

Referee comments - Luofeng Huang, University College London

The authors provide an interesting study on predicting Arctic sea ice condition and the associated shipping navigability. Overall I think the work is of importance under the trend of ongoing climate change, and it can provide valuable insights for relevant stakeholders such as shipbuilders and operators. Therefore, I am in favour of publishing this manuscript. However, I did find a list of issues existing in the current form, as follows:

Q1. It is rare to use the term “Northeast Passage (NEP)”. The common term is “Northern Sea Route (NSR)”.

A1: Thanks for your suggestion. Northeast Passage (NEP) was replaced with Northern Sea Route (NSR) in the revised manuscript.

Q2. Line 47-51, the authors say “Northeast Passage” is an alternative to Panama Canal and Suez Canal - this is an incorrect expression, because the Northwest Passage (NWP) is the alternative of Panama canal and the Northern Sea Route (NSR) is the alternative of Suez Canal. They should be stated separately and clearly.

A2: Thanks for your correction. This sentence was revised as “The Northern Sea Route (NSR) extends along the northern coast of Eurasia from Iceland to the Bering Strait and shortens the transit distance by approximately 15%–50% relative to the southern routes through the Suez Canal.”

Q3. Line 51-52, “It is navigable for approximately a month and half per year for ice-strengthened ships at the end of summer (Khon et al., 2010)”. Is this information outdated as reference is from more than ten years ago? Please check there is some recent reference for this, because the navigable season is probably already longer than 1.5 months nowadays.

A3: The navigable season has extended to about 3 months for ice-strengthened ships. This sentence was revised as “It is navigable for approximately three months per year for ice-strengthened ships at the end of summer and the beginning of autumn (Yu et al., 2020).”

[Ref] Yu, M., Lu, P., Li, Z. Y., Li, Z. J., Wang, Q. K., Cao, X. W., Chen, X. D.: Sea ice conditions and navigability through the Northeast Passage in the past 40 years based on remote-sensing data. Int. J. Digit. Earth, 1–20, <https://doi.org/10.1080/17538947.2020.1860144>, 2020.

Q4. Line 52-53, “The day at which open water (OW) ships can cross the NEP has reached 297±4 (October 24th) since 2010.” It is not clear in English, please rewrite.

A4: This sentence was rewritten as “The end of shipping season for open water (OW) vessels has reached October 24th since 2010 (excluding 2013).”

[Ref] Chen, S. Y., Cao, Y. F., Hui, F. M., and Cheng, X.: Observed spatial-temporal changes in the autumn navigability of the Arctic Northeast Route from 2010 to 2017 (in Chinese), Chinese Sci. Bull., 64, 1515–1525, <https://doi.org/10.1360/N972018-01083>, 2019.

Q5. Line 54-55, “However, navigability is still affected by the ice regime around the Severnaya Zemlya Islands, the Novosibirsk Islands, and the East Siberian Sea (Chen et al., 2019)” It is unclear what does the ice regime mean? And how does the ice regime influence shipping navigability?

A5: Thanks for your question. Ice regime mainly means ice thickness and ice concentration in Chen et al., 2019. Shipping navigability reduces with the increasing of ice thickness and concentration.

Q6. Introduction, Page 3: I suggest the authors provide a review of the geographical and political factors on the NWP and NSR. This is because the practicality for employing the NSR is currently greater than for the NWP. As introduced by Ryan et al. [Ref], The NWP is made up of straits through the Canadian Arctic Archipelago that are both narrow and shallow. These straits are easily clogged by free floating ice, and are still insufficiently surveyed, presenting the very real risks of grounding or becoming stuck in ice; By contrast, the NSR presents a less complex situation, yet has several choke points where ships must pass through shallow straits between islands and the Russian mainland. Apart from the geographical factor, politics has also been providing increasing impetuses for adopting the NSR; for example, China has indicated its plans to establish a Polar Silk Road as part of the Belt and Road Initiative, which aims to build infrastructure and perform voyages through the NSR.

[Ref] C. Ryan, G. Thomas, D. Stagonas, Arctic Shipping Trends 2050, University College London, 2021.

A6: The review, as shown below, for geographical and political factors on the NWP and NSR was made in the revised manuscript.

“Geographical and political factors also pose some challenges to the navigability of passages and choice of routes (Ryan et al., 2020). The straits along the NWP are at times narrow and shallow, which are easily clogged by free floating ice. NSR is greater than NWP in terms of geography, while it still has several choke points where ships must pass through shallow straits between islands and the Russian mainland (Streng et al., 2013). Apart from the geographical factor, the various organizations and groups formed between the surround-Arctic nations, as well as the disputes and agreements, give impetuses for adopting the NSR. Russia has committed several large infrastructure projects to support the NSR, such as Yamal-Nenets railway and emergency rescue centers (Serova, N. A. and Serova, V. A, 2019). China, which is characterized as a near-Arctic state, also outlined the plans to build a Polar Silk Road by building infrastructure and conducting trial voyages (Tillman et al., 2019).”

Q7. Introduction Page 4: I suggest the authors provide a table of Ice Class versus Operating Ice Thickness for ships. In the current manuscript, I feel the authors suddenly bring out the concept of Polar Class (PC) from Line 68 – this does not fit for a general audience if no background information is given.

A7: Thanks for your suggestion. The table of vessel class versus operating ice thickness was provided in the revised manuscript.

Table 1 *Vessel classes versus operating ice thickness*

<i>Vessel class</i>	<i>Maximum allowable ice type</i>	<i>Ice thickness (cm)</i>
<i>Polar class 3</i>	<i>Second year</i>	<i>No limit</i>
<i>Polar class 6</i>	<i>Medium first-year</i>	<i>70–120</i>
<i>Ordinary merchant</i>	<i>Open water/Grey</i>	<i>10–15</i>

Q8. End of Introduction: the authors should clearly state the novelty and contribution of this work, in comparison with previous studies, e.g. V. Khon, I. Mokhov, M. Latif, V. Semenov, and W. Park, “Perspectives of northern sea route and northwest passage in the twenty-first century,” *Climatic Change*, vol. 100, no. 3-4, pp. 757–768, 2010.

A8: Thank you. Compared with previous studies such as Khon et al., 2010, one novelty of this work is that the latest multi-model results from CMIP6 were used to evaluate the future changes of sea ice, and the other is that the filtration for multi-models to reduce the

uncertainties. Both of them were stated in the revised Introduction.

Q9. Line 223-224: “The number of vessels passing through the Arctic is increasing year by year, but OW ships usually need the guidance of icebreakers, which increases transportation costs.” I believe this is not a correct statement, because open water vessels only need icebreakers when encountering unnavigable consolidated ice.

A9: Thanks for your correction. This sentence was deleted.

Q10. Line 225: “The opening of Arctic passages for OW ships is profitable for ocean shipping companies” Some references to support this statement?

A10: This sentence was revised as “The opening of Arctic passages is profitable for ocean shipping companies (Chang et al., 2015)”.

Chang, K. Y., He, S. S., Chou, C. C., Kao, S. L., Chiou, A. S.: Route planning and cost analysis for travelling through the Arctic Northeast Passage using public 3D GIS. Int. J. Geogr. Inf. Sci., 29, 7–8, 1375–1393, <https://doi.org/10.1080/13658816.2015.1030672>, 2015.

Q11. Line 230-232: “Fortunately, the crucial straits, such as the Shokalskiy Strait, Vilkitsky Strait, Sannikov Strait, and Dmitrii Laptev Strait, will be accessible for OW ships.” I suggest the authors remove the word “fortunately”, because it is not academic writing and many readers may feel uncomfortable if you say the global-warming effect is fortunate.

A11: Thank you. The word “fortunately” was removed in the revised manuscript.

Q12. Section 3.3. The authors need to provide a more comprehensive description of ice conditions, such as level ice, pack ice, pancake ice, ice channels. These ice conditions are very different for different types of ships’ navigabilities and should be clarified. Some brief discussion of ship interactions with different ice types is required here, for which, I suggest the authors check more references. If different ice conditions are all assumed the same in your model, you should say more about the assumption and the associated limitation.

A12: Thanks for your suggestion. Ice conditions considered in this study were ice thickness and ice concentration, in which the function of ice thickness was regarded as a value according to the corresponding interval in formula (2-3). It is hard to distinguish different types of

ice, such as level ice, pack ice, and pancake ice in our calculation and Figure (6), but their different navigability for two types of ships has already been quantified based on the ice thickness and ice concentration. So ice conditions still have different functions in ATAM.

Q13. Results: seems only PC6 ships are studied in this work? What is the authors' opinion about other polar ships?

A13: Thanks for your question. The navigability of PC6 ships and OW ships was focused in this study. They also attached a lot of attention in previous researches, such as Smith and Stephenson, 2013 and Melia et al., 2017. Besides, PC3 was concerned in some work. In our opinion, the study for OW ships is more important to shipping industry. This study showed that the Arctic would be accessible to PC6 ships in September in the next 10 years. Certainly, PC3 ships would be navigable.

[Ref] Smith, L. C., and Stephenson, S. R.: New Trans-Arctic shipping routes navigable by midcentury, P. Natl. Acad. Sci. USA, 110, E1191–E1195, <https://doi.org/10.1073/pnas.1214212110>, 2013.

Melia, N., Haines, K., Hawkins, E., and Day, J. J.: Towards seasonal Arctic shipping route predictions. Environ. Res. Lett., 12, 084005, <https://doi.org/10.1088/1748-9326/aa7a60>, 2017.