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*Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality*

15th Sep 23

Dear Dr Cook,

Your manuscript titled "Recent shortening of shipping season lengths in regions of the Northwest Passage" has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to

- address these criticisms (that is, either to incorporate the suggestions or provide a compelling argument why the point made by the reviewer is not valid or relevant to the editorial threshold as outlined below)

AND

- meet our editorial thresholds as outlined below,

then we would be happy to look at a revised manuscript.

In the following, we list our minimum requirements for publication.

\*\*\* Present novel insights into changes in the length of the shipping season of the Northwest Passage in recent years based on the evidence presented and discuss your findings in light of earlier work, including an explanation of differences in the conclusions.

\*\*\* Provide comprehensive details of all data sources and derivations used in your analysis.

\*\*\* Communicate the limitations and uncertainties that arise from using only recent data in your analysis and tone down relevant claims to reflect these limitations.

If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at

Communications Earth & Environment or published elsewhere in the meantime.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers' comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

[link redacted]

**\*\* This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first \*\***

Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Martina Grecequet PhD  
Associate Editor,  
Communications Earth & Environment  
@CommsEarth

## EDITORIAL POLICIES AND FORMAT

If you decide to resubmit your paper, please ensure that your manuscript complies with our editorial policies and complete and upload the checklist below as a Related Manuscript file type with the revised article:

Editorial Policy [Policy requirements](#) (Download the link to your computer as a PDF.)

For your information, you can find some guidance regarding format requirements summarized on the following checklist: (<https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf>) and formatting guide (<https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf>).

## REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Comment on "Recent shortening of shipping season lengths in regions of the Northwest Passage" by Alison Cook et al.

By utilizing the Polar Operational Limit Assessment Risk Indexing System (POLARIS) and weekly regional ice charts provided by the Canadian Ice Service (CIS), this study aims to estimate the duration of the shipping season in the Northwest Passage (NWP). The article title is interesting to me because it seems to run counter to many published papers before. The authors find significant spatiotemporal variability exists in shipping season lengths for both the southern and northern routes of the NWP, with the latter exhibiting significant decreases of up to 6 weeks over the 15 years (2007–2021).

Although the Arctic communities may find these findings to be interesting, the manuscript's persuasiveness is limited by the absence of discussion surrounding the findings' uncertainties, in particular, the reasons why the findings and inference in this study contradict previous studies. In my opinion, this paper is not suitable for publication in *Communications Earth & Environment*.

#### General comments:

1. In contrast to what many studies (e.g., Melia et al., 2016; Mudryk et al., 2021; Smith and Stephenson, 2013) have projected, the authors come to the conclusion that the northern route of the NWP may not become operationally viable after simply analyzing the 15-year variation of shipping season length in the NWP. The analysis only covers a 15-year period, particularly after the significant Arctic sea ice loss in 2007. Additionally, the authors' conclusion relies solely on the linear trend observed during this period and does not take into account its level of uncertainty. I believe that the conclusion/inference cannot be confidently stated without analyzing longer periods for comparison and discussing the variation in navigability under different climate warming scenarios (e.g., different SSPs).
2. Additionally, it would be better to define these 'choke points' in the Abstract given that the authors demonstrate that the decreasing trends do not exist in all sections of the routes. I'd like to reiterate that I don't think the authors' conclusion holds true over the entire NWP. It will therefore be preferable to make this clearer in the Title or Abstract.
3. In Figure 4, why does the largest decrease occur in the mid-season?
4. The Method section of the article needs to be clearer. For instance, specific information regarding the Risk Index Value (RIV) calculation process, the spatial resolution of the CIS sea ice charts, and the ships' ice resistance should be provided.

#### Minor comments:

1. Line 18. The 'route' should be 'routes'.
2. Line 128. Is 'shipping variability' referring to the variability in the length of shipping seasons?
3. Line 235. 'acts' rather than 'act'?
4. Lines 150–152. Does the Viscount Melville Sound section have a 400 km length?
5. Line 161. Please specify the exact month for shoulder seasons as it first appears in your text, even though you previously did it in the Method section.
6. I think the figures presented now should be improved. For instance, the display format can be improved and the text annotation in the picture should be made larger for reading.

#### Reference

- Melia, N., Haines, K., & Hawkins, E. (2016). Sea ice decline and 21st century trans-Arctic shipping routes. *Geophysical Research Letters*, 43(18), 9720-9728. <https://doi.org/10.1002/2016GL069315>
- Mudryk, L. R., Dawson, J., Howell, S. E. L., Derksen, C., Zagon, T. A., & Brady, M. (2021). Impact of 1, 2 and 4 °C of global warming on ship navigation in the Canadian Arctic. *Nature Climate Change*, 11(8), 673-679. <https://doi.org/10.1038/s41558-021-01087-6>
- Smith, L. C., & Stephenson, S. R. (2013). New Trans-Arctic shipping routes navigable by midcentury.

Reviewer #2 (Remarks to the Author):

In the context of global warming, the Northwest Passage has an important impact on the change of the world shipping pattern and the development of surrounding communities. Based on POLARIS and CIS data, the authors calculated and analyzed the navigability change of the Northwest Passage from 2007 to 2021. These results contribute to a better understanding of the changes in the length of the shipping season of the route in recent years and the major 'choke points' areas affecting shipping. In my understanding, the manuscript is concise and majorly clearly written, and the methods and conclusions are reasonable, the authors cleverly converted the sea ice status of the Northwest Passage into a cumulative number of shipping weeks and analyzed it on this basis. While the study may be valuable for readers new to the subject or researchers from other disciplines, it may not offer sufficiently novel insights for those who have extensively studied the topic of Arctic sea ice and navigability in the Northwest Passage. Although the shipping season length obtained by statistics is of important reference for ships wishing to operate in the Northwest Passage for a long time, the authors did not provide a complete navigable window. In fact, the spatial distribution of sea ice in the Northwest Passage varies greatly from week to week, and the navigability of each section may not be consistent at the same time (week). For ships attempting a full transit of the Northwest Passage, relying solely on such coarse estimates of shipping season length may be insufficient for precise ship scheduling decisions. Hence, I think it is necessary for the author to provide a specific shipping season window for each section and the whole route. If the sole purpose is to compare the navigability of various segments along the route, one could easily identify 'choke points' by simply averaging the sea ice concentration of the season.

An important finding in the manuscript is that the shipping season length of the Northwest Passage (northern route) has decreased in recent years, which actually corresponds to the recent sea ice recovery/increase in the Northwest Passage shown in many studies. We know that 2007-2012 was the lowest period of sea ice in the Northwest Passage in history, and that these years would have been the longest navigation seasons, hence the reduction in shipping season length would have been a logical outcome if there had not been a similar extreme light ice year recently. The authors present a different viewpoint based on the results from this specific time period, suggesting that the Northwest Passage may become more dangerous despite the diminishing Arctic sea ice. However, this perspective may be biased, as other studies typically discuss this change over longer time spans, such as the study period from 1979. When compared to conditions during the early years of research, the current situation in the Northwest Passage has already shown significant improvement. Most studies predict that the Northwest Passage will become less dangerous in the future, often projecting towards 2050 or even 2100, while maintaining caution and conservatism about full navigability. Therefore, I believe that the authors' conclusions do not conflict with the conclusions of previous studies, but the authors emphasize the observation that the shipping season length of the Northwest Passage has been shorten since 2007. However, a conclusion about future long-term trends drawn from a historically light ice year as a starting point may not be accurate, and perhaps the Northwest Passage simply returned to a 'heavier' and 'stable' period (rather than a further sustained loss of sea ice) after an extreme ice year, similar to the situation after 1998. In addition, the authors' conclusion that the shipping season length of the Northwest Passage is shortened is mainly reflected in the M'Clure Strait and Viscount Melville Sound of the North route,

while the other regions such as Larsen Sound, Peel Sound and Prince Regent Inlet shown by the author has no obvious change trend. This is also an indication that the sea ice in the Northwest Passage has only returned to the years in which it flowed into the M'Clure Strait and Viscount Melville Sound areas, since several conditions are required for the passage to be ice-free, similar to the years of extreme light ice (as shown in the reference 34). Therefore, I think the authors should use a longer study period to illustrate changes in the shipping season length of the Northwest Passage. While the authors highlight the shift in sea ice types after 2007 as a reason for their focus on the study period, what the shipping season length was before the shift (according to POLARIS) is not well shown or explained.

Overall, although the results of the manuscript have some value for understanding the recent changes of the Northwest Passage, the specific content and findings lack sufficient scientific depth. The analysis of the reasons for the shorter shipping season length (or increased sea ice in the Northwest Passage) does not offer any novel insights. I would like recommend to reject the manuscript in its current form. Below, I have some other suggestions which might help improve the manuscript.

Some other specific comments :

(1) Since the main focus of the manuscript is on presenting the shipping season lengths along the routes, I believe the authors need to explain in the manuscript how the specific route grid was determined. As the entire passage can span to hundred kilometers in width in some sections, and the pixel grid size is 1km in the manuscript, because the distribution of sea ice changes from year to year has a large uncertainty, if it is a fixed route (rather than the optimal route determined by considering the pixel value), is the result accurate? There may be instances where a fixed route is impassable while the optimized route remains navigable.

(2) Fig. 2A shows the spatial distribution of the mean shipping season length of the Northwest Passage during 2007-2021, while Fig. 2B's analysis is based on three periods. Why is the distribution corresponding to the mean shipping season length of the three periods not provided? This may provide a more intuitive understanding of the changes in the three periods. Additionally, I suggest considering a different color scheme, such as a classified color ramp, instead of a stretched color scale. This modification might better distinguish the observed 'choke points' regions and make them more visually distinct and interpretable.

Reviewer #3 (Remarks to the Author):

In this study, the authors examined changes to shipping season lengths along the various NWP routes using Risk Index Outcome derived from the POLARIS. While the study extended previous research by assessing shipping seasons from 2007 onward, the findings and methodological approach are not new to me, especially in the context of earlier work such as Mudryk et al. (2021) and Howell et al. (2019). Specifically, one of the major conclusions that "decreased season length in the northern route seems to be due to multi-year ice being flushed southward from high latitude regions" is similar to the observations in Howell et al. (2009) and Howell et al. (2019). Furthermore, the study's emphasis on enhanced spatial resolution as a pivotal factor in addressing navigational risks at critical "chokepoints" is undoubtedly intriguing, yet regrettably lacks comprehensive elucidation. Moreover, the impact of bathymetry, ice thickness, and dynamics of sea ice floes within these critical "chokepoints" is a facet that remains inadequately investigated. Therefore, I would

encourage the authors to delve deeper into these intricate facets and provide a comprehensive, interesting, and in-depth perspective on this topic. Since this paper is the result of an important effort, I hope the authors can find some useful ideas to consider in a future resubmission.

Other comments:

L62-64: This statement is confusing to me. What do you mean by “almost completely ice-free for the first time” – the NWP should still be perceived as experiencing a seasonally ice-free condition, is that right? In addition, the phrase “even lighter condition” lacks clarity and doesn't convey a meaningful expression in this context.

Fig.1: It would be great to incorporate shading to represent ship tracks (1990-2018) using a density gradient. This enhancement would facilitate easier visualization of regions with higher traffic density, allowing for a more direct comparison with Fig. 2A.

Fig. 2: A more comprehensive explanation should be provided for interpreting Fig. 2B. While "W to E" appears to refer to the direction from west to east, it would be more reader-friendly for this to be explicitly stated rather than leaving it to the reader's inference. Does the scale in Fig. 2B correspond to that in Fig. 1A? Please explain the numbers outlined in Fig. 2A and elucidate their correspondence to distances in other subfigures. It is confusing to have a-b in Fig. 2B.

L113-114: What is the underlying cause for this notable increase? Please elaborate on the factors contributing to this substantial upsurge.

Fig. 4: What is the rationale for analyzing specific regions of M'Clure Strait and Viscount Melville Sound, apart from their short season length? For example, is there any socioeconomic significance associated with these regions that justifies their special consideration?

It is unclear to me how the CIS charts were converted into RIO values. Specifically, the method for establishing a relationship between RIV and the CIS ice charts is inadequately delineated within the Methods section. Additionally, it is imperative to specify the resolution of the ice data employed and to clarify whether ice thickness was factored into the computation of RIO. Both aspects hold crucial relevance in addressing the navigational challenges at the identified chokepoints.

Please provide references for your classification of early, mid, and late seasons, which would lend greater credibility to your chosen categorization scheme.

References:

Mudryk, L.R. et al. Impact of 1°, 2°, and 4°C of global warming on ship navigation in the Canadian Arctic. *Nature Climate Change* 11:673-679 (2021).

Howell, S. E. L. & Brady, M. The dynamic response of sea ice to warming in the Canadian Arctic Archipelago. *Geophysical Research Letters*, 46(22), 13119–13125 (2019).

Howell, S. E. L., Duguay, C. R. & Markus, T. Sea ice conditions and melt season duration variability within the Canadian Arctic Archipelago: 1979–2008, *Geophys. Res. Lett.*, 36, L10502 (2009).

## Response to Reviewer Comments

Thank you for the opportunity to revise our manuscript and to address the very useful and helpful comments provided to our team by three reviewers. Please see below our response to all comments.

**\*\*\* Present novel insights into changes in the length of the shipping season of the Northwest Passage in recent years based on the evidence presented and discuss your findings in light of earlier work, including an explanation of differences in the conclusions.**

The finding that some portions of the northern route of the Northwest Passage are becoming shorter in terms of season length is not directly contradicting previous studies that have noted that sea ice change is creating increased accessibility. Rather, the study represents a finer resolution scale analysis of how sea ice change may affect shipping at an operational/ship scale. That is, we acknowledge the overall larger scale warming leading to statistically significant reductions in sea ice – but – that the location of reductions and the mobility of ice into key areas of shipping routes is highly relevant at the operational scale. We have made significant edits to our text to ensure that this clarification is clearer now. That is that the study extends upon previous studies by focusing on a different scale vs. contradicting their findings overall.

**\*\*\* Provide comprehensive details of all data sources and derivations used in your analysis.**

Details on all data sources and derivations used in our analysis have been provided within edits directly in the main manuscript text and also within the methods section.

**\*\*\* Communicate the limitations and uncertainties that arise from using only recent data in your analysis and tone down relevant claims to reflect these limitations.**

The limitations and uncertainties from the study are now provided within the main manuscript and in a new part of the methods section. In observational studies, vs modelling based studies, the use of 15 years of data is considered sufficient. The reviewer seemed to be confusing observation studies with modelling via their reference to SSPs (i.e., used in model-based projection studies vs. observation studies) based studies where indeed 30+ years is desirable. Regardless, all study limitations are made more clear in the revised text and justification of the time period selected is also provided.

## REVIEWER COMMENTS:

### Reviewer #1 (Remarks to the Author):

By utilizing the Polar Operational Limit Assessment Risk Indexing System (POLARIS) and weekly regional ice charts provided by the Canadian Ice Service (CIS), this study aims to estimate the duration of the shipping season in the Northwest Passage (NWP). The article

title is interesting to me because it seems to run counter to many published papers before. The authors find significant spatiotemporal variability exists in shipping season lengths for both the southern and northern routes of the NWP, with the latter exhibiting significant decreases of up to 6 weeks over the 15 years (2007–2021). Although the Arctic communities may find these findings to be interesting, the manuscript's persuasiveness is limited by the absence of discussion surrounding the findings' uncertainties, in particular, the reasons why the findings and inference in this study contradict previous studies. In my opinion, this paper is not suitable for publication in Communications Earth & Environment.

We would like to thank Reviewer #1 for their interest in our study. We have taken onboard their comments regarding the lack of discussion surrounding the findings' uncertainties and have edited and improved our manuscript accordingly. We believe that the reviewer will now be satisfied that our work presents both interesting and persuasive results. Also see response to 'minimum requirements' (first comment) on the extent to which the study contradicts previous studies where rather it extends them. It is important to also note that previous studies referred to are projection-based (i.e. future) whereas our study is observationally based (historic). We believe that our study results can help to inform future projection-based studies considering the non-linear dynamics of sea ice change, including extensive sea ice mobility that has significant effects at the local / ship scale that are not possible to capture in studies at the national or global scale. It is noted here that studies at both / all scales are vital for enhancing overall understanding.

General comments:

1. In contrast to what many studies (e.g., Melia et al., 2016; Mudryk et al., 2021; Smith and Stephenson, 2013) have projected, the authors come to the conclusion that the northern route of the NWP may not become operationally viable after simply analyzing the 15-year variation of shipping season length in the NWP. The analysis only covers a 15-year period, particularly after the significant Arctic sea ice loss in 2007. Additionally, the authors' conclusion relies solely on the linear trend observed during this period and does not take into account its level of uncertainty. I believe that the conclusion/inference cannot be confidently stated without analyzing longer periods for comparison and discussing the variation in navigability under different climate warming scenarios (e.g., different SSPs).

We are grateful to the reviewer for making these very useful points. We have changed our text to make it clearer that our work is extending the previous work of these various authors by focusing at a smaller spatial scale (i.e., specific sections of the NWP route). Previous studies have examined navigability (observed and projected) at a large regional scale. However, at an operational scale, even if on average the region is increasing in terms of 'accessibility' or 'season length' if certain sections of a route are not accessible than this is not useful for ship operators. Thus, our work does not contradict previous studies as indeed there is an overall reduction of sea ice, but rather it enhances previous understanding by showing that the exact location of reductions vs. sea ice mobility and/or lack of reduction is highly relevant for ship operations. We have added text in the article to make this point clearer, while also toning down some previous statements about overall utility of the findings.

In order to increase the robustness of our analysis, we have included calculated uncertainties using statistical tests at each stage of our analysis. Firstly, we calculated the statistical significance of change along all of the routes using ANOVA tests, which has resulted in establishing 4 sections of the NWP where statistically significant change has occurred between the three 5 year time periods, at a 95% confidence level. Secondly, for each of these four sections, we show variability along the sections by calculating standard deviations of the mean full season values along the full length of these sections and show these on new graphs (Figure 4 and 5). Thirdly, the trends over time were calculated using Mann-Whitely and Sen's Slope tests, and we make our conclusions based only on those that have a P-value < 0.05. We show the results on the graphs in Figures 4 and 5. These tests were used because 15-years is considered insufficiently long for the standard tests (e.g. T-test) for identifying linear trends, but Mann-Whitely and Sen's Slope are well established statistical methods when assessing variation from the mean of two independent variables using non-parametric data. We hope the reviewer recognises that these results including uncertainties are now comprehensive and robust, and our conclusions can be stated confidently. In addition, we have edited the wording of our conclusions in recognition of the fact that 15 years is not long enough to conclude whether these regions will be increasingly challenging to ships in the future. We are reporting on past results, not the future, but we refer to studies that model future ice change in the region, including the references given here by the reviewer. Finally, a 15 year time period is sufficient for an observation-based study and the intention of this study was not to project future conditions (i.e., as was that of Stephenson et al. and Mydryk et al.) and thus the SSPs are not relevant here.

2. Additionally, it would be better to define these 'choke points' in the Abstract given that the authors demonstrate that the decreasing trends do not exist in all sections of the routes. I'd like to reiterate that I don't think the authors' conclusion holds true over the entire NWP. It will therefore be preferable to make this clearer in the Title or Abstract.

We feel the abstract word limit is too short for us to define each of the 'choke points'. However, we have toned down the wording in the title to indicate that the paper is about variability in the shipping season lengths of the NWP routes, not only the shortening seasons that occurred along sections of the northern route. However, the combined length of these sections does make up half of the northern route (in total, 600 km of the 1,200km total length of the northern route in this study), so we are justified in our wording in the abstract when we state "parts of the northern route". We think the abstract makes it clear we are not drawing conclusions for the whole northern route.

3. In Figure 4, why does the largest decrease occur in the mid-season?

We thank the reviewer for their question, and we have now explained in the text why the decrease occurs during the mid-season in the choke point locations. There is ice in these regions during the shoulder seasons, therefore the number of weeks open to shipping transit are minimal during these periods. Melt occurs during the mid-season, therefore there are more weeks that the region is open when compared to the shoulder seasons. The number of weeks during the mid-season is decreasing, however, because the MYI transits southwards into the channels during this time, causing greater risks to ships.

4. The Method section of the article needs to be clearer. For instance, specific information regarding the Risk Index Value (RIV) calculation process, the spatial resolution of the CIS sea ice charts, and the ships' ice resistance should be provided.

We give the description of the CIS sea ice charts, the methods established by the IMO to convert these to POLARIS charts and the method we used to convert these to shipping season length charts. Our opinion is that our explanation of the RIO calculation process is clear since this is an accepted methodology, and we give citations for the RIV derivations and Polar Code ship ice class values if readers require a fuller explanation.

Minor comments:

1. Line 18. The 'route' should be 'routes'. [Done](#)
2. Line 128. Is 'shipping variability' referring to the variability in the length of shipping seasons? [Reworded as "normal operation duration" to clarify](#)
3. Line 235. 'acts' rather than 'act'? [Done](#)
4. Lines 150–152. Does the Viscount Melville Sound section have a 400 km length? [Analysis has been re-done for 200 km sections. This has been reworded accordingly.](#)
5. Line 161. Please specify the exact month for shoulder seasons as it first appears in your text, even though you previously did it in the Method section. [This section has been re-written now that the new graphs have been produced, and these are all contained in one figure, with the shoulder seasons specified at the start of the results description.](#)
6. I think the figures presented now should be improved. For instance, the display format can be improved and the text annotation in the picture should be made larger for reading. [The figures have been reproduced following the new analysis and we believe now have better clarity and with larger font size.](#)

## References

- Melia, N., Haines, K., & Hawkins, E. (2016). Sea ice decline and 21st century trans-Arctic shipping routes. *Geophysical Research Letters*, 43(18), 9720-9728.  
<https://doi.org/10.1002/2016GL069315>
- Mudryk, L. R., Dawson, J., Howell, S. E. L., Derksen, C., Zagon, T. A., & Brady, M. (2021). Impact of 1, 2 and 4 °C of global warming on ship navigation in the Canadian Arctic. *Nature Climate Change*, 11(8), 673-679. <https://doi.org/10.1038/s41558-021-01087-6>
- Smith, L. C., & Stephenson, S. R. (2013). New Trans-Arctic shipping routes navigable by midcentury. *Proceedings of the National Academy of Sciences*, 110(13), E1191-E1195.  
<https://doi.org/10.1073/pnas.1214212110>

We have referenced the manuscripts that the reviewer lists here. We have also made it clear that our results do challenge some of the overarching conclusions of these studies, but only for very specific sections along the northern NWP shipping route. We do not claim that our conclusions apply to the wider Arctic regions, which is the scale of previous studies. In this regard, our study extends previous studies and focuses analysis at a finer scale than was conducted previously and as such is not in direct contradiction of existing findings (i.e., rather it builds on them spatially).

## **Reviewer #2 (Remarks to the Author):**

In the context of global warming, the Northwest Passage has an important impact on the change of the world shipping pattern and the development of surrounding communities. Based on POLARIS and CIS data, the authors calculated and analyzed the navigability change of the Northwest Passage from 2007 to 2021. These results contribute to a better understanding of the changes in the length of the shipping season of the route in recent years and the major 'choke points' areas affecting shipping. In my understanding, the manuscript is concise and majorly clearly written, and the methods and conclusions are reasonable, the authors cleverly converted the sea ice status of the Northwest Passage into a cumulative number of shipping weeks and analyzed it on this basis.

We would like to thank Reviewer #2 for their compliments about our paper. We appreciate their recommendations for improvement, and we address each of them here.

While the study may be valuable for readers new to the subject or researchers from other disciplines, it may not offer sufficiently novel insights for those who have extensively studied the topic of Arctic sea ice and navigability in the Northwest Passage.

Until now, there are no publications about the shipping seasons becoming shorter, and why this is taking place. Indeed, existing publications have stated that the shipping seasons are lengthening (we have listed these in our introduction). Ship operators may know that the season shortening is a fact, but academics do not know this. Our work shows novel insights about where the ship routes have been affected, and by how much, showing the number of weeks per year that are more risky to ships. In addition, we quantify how much the season lengths vary according to ship ice strengths. It is more localised, specifically along the popular shipping routes, than work done previously that assesses change over the whole region. We believe we have made these insights clearer in the text.

Although the shipping season length obtained by statistics is of important reference for ships wishing to operate in the Northwest Passage for a long time, the authors did not provide a complete navigable window.

We agree that these results will be an important reference for ships wishing to operate in the NWP. There are different ways in which a "complete navigable window" can be defined and calculated. Liu et al (2017) used a criteria that this window is the start/end date at which a ship is able to travel unassisted through sea ice. Using Table 4 in their manuscript, they calculated the earliest navigable window start date was 4<sup>th</sup> June (Lancaster Sound), up to 18<sup>th</sup> August (Viscount Melville Sound). The latest navigable window end date was 5<sup>th</sup> November (Leg 2). We have used all weekly ice charts between 1<sup>st</sup> April to 31<sup>st</sup> December, therefore we can be sure that this encompasses the navigable window for shipping throughout the region. We have referenced Liu et al (2017) for readers who would like the definition.

In fact, the spatial distribution of sea ice in the Northwest Passage varies greatly from week to week, and the navigability of each section may not be consistent at the same time (week). For ships attempting a full transit of the Northwest Passage, relying solely on such coarse estimates of shipping season length may be insufficient for precise ship scheduling decisions. Hence, I think it is necessary for the author to provide a specific shipping season window for each section and the whole route. If the sole purpose is to compare the navigability of various segments along the route, one could easily identify 'choke points' by simply averaging the sea ice concentration of the season.

The sea ice distribution does indeed vary from week to week, hence we have included all weekly ice charts across the region (1<sup>st</sup> April to 31<sup>st</sup> December). Our paper is not intended for precise ship scheduling decisions, but rather as an examination of trends in average season lengths. There are different methods that can be used to examine ice charts in relation to shipping, and ours is a new and innovative way to quantify shipping season length rather than the consistency of time of year that the route is navigable. Our Figure 3 addresses the time of year by showing navigability during shoulder and mid-seasons, and interannual changes during these times of year (Figures 4 and 5). More intricate localised studies could look into how navigability varies between each calendar week of the year between years, but we do not believe that this would be helpful in analysing total annual length of time that the passage is navigable on a more regional scale. In addition, calculation of a start/end date of a navigable window is not always best, as the dates are never clear-cut, with navigability changing throughout the season (therefore it does not start and end, but rather varies). By giving the total number of weeks that the route is navigable at any particular point gives a better idea of the length of time of this window. Modelling based studies will benefit from knowing these new findings for making better predictions.

An important finding in the manuscript is that the shipping season length of the Northwest Passage (northern route) has decreased in recent years, which actually corresponds to the recent sea ice recovery/increase in the Northwest Passage shown in many studies. We know that 2007-2012 was the lowest period of sea ice in the Northwest Passage in history, and that these years would have been the longest navigation seasons, hence the reduction in shipping season length would have been a logical outcome if there had not been a similar extreme light ice year recently. The authors present a different viewpoint based on the results from this specific time period, suggesting that the Northwest Passage may become more dangerous despite the diminishing Arctic sea ice. However, this perspective may be biased, as other studies typically discuss this change over longer time spans, such as the study period from 1979. When compared to conditions during the early years of research, the current situation in the Northwest Passage has already shown significant improvement. Most studies predict that the Northwest Passage will become less dangerous in the future, often projecting towards 2050 or even 2100, while maintaining caution and conservatism about full navigability. Therefore, I believe that the authors' conclusions do not conflict with the conclusions of previous studies, but the authors emphasize the observation that the shipping season length of the Northwest Passage has been shortened since 2007. However, a conclusion about future long-term trends drawn from a historically light ice year as a starting point may not be accurate, and perhaps the Northwest Passage simply returned to a

'heavier' and 'stable' period (rather than a further sustained loss of sea ice) after an extreme ice year, similar to the situation after 1998. In addition, the authors' conclusion that the shipping season length of the Northwest Passage is shortened is mainly reflected in the M'Clure Strait and Viscount Melville Sound of the North route, while the other regions such as Larsen Sound, Peel Sound and Prince Regent Inlet shown by the author has no obvious change trend. This is also an indication that the sea ice in the Northwest Passage has only returned to the years in which it flowed into the M'Clure Strait and Viscount Melville Sound areas, since several conditions are required for the passage to be ice-free, similar to the years of extreme light ice (as shown in the reference 34). Therefore, I think the authors should use a longer study period to illustrate changes in the shipping season length of the Northwest Passage. While the authors highlight the shift in sea ice types after 2007 as a reason for their focus on the study period, what the shipping season length was before the shift (according to POLARIS) is not well shown or explained.

We thank the reviewer for giving their insights, and we have been able to add some of these to our manuscript. By doing our new, more robust analysis, as well as our clearer explanation in the text of why we only focus on the period 2007-2021, we address the reviewer's points of concern. We have reworded much of the text to make it clear that conclusions are only based on this time period, that this methodology cannot be applied to earlier years due to the lesser frequency/regularity of ice charts before this time, and that we are not making conjectures about how long the shorter seasons will continue. We have made our time frames clearer, and have made provisory comments that the start of our study was during a period of lighter sea ice, and that not all regions have shown trends. Our study is observational; therefore we are able to discuss, but not conclusively prove, the reasons for the shorter shipping seasons. Our conclusions about statistically significant trends are fair and not biased, but we have revised our text to make the points about the conditions during the extreme light ice years in the NWP. Also see responses to previous queries.

Overall, although the results of the manuscript have some value for understanding the recent changes of the Northwest Passage, the specific content and findings lack sufficient scientific depth. The analysis of the reasons for the shorter shipping season length (or increased sea ice in the Northwest Passage) does not offer any novel insights. I would like recommend to reject the manuscript in its current form. Below, I have some other suggestions which might help improve the manuscript.

We hope that the reviewer now sees that our new content and findings do have good scientific depth. The novel insights are that it has not yet been shown that the shipping seasons have become shorter during recent years, and we have been able to show through using good quality data and statistical analysis, where this has occurred, by how many weeks in each region and by ships of differing ice strength. We have made our discussion and conclusion clearer to show the value of this improved understanding for shipping in the NWP.

Some other specific comments :

(1) Since the main focus of the manuscript is on presenting the shipping season lengths along the routes, I believe the authors need to explain in the manuscript how the specific route grid was determined. As the entire passage can span to hundred kilometers in width in some sections, and the pixel grid size is 1km in the manuscript, because the distribution of sea ice changes from year to year has a large uncertainty, if it is a fixed route (rather than the optimal route determined by considering the pixel value), is the result accurate? There may be instances where a fixed route is impassable while the optimized route remains navigable.

The optimal route for a ship on site is decided by the ship's captain, based on observations from onboard, and from the ice charts and other sources. Our study is scientific, showing the mean values along a consistent, fixed path, with change over regular time periods (weeks, per year, across 15 years). The ship route lines that we use are approximately along the centreline of the large number of ship tracks through the region (Figure 1), and they are the same as those used in other studies (e.g. Howell et al, 2022; Fig 1). We acknowledge that an optimized route may be passable when the fixed route is impassable, but our objective method allows quantification of change over time along an unchanging pathway.

(2) Fig. 2A shows the spatial distribution of the mean shipping season length of the Northwest Passage during 2007-2021, while Fig. 2B's analysis is based on three periods. Why is the distribution corresponding to the mean shipping season length of the three periods not provided? This may provide a more intuitive understanding of the changes in the three periods. Additionally, I suggest considering a different color scheme, such as a classified color ramp, instead of a stretched color scale. This modification might better distinguish the observed 'choke points' regions and make them more visually distinct and interpretable.

The reviewer describes what could be shown in a different study, about shipping season length changes region-wide. We explain more clearly in the text that our study is specifically looking at changes along the centre lines of the NWP shipping routes. The region is large, and ships do not pass through all areas throughout the region, and we keep our results focussed on where ships are known to transit. Our localised results are targeted at the pathways that matter to ships. Figure 2A shows the mean season length between 2007 and 2021 as the background image, to illustrate the generalised mean spatial distribution throughout the region, across the whole of our timeframe (15 years), to enable the reader to picture the region as a whole, but not to interpret change over the whole region. Producing the same map for the three time periods would not be worthwhile or accurate, because the variability between years is considerable and the mean values could be misinterpreted (as we explain in the text, regarding the mean values of data along the route centrelines).

### **Reviewer #3 (Remarks to the Author):**

In this study, the authors examined changes to shipping season lengths along the various NWP routes using Risk Index Outcome derived from the POLARIS. While the study extended previous research by assessing shipping seasons from 2007 onward, the findings and methodological approach are not new to me, especially in the context of earlier work such

as Mudryk et al. (2021) and Howell et al. (2019). Specifically, one of the major conclusions that “decreased season length in the northern route seems to be due to multi-year ice being flushed southward from high latitude regions” is similar to the observations in Howell et al. (2009) and Howell et al. (2019). Furthermore, the study's emphasis on enhanced spatial resolution as a pivotal factor in addressing navigational risks at critical "chokepoints" is undoubtedly intriguing, yet regrettably lacks comprehensive elucidation. Moreover, the impact of bathymetry, ice thickness, and dynamics of sea ice floes within these critical "chokepoints" is a facet that remains inadequately investigated. Therefore, I would encourage the authors to delve deeper into these intricate facets and provide a comprehensive, interesting, and in-depth perspective on this topic. Since this paper is the result of an important effort, I hope the authors can find some useful ideas to consider in a future resubmission.

Thank you Reviewer #3, we have taken your comments onboard and they have helped us to improve our manuscript. These comments helped us to realise that some aspects of our study have been misunderstood. We would like to clarify the purpose of our study by explaining that we do not intend to use our results to demonstrate that MYI is being “flushed down from high latitude regions” (which we do recognise has been observed and published already), but rather to highlight the impact that this has on ships travelling in the region. Our findings about the length of shipping seasons are new and we believe important for furthering understanding of how this might affect ships attempting to transit the NWP. We believe these findings should be taken into consideration by vessel captains and others who travel through the NWP, and the insights will enable modellers to factor in the impacts of the shorter seasons for ships of different ice strengths. It is novel because our methods have not been used before, and the POLARIS charts that we converted into shipping season length charts offer valuable and reliable new datasets for exploring the risks to ships from sea ice over recent years. We do not examine the “choke points” regarding other variables such as bathymetry or ice dynamics, because we believe our findings from the charts tell a strong story without need for further data analyses. Our main conclusions are about shipping rather than regarding the physics of the mobility of sea ice, which can be analysed from the sea ice charts themselves rather than our converted shipping season length charts. Even if others have thought that the movement of MYI southwards is impacting the safety of passage by ships in the region, our results quantify the number of weeks that ships of different ice strength have been able to travel, and that this is decreasing in particular regions, and increasing in eastern Lancaster Sound. We have reworded much of our manuscript to make our objectives and conclusions clearer, and we hope as a result that the reviewer is happy about the strength and importance of our research.

Other comments:

L62-64: This statement is confusing to me. What do you mean by “almost completely ice-free for the first time” – the NWP should still be perceived as experiencing a seasonally ice-free condition, is that right? In addition, the phrase “even lighter condition” lacks clarity and doesn't convey a meaningful expression in this context.

We have reworded this sentence to clarify what we mean.

Fig.1: It would be great to incorporate shading to represent ship tracks (1990-2018) using a density gradient. This enhancement would facilitate easier visualization of regions with higher traffic density, allowing for a more direct comparison with Fig. 2A.

The greyed-out ship tracks give the reader an idea of where ships travel, whereas a colour graded grid to show density detracts from the purpose of our paper and could be distracting. The shipping routes are established and used in other publications, and the coloured lines show where they are located. Fig 1 is regarded as a location map, and a grid showing a shipping density gradient will make the map too cluttered.

Fig. 2: A more comprehensive explanation should be provided for interpreting Fig. 2B. While "W to E" appears to refer to the direction from west to east, it would be more reader-friendly for this to be explicitly stated rather than leaving it to the reader's inference. Does the scale in Fig. 2B correspond to that in Fig. 1A? Please explain the numbers outlined in Fig. 2A and elucidate their correspondence to distances in other subfigures. It is confusing to have a-b in Fig. 2B.

We have added the words "west to east" for each graph shown in Fig 2B as suggested. The x-axis of the graphs is distance along the routes with labels at every 100 km. The routes are shown on the map with points marking every 100 km, which are numbered every 500 km, so the reader can refer directly between the graph and map to locate corresponding points. The horizontal scale of the graphs is approximately the same as the route distances on the map, but not exactly the same because as is shown, the routes are not on a straight path. The purpose of Figures 2A and 2B together are to enable the reader to locate the sections along the routes showing shipping season lengths. The letters a-d in Fig 2B relate to the routes a-d as shown on the map. We are confident that figures 2A and 2B are clear, but the reviewer has shown that the reader needs assistance to understand them. Accordingly, we've made the Figure 2 caption clearer.

L113-114: What is the underlying cause for this notable increase? Please elaborate on the factors contributing to this substantial upsurge.

We have rewritten this section following our reanalysis of the data. We mention the increase in season length in Bellot Strait, with the proviso that this is not a statistically significant increase and varies considerably year to year. We therefore do not draw conclusions from this observation.

Fig. 4: What is the rationale for analyzing specific regions of M'Clure Strait and Viscount Melville Sound, apart from their short season length? For example, is there any socioeconomic significance associated with these regions that justifies their special consideration?

In our first version of the manuscript, we chose these as regions of interest, not based on any reason other than their short season length and the changes we observed visually between the 5-year periods as shown in Figure 2. In our new manuscript, we have re-

produced Figure 4 for the four regions that have shown a statistically significant change over time. This is a more robust methodology and rationale.

It is unclear to me how the CIS charts were converted into RIO values. Specifically, the method for establishing a relationship between RIV and the CIS ice charts is inadequately delineated within the Methods section. Additionally, it is imperative to specify the resolution of the ice data employed and to clarify whether ice thickness was factored into the computation of RIO. Both aspects hold crucial relevance in addressing the navigational challenges at the identified chokepoints.

In the methodology section, we run through the consecutive steps of the process. Firstly, the description of the CIS charts and a reference to their production and source; then, the explanation for the conversion to POLARIS RIO, which includes the established RIO calculation equation, and we include the reference to this. The RIV values are given in Table 11 within the reference document ([https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/ABS\\_Polar\\_Code\\_Advisory\\_15239.pdf](https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/ABS_Polar_Code_Advisory_15239.pdf)), and the table includes the sea ice types that are used together with the ship ice strengths. The table shows that the RIV is based specifically on increasing ice thickness (severity) graded as a description of ice type. This demonstrates that ice thickness is factored in to the computation of RIO as is an accepted method, used by the IMO.

Please provide references for your classification of early, mid, and late seasons, which would lend greater credibility to your chosen categorization scheme.

There is no published definition of the two monthly periods for early, mid and late seasons, but the seasons are generally recognised at the operational level. Example dates for approximately the middle of each season are given by Copland et al. (2021) for the early (~25<sup>th</sup> June), mid (3<sup>rd</sup> September) and late (15<sup>th</sup> October) seasons. We have added this citation in Methods, at our description of the seasons.

#### References:

- Mudryk, L.R. et al. Impact of 1°, 2°, and 4°C of global warming on ship navigation in the Canadian Arctic. *Nature Climate Change* 11:673-679 (2021).
- Howell, S. E. L. & Brady, M. The dynamic response of sea ice to warming in the Canadian Arctic Archipelago. *Geophysical Research Letters*, 46(22), 13119–13125 (2019).
- Howell, S. E. L., Duguay, C. R. & Markus, T. Sea ice conditions and melt season duration variability within the Canadian Arctic Archipelago: 1979–2008, *Geophys. Res. Lett.*, 36, L10502 (2009).

17th Apr 24

Dear Dr Cook,

Your manuscript titled "Recent variability of the shipping season lengths along the routes of the Northwest Passage" has now been seen by our reviewers, whose comments appear below. Please note that due to absence of reviewers 1 and 3 we have assigned new reviewer 4. In light of reviewer's advice, we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper to clarify and discuss the influence of the time period selection (2007-2012) on the credibility of the results as requested by reviewer 4. At the same time, we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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Best regards,

Martina Grecequet, PhD  
Associate Editor,  
Communications Earth & Environment  
@CommsEarth

#### REVIEWERS' COMMENTS:

##### Reviewer #2 (Remarks to the Author):

This study shows for the first time that the shipping season in northern passages of NWP has been shortening since 2007 due to large annual variations exist in some choke points. I am more than satisfied with that the authors added more discussions on the overflow ice from Arctic in the revised manuscript. I agree to publish in Communications Earth & Environment.

##### Reviewer #4 (Remarks to the Author):

The claim of this paper is that navigation time of the NWP has decreased in the past 15 years, which challenges our already established cognition that the decrease in sea ice leads to the prolongation of the navigable time. The conclusion is the first time within my personal knowledge that this has been explicitly stated, thus the novelty of this work is beyond doubt.

In terms of the authors' methodology, the conclusion is convincing, and at least for the 15 years of the authors' focus (2007-2021), it is possible to obtain a clear conclusion that "the navigation time of some segments of the NWP has been shortened". I have also carefully read the reviewers' comments and the authors' responses, in which Reviewer #2 mentioned about the influence of the time period selection (2007-2012 was the lowest period of sea ice in the Northwest Passage in history) on the credibility of the results. The authors still haven't given a convincing answer to the comment. The CMIP6 models forced by SSP-RCP scenarios can indeed be used to accomplish a similar task, but the discrepancy between simulations and observations may result in projections that do not support the authors' current conclusions. A point that the authors could have clarified by using the results of historical experiments of CMIP6 models in the concurrent time period (2007-

2021) against the observed facts, to dispel readers' doubts as to the possibility of recreating the "shorter seasons in the NWP" in the projections. It also partially explains the contradiction between the generally accepted "longer navigation season" and the author's proposal of "shorter segments". From a subjective point of view, this article gives challenging conclusions in the field of navigability research of the Arctic shipping routes, which will definitely promote the research in this field to be more specific to specific passages. Such work also has social topics, and I think it is worth publishing in Communications earth& Environment.

#### Reviewer #4 (Remarks to the Author):

The claim of this paper is that navigation time of the NWP has decreased in the past 15 years, which challenges our already established cognition that the decrease in sea ice leads to the prolongation of the navigable time. The conclusion is the first time within my personal knowledge that this has been explicitly stated, thus the novelty of this work is beyond doubt. In terms of the authors' methodology, the conclusion is convincing, and at least for the 15 years of the authors' focus (2007-2021), it is possible to obtain a clear conclusion that "the navigation time of some segments of the NWP has been shortened". I have also carefully read the reviewers' comments and the authors' responses, in which Reviewer #2 mentioned about the influence of the time period selection (2007-2012 was the lowest period of sea ice in the Northwest Passage in history) on the credibility of the results. The authors still haven't given a convincing answer to the comment. The CMIP6 models forced by SSP-RCP scenarios can indeed be used to accomplish a similar task, but the discrepancy between simulations and observations may result in projections that do not support the authors' current conclusions. A point that the authors could have clarified by using the results of historical experiments of CMIP6 models in the concurrent time period (2007-2021) against the observed facts, to dispel readers' doubts as to the possibility of recreating the "shorter seasons in the NWP" in the projections. It also partially explains the contradiction between the generally accepted "longer navigation season" and the author's proposal of "shorter segments". From a subjective point of view, this article gives challenging conclusions in the field of navigability research of the Arctic shipping routes, which will definitely promote the research in this field to be more specific to specific passages. Such work also has social topics, and I think it is worth publishing in Communications earth& Environment.

#### Response to Reviewer #4

We would like to thank the reviewer for their comments, and we have been able to revise our paper to clarify the credibility of the results regarding the time period 2007-2012.

With respect to CMIP6 models, we feel that they are really not useful in the NWP (and perhaps give a false sense of optimism) because most models do not connect the northern CAA with the southern CAA via the Parry Channel, and hence, do not capture the flow of ice from north to south in the CAA.

We think we have justified that starting in 2007 (i.e. low ice year) does not influence the credibility of the results. The point we emphasize is that the processes (i.e. ice dynamics) that contribute to the recovery of sea ice in the NWP are continuing to operate during low ice years. That is, even during this low ice period from 2007-2012 ice continued to accumulate in the chokepoint regions thus making navigation difficult. If 2007-2012 was a normal period per se we could argue that the reductions in shipping season length would be even greater, such as with the rapid recovery from 1998. It is also important to note that the 2007 start year marks the time

period when the Arctic shifted from a MYI regime to a FYI regime and is more representative of the current lighter ice conditions across the Arctic. We argued that the process of southward ice transport will continue to occur as long as the supply of the Arctic's oldest and thickest ice resides along the north facing coast of the CAA. Even when the Arctic becomes sea ice-free during the summer this ice will still be present and flow southward. Indeed, as ice in this region continues to decline towards mid-century and beyond, the process of southward ice transport will also decline BUT it won't stop and thus still be problematic to navigation. We have revised our text in the Discussion accordingly.