Response to Reviewers

We thank the reviewers and editor for their constructive comments on our manuscript. We believe these have led to notable improvement. Below, please find our responses in blue and any text that is a direct quote from the revised manuscript in green.

Response to Reviewer 1 (Minghu Ding)

This study focuses on the limitations that seasonal sea ice in Hudson Bay imposes on navigable access to the Port of Churchill. By correcting climate model biases and introducing a novel path-finding approach that requires continuous navigable routes, it provides a relatively detailed projection of future shipping navigable periods. The navigability of Type E vessels is evaluated under two criteria. While the study has certain value in terms of methodological improvements and scenario analysis, several issues still require clarification or improvement.

Major comments:

1. The goal of the paper is to evaluate different navigability assessment methods and simulation bias-correction methods. Therefore, the authors should more clearly and objectively quantify the degree of improvement that different methods bring to the results. Although Figs. 8 and 9 provide information, it is very difficult to precisely read the NP values for specific years or specific warming levels and the differences among methods from the figures. I would suggest the addition of a quantitative table to present the results more clearly and objectively. For example, in the historical period, which method or combination of methods yields NP closest to observations? By how much is the multi-model ensemble bias reduced? What are the projected results of each method?

Table 2. Median navigable period (in days) for type E vessel under different global surface air temperature (GSAT) anomaly levels and SSP5-8.5 across the ice-free and low-risk conditions for the Labrador Sea and Chesterfield Inlet routes.

GSAT anomaly (°C)	Ice-free		Low-risk	
	Labrador Sea	Chesterfield Inlet	Labrador Sea	Chesterfield Inlet
1.00–1.50	128	139	157	157
1.50–2.00	147	154	175	173
2.00–2.50	162	165	193	187
2.50–3.00	177	177	206	202
3.00–3.50	192	194	222	218
3.50–4.00	215	207	246	237
4.00–4.50	236	226	270	263
4.50–5.00	265	246	304	284

Thank you for this great suggestion. We agree that a quantitative comparison is important for objectively evaluating the differences among the navigability assessment and bias-correction methods. To address this concern, we have added Tables 2 and 3, which provide the specific NP values from Fig. 8 and 9, respectively. We also revised the manuscript as follows.

Table 3. Projected navigable period (in days) over time for type E vessel under SSP5-8.5 across the ice-free and low-risk conditions for the Labrador Sea and Chesterfield Inlet routes using two bias correction methods.

Year	Delta Shift				Weighted Average			
	Ice-free		Low-risk		Ice-free		Low-risk	
	Labrador Sea	Chesterfield Inlet	Labrador Sea	Chesterfield Inlet	Labrador Sea	Chesterfield Inlet	Labrador Sea	Chesterfield Inlet
2020	123	140	151	159	152	173	161	181
2030	138	147	168	167	153	182	170	190
2040	143	156	173	174	164	185	178	195
2050	164	171	194	192	177	200	192	212
2060	178	181	209	203	194	212	207	222
2070	196	193	228	219	206	218	219	229
2080	221	211	257	242	234	240	250	256
2090	239	230	281	267	268	268	294	290
2099	279	267	307	292	309	291	332	317

Line 462: Table 2 summarizes how the median NP varies with increasing GSAT anomalies for the ice-free and low-risk definitions along the Labrador Sea and Chesterfield Inlet routes. Overall, the rate of lengthening NP with continued warming varies from 42 d °C−1 for the low-risk definition and Labrador Sea route to 31 d °C−1 for the ice-free definition and Chesterfield Inlet route. The sensitivity increases above a GSAT anomaly of 3.5 °C, with average rates of approximately 27–33 d °C−1 below 3.5 °C compared with approximately 35–55 d °C−1 above 3.5 °C, depending on route and definition.

Line 502: Table 3 summarizes the projected navigable period (in days) over time under SSP5-8.5 for the ice-free and low-risk conditions along the Labrador Sea and Chesterfield Inlet routes using two bias correction methods. Collectively, these results show that both correction methods broadly capture the long-term increase in NP, although their projected values diverge substantially in some years, particularly in several late-century projections and for the ice-free definition. The discrepancies range from approximately 2 to 38 days (about 1–24%, depending on method, route, and year), highlighting the sensitivity of NP projections to the choice of bias correction method.

2. 2.3: “shipping routes were represented as a 200 km-wide zone”. A 200 km resolution is overly coarse, and the choice of this width lacks sufficient justification. Many CMIP6 models have resolutions around 100 km. The 200 km choice sacrifices specific precision, though it remains meaningful for regional accessibility. I would suggest that the models should first be interpolated to a uniform resolution (e.g., the same 25 km as the observations) before calculations are performed, and that the sensitivity of the results to resolution be examined. Thank you for this comment. We agree that the width of the shipping zone and the differences in spatial resolution among CMIP6 models require clarification. We note first that the 200-km width refers to the width of the geographic assessment zone, rather than a 200-km model resolution. The purpose of using a finite-width zone is to represent shipping accessibility at a regional scale rather than constrain navigability to a single prescribed track. This width-based approach allows for spatial variability in potential navigable pathways in the region depending on ice conditions

while providing a consistent framework for comparison across models with different spatial resolutions and grid structures. We clarified this in the revised manuscript.

Line 167: In this study, shipping routes were represented as a 200 km-wide zone (Figure 1). This buffer was selected to represent regional-scale shipping accessibility rather than a single prescribed track, thereby allowing for spatial variability in potential navigable pathways in the region depending on ice conditions while providing a consistent framework for comparison across models with different spatial resolutions and grid structures.

Also, please see the response to the next comment for further details regarding the interpolation and the concern about spatial resolution.

3. When the authors apply sea-ice data from different models to the same 200 km-wide shipping zone for assessment, do they first interpolate all model data onto a uniform spatial grid? If no uniform interpolation is performed, then a considerable portion of the inter-model differences shown in Figs. 5–7 may arise from differences in model spatial resolution. For example, lower-resolution models may be unable to resolve the narrow islands and channels in Hudson Strait, thereby systematically overestimating navigability.
Thank you for your comment -- this is an important point. Lower-resolution models may not adequately resolve complex coastlines features and could therefore produce systematically different estimates of sea ice conditions and in turn navigability.

No, we did not interpolate or re-grid all model data onto a common spatial grid. The primary reason is that re-gridding the data to a common resolution would not necessarily eliminate the underlying differences in spatial representation among the models. In other words, interpolation to a common grid cannot recover sub-grid scale geographic features that are unresolved in the original model. For example, if a model does not resolve the narrow channels or islands in Hudson Strait, then when the model's sea ice component is running, there will be no impact of those islands on sea ice dynamics. Post-hoc interpolation of the model's output to a finer common grid will not restore those physical limitations. Additionally, interpolation could potentially give a misleading impression of spatial consistency.

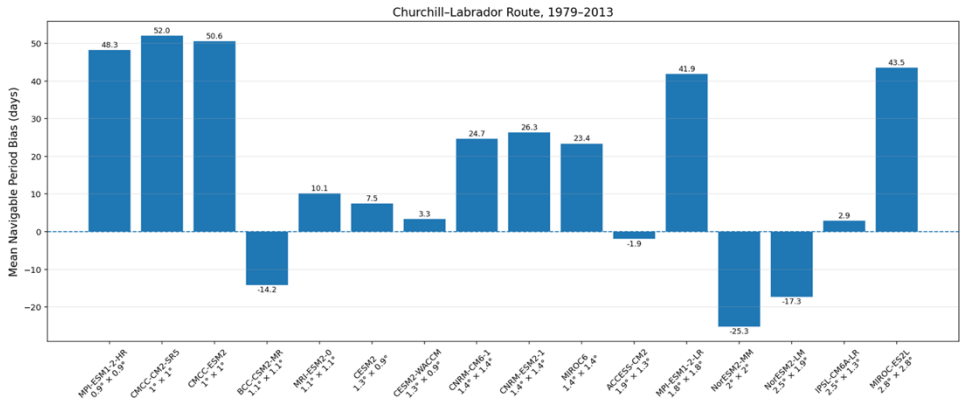
Instead, we retained each model's original spatial resolution and evaluated the sea ice conditions within the same geographic shipping zone. This approach preserves the information as represented by each model and avoids introducing an additional interpolation step that could alter the original sea ice fields or introduce artifacts. We acknowledge that this means the inter-model differences reflect not only differences in the simulated sea ice conditions and model physics, but also differences in model spatial resolution and the associated representation of coastlines, islands, and narrow channels.

We have clarified this point in the revised manuscript and now explicitly acknowledge spatial resolution as an additional source of uncertainty when interpreting the inter-model differences.

Caption Fig 1 added this: (100 km on either side of the route).

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.

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).

4. Type E (pleasure craft) vessels are selected as the assessment object. Type E vessels are defined as "non-ice-strengthened" in the POLARIS system. Are Type E vessels the main vessel type currently or in the future operating at the Port of Churchill? Using the Type E vessels as the baseline will systematically underestimate future navigable periods. It is recommended that the authors investigate the main vessel types operating at the port before conducting the assessment, and/or add discussion to clearly state the rationale and limitations of adopting Type E vessels. 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.)

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

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 also acknowledge the reviewer's point that using Type E vessels will result in a more conservative estimate of the navigable period than would be obtained for ice-strengthened commercial vessels. This should therefore not be interpreted as an estimate of the full commercial shipping season or the maximum future navigability of the Port of Churchill. Rather, it represents the potential accessibility period for economically attractive open-water shipping under ice-free conditions. We have clarified this point in the revised manuscript in the methods section:

Line 212: Type E vessels are the primary focus of this study because they historically have been the dominant commercial vessel class operating at the Port of Churchill (Andrews et al., 2016). 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 defines a minimum-length economically accessible shipping period; longer navigable periods would be achievable by ice-strengthened vessels (see Section 3.5).

We also make the predominance of non-ice-strengthened vessels at the Port of Churchill clearer in the Introduction with revised lines 29-31:

One constraint is its short operational season, which historically extends from mid-July through October (Andrews et al., 2017), as nearly all historical grain shipments have been via non-ice-strengthened bulk carriers (Andrews et al., 2016).

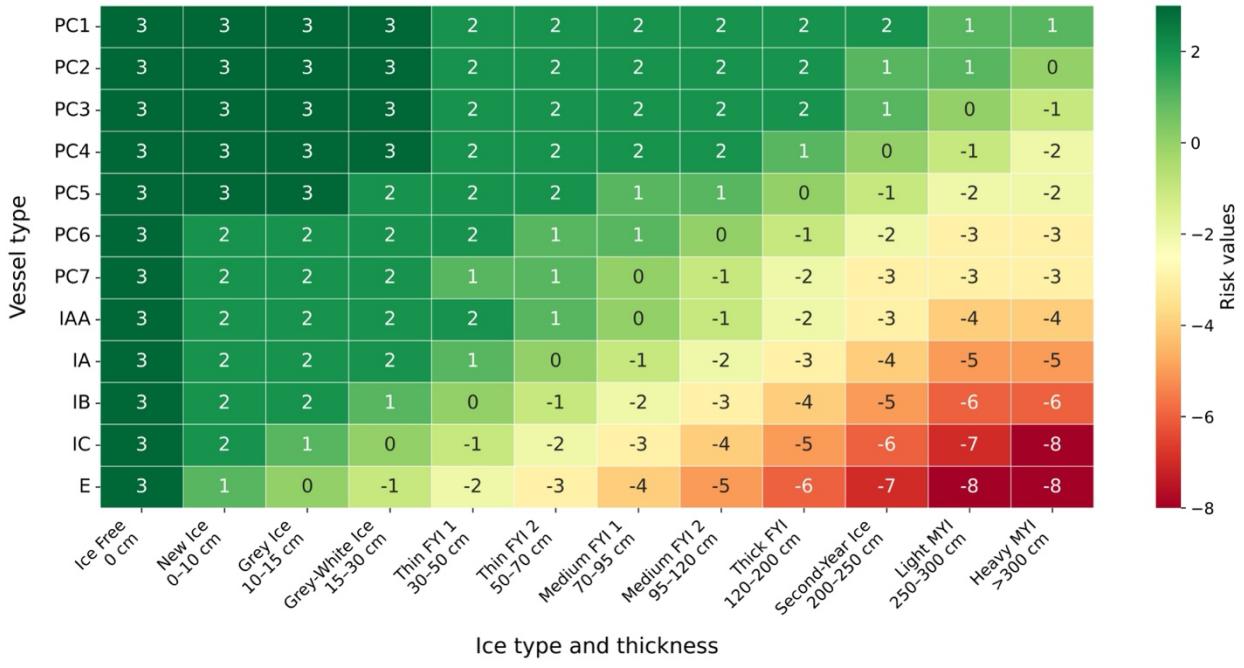
Additionally, based on your comment, we have updated Figure 2 panel (a) and included more vessel types. We have also added results for different vessel types in Section 3.5, along with a new Figure 9.

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



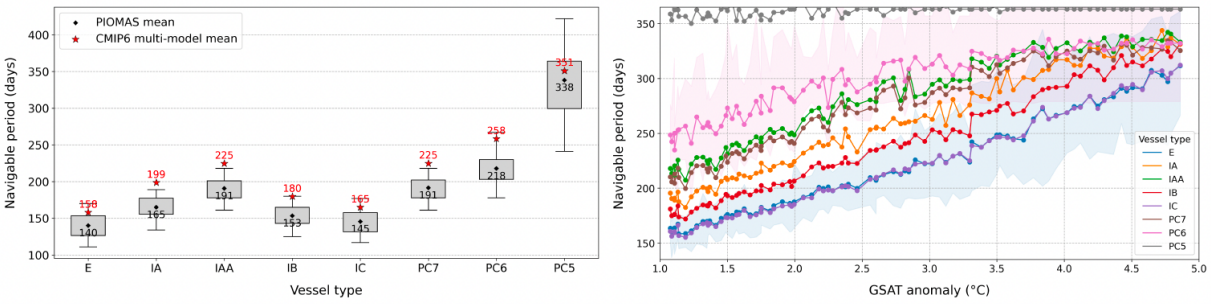
SSP5-8.5 scenario, indicating that year-round shipping would still require vessels with greater ice capability throughout the 21st century.

Minor comments:

1. The authors state in the introduction that "the southern route is currently the preferred operational route". But in the manuscript, they set up two routes. These two routes differ completely in destination distance, so a direct comparison between them lacks persuasiveness. And, what is the purpose of presenting this comparison? This should be clearly explained in the text. If there is no special objective, results for routes within the region are suggested to be merged for analysis as SI. The purpose of retaining both routes is to assess two distinct aspects of maritime accessibility from the Port of Churchill: the Churchill–Labrador Sea route represents international connectivity and access to global markets, whereas the Churchill–Chesterfield Inlet route represents regional connectivity to northern communities. This distinction is also reflected in our study objectives and route design.

   We have revised the manuscript to clarify that the comparison is intended to examine regional versus international accessibility and their respective responses to changing sea ice conditions, rather than differences attributable to route distance. To improve the clarity and focus of the main text, the three additional regional routes to Arviat, Whale Cove, and Rankin Inlet (which show broadly similar patterns because of their geographic proximity) are included in the Supplementary Material.

   We have also clarified that the statement that the "southern route is currently the preferred operational route" refers specifically to the southern passage through Hudson



(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.

Strait within the Churchill–Labrador Sea route, which is favored because of its shorter

transit distance, rather than implying that the Labrador Sea and Chesterfield Inlet routes are alternative routes to the same destination.

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).

2. Line 190:

To make the utility of this equation more apparent, we have embellished the explanation.

"…this equation implies that the RV is 0 for the open water part of a cell, making it less permissive than Equation 1, which uses a value of 3 for open water. In other words, 2 shows the impact of considering only SIT in determining a grid cell's RIO instead of both SIT and SIC."

3. 2.6: The definitions of OD, CD and NP are very complex and obscurely worded. How is the start day of the "sea ice year dynamically" determined? Specifically, which day is it? The text mentions "zones where the timing of maximum ice extent", but provides no operable algorithm. The determination of OD and CD involves concepts such as "the median day for which a route is open/close", "last day the route was closed", and "the first closed day", making it difficult for readers to intuitively understand their physical meaning. In particular, when NP exceeds 365 days, OD and CD become "undefined" and are specially treated, introducing an artificial discontinuity. Since the assessment is oriented toward the full year, it is recommended to define OD, CD and NP based on the simplest and most intuitive calendar year.

Defining the sea ice year "dynamically" means that there is not necessarily a consistent day on which the sea ice year begins and ends. Using a calendar year is not appropriate because the sea ice in Hudson Bay has a highly erratic seasonal cycle. Blockage of the routes by sea ice may happen in winter or in spring, so it is quite common for PC5 vessels to have most of the year navigable but just a short period in April, May, or June be closed because thick ice blocked part of Hudson Strait. For example, in 1983, the Churchill-Labrador route was closed to PC5 vessels from April 18 through June 14. In 1984, it was closed much longer, February 11 through June 25. Therefore, the navigable period for 1983 is most intuitively June 15, 1983, through February 10, 1984. It does not fit neatly into a single calendar year because the navigable period crosses January 1.

Based on those two examples, it might seem logical to use May 1 to April 30 as a "sea ice year", but this is also problematic. Again, looking at PC5 vessels and the Churchill-Labrador route, consider 2005 and 2006. In 2005, the route was closed April 13 to May 31, and in 2006 the route was closed April 16 to April 17 – just two days. Therefore,

there was a continuous navigable period from June 1, 2005, through April 15, 2006 – which still fits within a fixed May 1 to April 30 "year". However, another navigable period starts April 18, 2006, and that one is a problem. That navigable period straddles May 1, so if you use May 1 to April 30 as a sea ice year, you will erroneously miss 13 days. This is why using a fixed date for the sea ice year – any fixed date – is problematic. It will never overestimate the longest continuous navigable period, but it will sometimes underestimate. That leads to a bias.

Instead, a dynamic sea ice year, which responds to what the sea ice is doing instead of making an artificial temporary boundary, is more appropriate. We did include an operable algorithm in Section 2.6: "The start of each sea ice year is defined as the median day January through April for which the given route is closed." This solves the problem of sea ice (especially sea ice thickness) having highly variable seasonality year to year. This method is also well-tested: it been previously employed by several peer-reviewed works, including Crawford et al. (2021), Crawford et al. (2023), and Mudryk et al. (2026). We stand by this method and the fact that it is superior to using a calendar year (or any fixed date for dividing years).

But there is a big downside, as the reviewer points out: it's much less simple to describe a dynamic year definition than "a calendar year" or any fixed date for years. We appreciate that the description was long and detailed and therefore cumbersome for readers. In other words, we concede a communication problem despite standing by the method. We also hope we have come up with a satisfactory solution to simplify the description.

The solution comes from the fact that the definition we use in the code is a general definition that is applicable to the entire Arctic. For our study area, however, all routes are always navigable for all vessel types on September 1 in every year considered. Therefore, we are able to describe the process in reference to September 1 instead of in reference to the "start day" of a "sea ice year". This greatly simplifies the description, although the code has not been changed. We also removed details for some of the fringe cases that result to focus on the essential steps that would be needed to replicate the results.

Here is the new text:

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.

4. Line 275: "Model skill and projections are also evaluated using percentiles (median, 10th, 90th) against a reference dataset." How exactly is this done? Thank you for pointing this out. For each route and navigability criterion, the 10th, 50th (median), and 90th percentiles are calculated across the model ensemble to characterize the spread of simulated OD, CD, and NP. Model performance is evaluated separately by comparing these results with the corresponding observational reference dataset (OSISAF for the ice-free method and PIOMAS for the low-risk method). Only the first realization from each model is used to ensure equal model weighting. We revised the manuscript.

   Line 271: For each route and navigability criterion, the 10th, 50th (median), and 90th percentiles are calculated across the model realization to characterize the spread of estimated OD, CD, and NP. Model performance is evaluated separately by comparing these results with the corresponding observational reference dataset (OSISAF for the ice-free method and PIOMAS for the low-risk method). Only the first realization from each model is used to ensure equal model weighting.

5. Line 285: Are the weights independent of time? Then are the observations and simulations using climatological means? This should be clarified. Thank you for bringing this to our attention. We clarify that the model weights are time independent. For the final weighting procedure, the observational reference is first averaged over the historical evaluation period (1979–2024) to obtain the climatological mean of OD and CD. The corresponding historical model values are used to calculate each model's distance from the observational reference and inter-model similarity, from which a single weight (w_i) is assigned to each model realization. These weights are then held fixed and applied to the model output at each time step when calculating the weighted projection. Thus, the weights are derived from historical climatological means, whereas the weighted projections retain their temporal variability. We have revised Section 2.7.2 to make this point explicit.

   Line 301: It is noteworthy that the weights are calibrated using the 1979–2024 climatological mean of OD and CD and are subsequently held fixed when applied to the time-varying model projections.

6. Line 350: "the opening day exhibits greater variability…2000s." The authors attribute this to internal variability. In reality there is also the cause of fragmented drift ice, see Cook et al. (2024): Cook, A.J., Dawson, J., Howell, S.E.L. et al. Sea ice choke points reduce the length of the shipping season in the Northwest Passage. Commun Earth Environ 5, 362 (2024). https://doi.org/10.1038/s43247-024-01477-6 Thank you for this comment. When we use the term "internal variability", we are referring to internal variability of the climate system, which includes any year-to-year variation in ocean and atmospheric circulation that may, in turn, lead to year-to-year variability in sea ice dynamics. The term "internal variability" in this case meant to distinguish from long-term climate change. However, you are correct, that one of the effects of climate change is

increased sea ice mobility, which has resulted in increased presence of MYI within the channels and straits of the CAA, and Cook et al (2024) illustrates the impact of such MYI on ship navigability within the NWP passage. To clarify these different processes, we have specified "internal **climate** variability" in the text. We also cite Cook et al. (2024) as an example.

This variability can result from multiple processes: for example, both internal climate variability and as well as changes in the dynamic redistribution of sea ice, including the persistence or drift of fragmented ice into localized choke points, which can delay route opening (Cook et al., 2024). The opening day is more variable than the closing day because it is governed not only by the cumulative impacts of sea ice dynamics, but also by summer sea ice melt processes, both of which are greatly influenced by year-to-year atmospheric variability (Hoccheim and Barber, 2014; Crawford et al., 2023).

Response to Reviewer 2

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 (Andrews et al., 2016). Their predominant usage for the Port of Churchill was, in fact, a major impetus for the Arctic Gateway Group (which owns and operates the Port of Churchill) funding this research. This is distinct from Hudson Strait, where FedNav operates ice-strengthened vessels year-round (e.g., as described in Babb et al., 2021).

Therefore, although ice-strengthened vessels could be used to further lengthen the shipping season, Type E vessels act as a conservative baseline representing ice-free accessibility. The objective of this stud 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 in the methods section:

Line 212: Type E vessels are the primary focus of this study because they they historically have been the dominant commercial vessel class operating at the Port of Churchill (Andrews et al., 2016). 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 defines a minimum-length economically accessible shipping period; longer navigable periods would be achievable by ice-strengthened vessels (see Section 3.5).

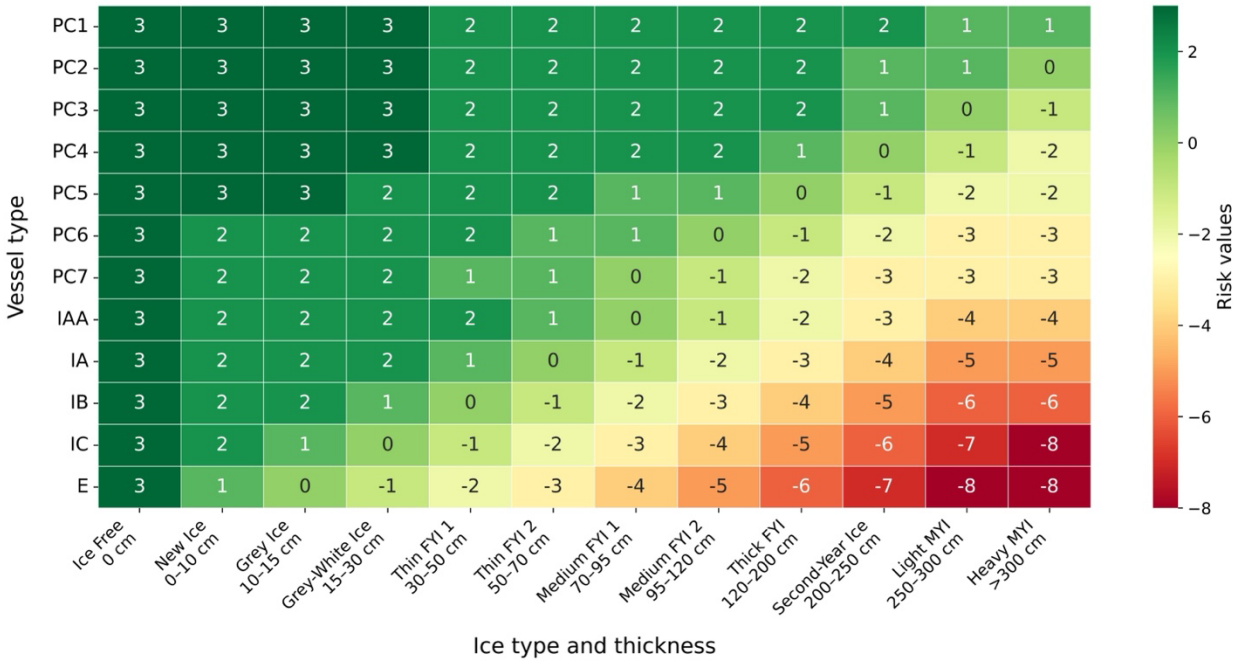
We also make the predominance of non-ice-strengthened vessels at the Port of Churchill clearer in the Introduction with revised lines 29-31:

One constraint is its short operational season, which historically extends from mid-July through October (Andrews et al., 2017), as nearly all historical grain shipments have been via non-ice-strengthened bulk carriers (Andrews et al., 2016).

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.

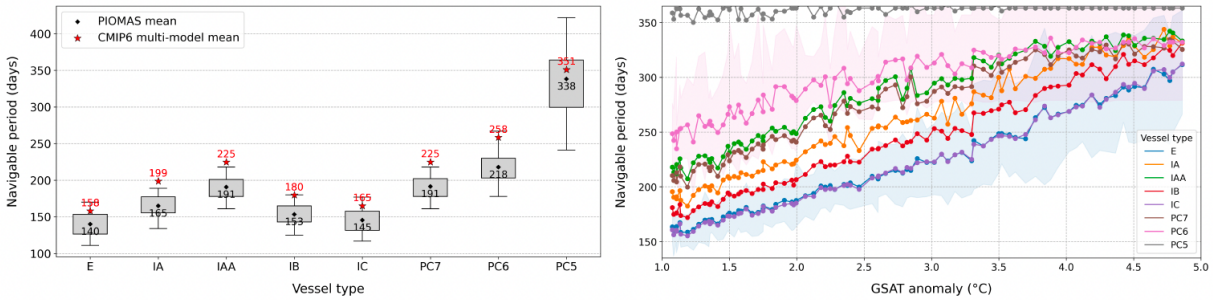


In panel (a), the CMIP6 multi-model mean NP increases from 158 days for Type E vessels to 225 days for Type IAA vessel, compared with the corresponding PIOMAS means of 140 and 191 days, respectively. The more ice-capable polar classes exhibit substantially longer navigable periods, with PC6 and PC5 reaching 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.

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



(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.

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.

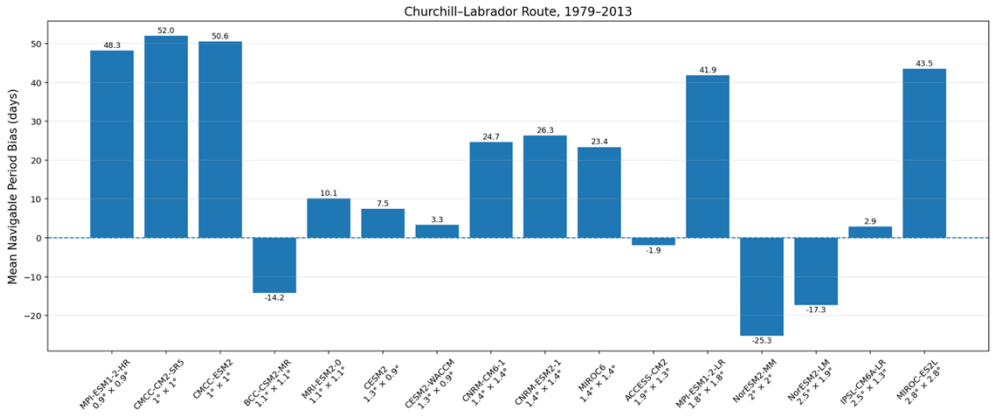
5. The sensitivity of the path-continuity analysis to spatial resolution should be considered and discussed. The manuscript emphasizes the importance of requiring connected navigable grid cells rather than evaluating a spatial average, but the datasets and CMIP6 models have different spatial resolutions. 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.

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.

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

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).

Response to Editor Comment

Both reviewers question why you focus your analysis on Type E vessels. Reviewer 2 wrote: "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." In your response, you wrote that "Type E vessels are indeed the dominant commercial vessel class currently operating at the Port of Churchill during its limited summer operating period." I would like you in the revised manuscript to include a reference for this claim.

Short answer: Yes, thank you, that is a good point. We have added Andrews et al., (2016) as a reference for the statement and tweaked the language to say “historically” instead of “currently” to make the statement relevant even if practices shift toward more ice-strengthened vessels.

Long answer: The best reference might be a “personal communication” with the Arctic Gateway Group, which owns the Port of Churchill and has their own records of the ships that operate there. The Arctic Gateway Group’s interest in the open water shipping season – i.e. the period during which even non-ice-strengthened vessels could operate -- was the reason they partially funded this research in the first place. Two problem with this reference is that it is a personal communication, not ideal for a peer-reviewed journal article.

A more academic reference (and the one we have included in lines 29-31 and then lines 212-216) is the Andrews et al. (2016) report regarding shipping at the Port of Churchill. That report was a case study for Environment and Climate Change Canada and very clearly states that non-ice-strengthened vessels are the dominant type operating at the Port of Churchill.

However, one potential quibble with that report is that it is ten years old. Recent activity in 2026 included the first grain shipment since 2020 on the Taiga Desgagnes, a non-ice-strengthened vessel (https://www.arcticgateway.com/agg-news/newsroom/first-grain-export-since-2020-loaded-at-port-of-churchill-bound-for-europe ; https://atlas.flexport.com/vessel/imo:9303302/mmsi:316335000/name:taiga-desgagnes), but also a potash shipment on the Alaskaborg (Type-IA vessel; https://www.insidelogistics.ca/milestones/first-critical-mineral-shipment-from-port-of-churchill-in-decades/; https://www.wagenborg.com/fleetlist/a-class?_gl=1*1n8j1ct*_up*MQ..*_ga*MTYyOTQ4MTc2MS4xNzkwNjkzMTcy*_ga_3KHYFXRQNK*czE3OTA2OTMxNzEkbzEkZzAkdDE3OTA2OTMxNzEkajYwJGwwJGgyODE2NzAzMjU). Therefore, both ice-strengthened and non-ice-strengthened vessels have been used in 2026. This means we need to emphasize ‘historical’ in the statements about Type E vessels being predominant. That is reflected in the final edits made in the response to the reviewers.

That all considered, if there is any doubt about the relative frequency of various vessel types, two other changes have been made. 1) We now also frame the Type E vessel navigable periods as a conservative minimum in the methods section. 2) We added Section 3.5, which shows results for ice-

strengthened vessels. These additional edits are described in more detail in the responses to Reviewer 1 (major comment 4) and Reviewer 2 (major comment 1).

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