Major comments

1. There is a mismatch between the vessel class analyzed and the operational/commercial shipping motivation of the paper. The paper is framed around the strategic economic importance of the Port of Churchill and integration into international markets. However, the analysis focuses on Type E vessels, which Figure 2 identifies as pleasure craft and which represent the least ice-capable vessel class considered. This vessel class is not representative of the cargo vessels currently operating in western Hudson Bay and Hudson Strait, nor of Canadian Coast Guard icebreaking vessels that are also in the area. The authors should either provide a stronger justification for why Type E is appropriate for the shipping questions posed in the introduction. Otherwise, the authors should narrow the framing of the manuscript to open-water/non-ice-strengthened vessel accessibility and reframe the need for such a study in the introduction/conclusion, or extend the analysis to one or more vessel classes representative of commercial shipping in the study area. The justification for the vessel class should also appear much earlier in the manuscript, such as in the Introduction or Methods section. (i.e. the current Introduction frames the study for an analysis of vessels in polar classes 2 to 7).

   Thank you for raising this important point. We agree that the selection of Type E (Pleasure Craft) vessels requires further clarification.

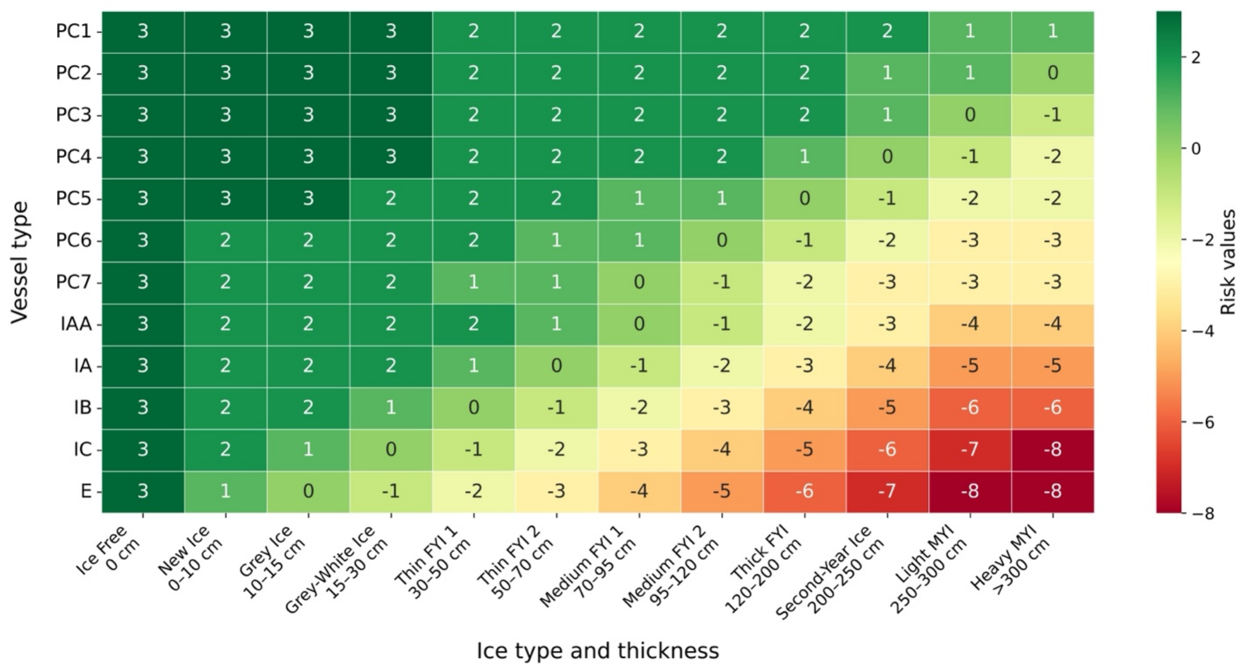
   Type E vessels are indeed the dominant commercial vessel class currently operating at the Port of Churchill during its limited summer operating period. They were selected as a conservative baseline representing ice-free accessibility. The objective is to characterize the period during which the route can be accessed by standard open-water, non-ice-strengthened vessels, rather than to estimate the maximum navigable period achievable by ice-strengthened vessels. (And as shown below, some vessels can already operate year-round along this route under present-day conditions.)

   This distinction is important from an operational and economic perspective. Standard open-water vessels generally have lower construction, operating, and insurance costs than ice-strengthened vessels (Solakivi et al., 2018) found that higher ice-class vessels can involve substantially higher capital and fuel costs and reduced cargo-carrying capacity. Polar Class vessels can cost up to approximately three times as much to build and may carry approximately 20% less cargo than comparable reference vessels. Consequently, although ice-strengthened vessels can operate under more severe ice conditions and therefore have longer navigable periods, their use does not necessarily represent the most economically attractive option for seasonal transportation of commodities such as agricultural products and minerals.

   We have clarified this point in the revised manuscript.

   Line 210: It is noted that Type E vessels are the primary focus of this study as they represent the dominant commercial vessel class currently operating at the Port of Churchill during its short summer season, serving as a conservative baseline for open-water accessibility. Standard non-ice-strengthened vessels generally have lower construction, operating, and insurance costs than ice-strengthened vessels, making them more economically attractive for seasonal shipping (Solakivi et al., 2018). Accordingly, the use of Type E vessels provides a conservative estimate of economically accessible shipping conditions; longer navigable periods are achievable by ice-strengthened vessels

Additionally, based on your comment, we have updated Figure 2 panel (a) and included more vessel types. We have also added results for different vessel types in Section 3.5, along with a new Figure 9.

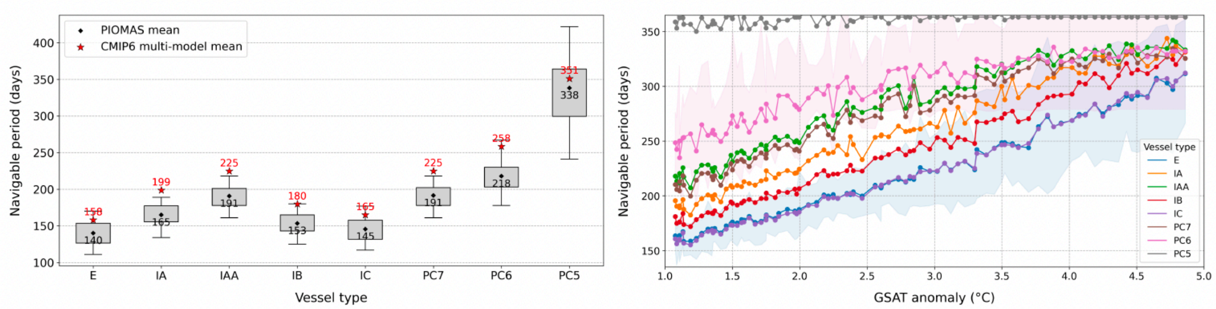


Section 3.5 Navigable Period for Different Vessel Types:

Figure 9 examines how different vessel types affect the NP under historical period (1979–2013; panel a) and future warming levels (panel b) for the Labrador Sea route using the low-risk method.

In panel (a), the CMIP6 multi-model mean NP increases from 158 days for Type E vessels to 225 days for Type IAA vessel, compared with the corresponding PIOMAS means of 140 and 191 days, respectively. The more ice-capable polar classes exhibit substantially longer navigable periods, with PC6 and PC5 reaching 258 and 351 days, respectively, compared with the corresponding PIOMAS means of 218 and 338 days. These results demonstrate that vessel ice capability is an important determinant of historical route accessibility and that the Type E results represent a conservative lower bound on navigability rather than conditions representative of all vessel types.

In panel (b), the NP under the delta-shift bias-corrected CMIP6 multi-model mean for SSP5-8.5 generally increases with GSAT anomaly across all vessel types, although the magnitude of the response varies substantially by vessel type. The least ice-capable Type E vessels show a pronounced increase in NP, from approximately 160 days at 1.0–1.5°C warming to more than 300 days at 4.5–5.0°C, indicating a transition toward near year-round accessibility under high-end warming. Intermediate vessel classes (IA, IAA, IB, and IC) also exhibit progressively longer NPs, while the more ice-capable PC classes maintain substantially longer navigation windows throughout the warming level, with PC5 remaining close to year-round accessibility. Vessel types with greater ice capability than PC5 (PC4 to PC1) reach year-round accessibility and are therefore not shown here. Nevertheless, Type E vessels do not achieve continuous navigability under the high-end SSP5-8.5 scenario, indicating that year-round shipping would still require vessels with greater ice capability throughout the 21st century.



(a) Historical navigable period, Labrador Sea

(b) Projected navigable period, Labrador Sea

Fig. 9. Navigable period (in days) for different vessel types in the Labrador Sea using low-risk definition: (a) Historical navigable period during 1979–2013 for the CMIP6 multi-model mean and PIOMAS mean, (b) Projected navigable period under SSP5-8.5 for the delta-shift bias-corrected CMIP6 multi-model mean. The CMIP6 10th–90th percentile range is shown as a shaded area for Type E and PC6 vessels for illustration.

2. Several conclusions concerning higher vessel classes extend beyond the analysis that was performed. In the Discussion, the authors state that "the deployment of higher-class vessels, such as those built to polar standards, would considerably extend the NP since these vessels can navigate through thicker ice without significant difficulty." This has not been quantified in the analysis. I suggest either conducting the analysis for representative higher vessel classes or revising this statement. Similarly, the statement that "even with extreme warming scenarios and the most permissive criteria, ice-strengthened vessels would still be necessary for 12-month shipping along these routes" follows logically from the finding that Type E vessels do not achieve year-round navigability. However, given the operational importance of higher vessel classes in this region, it would be considerably more useful to quantify how the opening date, closing date, and navigable period change across representative Polar Classes. Thank you for your comment. This point has been addressed in our response to the previous comment.

3. The choice of PIOMAS rather than Canadian Ice Service charts as the historical reference for the POLARIS analysis requires more justification. Around line 136, the manuscript states that Canadian Ice Service charts are preferred for operational purposes, but that PIOMAS is preferred for comparison with climate models because PIOMAS and CMIP6 both use sea ice thickness rather than ice type. However, POLARIS itself is defined in terms of sea ice type, and the conversion from modeled sea ice thickness ranges to POLARIS risk values is therefore already an approximation. The manuscript should explain more clearly why similarity in the variable is preferable to using an operational ice product that more directly represents the ice types used by POLARIS. The statement that PIOMAS is a "more homogeneous" dataset should also be clarified. Thank you for highlighting this missing justification. We use PIOMAS as our historical reference for two key reasons:

   Length of record. Daily digital ice charts are available from 2006, which does not provide a sufficiently long record to characterize multi-decadal changes in navigable periods or to evaluate CMIP6 historical simulations, which span 1950-2013. In contrast, PIOMAS provides a continuous daily record of SIC and SIT extending back to 1979, allowing the historical reference and CMIP6 simulations to be evaluated over a multi-decadal period (1979-2013).

   The use of PIOMAS provides a more methodologically consistent gridded reference for our analysis. Because our low-risk criterion calculates a POLARIS-based Risk Index Outcome (RIO) from quantitative sea ice thickness, PIOMAS allows the same formulation to be applied spatially and temporally to the historical reference as is applied to the CMIP6 simulations. This avoids introducing a separate conversion from categorical CIS ice types to representative thicknesses or POLARIS risk values. While less of a concern for our analysis, there are also higher uncertainties associated with CIS ice classifications beyond the ice-growth season (see Soleymani, 2024), where the CIS ice types span broader thickness ranges.

   Taken together, these two characteristics mean that a gridded historical record generated from PIOMAS data is better is better suited to the specific purpose of evaluating multi-decadal CMIP6 simulations and applying the same quantitative SIT-based methodology to historical and future data [although we acknowledge there may be unevaluated inaccuracies in both products].

   We have revised the manuscript as below to include the above rationales and replaced the term "more homogeneous" with "methodologically consistent" to avoid implying that PIOMAS is necessarily more accurate than CIS for operational navigation.

   Line 139: CIS ice charts are preferred for operational applications because they provide ice-type information directly relevant to navigation. However, daily CIS ice charts are available only from 2006 onward, which is insufficient for the multi-decadal analysis required here. In addition, CIS charts rely on expert interpretation of multiple observational sources, whose availability and resolution vary over time (Soleymani et al.,2023). Their accuracy is also affected by atmospheric conditions (MANICE, 2005), while ice-type classifications may become less reliable after the ice-growth season (Soleymani, 2024). These factors introduce additional uncertainty into long-term trend analyses. Therefore, PIOMAS is used primarily for its temporal coverage and methodological consistency, rather than as an operationally superior alternative to CIS ice charts. The CIS-derived NP is used as a complementary independent benchmark for evaluating the thickness-based bias-correction approach.

4. Given that the bias correction is ultimately applied to derived navigability metrics (OD, CD, NP) rather than directly to sea ice thickness, could Canadian Ice Service charts instead provide the historical benchmark? The delta-shift correction is applied to quantities such as opening day, closing day, and navigable period. Therefore, it is not obvious that the historical reference dataset must contain the same underlying physical variable as CMIP6. Could POLARIS navigability calculated directly from CIS chart ice types be compared with historical CMIP6-derived navigability over their overlapping period, with that bias correction then carried forward into the CMIP6 future projections? Even if the authors ultimately retain PIOMAS, this alternative should be discussed and the reasons for not using it made explicit. Yes, it could. Please see our response to the previous comment.
   We agree that CIS ice charts could, in principle, be used to construct a historical navigability benchmark. Ice type and ice thickness are closely related within the operational ice-classification framework. The Canadian Ice Service MANICE manual notes that references to thicker ice correspond to older ice types, while thinner ice corresponds to younger ice types. Furthermore, the POLARIS framework (Figure 11 from Polar Code Advisory) itself relates ice types to ice thickness classes, with the POLARIS table providing both representations. This thickness–ice-type relationship has also been used in previous Arctic navigation studies, including Cook et al. (2024), Mudryk et al. (2021), and Mudryk et al. (2026).
   Therefore, it would be technically feasible to calculate POLARIS-based OD, CD, and NP directly from CIS ice types and compare these historical navigability metrics with those derived from CMIP6. We acknowledge that this provides a potentially useful independent benchmark and have clarified this point in the revised manuscript.
   We nevertheless retain PIOMAS as the historical reference for the bias correction because our methodology is designed around sea-ice thickness as the common physical variable between the historical reference and the CMIP6 simulations. This allows the historical bias to be evaluated at the physical-variable level before applying the POLARIS classification consistently to both historical and future simulations. In contrast, a CIS-based correction would compare two navigability products after each has undergone a different transformation from the underlying ice state—CIS through expert-derived ice-type classifications and CMIP6 through simulated sea ice thickness. The resulting correction could therefore incorporate differences associated with the

classification and representation of ice conditions, rather than only the systematic bias in the CMIP6 ice field.

Thus, our choice of PIOMAS is not based on the assumption that CIS ice types cannot represent the thickness information required by POLARIS, nor does it imply that PIOMAS is operationally superior to CIS. Rather, PIOMAS provides a consistent thickness-based reference for the CMIP6 thickness-based methodology, while CIS-derived POLARIS navigability represents a valuable complementary benchmark that could be used for independent validation.

Line 147: The CIS-derived NP can be used as a complementary independent benchmark for evaluating the thickness-based bias correction approach.

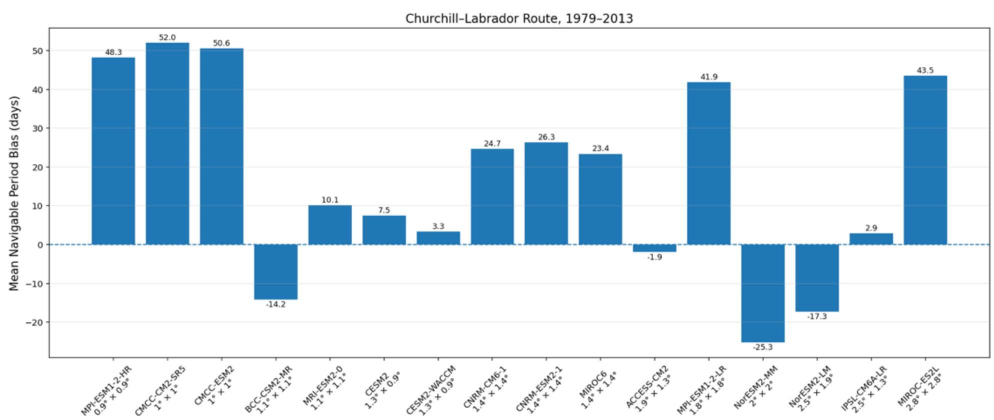
5. The sensitivity of the path-continuity analysis to spatial resolution should be considered and discussed. The manuscript emphasizes the importance of requiring connected navigable grid cells rather than evaluating a spatial average, but the datasets and CMIP6 models have different spatial resolutions. This could influence the probability of finding a continuous navigable path. It would be helpful to report the approximate number of grid cells spanning the 200-km corridor for the different datasets/model resolutions and to discuss resolution dependence as a limitation of the path-finding approach. The authors criticize the use of regional averaging in previous studies but using this approach with a coarse resolution approaches the same result as regional averaging, so it should be made clear how much higher the resolution of this study is than regional averaging to highlight the benefits of this approach. Also, is the blockiness of the grid cells in figure 1 representative of the grid cell size used in the study's analysis? Thank you for raising this point. We clarify that the blocky appearance of the route mask in Figure 1 represents the approximately 25-km EASE2 grid. It does not represent a uniform grid resolution used for all analyses. The CMIP6 models retain their native spatial grids, which vary substantially in resolution and land–sea representation. The 200-km-wide route zone is applied consistently across these grids, with each model's grid cells within the predefined zone used to evaluate route continuity. Thus, the apparent cell size in Figure 1 should not be interpreted as the spatial resolution of the CMIP6 model analysis.

   For example, in Fig 1 Panel a, for Churchill to Labrador Sea route this buffer consists of 605 grid cells (25-km EASE2 grid).

   Caption Fig 1: … with a 200 km-wide zone in dark blue color (100 km on either side of the route) on the 25-km Equal-Area Scalable Earth grid.

   Also, in Supplementary Table S1, we added another column to this table for "# Grid cells" and revised the caption: Summary of CMIP6 models used in this study, including the modeling center, country of origin, horizontal spatial resolution, and the number of grid cells covering the 200-km-wide route buffer for each model. For OSISAF and PIOMAS, the corresponding number of grid cells are 605 and 313, respectively.

Additionally, for the historical period (1979–2013) for Churchill-Labrado Sea route, we assessed the sensitivity of NP bias (defined as CMIP6 - PIOMAS) to differences in model spatial resolution (please see the figure below). We found no clear relationship between spatial resolution and NP bias. Models with similar spatial resolutions exhibited substantially different biases, indicating that spatial resolution alone does not explain the inter-model differences in estimated NP. This is consistent with previous results by Crawford et al. (2023; see Section 5.5 and Fig. S7).



Minor comments

1. As the paper stands now, I suggest specifying "low-ice or ice-free navigability" in the title. The paper specifically evaluates expansion of the ice-free/low-risk season and does not quantify the portion of the year that remains navigable for more ice-strengthened vessels. However, the framework could be used for the entire shipping season beyond low-ice or ice-free navigability if the authors choose to conduct that analysis. Thank you for your comment. We have included the results to quantify the portion of the year that remains navigable for more ice-strengthened vessels.
2. There is a grammatical error in the abstract: "representing and increases of 137 days" should be "representing an increase of 137 days." Fixed – thank you.
3. Figure 2 includes POLARIS classes PC2 through PC7 even though only Type E is analyzed. The inclusion of additional classes in the figure emphasizes the need to explain clearly why Type E was selected. Updated – thank you.
4. Check the grammar around line 114: "…and therefore in the operational shipping season." Fixed – thank you.
5. "Charts" around line 136 should not be capitalized. Fixed – thank you.
6. The shipping zone in Figure 1 is captioned as "dark grey color," but it appears dark blue for me when printed. Canadian spelling ("colour") may also be more appropriate. Fixed – thank you.
7. Around line 160, the discussion of northern and southern Hudson Strait routes is initially confusing because the manuscript has already introduced the Churchill–Labrador Sea

route and the Churchill–community routes, neither of which is north/south. Since the difference between the northern and southern Hudson Strait passages is negligible at the scale of Figure 1, I suggest stating that the shipping zone was defined broadly enough to encompass both the northern and southern entrances to Hudson Strait. Thank you. We revised it.

Line 171: Each route is defined by a start and end node, with the start node corresponding to the marine grid cell containing the Port of Churchill and the end node corresponding to the marine grid cell containing the destination point. We examined two distinct shipping corridors: the Churchill–Labrador Sea route, representing international access to global markets, and the Churchill–Chesterfield Inlet route, representing regional connectivity to northern communities, including Arviat, Whale Cove, and Rankin Inlet. For the Churchill-Labrador Sea route, the southern passage through Hudson Strait is currently favored because of its shorter transit distance (Pizzolato et al., 2016).

8. The heading "Shipping Route Mask Setup" is confusing because this section is defining the possible shipping area rather than masking an area out. A heading such as "Shipping Zone Definition" would be clearer. Fixed – thank you.
9. Around line 167, I suggest changing "two methods are used to define navigability" to "two definitions" or "two sets of criteria are used to define navigability." I don't quite think it's a method. Fixed – thank you.
10. Section 2.4 would be clearer if it were framed explicitly as the classification of individual grid cells rather than route detection. A title such as "Grid-Cell Navigability Classification" or "Navigability Assignment" would better distinguish it from Section 2.5, where the path-finding algorithm actually determines whether navigable cells form a continuous route. Related wording in Section 2.4 should refer to grid-cell navigability rather than saying that a "route" is low risk before route connectivity has been assessed. Fixed – thank you.
11. The heading "Path continuity framework" should be capitalized consistently with the other section headings. Fixed – thank you.
12. I suggest rewriting the first two sentences of Section 2.5 to more directly explain that route navigability is determined by whether connected navigable grid cells form a continuous path between origin and destination, i.e. "A path continuity framework ensures navigability is assessed as a route of connected navigable grid cells between the origin and destination." But this is at your discretion. Thank you for this suggestion. We have revised the opening of Section 2.5 to clarify that route navigability is determined by whether connected navigable grid cells form a continuous path between the origin and destination.

    Line 219: The spatial connectivity framework is built upon a graph-based representation of the route buffer (200 km-wide zone), where each grid cell constitutes a node and adjacent cells are connected through weighted edges (orthogonal or diagonal). Navigability is first determined at the cell level using either the ice-free or low-risk definition, resulting in a binary mask (e.g., Figure 3, panel (e)). This mask is then combined with the predefined route buffer to construct a constrained graph in which only admissible cells are retained. To evaluate continuity, a modified A* path-finding algorithm is applied (in Python using the *tcod* library) to determine whether a continuous path exists between the start and end nodes. A daily route is considered navigable only when a continuous sequence of connected, navigable grid cells form an unbroken path between the origin and destination. In the absence of such connectivity (e.g., sea ice present at a choke point), the route is classified as non-navigable, even if individual cells satisfy the SIC/SIT navigability criteria. This binary classification of daily route availability (1 = continuous path exists; 0 = no path), evaluated throughout the year, forms the basis for determining the opening day (OD), closing day (CD), and NP.

13. It would be helpful to report the approximate grid-cell width of the 200-km shipping zone for each dataset or model resolution rather than stating only the physical width of the corridor. (The authors state the resolution of OSISAF and PIOMAS, but not CMIP6, or how varying grid cells were handled despite stating in section 2.3 there were varying resolutions). Thank you for your comment. The CMIP6 resolution is included in Supplementary Table S1. We added another column to this table for "# Grid cell" and revised the caption: Summary of CMIP6 models used in this study, including the modeling center, country of origin, horizontal spatial resolution, and the number of grid cells covering the 200-km-wide route buffer for each model. For OSISAF and PIOMAS, the corresponding number of grid cells are 605 and 313, respectively.

Table S1. Summary of CMIP6 models used in this study, including the modeling center, country of origin, horizontal spatial resolution, and the number of grid cells covering the 200-km-wide route buffer for each model. For OSISAF and PIOMAS, the corresponding number of grid cells are 605 and 313, respectively.

Model	Country	Resolution	# of Grid cells
ACCESS-CM2	Australia	1.9°×1.3°	149
BCC-CSM2-MR	China	1.1°×1.1°	73
CESM2	USA	1.3°×0.9°	176
CESM2-WACCM	USA	1.3°×0.9°	176
CMCC-CM2-SR5	Italy	1°×1°	184
CMCC-ESM2	Italy	1°×1°	184
CNRM-CM6-1	France	1.4°×1.4°	184
CNRM-ESM2-1	France	1.4°×1.4°	184
IPSL-CM6A-LR	France	2.5°×1.3°	184
MIROC-ES2L	Japan	2.8°×2.8°	116
MIROC6	Japan	1.4°×1.4°	116
MPI-ESM1-2-HR	Germany	0.9°×0.9°	467
MPI-ESM1-2-LR	Germany	1.8°×1.8°	206
MRI-ESM2-0	Japan	1.1°×1.1°	142
NorESM2-LM	Norway	2.5°×1.9°	251
NorESM2-MM	Norway	2°×2°	251

We also revised the manuscript to clarify how differences in spatial resolution are handled.
Line 161: It should be noted that, to preserve the native spatial characteristics of each model and avoid potential artifacts introduced by interpolation, all data were evaluated at their original model resolutions. Consequently, differences among the models may partly reflect variations in spatial resolution and in their representation of complex features, such as narrow channels and coastal areas.

14. There appears to be a formatting problem around line 253, where text or mathematical notation is missing beside the Gamma function? Fixed – thank you.
15. There also appears to be missing text around line 273. Fixed – thank you.
16. N_eff is defined on line 290 but then no longer referenced or used. Fixed – thank you.
17. I do not understand the term "projection time" around line 406. This should be explained. Revised to "Time". Thank you.
18. Figure 3 contains a category labelled "too distant," but this category is not explained in the text. If it means that a cell lies outside the permitted 200-km shipping zone or beyond an allowed connection distance, this should be explicitly stated or the category should be renamed. Thank you for pointing this out. The "too distant" category refers to grid cells located outside the predefined 200-km-wide shipping route zone and therefore excluded from the path-finding analysis. We have renamed this category "outside route zone" in Figure 3.
19. The description of opening and closing dates in Section 2.6 is difficult to follow. The section begins by defining the sea ice year before explaining how the opening and closing dates themselves are identified, whereas readers may initially expect a direct definition of opening and closing dates. The repeated use of "median day" also makes the sequence difficult to reconstruct. I suggest revising this section so that the logic and order of the calculations are stated more explicitly and the terms "median open day," "median closed day," opening day, and closing day are clearly distinguished. Thank you, we revised the manuscript.

    Line 234: To characterize the seasonal accessibility of the defined routes, we define three key indices for each route and year following the method of Crawford et al. (2021,2023): opening day or OD, closing day or CD, and navigable period or NP. These indices are derived from daily binary assessments of route navigability using either the ice-free or low-risk method. Because September 1 is always navigable for every ship class along every route for every year of study, the NP can be defined as the continuous period of navigable conditions that encompasses September 1. The OD is the day after the last day prior to September 1 for which the route is closed. The CD is the first day after September 1 for which the route is closed. Note that the CD often falls within the following calendar year, especially for ice-strengthened vessels and/or the late 21st century. Also note that if a route is permanently open, that the NP is assigned 365 days per year (366 days in leap years) and the OD and CD are undefined.

20. The authors should acknowledge in the Discussion that the ice-free or low-ice defined navigable period does not necessarily correspond directly to the operational shipping season. There are regulatory constraints that limit whether vessels can proceed in earlier or later navigability. Refer to Andrews et al., 2017 for this. Thank you for highlighting this distinction. We agree that the ice-free and low-risk periods estimated in this study should not be interpreted as the actual operational shipping season. We have added a statement to the Discussion clarifying that regulatory and other operational constraints can restrict vessel operations beyond the sea-ice conditions considered here, following Andrews et al. (2017).

    Line 643: Finally, it is important to note that the ice-free and low-risk NPs estimated here do not necessarily correspond directly to the operational shipping season. Actual vessel operations are also influenced by regulatory requirements, vessel characteristics, insurance considerations, and other operational constraints, which may restrict navigation during periods that meet the sea ice criteria (Andrews et al., 2017).

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