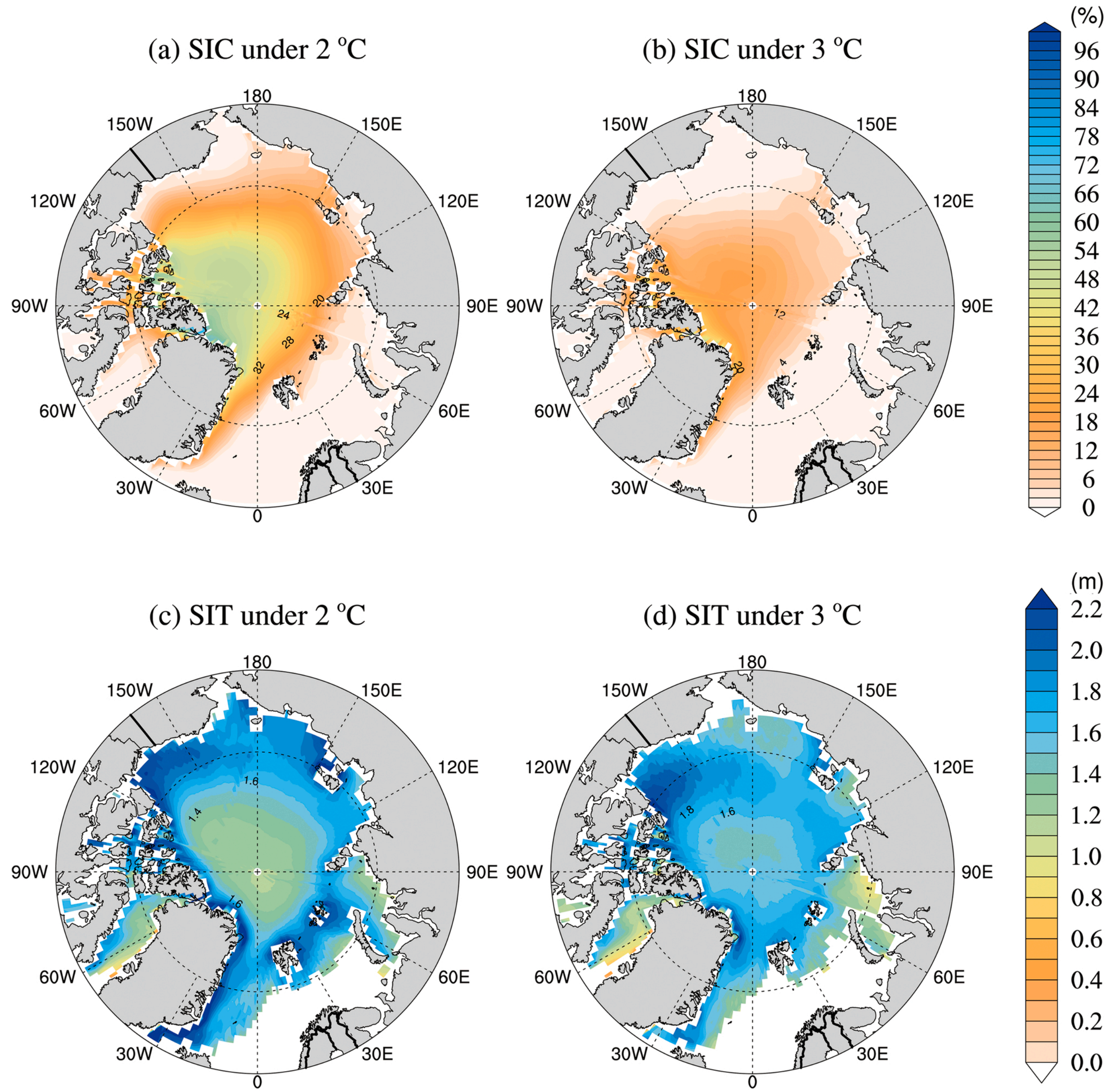

Fig. 3. Distribution of the Arctic sea ice concentration (SIC) and sea ice thickness (SIT) in August–October under global warming of 2 °C and 3 °C.

with the Northwest Passage, the Northern Sea Route is easier to navigate (Chen et al., 2021a, 2021b) with better navigational infrastructure along the route, such as historic ports and a fleet of Russian-supplied ice-breakers (Buixadé et al., 2014). The Transpolar Sea Route is the shortest sea passageway connecting Asia and Europe through the high seas of the Arctic Ocean near the North Pole. This route remains largely hypothetical, as its opening would require a largely ice-free Arctic basin; this basin is still covered by multiyear ice.

2.3. Data and quality control

Compared with CMIP5, CMIP6 provides a more realistic estimate of Arctic sea ice (SIMIP Community, 2020). The shared socioeconomic pathways (SSPs) (https://esgf-node.llnl.gov/search/cmip6) in CMIP6 represent different radiative forcing by the end of the century. It was designed to study the impacts of climate change, mitigation, and adaptation using plausible alternative trends reflecting the evolution of society and natural systems over the 21st century (O'Neill et al., 2014). According to assessments for global warming of 2 °C and 3 °C in the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6) (IPCC. Climate change, 2021), we used the periods (Table 1) when global warming reached 2 °C and 3 °C above preindustrial levels under SSP2 – 4.5, SSP3 – 7.0, and SSP5 – 8.5 to calculate the corresponding states of sea ice. The period SSP2 – 4.5 indicates a combination of moderate social vulnerability and moderate radiative compulsion. SSP3 – 7.0 represents moderate baseline results produced by energy system models. SSP5 – 8.5 is the most difficult path for passage, along which anthropogenic radiative forcing reaches 8.5 W/m^2 by 2100 (O'Neill et al., 2016).

We selected models by comparing the historical trend of Arctic sea ice extent in simulations with remote sensing observations during 1979–2012. The observation data came from the Sea Ice Index of the National Snow and Ice Data Center (https://nsidc.org/data). The models selected have a correlation coefficient between the original simulations

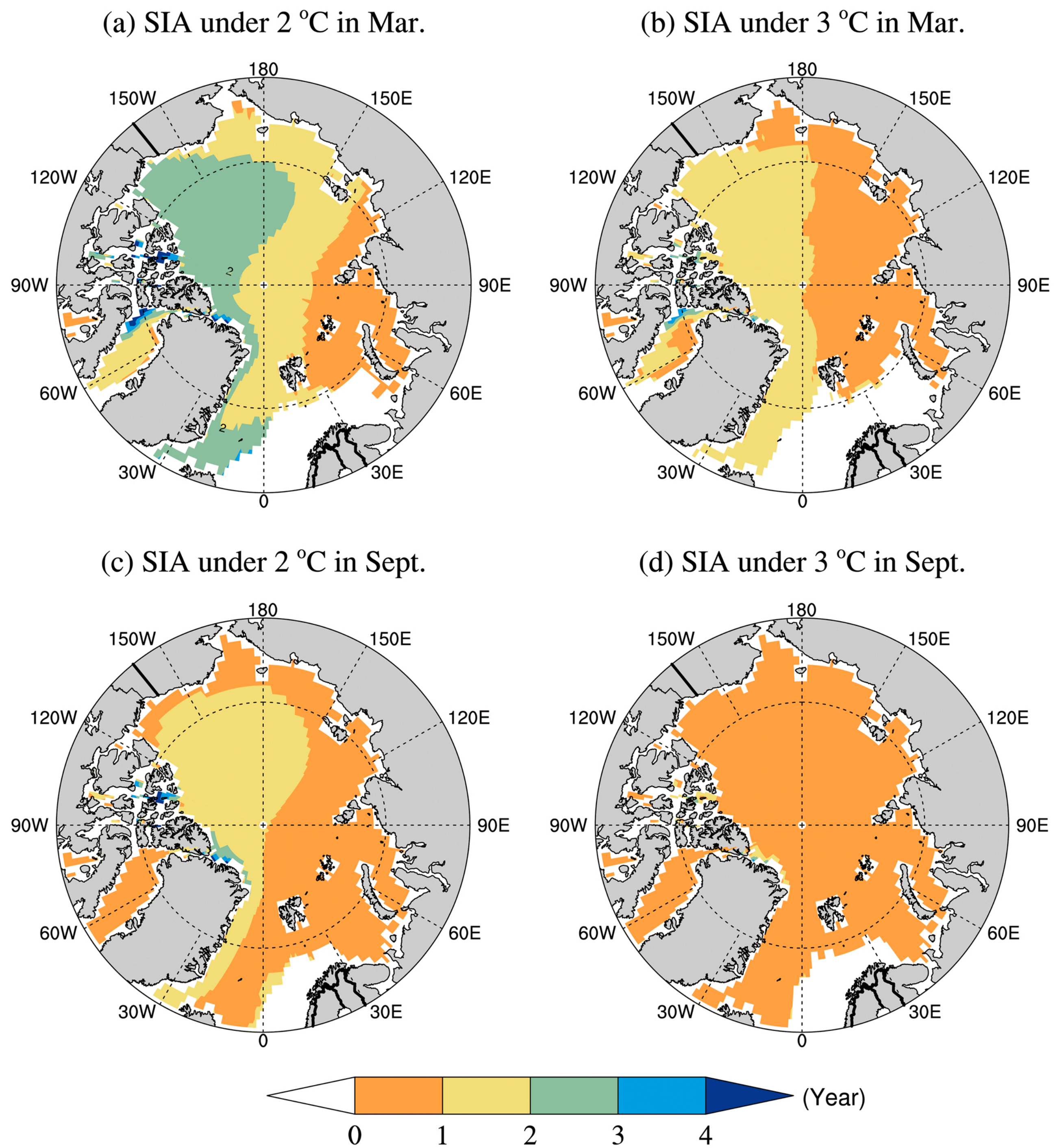

Fig. 4. The distribution of sea ice age (SIA) in the Arctic in March and September under global warming of 2 °C and 3 °C, respectively.

and observations greater than 0.8 for the month of September. The models passing the test are ACCESS-ESM1–5, CESM2, CESM2-WACCM, MPI-ESM1–2-HR, MPI-ESM1–2-LR, MRI-ESM2–0, NorESM2-LM, and NorESM2-MM. However, sea ice age has only been released for CESM2-WACCM, NorESM2-LM, and NorESM2-MM. To further reduce the uncertainty in the models, the following algorithm further constrains the simulated sea ice concentration, sea ice thickness, and sea ice age (Melia et al., 2015):

$$M_{cor} = (M_{ori} - \widetilde{M_{ori}}) * \frac{\sigma_{O-hist}}{\sigma_{M-hist}} + \widetilde{M_{ori}} * \frac{\overline{O_{\mathrm{hist}}}}{\overline{M_{hist}}} \quad (1)$$

where $M_{cor}$and M_{ori} are the corrected and original model outputs from 1979 to 2100, respectively. $\widetilde{M_{ori}}$ is the 11-year running mean of M_{ori}. $\overline{O_{\mathrm{hist}}}$ and $\overline{M_{hist}}$ are the time means of the observations and simulations during the historical period (1979–2014), respectively. σ_{O-hist} and σ_{M-hist} are the standard deviations of the detrended observations and simulations, respectively. We normalized the spatial resolution of the models to $1^\circ \times 1^\circ$ by bilinear interpolation. Multi-model ensemble means of the surface air temperature (2 m), sea ice thickness, sea ice concentration, and sea ice age were then generated under global warming of 2 ℃ and 3 ℃, respectively.

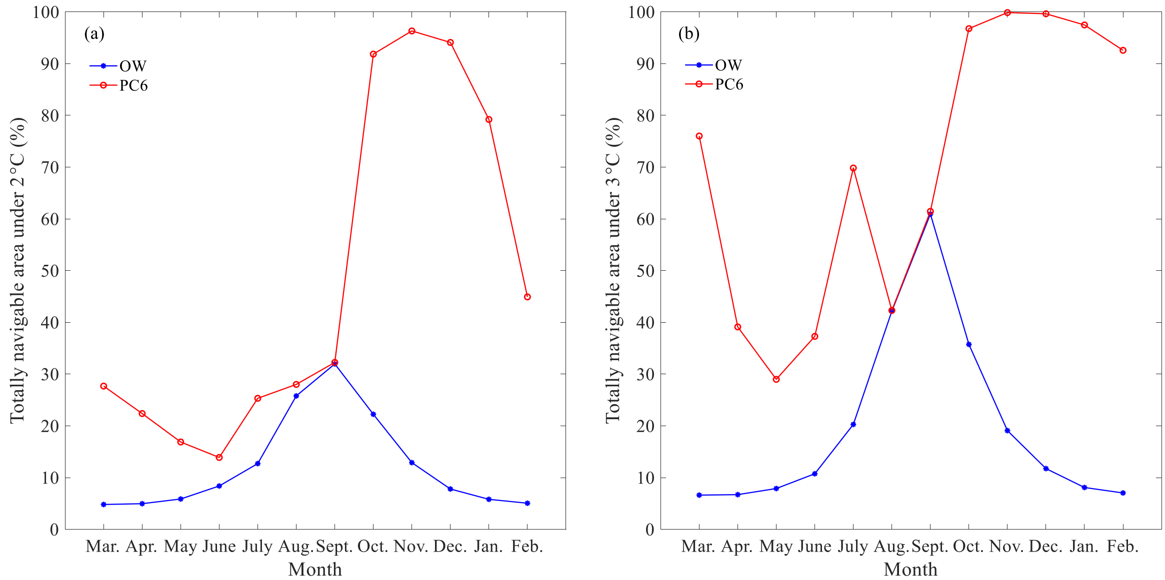

Fig. 5. The percentage of navigable grids for OW ships and PC6 ships in the Arctic under global warming of 2 ℃ and 3 ℃, respectively.

2.4. Evaluation of navigability

Sea ice conditions and the ice-breaking ability of ships are two factors mainly considered in evaluations of navigability (Smith and Stephenson, 2013). Sea ice conditions usually indicate the sea ice thickness and sea ice concentration. The ice-breaking ability of ships refers to the international ship classification system, such as POLARIS and the Arctic Transportation Accessibility Model. POLARIS was adopted by the International Maritime Organization in the International Code for Ships Operating in Polar Waters to assess the navigability of a ship in the Arctic (Deggim, 2018). It is an evaluation of the risks posed to a ship by ice conditions in relation to the ship's assigned ice class. A Risk Index Outcome (RIO) in formula (2) is assigned to a ship based on the ice class and ice types. It has adopted the management concepts of the Canadian Arctic Ice Navigation System and the Russian Ice Navigation Permit and introduced the management experience of other maritime traffic and coastal management agencies.

$$RIO_V = \sum C_T \times RV_{V,\quad T} \tag{2}$$

T refers to different types of sea ice, which is divided by sea ice thickness in Table 2. C_T is the concentration of T-type sea ice. $RV_{V,\ T}$ is the risk value of a V-type ship under T-type sea ice and ranges from − 6–3. A negative value indicates high navigable risk and that a ship is not suited for navigation. A positive value indicates navigability, and a higher value represents higher navigability. This study investigated the navigability of OW ships and PC6 ships without the assistance of ice breakers. Open water ships and PC6 ships are vessels without ice strengthening and moderate strengthening, respectively (IMO, 2002; Stephenson et al., 2013). The corresponding risk values for OW ships and PC6 ships are shown in Table 2.

3. Results

3.1. Surface air temperature

As shown in Fig. 2, most regions are covered by subzero temperatures in March. The cold center is always in Greenland under the two warming scenarios. The surface air temperature is also very low within the Canadian Arctic Archipelago, but it eases in the southern part and the water along the Parry Channel (Fig. 1) under the 3 °C period. The southeastern Greenland Sea has positive temperatures under the 2 °C period and expands to the southeastern Barents Sea (Fig. 1) under the 3 °C period.

Meanwhile, the temperature also rises in the seas along the Northern Sea Route (Fig. 1). The water south of the New Siberian Islands, Severnaya Zemlya, Franz Josef Land, and Svalbard exceeds zero degrees in September under 2 °C warming (Fig. 1), but the Parry Channel is still covered by subzero temperatures. With the increase in temperature, the positive surface air temperature runs north under 3 °C warming. The negative temperatures are only concentrated in the Arctic basin, the northern part of the Canadian Arctic Archipelago, and Greenland. The navigability of the Arctic passages would improve with the shrinkage and retreat of cold areas. The Northern Sea Route (Fig. 1) therefore might provide more choices for routes, and the Parry Channel (Fig. 1) might be accessible in September under 3 °C warming.

3.2. Future changes in sea ice

The spatial characteristics of sea ice concentration and sea ice thickness (Fig. 3) provide a picture of the future sea ice conditions in the Arctic under global warming of 2 °C and 3 °C. The sea ice concentration is more than 20% lower in the seas along most routes of the Northern Sea Route and the Northwest Passage (Fig. 1). The concentration is still more than 30% in the Parry Channel during the 2 °C period. The Arctic Ocean north of Greenland and the water within the Queen Elizabeth Islands (Fig. 1) have a large sea ice concentration of more than 40%. With continued global warming, the sea ice concentration dramatically decreases to less than 20% in the Arctic. It will be close to 0 in coastal areas. In most seas along the Northern Sea Route and the Northwest Passage, the concentration of sea ice is lower than 5% under 3 °C warming.

The thickness of sea ice is small in the Arctic Ocean. It is very large, however, in a band starting from the seas around the Beaufort Sea to the waters north of the Canadian Arctic Archipelago and Greenland. Sea ice around the New Siberian Islands, Franz Josef Land, and Svalbard also has a large thickness. This thickness might affect the navigability of some straits, such as the Sannikov Strait and Dmitrii Laptev Strait. The thickness of the sea ice is not conducive to the opening of the Arctic passages, especially to the Northwest Passage. The situation for passage improves under 3 ℃ warming. Sea ice thickness is small in the seas in northern Europe, but it is still large in the eastern Beaufort Sea and the water within the Canadian Arctic Archipelago. This scenario means that ice conditions remain severe in the Northwest Passage.

The structure of the sea ice age changes with increasing air

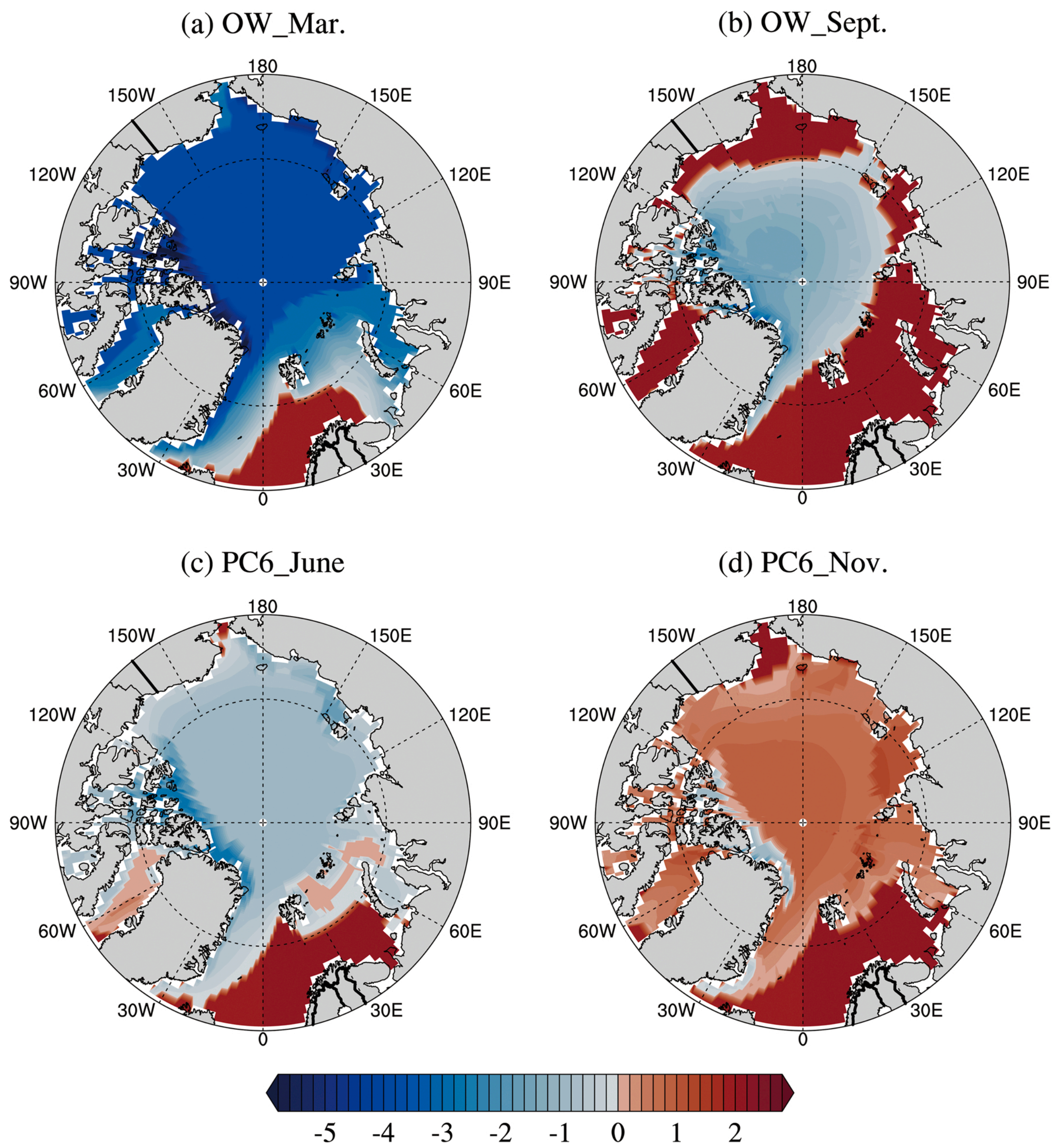

Fig. 6. Risk index outcomes for OW ships and PC6 ships in corresponding minimum and maximum navigable months, respectively, under global warming of 2 ℃.

temperature and decreasing thickness of the sea ice. Researches have indicated that the cover of sea ice would remain younger and thinner than during the 1980 s, 1990 s, and early 2000 s (AMAP, 2021). As shown in Fig. 4, sea ice more than 3 years old occurs only in some straits within the Canadian Arctic Archipelago in March under 2 °C warming. Ice with an age of 2 − 3 years mainly is found in part of the Arctic Ocean near the northern Beaufort Sea and in water north of the Canadian Arctic Archipelago. In addition, in March, the waters to the north and east of Greenland have ice that older than 2 years. Except for some small waters within the Queen Elizabeth Islands and north of Greenland, the Arctic is covered by ice less than 2 years old both in March under 3 °C warming and in September under 2 °C warming. Ice with ages of 1-year and 2-years mainly occur in the waters of the European and North American sides, respectively. Under global warming of 3 °C, the Arctic is almost dominated in September by ice less than 1 year in age. The decreasing age of the sea ice is favorable for opening the Northern Sea Route and Northwest Passage; however, the Northern Sea Route has better ice conditions than that of the Northwest Passage.

3.3. Future navigability in the arctic

The percentage of accessible areas for the different types of ships indicates the navigable potential of the Arctic. As shown in Fig. 5, the navigable area represents the percentage of grids where the Risk Index Outcome (RIO) is equal to or greater than 0 for the total grids in the Arctic. The navigable areas for OW ships are shown as a unimodal curve under 2 ℃ and 3 ℃, with a peak in September (32.0% and 60.9%, respectively) and a valley in March (4.8% and 6.6%, respectively). The time of the maximum navigable area for PC6 ships, however, extends to December (96.3% and 99.9%, respectively). The times of the minimum navigable area is in June (13.9%) and May (29.0%) under global warming of 2 ℃ and 3 ℃, respectively.

Compared with OW ships, the peaks and valleys of PC6 ships are hysteretic, but the navigable potential is still large in other months. For PC6 ships, navigability greatly improves from December to June with increasing temperature but for OW ships, it remains very small. In addition, the navigable potential of PC6 ships rapidly increases from

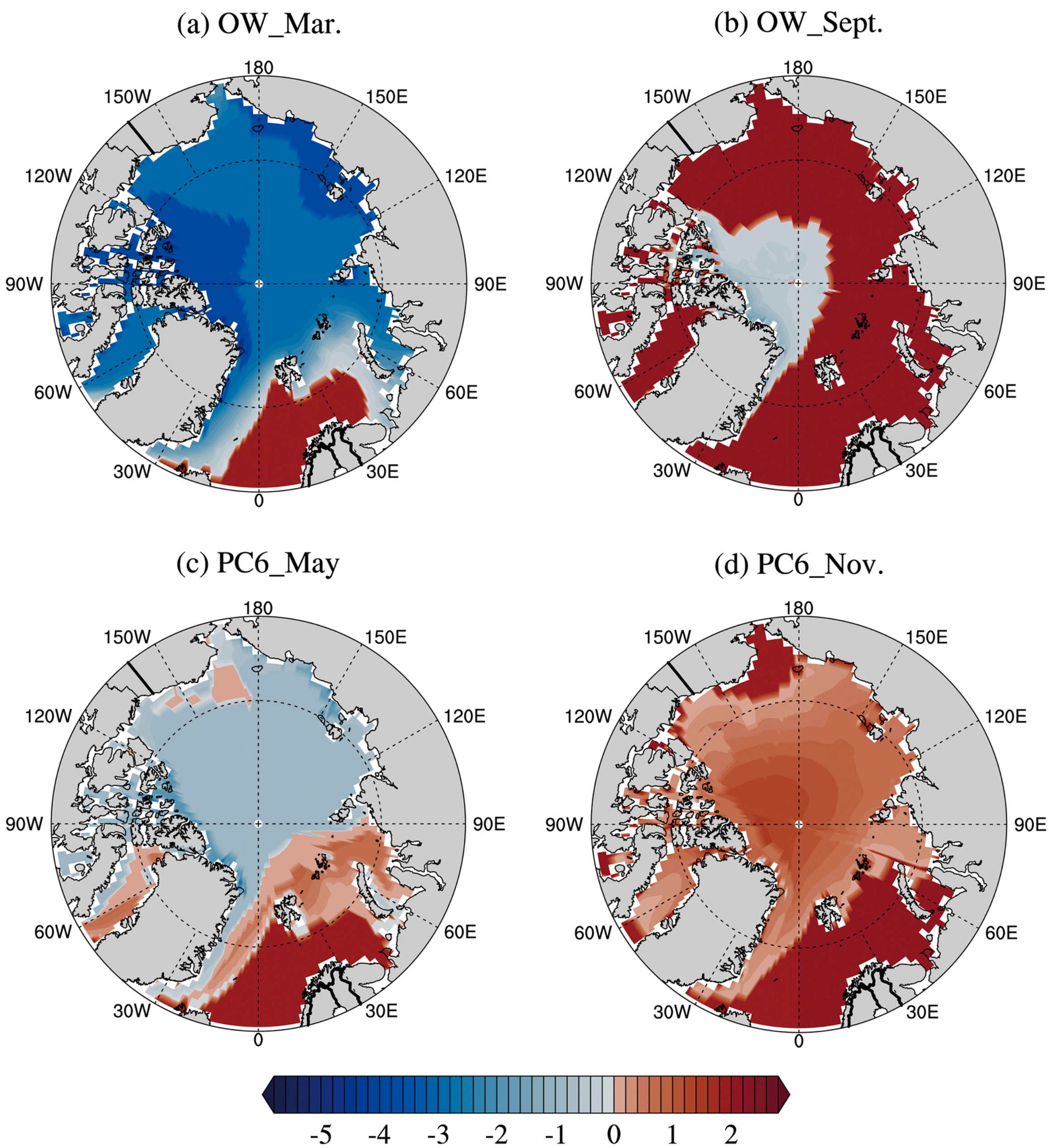

Fig. 7. Risk index outcomes for OW ships and PC6 ships in corresponding minimum and maximum navigable months, respectively, under global warming of 3 ℃.

September to October. This increase may be attributable to the degeneration of 1st year and 2nd year sea ice to the medium 1st year ice in October. The degeneration may last until December and February during the 2 °C and 3 °C periods, respectively. Under global warming of 2 °C, more than 80% of the Arctic area will be navigable for PC6 ships from October to December due to the accessibility of the Northern Sea Route and Northwest Passage. This scenario could extend from October to February during the 3 °C period.

As shown in Figs. 6 and 7, OW ships are incapable of passing any Arctic routes in March under global warming of 2 ℃. The same scenario applies to PC6 ships in June. Most regions in the Laptev Sea, Kara Sea, and Barents Sea along the Northern Sea Route and the Beaufort Sea along the Northwest Passage (Fig. 1), however, will be on the verge of accessibility for PC6 ships.

September is the most likely navigable window for OW ships, as the ice situation is optimistic for them during the 2 °C period. Some areas, however, are still impassible. The inaccessible areas along the Northern Sea Route are mainly in the East Siberian Sea and waters north of the New Siberian Islands, Severnaya Zemlya, Franz Josef Land, and Svalbard (Fig. 1). Crucial straits, such as the Shokalskiy Strait and Vilkitskty Strait, optimistically have favorable ice conditions.

However, the Northwest Passage is impassable for OW ships in most straits within the Canadian Arctic Archipelago, although in November ships in Polar Class 6 seem unimpeded along the Northern Sea Route and Northwest Passage. Open water ships are still not passable through the Arctic passages in March under global warming of 3 °C. Compared with the 2 °C warming, during the 3 °C period, the East Siberian Sea, Laptev Sea, Kara Sea, and Barents Sea along the Northern Sea Route are navigable in September. The Northwest Passage should be accessible, though navigation would require care due to complex sea ice conditions in the straits within the Canadian Arctic Archipelago, especially in the Parry Channel. The Arctic passages are not passable to ships in Polar Class 6 in May, though the sea ice conditions have improved. The Risk Index Outcome scores are close to 0 overall. This scenario indicates that the opening of the Arctic passages could occur in the near future. All the routes along the Northern Sea Route and Northwest Passage are accessible for PC6 ships in November. The open window may extend from October to January, when navigability is nearly 100%, for navigable areas of the Arctic.

4. Discussion

Projections of sea ice future changes and Arctic navigability under global warming of 2 ℃ and 3 ℃ may serve as a reference to gain better knowledge of climate change influences in the Arctic. Such knowledge can help plan shipping enterprises, including the dates and routes of navigation. The Polar Operational Limit Assessment Risk Indexing System, however, upon which this study is based, only takes into account the thickness and concentration of sea ice. Insufficient classification and low resolution (one value in one grid) were therefore limiting. In addition, the absence of some potential factors, such as the real-time conditions of sea ice (ice roughness and ice lanes), the real-time sea state (seawater depth, channel width, wind speed, and sea fog), and ship conditions (tonnage of ship and depth of immersion), reduces the practical application value of this model. In addition, current climate models are conservative regarding the parameters of sea ice, and the results (especially for multiyear ice) vary widely (Bateson et al., 2020). The future navigation potential might therefore be underestimated with great uncertainty.

A long-range statistical projection suggested an almost 60% chance of an effectively ice-free Arctic Ocean sometime during the 2030 s (Diebold and Rudebusch, 2021). This is much earlier than the average projection from the global climate models. Geopolitics and ecological and environmental risks also affect the development of the Arctic passages (Bennett et al., 2020). The economic and environmental benefits and risks associated with opening Arctic routes are controversial, however (Cheaitou et al., 2020). Further studies to assess the comprehensive influence of the potential risks and benefits of shipping routes are necessary.

Observations from remote sensing of sea ice and sea state parameters with high spatial and temporal resolutions are also important in Arctic shipping operations. It can help to obtain the transient ice cover, the complexity of ice changes, and the rapid changes in sea state (Hui et al., 2017). Therefore, the development of ice satellite constellations dedicated to observations of polar region should be considered for multi-parameter observations and inversions with a large range and high spatial and temporal resolutions. The results from the satellites can be integrated with advanced ice navigation risk assessment models to support accurate and rapid assessment of navigational risks to ships and provide decision support for commercial shipping activities (Lensu and Goerlandt, 2019).

5. Conclusion

Analyses of sea ice changes and Arctic passage navigability under global warming of 2 °C and 3 °C provide answers to the research questions posed in this paper. First, the findings show that, under global warming of 2 °C, the cold center consistently occurs in Greenland in March. Warm waters, with a lower concentration of sea ice, occur in the Seas along the Northern Sea Route and the Beaufort Sea and southern Canadian Arctic Archipelago along the NWP in September. The thickness of sea ice is large, however, in the Beaufort Sea and the waters north of the Canadian Arctic Archipelago and Greenland. The warm region runs north and is mainly controlled by sea ice less than 2 years old under 3 °C warming. The concentration of sea ice and thickness dramatically decrease in the coastal seas.

Second, with respect to the navigability of the Arctic passages for open water ships and Polar Class 6 ships, OW ships are incapable of passing the Arctic passages under global warming of 2 °C. The difficulties arise in the East Siberian Sea and the Canadian Arctic Archipelago due to ice conditions. However, under 3 ℃ warming. The Northern Sea Route opens for several months around September. During the 2 °C warming, ships in Polar Class 6 can most likely pass in the Arctic Ocean from October to December. The navigable period increases under global warming of 3 °C.

These findings provide a benchmark for possible changes in sea ice and the navigability of the Arctic in response to global warming. Even with uncertainty in the model projections, such knowledge is useful for planning future possibilities in terms of transportation, shipping routes and dates. Such information is especially helpful under a rapidly changing and uncertain future.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Declaration of Competing Interests

The authors declare that they have no conflict of interest.

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