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The Cryosphere Discussions
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Interactive comment on "Long-term variation of sea ice and its response to thermodynamic factors in the Northwest Passage of the Canadian Arctic Archipelago" *by* Xinyi Shen et al.

Xinyi Shen et al.

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Major comments

1. Shipping along the NWP is given as a motivator for this work, but there is very little actual discussion of shipping along the NWP. I would suggest that the authors provide a detailed introduction to shipping along the NWP that discusses its benefits (shorter route), its limitations (sea ice), the recent increase in ships along the NWP, its seasonality (which is key), and the projected potential for shipping along the NWP in a warming Arctic. In particular I would recommend the authors look at the following list of works and really strengthen the motivation for this work. Pizzolato et al., (2014), Changing

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sea ice conditions and marine transportation activity in Canadian Arctic waters from 1990 and 2012, Climatic Change, 123, 161-173, doi: 10/1007/s10584-013-1038-3. Pizzolato et al., (2016), The influence of declining sea ice on shipping activity in the Canadian Arctic, Geophysical Research Letters, 43, doi: 10.1002/2016GL071489. â ËŸ A′ c Melia, Haines and Hawkins (2016), Sea ice decline and 21st century trans-Arctic shipping routes, GRL, 43, doi: 10.1002/2016GL069315 Ng, Andrewsm Babb, Lin, Becker (2018), Implications of climate change for shipping: Opening the Arctic Seas, WIRES. â ËŸ A′ c Dawson et a., (2018), Temporal and Spatial patterns of ship traffic in the Canadian Arctic from 1990 to 2015, Arctic, 71(1), doi:10.14430/arctic4696 Based on this revised discussion I think the discussion of shipping pathways needs to be heavily revised or removed. Basing a pathway on the probability of sea ice being lighter than the historical mean isn't realistic, because an ice cover that is thinner than the mean may still be too thick for a majority of vessels to travel through. Instead, I would suggest using polar codes or literature on arctic shipping to define thresholds and then examine when ice conditions that meet those thresholds exist. This would be much more practical, but is likely moving away from your thermodynamic analysis and more into the realm of shipping focused papers.

Answer: We appreciate the reviewer's helpful comments. We will revise the manuscript to add a detailed introduction to shipping along the NWP following the listed works and add the references the reviewer recommended. For the discussion of shipping pathways, we apologize that some statements cause the misunderstanding for the reviewer. We do not aim to choose the shipping pathway which is suitable for the present navigation. As the reviewer mentioned, due to the heavy sea ice condition, the NWP is hard to be used in the most time of the year. Even if using polar codes or literature on arctic shipping to define thresholds, it is still difficult to find a specific pathway for shipping. The specific pathway we selected is mainly about a statistical analysis to examine the locations in the NWP which have larger probability of light sea ice condition based on the historical data. Then we connected these locations together and got the specific pathway which has larger potential opportunity for navigation in the

future. We appreciate the reviewer's helpful comments and we will revise the statement and make it clear.

2. For all of the correlation and trend analysis, I would suggest only presenting significant ($p < 0.05$) values. This would highlight real changes and remove some questionable results like small trends towards increasing sea ice concentration during winter and spring.

Answer: We have revised the pictures (Figure 1-5) and will revise the analysis.

3. With respect to the Cryosat2 ice thickness data. Since it is only used to quickly assess the accuracy of the modelled ice thickness then I would suggest moving this discussion and Figure 5 to your methods sections. I would also suggest only using the CS2SMOS product as it is much more accurate over areas of thin ice (which you note with its accuracy during fall) and as opposed to presenting the comparison in a time series, present it as a scatterplot of monthly means. Further to this comment and this section a. L 81-82: What areas of the NWP did the CS2SMOS product not cover? b. L82 - 83: It's worth noting here why there is no ice thickness data from Cryosat-2 during the melt season. c. L83-84: Beyond saying the modeled ice thickness was "reasonably validated" please provide an exact measure of correlation or bias here. Also consider rewording as you don't use the modelled ice thickness to "fill the temporal and spatial gaps" but you instead use it throughout your full analysis.

Answer: We appreciate the reviewer's comment and we will revise the manuscript. We have removed the comparison between AO-FVCOM and CryoSat2 sea ice thickness and added the comparison between AO-FVCOM and CS2SMOS as a scatterplot of monthly means (Figure 6). In addition, we have added the new comparison with observed sea ice thickness of Canadian Ice Services (CIS) and provided the detailed comparison of mean absolute differences, correlation coefficient and RMSE (Table 1). Through adding the new comparison, we will show the seasonal variation and trend of sea ice thickness in different station. CS2SMOS could not cover the Coronation Gulf,

part of Queen Maud Gulf, Prince of Wales Strait, Peel Sound and part of Barrow Strait and Lancaster Sound. The number of valid data is different in different time. We will add this introduction into the manuscript. We have revised the incorrect statement “fill the temporal and spatial gaps”.

4. The correlation section is very difficult to understand and doesn’t provide a clear result. I also think it needs to be reinforced that this is a thermodynamic analysis and as Howell has shown in several papers, dynamics, particularly the transport of multiyear ice within the CAA and along the NWP is an important process.

Answer: We will revise the manuscript to add more discussion with previous studies.

Minor comments

1. L 12: This comment applies throughout the paper, but when referring to your study region it is the Canadian Arctic Archipelago and the NWP runs through it. I would suggest revising this sentence to read “... we studied the temporal and spatial characteristics of sea ice from 1979 to 2017 in the CAA and evaluated the sea ice conditions along the southern and northern routes of the NWP”.

Answer: Actually, our study region is the area where the NWP runs through the Canadian Arctic Archipelago. We will revise the related description.

2. L 14-15: The term “heavy” ice conditions isn’t really clearly defined, so I would suggest revising to “the region remained ice covered throughout winter and spring during this period”. Additionally based on my suggestion to present only significant trends, I think the text about there being a slight increasing trend can be removed.

Answer: We will revise the manuscript.

3. L 17: I don’t see evidence from Figure 3 of increasing SIC in Lancaster Sound. Please check this statement

Answer: In L17, it is said “The sea ice thickness in most subregions of the NWP showed

a decreasing trend, with the exception of Lancaster Sound". It is about sea ice thickness, not SIC. Please check Figure 2 in this response.

4. L 18: replace "Based on the sea ice concentration and thickness, however the sea ice conditions ..." with "Generally, sea ice conditions were heavier along the northern route than the southern route, with a longer ice season and thicker ice".

Answer: We revised the manuscript.

5. L 20-24: I have other comments about the correlation analysis that will likely cause this text to be revised. But when your revising this please be specific in your statements. An example is "...Thermodynamic factors had a greater impact on sea ice in the summer and fall, than during winter and spring".

Answer: We revised the manuscript.

6. L 24-26: I don't think "residual" is the correct word for this. You're talking about the remaining ice that persisted through summer and already exists at the start of fall freeze-up. Also this remaining ice is not only influenced by fall SST and SAT, but also summer SST and SAT. I think this statement needs to be revised.

Answer: We revised the statement as: The remaining amount of sea ice concentration and thickness in the fall, associated with the SAT and SST in summer and fall, contributed to the formation of sea ice in the following winter and spring.

7. L 30-34: Back to one of my major comments, but this introductory text can be strengthened. The NWP connects Europe and Asia > it is shorter than the Panama Canal Route, but historically it has been ice covered and unsafe for marine vessels. However, as ice declines the NWP is becoming increasingly accessible... I would then reference the works of Pizzolato and Dawson about increase shipping activity along the NWP.

Answer: We will revise the manuscript.

8. L 33: “The opening of the NWP will bring huge economic benefits”, please provide a reference for this and specify who will benefit? Also what about the additional risk for communities and the environment around the NWP?

Answer: We will revise the manuscript.

9. L 34 – 35: Remove “the” from in front of M’Clure Strait and Barrow Strait.

Answer: Revised.

10. L 36: Note right away that there are 3 southern routes that all rely on Lancaster Sound and Amundsen Gulf but pass through different channels in the central part of the CAA. Essentially, this description of the routes can be tightened up.

Answer: We revised the manuscript.

11. L 48-55: This text on sea ice in the CAA is good, but to the point of warming increasing ice severity along the NWP, I think it should be noted that MYI enters the northern CAA from the Arctic Ocean and migrates through to the southern CAA during summers as the ice cover opens up. Additionally, Haas and Howell (2015) observed modal thicknesses of 1.8 and 2.0 m along the NWP with deformed MYI having a mode of 3.0 m. This would be good to include so you can refer back to it later when presenting your modeled ice thicknesses. Also it would be worth noting the previous minima in 1998 and 2007 described by Howell et al., (2010) Haas and Howell (2015), Ice thickness in the Northwest Passage, GRL, 42, doi: 10.1002/2015GL065704. Howell, Tivy, Agnew, Markus, Derksen (2010), Extreme low sea ice years in the CAA: 1998 versus 2007, JGR, 115, doi: 10.1029/2010JC006155. When discussing sea ice within the CAA it needs to be clear that the ice is mobile and there is a mix of first year and multiyear sea ice in the CAA. Specifically the Drain trap mechanism for MYI in the central part of the CAA described by Howell et al., 2008 should be described. As well as the fact that ice is imported and exported from the three gateway regions (Amundsen, M’Clure and Lancaster), particulary during spring and summer.

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Answer: We will revise the abstract and add the comparison in the section of temporal variation of sea ice thickness.

12. L 59-60: This connects back to a previous comment, but when expanding the discussion of shipping through the NWP note the difference between the open water shipping season and potential for ice-breakers. The difference in vessels is critical for shipping along the NWP.

Answer: We appreciate the reviewer's helpful comments. The same answer with Major Comment 1.

13. L 63: revise "we utilize a combination of remotely sensed sea ice concentration data and modelled ice thickness data to examine the sea ice conditions ...."

Answer: Revised.

14. L 68-69: There's a comment below about this selection of a ship path, but I think this needs to be explained in more detail and presented as the "optimal" or "route through the lightest ice conditions".

Answer: We will revise the manuscript.

15. L 74-76: Please elaborate on the description of this dataset. Howe is it collected and what are its limitations. In particular passive microwave data is known to underestimate sea ice concentration during the melt period. This error should be consistent through the time series so it wont dramatically affect your results, but it should be discussed. Regarding the interpretation of sea ice concentration data, you commonly refer to extent, but I believe you are calculating sea ice area. This is good, but the figure labels and text need to be revised. Also please add a sentence about this in the methods. Regarding sea ice concentration data in Prince of Wales Strait – this is a fairly narrow channel and with 25 km resolution I'm wondering how many actual sea ice pixels are contained in this channel and how reliable that data is. Also I haven't seen this channel discussed as part of the NWP before, typically there is one of the

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two southern routes or the northern route through M'Clure.

Answer: We will revise the manuscript. We are calculating sea ice extent. The ice extent was calculated by the ice concentration and the control area of each grid. The ice extent was the sum of areas with sea ice concentration greater than 0.15 in the NWP. We will add the formula in the manuscript. The route through Prince of Wales Strait was a modification of north route through M'Clure Strait (Byers and Michael, 2009). Considering it is narrow, few studies have studied it as a separate area, but it has been mentioned in the introduction of the NWP (Sou and Flato, 2009; Pizzolato et al., 2016). In Prince of Wales Strait, there are 16 and 244 sea ice pixels contained from NSIDC and AO-FVCOM, respectively. Reference: Byers, M., & Lalonde, S. (2009). Who controls the northwest passage? Vanderbilt Journal of Transnational Law, 42. Sou, T., & Flato, G. (2009). Sea ice in the Canadian Arctic Archipelago: modeling the past (1950-2004) and the future (2041-60). Journal of Climate, 22(8), 2181-2198. Pizzolato, L., Howell, S. E. L., Dawson, J., Laliberté, Frédéric, & Copland, L. (2016). The influence of declining sea ice on shipping activity in the Canadian Arctic. Geophysical Research Letters, 43(23), 12,146-12,154.

16. L 88: resolution is up to 1 km, but what is the range?

Answer: In the NWP, the range of resolution is from 1 km to 10 km.

17. L 95: It is just ICESat, not ICESat-2.

Answer: Revised.

18. L 94 – 100: In this text please note that all of this work was presented by Zhang et al., (2016). Adjust the start of this text from "We conducted..." to "Zhang et al., (2016) validated ice thickness from AO-FVCOM with a multisource dataset...".

Answer: Revised.

19. L 102-104: Which ERA reanalysis did you use? -Interim or -5? Please specify.

Answer: We used ERA-5 reanalysis data, and we will revise the manuscript.

20. L 108 and throughout: revise the text “significant spatial distribution differences” to “ significant differences in the spatial distribution” or “significant spatial differences”. As it’s written it is tricky to read.

Answer: Revised.

21. L116 – 120: I’m not sure these means are really worth presenting given the significant negative trends you are about to present in the next section. I think the 1979-2017 mean shows the general pattern of ice loss, but I wouldn’t get too focused on the actual values.

Answer: We will revise the manuscript.

22. L 120: “After September, the sea ice started to freeze”, this is pretty informal, I’d suggest adding some more detail here.

Answer: We will revise the manuscript.

23. L 124-125: Again check that these trends are significant. The Prince of Wales Strait is not significant, so this text needs to be revised. Also just a note that the figures show sea ice extent (area) and the trends are presented. Perhaps provide both the trend in extent and then provide the % for further context.

Answer: We will revise the manuscript.

24. L 126-127: back to one of the major comments, but I am really suspicious of this increasing trend during winter. There may be some variability, but that is likely due to the error of passive microwave sea ice concentration retrievals and not real.

Answer: We will revise the manuscript. The increasing trend in the CAA which was consist with Cavalieri and Parkinson (2008). But considering Cavalieri and Parkinson (2008) also used passive microwave sea ice concentration, we will revise our statement as: Figure 3 exhibited significant differences in the spatial distribution of change rate of

sea ice concentration in the NWP during 1979 to 2017 that the significant decreasing trend occurred in summer and fall and slighter change rate in winter and spring. Reference: Cavalieri, D.J. & Parkinson, C.L. (2008). Antarctic sea ice variability and trends, 1979-2006. J. Geophys. Res. Oceans. 6.

25. L 143 – 147: With respect to Figure 4, the key takeaway is the negative trends in each sub-region. I don't think discussing the mean annual sea ice concentration in each region over the 38 year record is that useful, especially given the substantial changes taking place.

Answer: We will remove the discussion of mean annual sea ice concentration.

26. L 153: Replace "The larger sea ice extent" with "A near complete ice cover..."

Answer: Revised.

27. L 154: The change that occurred around 1997 is related to the 1998 minimum discussed by Howell et al., 2010. Please add the reference of 1998 to the introduction and then you can refer back to it here. Howell, Tivy, Agnew, Markus, Derksen, 2020,Extreme low sea ice years in the Canadian Arctic Archipelago: 1998 versus 2007, GRL.

Answer: We will revise the manuscript.

28. L 163: "Larger sea ice extent resumed in October..." this is a part of fall freeze-up. Beyond listing the regions, I think it would be more useful to state that freeze-up begins earlier in the central and northern part of the CAA (M'Clintock, Peel, Prince of Wales, M'Clure, Viscount, Barrow) in October and then expands to the southern and peripheral part of the CAA during November.

Answer: We will revise the manuscript.

29. L 178: Remove the 2 from ICESat-2.

Answer: Removed.

30. L 182: revise “significant spatial distribution differences”

Answer: Revised.

31. L 183 – 184: As opposed to saying “the sea ice thickness was larger in spring and small in late summer and early fall”, simply say “the sea ice was thicker in spring and thinner in later-summer and early fall”.

Answer: Revised.

32. L 186 – 187: Thicker ice is located in the Queen Maud Gulf, M’Clintock Channel, and Peel Sound because it operates as a drain trap for Multiyear ice within the CAA as described by Howell et al., 2008. Please add discussion of this to your introduction so you can refer back to it here. Howell, Tivy, Yackel, McCourt (2008), Multi-year sea ice conditions in the western Canadian Arctic Archipelago Region of the northwest passage: 1968-2006, Arctic.

Answer: Revised.

33. L 203 and Figure 8: Again please only display and discuss the significant trends.

Answer: Revised.

34. L 205 – 206: With respect to the increasing trend in the Labrador Strait, first is this significant? If so what is the mechanism for this?

Answer: It is significant in spring and summer. Lancaster Sound was a main pathway for sea ice transport to flow out. During 1978 to 2017, the sea ice area flux showed increasing trend by 7.5$\times$103 km2/10a (Bi et al., 2019) which may result in the thicker MYI from Arctic transporting to Lancaster Sound. We will add the discussion into the manuscript. Reference: Bi, Haibo & Zhang, Zehua & Wang, Yunhe & Xu, Xiuli & Liang, yu & Huang, Jue & Liu, Yilin & Fu, Min. (2019). Baffin Bay sea ice inflow and outflow: 1978–1979 to 2016–2017. The Cryosphere. 13. 1025-1042. 10.5194/tc-13-1025-2019.

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35. L 223: “deepest” I think this is in reference back to Figure 1, but the bathymetry of the CAA isn’t actually shown in that figure. Please revise or add a reference to this point.

Answer: We will revise the manuscript and add the reference.

36. L 226-228: The process of selecting pathways based on “light sea ice conditions” needs to be revised and considerably improved. Thinner ice doesn’t necessarily make a route passable of the ice is still relatively thick and therefore hazardous for all but a few ships. This goes back to the first major comment, a better introduction of shipping along the NWP and the focus on the open water shipping season is needed before this discussion is suitable. Also, if basing the route on the change relative to the historical mean, its important to note the historical mean represents a concentrated, thick ice cover that didn’t break up during summer.

Answer: Same answer with Major Comments #1.

37. L263-264: “the low temperatures did not affect the sea ice melting”, I’m not sure what is meant by this statement.

Answer: Although SAT showed increasing trend, the temperatures was too low to affect sea ice melting. We will revise it.

38. L 264-265: How are the SST’s observed during winter? Are they simply set to be at the freezing point when under sea ice? This should be discussed in the methods and will likely cause this text to be revised.

Answer: We will revise the manuscript.

39. L 311: “Suggest” instead of “suggested”

Answer: Revised.

40. L 311: I’m not sure “residuals” is the right word for what you’re describing here. This is the state of the ice cover after the September minimum and at the start of

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fall-freeze-up.

Answer: We will revise the statement. It is the averaged value of sea ice concentration and thickness in fall including September, October and November.

41. L 321-323: Connecting the state of the ice cover in fall to the state of the ice cover at the end of winter is interesting, but the last sentence about fall SAT and SST affecting sea ice thickness the following winter is a little misleading, because the state of the ice cover in fall is predominantly dictated by the summer conditions and not just fall.

Answer: We will revise the manuscript.

42. L 325: remove the “ed” from “exerted”.

Answer: Revised.

43. L 329: Based on a previous comment, you don’t really use observed sea ice thickness data. It’s all from the model.

Answer: Revised.

44. L 336 and in other places within the paper: Please be consistent and present sea ice concentration as a percentage (%) as opposed to just “1”.

Answer: We appreciate the reviewer’s helpful comments. We apologize some statements cause the misunderstanding for the reviewer. We present sea ice concentration as “1”. Percentage in trend showed the change rate of sea ice concentration just same as the trend of SAT and SST. We will revise the change rate of sea ice concentration from “%/10a” to “/10a”.

45. L 339: Another instance the “increasing trend” during winter. Please check that this is significant.

Answer: Revised.

46. L 343: revise the first sentence to read “from 1979-2017, sea ice thickness in the

NWP decreased..."

Answer: Revised.

47. L 344: Revise "The multiyear mean seasonal sea ice thickness" to read "The monthly mean sea ice thickness..."

Answer: Revised.

48. L 347-348: Remove "the" from "In the most..." and "Lancaster Sound, the sea ice...".

Answer: Revised.

49. L 348: In the conclusions provide a value for these trends.

Answer: We will revise the manuscript.

50. L 361: Revise the word "dominant", the end of winter ice cover is influenced by the fall ice cover, but I don't think it is the dominant factor.

Answer: Removed.

51. Figure 1: Note that you don't actually show bathymetry in the CAA so I would suggest removing bathymetry from this figure.

Answer: Removed (Figure 7).

52. Figure 3: Is the top panel the trends in the annual mean sea ice concentration? I would suggest removing that and focusing on the seasonal means.

Answer: Removed (Figure 1).

53. Figure 4: For the inset of annual cycles can you provide some bounds of the standard deviation or

Answer: Revised (Figure8).

54. Figure 5: This figure can very likely be removed based on comments above.

Answer: Revised.

55. Figure 6: I'd suggest removing "distribution" from the caption as an ice thickness distribution is something other than this figure.

Answer: Revised.

56. Figure 7: Note in the caption that this is the "annual mean thickness".

Answer: Revised.

57. Figure 8: Again, only show the significant trends and consider removing the annual mean.

Answer: Revised (Figure 2).

58. Figure 10: Are these the annual mean changes in SAT and SST? Also, instead of the % please consider revising to show the magnitude (âÛę C) of the trends and only showing the significant trends.

Answer: These are the annual mean changes in SAT and SST, we revised the title and change unit to " âÛę C/10a" (Figure 3).

59. Figure 11 and 12: It is slightly counter intuitive to flip the colorbar so that blue is positive correlations and red is negative. Also, once again consider showing only the significant correlations.

Answer: Revised (Figure 4, Figure 5).

We are working on the revised manuscript and we will attach a draft revision and highlight the revised places. After getting the comments from other reviewers, we will make further revision. Hopefully, these answers and revisions could meet the reviewer's requirement.

Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2020-215, 2020.

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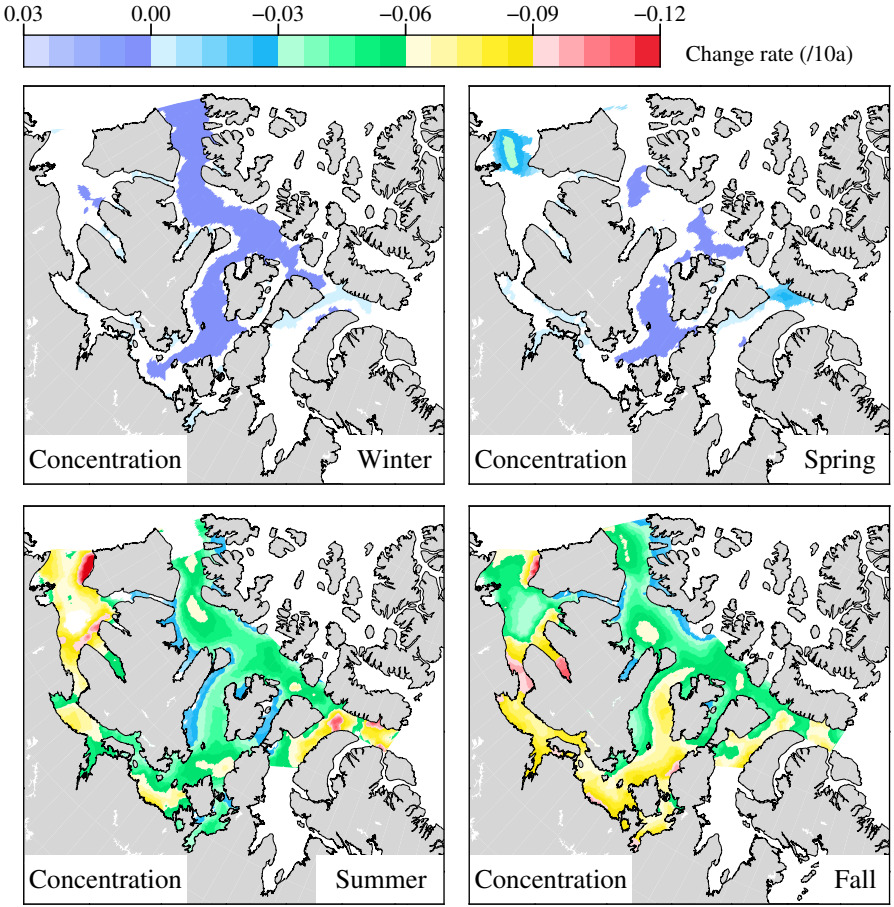

Fig. 1. Seasonal mean change rate distribution of sea ice concentration from 1979–2017.

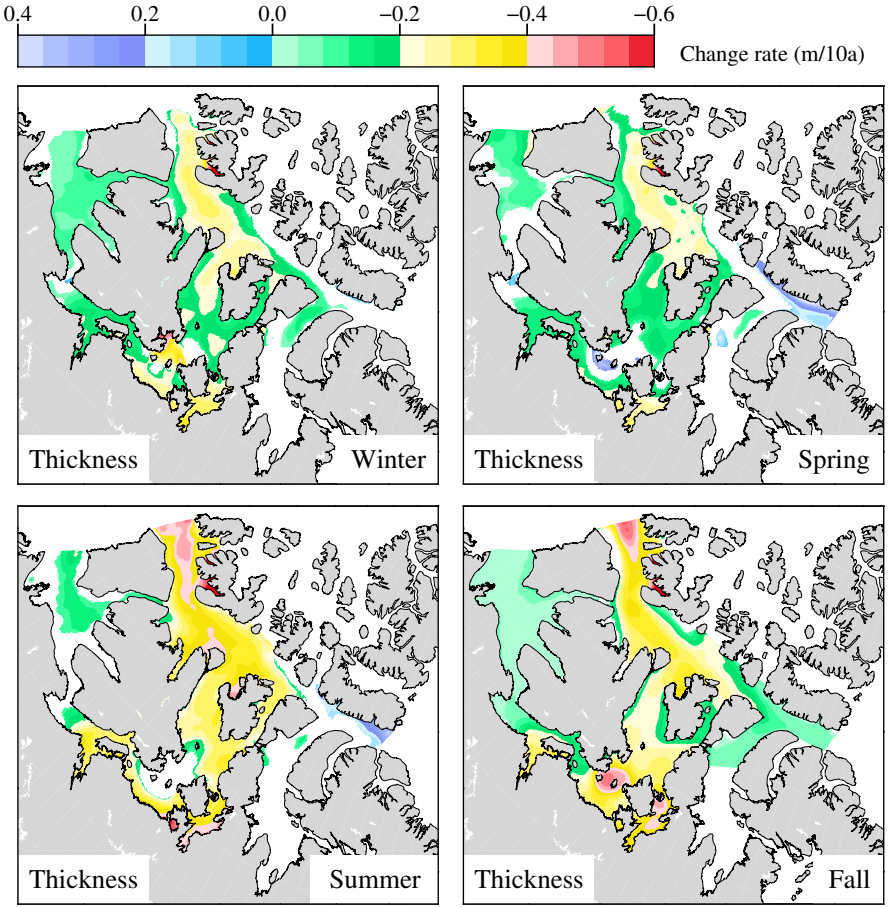

Fig. 2. Seasonal mean change rate distribution of sea ice thickness from 1979–2017.

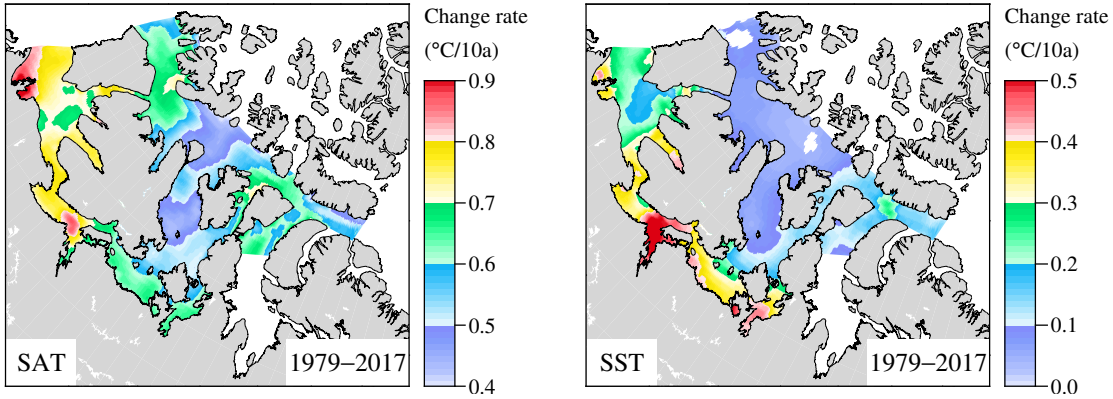

Fig. 3. Distribution of change rates of SAT and SST in the NWP from 1979 to 2017.

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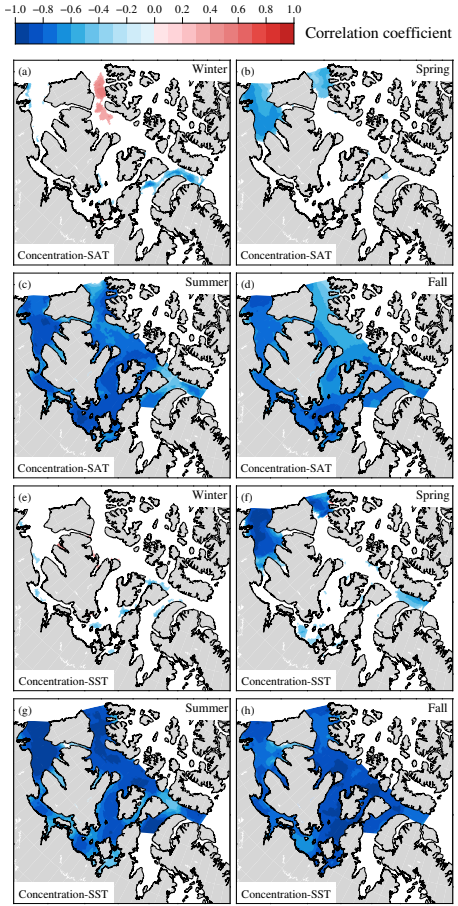

Fig. 4. Distribution of seasonal correlation coefficients between sea ice concentration and SAT and SST in the NWP.

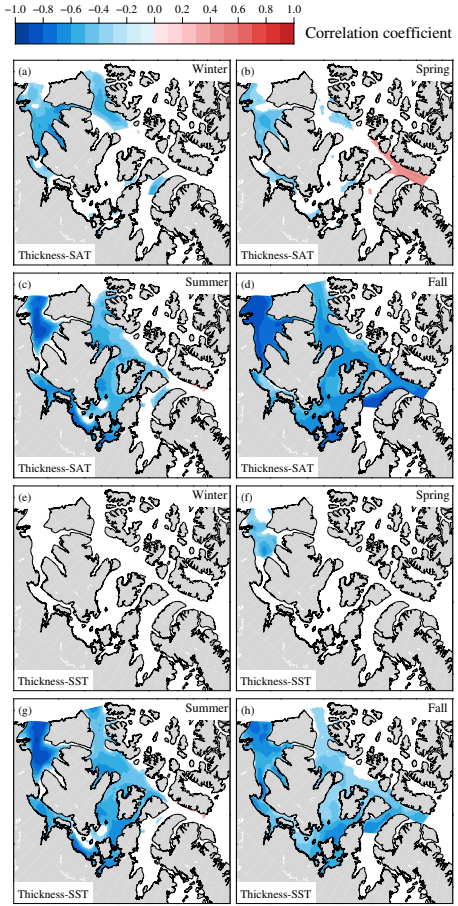

Fig. 5. Distribution of seasonal correlation coefficients between sea ice thickness and SAT and SST in the NWP.

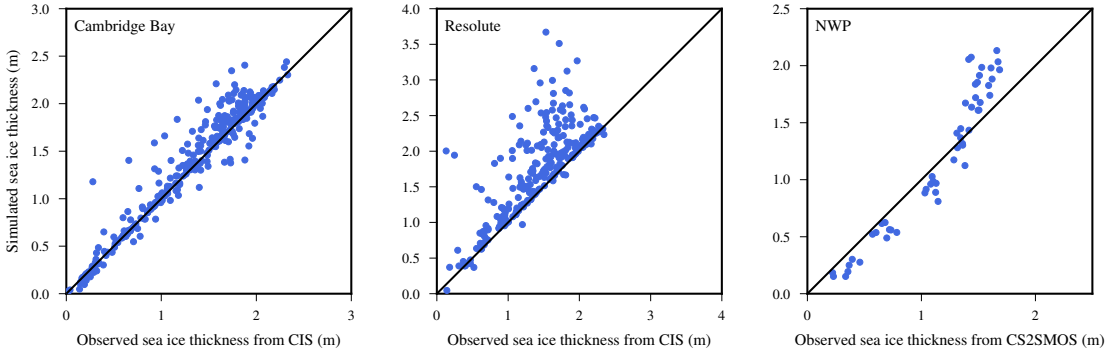

Fig. 6. Comparison of AO-FVCOM sea ice thickness with sea ice thickness observations over the period 1979–2017.

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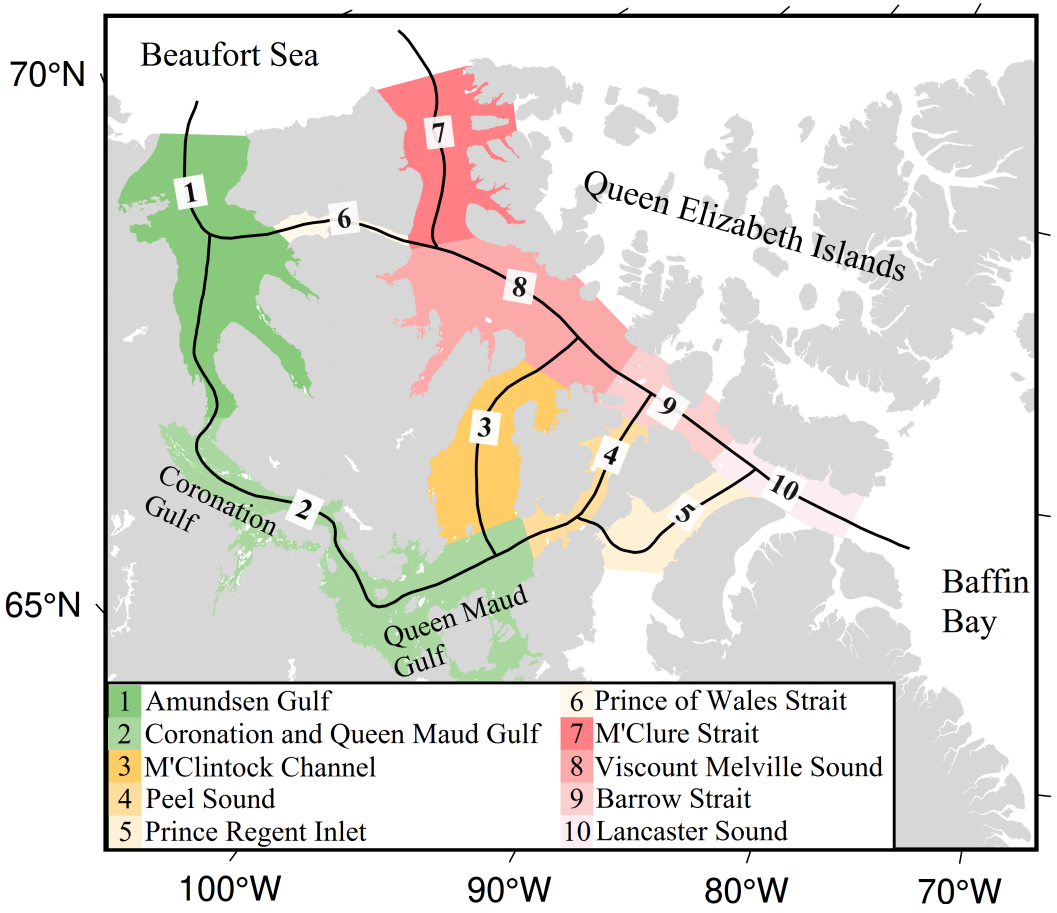

Fig. 7. Bathymetry of the Canadian Arctic Archipelago and 10 subregions of Northwest Passage routes.

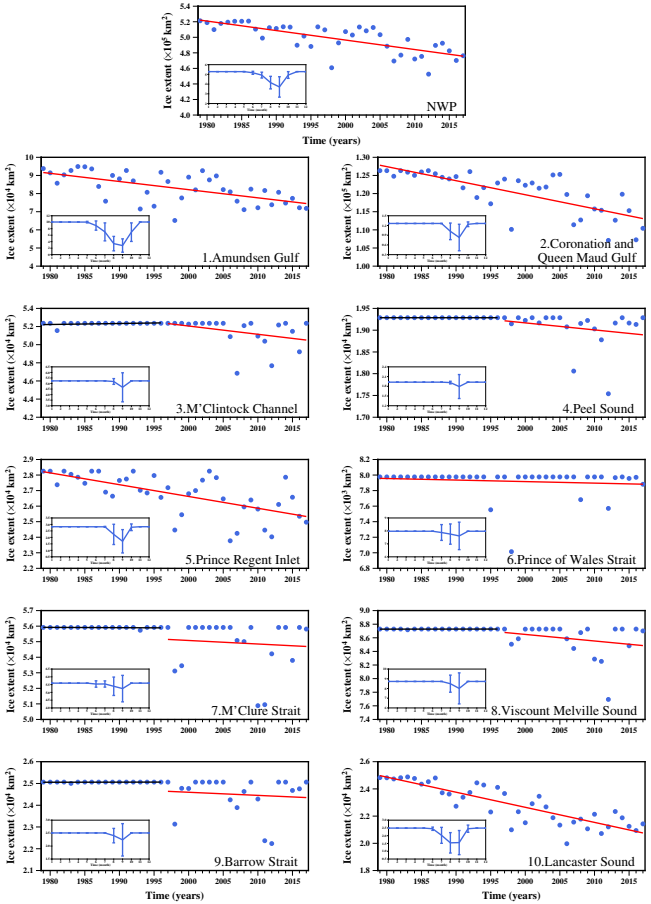

Fig. 8. Annual mean sea ice extent (blue dots) for the NWP and 10 subregions of the NWP from 1979 to 2017. Red lines indicate the linear regression trends.

Table 1. Mean sea ice thickness, trend and maximum sea ice thickness trend of observations and AO-FVCOM in the Cambridge Bay and Resolute, and mean absolute differences, correlation coefficient, RMSE between observations and AO-FVCOM.

	Cambridge Bay		Resolute		NWP	
	Observations	Simulation	Observations	Simulation	CS2SMOS	Simulation
Mean sea ice thickness (m)	1.32	1.38	1.41	1.73	1.13	1.19
Trend of sea ice thickness (m/10a)	-0.07 ($p<0.05$)	-0.12 ($p<0.01$)	0.03	0.00	-0.02	-0.09
Trend of maximum sea ice thickness (m/10a)	-0.07 ($p<0.05$)	-0.12 ($p<0.01$)	-0.07 ($p<0.05$)	-0.06	-0.15	-0.15
Mean absolute differences (m)	0.10		0.33		0.20	
Correlation coefficient	0.96 ($p<0.01$)		0.77 ($p<0.01$)		0.96 ($p<0.01$)	
RMSE (m)	0.18		0.52		0.25	

Fig. 9.

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