LETTER

Projections of Arctic sea ice conditions and shipping routes in the twenty-first century using CMIP6 forcing scenarios

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Abstract

The accelerated decline in Arctic sea ice in recent decades suggests the possibility of future trans-Arctic shipping routes linking the Atlantic and Pacific oceans, with significant implications for the global economy. We present a projection of Arctic sea ice conditions and shipping activities during the 21st century based on 16 CMIP6 models calibrated to remove spatial biases. The multimodel ensemble mean shows that the Arctic is likely to be ice-free in September by 2076 and 2055 under the SSP2-4.5 and SSP5-8.5 scenarios, respectively, whereas the extent of sea ice is >2 × 10^6 km^2 throughout the 21st century under the SSP1-2.6 scenario. The Arctic sea ice in September thins over time, leading to a reduction in the area with an ice thickness >120 cm (i.e. the threshold over which sea ice is inaccessible to Type A vessels) by 34−100% by the late 21st century (2086−2100) under the three scenarios. Given the declines in the extent and thickness of sea ice, the most commonly traversed route along the North West Passage tends to migrate from the southern to the northern route during the 21st century. The optimum route along the Northern Sea Route shifts northward with time, with the Transpolar Sea Route becoming available. Quantitatively, the maritime accessibility to Type A vessels via the Transpolar Sea Route increases from ~6.7, 4.2 and 2.1% in 2021−2035 to 14.7, 29.2 and 67.5% in 2086−2100 under the SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios, respectively. The season for trans-Arctic shipping extends from 5 to ~7.5 (9) months by the late 21st century under the SSP1-2.6 (SSP2-4.5) scenario and the Arctic becomes navigable all year round under the SSP5-8.5 scenario. These findings may aid in developing strategic planning by governments for the Arctic and providing strategic advice for the global maritime industry.

1. Introduction

One of the most dramatic effects of global warming is the accelerated decline in Arctic sea ice, with a rate of ~13% per decade in September during the time period 1979−2017 (Serreze and Meier 2019). The projections of climate models under a high emissions scenario indicate that the decreasing trend is likely to continue, leading to a seasonally ice-free Arctic Ocean around the middle of the 21st century or even earlier (Massonnet et al 2012, Wang and Overland 2012, Liu et al 2013, Melia et al 2015, Senftleben et al 2020). This reduction in Arctic sea ice has far-reaching effects on the global climate system and human activities. In particular, the decline in sea ice favours the establishment of new trade passages across the Arctic as a result of its influence on navigation routes (e.g. Stephenson et al 2011, Smith and Stephenson 2013, Melia et al 2016). These potentially new routes use the Arctic Ocean as the shortest maritime link between North Atlantic and Asia Pacific ports, saving shipping times and reducing fuel consumption.

The Northern Sea Route (NSR) along the Russian coast and the Northwest Passage (NWP) through the Canadian Arctic Archipelago are currently the fastest maritime routes between North Atlantic and Asia Pacific ports. Based on the recorded density of ships in the Arctic, there was an increase in transit
traffic through the NSR and NWP from 2010 to 2014 (Eguíluz et al., 2016), although Arctic shipping is seasonal and experiences large interannual variations. Efforts have been made to predict the variation in Arctic shipping routes in the 21st century based on simulations from the Coupled Model Intercomparison Project Phase 3 (CMIP3) and Phase 5 (CMIP5). It has been widely suggested that the decline in sea ice has enabled the establishment of robust transoceanic routes in the Arctic (Stephenson et al., 2011, Smith and Stephenson 2013, Melia et al., 2016), with an expanded and even year-round sailing season (Khon et al., 2016, Stephenson and Smith, 2015, Melia et al., 2016). Future reductions in sea ice will make travel faster and increase access to Arctic resources and exclusive economic zones (Stephenson et al., 2013, Melia et al., 2016, Aksenov et al., 2017).

The projected sea ice extent and shipping routes are dependent on both the model and scenario used (Stephenson and Smith, 2015, Melia et al., 2016). Sea ice projections from climate models participating in CMIP6 have recently been released. CMIP6 includes the latest generation of comprehensive earth system models (Eyring et al., 2015), with improved physical processes and/or a higher horizontal resolution relative to the CMIP5 models. This may facilitate the analysis of sea ice over narrow straits (e.g. near the Queen Elizabeth Islands) and provide additional information about shipping activities (Stephenson and Smith, 2015). CMIP6 uses the Shared Socioeconomic Pathways (SSPs) scenarios generated with updated versions of integrated assessment models and emissions datasets (O’Neill et al., 2016). These newly developed scenarios cover a wider range of warming responses than the Representative Concentration Pathways (RCPs) used in CMIP5 (Tokarska et al., 2020). It is therefore meaningful to examine how Arctic shipping routes may vary in the 21st century using the latest CMIP6 projections.

Most of the CMIP5 models show a clear bias in reproducing the present day sea ice conditions in terms of both temporal variability and spatial patterns (Shu et al., 2014, Stroeve et al., 2014, Melia et al., 2015), which may introduce large uncertainties in future projections. The CMIP6 models show similar skills to the CMIP5 models in depicting the observed decreasing trend in Arctic sea ice (Shu et al., 2020), but perform better in estimating the sensitivity of Arctic sea ice to CO2 emissions (SIMIP Community, 2020). The performance of CMIP6 models in depicting the spatial patterns of the extent and thickness of sea ice remains elusive. It is important to further assess the spatial biases in CMIP6 models and to correct them, which will help to increase the robustness of the projections for the extent and thickness of sea ice and hence shipping routes (Melia et al., 2015, 2016).

Here, we investigate the evolution of Arctic sea ice conditions in the 21st century and the accessibility of trans-Arctic shipping under the SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios based on 16 climate models in CMIP6. The remainder of this paper is organized as follows. We briefly introduce the datasets and methods used in this study in section 2. Section 3 evaluates the performance of the climate models and uses a statistical bias correction procedure to reduce the spatial bias in the models. The future evolution of the extent and thickness of Arctic sea ice and shipping routes are presented in section 4 based on these bias-corrected simulations. We summarize and discuss our results in section 5.

2. Methodology

2.1. Model outputs

Table 1 lists the 16 climate models in CMIP6 used here. These models are selected based on the following criteria: (i) the model currently provides the outputs of both sea ice thickness (SIT) and sea ice concentration (SIC) and (ii) these two variables are currently available for both the historical simulations (1979–2014) and future simulations (2015–2100) under all the SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios. Note that several models listed in table 1 come from the same institution and hence are not fully independent. SSP1-2.6 represents the low end of the range of future forcing pathways and updates the RCP2.6 pathway used in CMIP5. It is anticipated that SSP1-2.6 will produce a warming of <2 °C relative to pre-industrial temperatures by 2100. SSP2-4.5 and SSP5-8.5 are the middle and high end of the range of future forcing pathways, respectively, updating the RCP4.5 and RCP8.5 pathways. For each model, the monthly outputs of SIC and SIT are converted to a resolution of 25 × 25 km using nearest-neighbour interpolation to facilitate model–data and model–model comparisons.

2.2. Taylor diagram

We use a Taylor diagram to assess the capability of the CMIP6 models in simulating the present day Arctic sea ice conditions. The Taylor diagram provides a statistical summary of how closely the modelled spatial patterns match the observations (Taylor, 2001). The similarity between the simulations and observations is measured by the spatial correlation, the centred root-mean-square error, and the normalized standard deviation (i.e. the ratio of their variances). The pattern correlation between simulations and observations is given by the azimuthal position in a Taylor diagram. The centred root-mean-square error is proportional to the distance to the REF point (i.e. observations) on the x-axis and the standard deviation is proportional to the radial distance from the origin. In general, the simulated patterns that match well with the observations lie nearest to the REF point.

The observations used to assess the model outputs include the SIC from the National Snow and Ice Data Center (Meier et al., 2013) and the SIT from the
Table 1. Basic information about the 16 CMIP6 models used in this study.

| Model                | Sea ice component | Spatial resolution                                      |
|----------------------|------------------|--------------------------------------------------------|
| ACCESS-CM2           | CICE5.1.2        | Tripolar (primarily 1°); 360 × 300 (longitude × latitude) |
| ACCESS-ESM1-5        | CICE4.1          | Tripolar (primarily 1°); 360 × 300 (longitude × latitude) |
| CESM2                | CICE5.1          | 320 × 384 (longitude × latitude)                        |
| CESM2-WACCM          | CICE5.1          | 320 × 384 (longitude × latitude)                        |
| EC-Earth3            | LIM3             | Tripolar (primarily 1° with meridional refinement down to 1/3° in the tropics); 362 × 292 (longitude × latitude) |
| EC-Earth3-Veg        | LIM3             | Tripolar (primarily 1° with meridional refinement down to 1/3° in the tropics); 362 × 292 (longitude × latitude) |
| GFDL-CM4             | GFDL-SIM4p25     | Tripolar (nominal 0.25°); 1440 × 1080 (longitude × latitude) |
| GFDL-ESM4            | GFDL-SIM4p5      | Tripolar (nominal 0.5°); 720 × 576 (longitude × latitude) |
| IPSL-CM6a-LR         | NEMO-LIM3        | Tripolar (primarily 1°); 362 × 332 (longitude × latitude) |
| MIROC6               | COCO4.9          | Tripolar (primarily 1°); 360 × 256 (longitude × latitude) |
| MPI-ESM1-2-HR        | Unnamed          | Tripolar TP04 (~0.4°); 802 × 404 (longitude × latitude) |
| MPI-ESM1-2-LR        | Unnamed          | Bipolar GR1.5 (~1.5°); 256 × 220 (longitude × latitude) |
| MRI-ESM2-0           | MRI.COM4.4       | Tripolar (primarily 0.5° latitude/1° longitude with meridional refinement down to 0.3° within 10° north and south of the equator); 360 × 364 (longitude × latitude) |
| NESM3                | CICE4.1          | 384 × 362 (longitude × latitude)                        |
| NorESM2-LM           | CICE             | −1°; 360 × 384                                          |
| NorESM2-MM           | CICE             | −1°; 360 × 384                                          |

Pan–Arctic Ice Ocean Model and Assimilation System (Zhang and Rothrock 2003). The SIC datasets are provided as monthly values from 1979 to the present day on a polar stereographic projection (25 × 25 km). The SIT datasets have a resolution of ~20 km during the time period 1978—present, which agree well with in situ observations and submarine, airborne and satellites measurements (Schweiger et al 2011).

2.3. Correction of model bias

To reduce the uncertainty in the models, we constrain the simulated SIC and SIT to observations using the methods developed by Melia et al (2015):

\[
M^* = (M - M) \frac{\sigma_{Oh}}{\sigma_{MB}} + M \frac{\bar{Oh}}{\bar{MB}}.
\]

where \( M^* \) and \( M \) are the corrected and original model outputs from 1979 to 2100, respectively, \( \bar{M} \) is the 11-year running mean of \( M \), \( \bar{Oh} \) and \( \bar{MB} \) are the time mean of the observations and simulations during the historical period (1979–2014), respectively, and \( \sigma_{Oh} \) and \( \sigma_{MB} \) are the standard deviation of the detrended observations and simulations during the time period 1979–2014, respectively. This technique has been proved to successfully remove the spatial biases in climate models (Melia et al 2015).

2.4. Calculation of shipping routes

Arctic shipping routes are computed in two steps: (1) calculating the technical accessibility to shipping and (2) finding the fastest Arctic route. In the first step, we use the methods of Stephenson et al (2011) to calculate the technical accessibility to shipping, which is determined by the SIT and the capability of the vessel. Specifically, the ability of a ship to enter a particular ice regime can be estimated by the ice number (IN):

\[
IN = \sum_{i=1}^{n} (C_i \times IM_i),
\]

where \( C_i \) is the concentration in tenths of ice type \( i \) and \( IM_i \) is the ice multiplier of ice type \( i \). Sea ice is classified into six types based on its thickness, including grey ice (10–15 cm), grey–white ice (15–30 cm), thin first-year first stage ice (30–50 cm), thin first-year second stage ice (50–70 cm), medium first-year ice (70–120 cm) and thick first-year ice (>120 cm). We focus here on Type A commercial cargo-carrying ships, which are nominally equivalent to the moderately ice-strengthened Polar Class 6 vessel in accordance with Polar Class nomenclature (IMO 2002) and may proceed freely through all first-year ice and some older ice types in a controlled manner. Ice multipliers for Type A vessels are dependent on the type of ice and range from 2 to −4 (Transport Canada 1998). Using the SIC and SIT from each model under each scenario, the IN is calculated for each grid at monthly intervals from 2015 to 2100. Areas with non-negative IN values are identified as accessible to Type A ships.

We then calculate the navigation paths for the NWP, NSR and the Transpolar Sea Route (TSR). The NWP is assumed to run from Halifax to the Bering Strait, with the NSR and the TSR running from Rotterdam to the Bering Strait. The ship travel time is computed for all accessible grids using the IN–vessel speed relationships (Mccallum 1996). We then use the least-cost path algorithm in a geographical information system to obtain the optimum navigation route that accumulates the shortest travel time between the origin and destination.
3. Model evaluation and bias correction

To ensure the reliability of future projections, it is crucial to evaluate the performance of the CMIP6 models in capturing the observed spatial distribution of Arctic sea ice. The Taylor diagram shows that most of the CMIP6 models have limited skills in reproducing the distributions of SIC and SIT in September (figure 1). Most of the CMIP6 models overestimate the amplitude of the observed variation in SIC (i.e. a larger standard deviation; figure 1(a)), especially the ACESS-CM2, ACESS-ESM1-5, EC-Earth3, EC-Earth3-veg and NorESM2-MM models, producing an almost two-fold variance compared with the observations. Fourteen of the 16 models show a centred root-mean-square error >0.5 (>1 in five models), although the pattern correlation is relatively high. There is a large spread in the capability of CMIP6 models in predicting the SIT (figure 1(b)). The spatial correlation coefficients between the simulations and observations range from <0.1 (CESM2 and EC-Earth3-veg) to >0.85 (MIROC6 and MPI-ESM1-2-HR). However, all 16 CMIP6 models predict a relatively large centred root-mean-square error (>0.5), among which seven models have a root-mean-square error >1.

We examine the mean bias in the CMIP6 models, which is defined as the difference in SIC/SIT averaged over the Arctic between the simulations and observations and is not quantified in the Taylor diagram. Table 2 shows that the CMIP6 models largely underestimate the September SIC over the Arctic by ~22.6%−73.8% and show large biases in the SIT ranging from −87.3 to +160.9%. Even for the multimodel ensemble mean, the CMIP6 models produce virtual sea ice in September around the Bering, Norwegian and Labrador seas, but underestimate the SIC over the central Arctic (figures 1(c), (d)). The September SIT is much thicker over the Beaufort Sea, the East Siberian Sea and the Canada Basin in the multimodel ensemble mean (figures 1(f), (g)). Overall, these results indicate that most of the CMIP6 models have limited skills in reproducing the spatial patterns of the climatological Arctic sea ice.

We performed a statistical correction to reduce the spatial biases in the CMIP6 models. According to the Taylor diagram (figures 1(a), (b)), the capability of the bias-corrected models is significantly improved compared with the uncorrected models, with a greatly reduced model spread. The spatial correlation coefficients between the bias-corrected models and the observations reach >0.9 for both the SIC and SIT, with a smaller root-mean square error (<0.5) and similar amplitude of variations. The bias in the SIC and SIT reduces remarkably to ~4.4–22.6 and 0.2–22.7%, respectively (table 2). Based on the multimodel ensemble mean, the corrected SIC and SIT clearly remove the spatial biases in the original model outputs, showing a higher spatial consistency with the observations (figures 1(c)–(h)). These results suggest that this correction technique improves the skills of the models. The future projections were therefore also corrected and then used to estimate the evolution of sea ice and shipping routes in the 21st century.

4. Projections of Arctic sea ice and shipping routes

Figure 2 shows the bias-corrected sea ice extent (defined as the total marine area where the SIC ≥ 15%) and the SIT from 1979 to 2100 under different scenarios. Under the scenarios with high CO2 emissions and limited climate change mitigation (i.e. SSP5-8.5 and SSP2-4.5), global warming leads to a rapid decline in sea ice in the 21st century (figures 2(a), (c)). Based on the multimodel ensemble mean, Arctic summers are probably ice-free by 2055 and 2076 under the SSP5-8.5 and SSP2-4.5 scenarios, respectively. The projected ice-free conditions around the 2050s under the SSP5-8.5 scenario are similar to the timing predicted by the CMIP5 models under the RCP8.5 scenario (Liu et al 2013, Melia et al 2013, Senfleben et al 2020). If we use the multimodel ensemble mean of the uncorrected models, then the disappearance of Arctic sea ice occurs 18 years later under the SSP5-8.5 scenario. By contrast, the Arctic sea ice in September reduces to ~2 × 106 km2 by 2100 under the SSP1-2.6 scenario with substantial reductions in emissions and hence is unlikely to disappear. However, there is a large spread in the projected extent of sea ice in the 21st century. For example, the timing of ice-free conditions spans from 2028 to 2077 under the SSP5-8.5 scenario and from 2035 to later than 2100 under the SSP2-4.5 scenario.

The September SIT shows a modest decreasing trend during the 21st century based on the multimodel ensemble mean under the SSP5-8.5 scenario (figure 2(b)), whereas no clear long-term trend is observed under the SSP2-4.5 and SSP1-2.6 scenarios. The projected SIT has a reduced spread across scenarios compared with the evolution of the extent of sea ice, but shows a larger spread across models (figures 2(a), (b)). By the late 21st century (2086−2100), the area that is completely inaccessible to Type A ships (i.e. SIT ≥ 120 cm) reduces from 4.1 × 106 to 2.6 × 106 and 2.7 × 106 km2 in September under the SSP1-2.6 and SSP2-4.5 scenarios, respectively, whereas the Arctic becomes fully open to Type A ships in summer under the SSP5-8.5 scenario (figure 2(d)). The projected rapid thinning and disappearance of sea ice will break geographical restrictions and increase maritime accessibility. Figure 3 shows that the accessibility required for Type A ships to complete trans-Arctic voyages along the NSR, NWP and TSR in September increases in frequency and
expands geographically in the 21st century. Specifically, the optimum September routes along the NSR tend to shift northward away from the Russian Federation coast and the TSR becomes navigable over time. The most commonly traversed route along the NWP gradually changes from the southern route (Lancaster Sound—Barrow Strait—Peel Sound—Franklin Strait—Victoria Strait—Coronation Gulf—Amundsen Gulf) to the northern route (Lancaster Sound—Barrow Strait—Viscount-Melville Sound—M’Clure Strait). The change in the Arctic shipping routes is most remarkable toward 2100 and under a high emissions scenario.

Under the SSP5-8.5 scenario, the probability of a September transit for Type A vessels via the TSR is only 2.1% in the early 21st century (2021–2035), but increases to 67.5% by the late 21st century (2086–2100) (figure 4(a)). The probability reduces to 29.2 and 14.7% by the late 21st century under the SSP2-4.5 and SSP1-2.6 scenarios, respectively. The probability of shipping passing through the TSR in April, when it is most difficult to navigate (e.g. Melia et al 2016), reaches 48.8% by the late 21st century under the SSP5-8.5 scenario (figure 4(b)), whereas the TSR remains almost inaccessible under the SSP2-4.5 and SSP1-2.6 scenarios, with a probability of 13.3

Figure 1. (a), (b) Taylor diagrams summarizing the skill of each model in simulating the present day (1979–2014) spatial pattern of (a) sea ice concentration (SIC) and (b) sea ice thickness (SIT). The standard deviation of the modelled field is the radial distance from the origin and the centred root-mean-square error is the distance to the REF point. The azimuthal position gives the spatial correlation coefficient. A number is assigned to each model, with red colours for the original outputs and blue colours for the corrected outputs. Spatial distribution of the present day SIC in September based on (c) observations and the multimodel ensemble mean of the (d) uncorrected and (e) corrected CMIP6 models. Spatial distribution of the present day SIT in September based on (f) observations and the multimodel ensemble mean of the (g) uncorrected and (h) corrected CMIP6 models.
Table 2. Bias (%) of the CMIP6 models in modelling the present-day SIC and SIT.

| Model            | Original SIC | Corrected SIC | Original SIT | Corrected SIT |
|------------------|--------------|---------------|--------------|---------------|
| ACCESS-CM2       | −54.5        | −13.7         | 31.4         | −4.9          |
| ACCESS-ESM1-5    | −73.8        | −17.3         | 21.7         | −0.2          |
| CESM2            | −66.0        | −22.5         | 35.4         | −8.0          |
| CESM2-WACCM      | −52.8        | −16.4         | 52.5         | −8.2          |
| EC-Earth3        | −41.0        | −10.5         | 160.9        | −0.9          |
| EC-Earth3-Veg    | −44.4        | −12.5         | 137.3        | 13.8          |
| GFDL-CM4         | −25.0        | −9.6          | −84.7        | −5.9          |
| GFDL-ESM4        | −29.6        | −11.7         | −87.3        | −6.4          |
| IPSL-CM6a-LR     | −54.1        | −22.1         | 22.8         | 27.7          |
| MIROC6           | −22.6        | −7.7          | 51.1         | 9.1           |
| MPI-ESM1-2-HR    | −37.6        | −7.7          | −15.8        | 20.7          |
| MPI-ESM1-2-LR    | −32.5        | −4.4          | −3.1         | 16.8          |
| MRI-ESM2-0       | −50.0        | −18.5         | −2.5         | 0.9           |
| NESM3            | −70.1        | −16.9         | −74.9        | −7.5          |
| NorESM2-LM       | −48.9        | −13.3         | 70.3         | −9.0          |
| NorESM2-MM       | −36.3        | −10.5         | 89.8         | −11.0         |

Figure 2. Evolution of sea ice (a) extent and (b) thickness from 1979 to 2100 under different scenarios based on the bias-corrected models. The thick lines during 2015–2100 represent the multimodel ensemble mean, with the vertical lines showing the standard deviation of the 16 CMIP6 models. The black (grey) lines for 1979–2014 show the observed and simulated sea ice extent (thickness). (c) Spatial distribution of modern sea ice concentration (shading). The coloured contours represent the sea ice extent at the end of the 21st century (2086–2100) based on the multimodel ensemble mean under the SSP1-2.6 (red), SSP2-4.5 (green) and SSP5-8.5 (purple) scenarios. (d) Spatial distribution of modern SIT (shading). The coloured contours represent the isolines of 120 cm at the end of the 21st century (2086–2100) based on the multimodel ensemble mean under the SSP1-2.6 (red), SSP2-4.5 (green) and SSP5-8.5 (purple) scenarios.

and 5.8%, respectively. The probability of a September transit through the northern route of the NWP increases from 19.6% in the early 21st century to 76.7% by the late 21st century under the SSP5-8.5 scenario.

In addition to the geographical changes, the shipping season is extended in response to the decline in sea ice. The trans-Arctic routes are generally open for 5 months of the year (from August to December) in 2015 based on the multimodel ensemble mean (figure 4(c)), but are open for ~7.5 and 9 months by the late 21st century (2086–2100) under the SSP1-2.6 and SSP2-4.5 scenarios, respectively. The trans-Arctic routes become navigable all year.
Figure 3. Optimum shipping routes for Type A vessels from Halifax to the Bering Strait (red lines) and from Rotterdam to the Bering Strait (blue lines) under the SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios in the early 21st century (2021–2035), mid-21st century (2051–2065) and late 21st century (2086–2100). Each period includes 15 consecutive Septembers from the 16 CMIP6 models, equating to 240 simulations. The line weights indicate the number of transits using the same route.

Figure 4. (a), (b) Time series of the probability of shipping routes for Type A vessels through the Transpolar Sea Route (TSR) in (a) September and (b) April based on the 16 CMIP6 models under the SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios. The horizontal solid lines show the mean probability in the early 21st century (2021–2035), mid-21st century (2051–2065) and late 21st century (2086–2100). (c) Time series of the months for which the Arctic is accessible to Type A vessels under the SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios. The thick lines show the multimodel ensemble mean and the vertical lines represent the standard deviation.

The shipping season varies greatly across models (figure 5), as seen in the CMIP5 projections (Stephenson and Smith 2015, Melia et al 2016). Under the SSP5-8.5 scenario (figure 5(c)), trans-Arctic routes are open for 12 months by the mid- to late 21st century in 12 CMIP6 models and by the early to mid-21st century in two models (EC-Earth3 and EC-Earth3_veg), whereas they are still inaccessible in April in the GFDL-ESM4 and MPI-ESM1-2-LR models. Under the SSP2-4.5 scenario (figure 5(b)), five of the 16 models predict year-round accessible trans-Arctic routes by the mid- to late 21st century, whereas the remaining models suggest that the routes are still inaccessible for Type A ships in March–April–May by 2100. Most of the CMIP6 models indicate that the shipping season is open for half the year by 2100.
under the SSP1-2.6 scenario (figure 5(a)), but the EC-Earth3 model predicts trans-Arctic routes all year round by 2075.

5. Conclusions

The accelerated decline in Arctic sea ice during recent decades suggests the potential for establishing new trans-Arctic routes and increasing access to natural resources. We studied the evolution of Arctic sea ice conditions and shipping routes for Type A ships in the 21st century under the SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios based on 16 CMIP6 models. Our results show that the CMIP6 models generally show limited skills in reproducing the present day spatial patterns of SIC and SIT, but their performance is significantly improved using a statistical bias correction technique. Based on the multimodel ensemble mean of the bias-corrected simulations, we suggest that the Arctic is likely to be ice-free in September by 2055 under the SSP5-8.5 scenario and by 2076 under the SSP2-4.5 scenario. By contrast, if we reduce global emissions rapidly (i.e. the SSP1-2.6 scenario), Arctic sea ice is unlikely to disappear by the end of the 21st century.
safety (Stephenson et al 2011) area, lengthened sailing season and enhanced ship navigation as a result of a more exposed navigable of accessible trans-Arctic routes varies across models. Also confirmed by the CMIP6 models, but the timing of the TSR becomes accessible by the late 21st century under the SSP5-8.5 scenario.

In the mid-century decreases from ~9 months for Type A vessels to 0% for open water vessels by late 21st century under the RCP8.5 scenario. Stephenson and Smith (2015) suggested that the shipping season by mid-century decreases from ~9 months for Type A vessels to 5 months for open water vessels. Besides, maritime activities also depend on the weather conditions and numerous non-geophysical factors, including economics and infrastructure. More comprehensive projections are therefore needed to develop strategic planning by governments and to provide strategic advice for the global maritime industry.

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Data availability statement

No new data were created or analysed in this study.

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