Reviewer 3

Authors‘ responses shown in blue.

General comments

The manuscript “Changes of the Arctic marginal ice zone” by R. Rolph, D. Feltham, and D. Schröder provides a clear analysis of evolution in Arctic marginal ice zone (MIZ) extent relative to total sea ice extent (SIE) in a changing climate. In highlighting, based on an operational definition, that the MIZ extent shows no significant trend over the last 40 years despite a decline and well-defined trend in total SIE, this analysis underscores the need for a universal definition for the MIZ, identification of relevant variables in addition to extent for its characterization, and improved understanding of implications in a changing climate for communities influenced by MIZ processes.

This paper addresses relevant scientific questions including characterization of the MIZ, and presents novel analysis that contributes to an understanding of changes in the sea ice cover, and in particular poleward migration in MIZ and total SIE, in the context of a changing climate.

We thank the reviewer for the helpful comments to improve the manuscript. Following suggestions from reviewer Court Strong, we added timeseries of the mean MIZ latitude (Figure 3 of the revised manuscript) and width (Figure 2 in the response to Court Strong). These illustrate a consistent picture that the northward shift compensates the widening of MIZ such that the MIZ extent remains constant with time.

Also of interest however is the sensitivity of this analysis to the mathematical and physical definition for the MIZ; investigation of additional techniques used to analyse total SIE (i.e. geographic muting described in Eisenman, 2010) applied to the MIZ that could perhaps explain the absence of statistically significant trends in MIZ extent over the past 40 years and, as noted by other reviewers; further exploration of reasons for the absence of changes in MIZ extent; in addition to alternative MIZ variables/aspects (area, regional variability, zonal mean MIZ edge as in Eisenman, 2010) that do reflect changes in the zone between fully ice-covered and ice-free regions in response to global warming. This is therefore to recommend that the manuscript be published following revisions that address MIZ definitions and analysis. Please find below more specific comments for consideration.

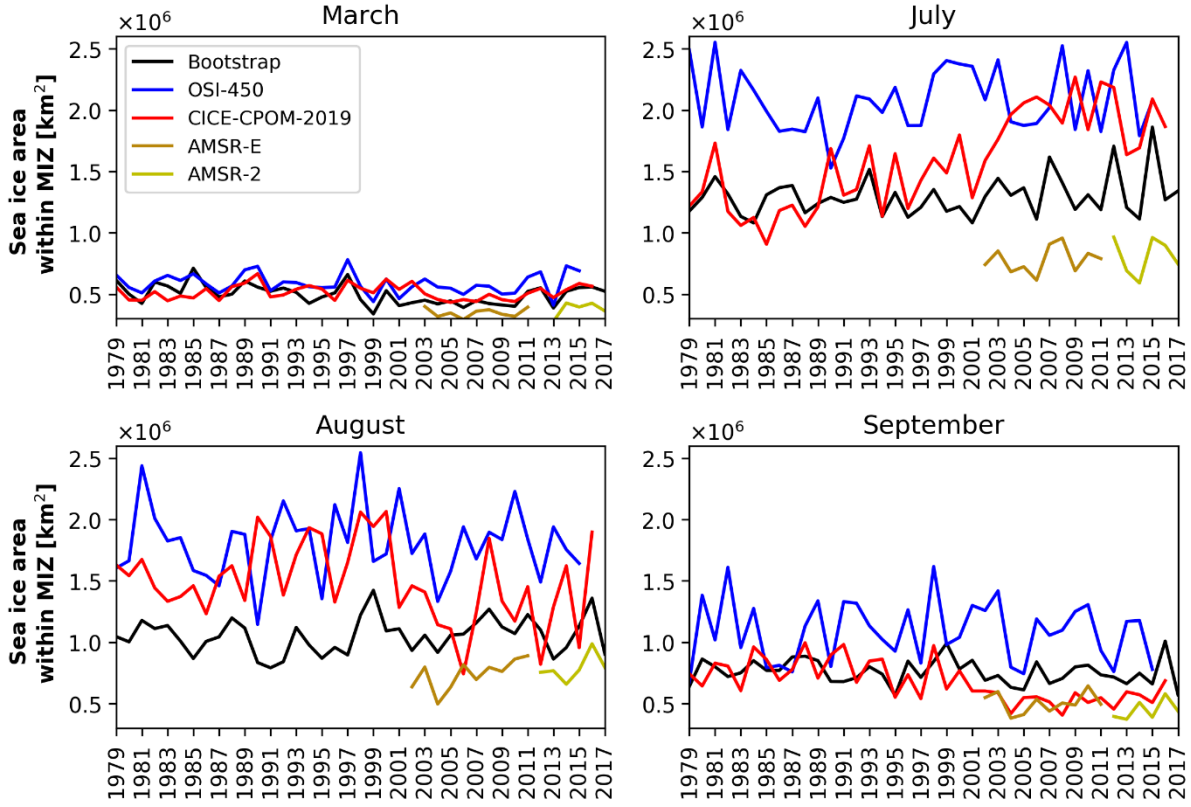
We note that geographic muting only applies to those months where the sea ice would extend beyond the limit of land, if the land was not present. So, during the summer months, the geographical muting would not well explain the lack of change in the MIZ. We have added a statement reflecting this point in Section 5.1, starting at line 304. As indicated above and in our response to Court Strong, our additional analyses of mean MIZ latitude and width provide extra insight into these conjoining factors involved in the evolution of the MIZ.

We note that the reviewer refers to the term ‘MIZ area’ above, and we have taken this to mean the sea ice area within the MIZ, given that the MIZ extent has already been calculated. As the reviewer has suggested, we have found the sea ice area within the MIZ for March, July, August and September (Figure 1 below and as an added Figure 4 in the revised manuscript). We found no significant trends of the sea ice area within the MIZ in March except for a slight negative trend for the Bootstrap dataset (-0.0025 x 10^6 km^2/year). In July, there is a significant positive trend for the model at 0.027 x 10^6 km^2/year and in September, a slight negative trend for the model at -0.0092 km^2/year. The other datasets showed no significant

trend in sea ice area within the MIZ. This has been added to the Results Section 4.3, starting at line 280.

Due to the clearly large inconsistencies in the observations in the regional location of MIZ (please see Figure 5 in the revised manuscript), analyses of the regional trends and locations of the MIZ do not give much indication of the regional trends in reality. Until the observations of the sea ice concentration are improved and the observational datasets agree more with each other in both spatial and temporal variability, a regional trend analysis would give unrealistic (or impossible to validate) results. We have added a statement in the Results Section 4.3, line 284: 'The spatial variability of the MIZ is poorly constrained by observations.'

Figure 1. Sea ice area within the MIZ. Monthly averaged from daily data.



Specific comments

Abstract

p. 1, lines 6 – 8. "It does not logically follow, however, that the extent of the marginal ice zone (MIZ), here defined as the area of the ocean with ice concentrations from 15 to 80%, is also changing". What are the implications of assumptions associated with a changing MIZ extent?

Some implications of assumptions associated with MIZ extent are:

- If one were to assume the MIZ extent is changing, we may be focusing on the wrong aspect (e.g. instead of the MIZ moving northward and widening) with regard to change in other parts of the climate system (e.g. phytoplankton populations).
- A changing MIZ extent would have implications for the level of atmosphere and ocean mixing within the ice-covered region, e.g. if the MIZ extent were to increase, we

would likely see an increase in the heat flux between the ocean and atmosphere in these partially ice-covered regions.

- An increase in MIZ extent could increase the level of gas exchange and could have consequences for the amount of greenhouse gases absorbed and released by those regions of the ocean containing sea ice.
- MIZ extent is a metric for the area of vital habitat for important Arctic biological life and also for Arctic primary productivity. A change in the MIZ extent would result in further changes to the extent of this habitat. For example, ice algae grow on the underside of (and within) the sea ice and are an early important food source for zooplankton and ice fauna (Horner et al. 1992; Hegseth, 1998; Søreide et al., 2013). The deformed ice in the MIZ creates ridged habitats underwater for animals such as polar cod (Hop and Gjøsæter, 2013) and also habitats above the sea ice for animals such as seals, polar bears, and seabirds (Hamilton et al., 2017). These statements along with the references have been added at the end of Discussion Section 5.2.

We have added a statement to the Abstract lines 7 – 9: 'Changes in the MIZ extent has implications for the level of atmospheric and ocean heat and gas exchange in the area of partially ice-covered ocean, as well as for the extent of habitat for organisms that rely on the MIZ, from primary producers like sea ice algae to seals and birds.'

p.1, lines 14-16. "Given the results of this study, we suggest that future studies need to remain cautious and provide a specific and clear definition when stating the MIZ is 'rapidly changing'." Perhaps provide an appropriate definition and context for the statement of a 'rapidly changing' MIZ. As is noted below, additional MIZ definitions and changes in additional MIZ characteristics over the past 40 years could be evaluated and compared with MIZ extent to determine whether these properties and attributes capture a rapidly changing MIZ.

- The statement has been changed (also taking into consideration the comment from Reviewer #2) to: 'Given the results of this study, we suggest that references to 'rapid changes' in the MIZ should remain cautious and provide a specific and clear definition of both the MIZ itself and also the property of the MIZ that is changing.'
- An additional MIZ characteristic we have now evaluated is the sea ice area within the MIZ, and has been added to the manuscript. Please see the Results section 4.3 starting at line 280.

Introduction

p. 2, line 45. Perhaps include 'extent' following 'MIZ'.

- This statement has 'extent' left out to suggest that future authors should define very specifically what about the MIZ is changing, whether it be extent or other properties. We have changed the sentence so it now reads as: 'Thus, we need to remain cautious and provide a specific and clear definition of the property of the MIZ when stating that 'the MIZ is rapidly changing.'' This statement is now at line 48.

p. 2, lines 45 – 46. "It also follows that we need to be aware of the extent to which our observations are able to constrain any model of the MIZ". Does this study also highlight the need for a universal and/or alternative definition for the MIZ?

- The statement here was meant to inform the reader that because there is no clear observational value of MIZ extent, any model which shows MIZ location (as defined by sea ice concentration at least) cannot be well-validated in this context through observation.
- If one were to change the definition of the MIZ such that it could then be constrained by observations, this would likely require further definitions/analysis to answer the MIZ research question involved and still presents an issue. Please see also the response below (for p.2. L57).

p. 2, line 57. "Here we also describe how we defined the MIZ and sea ice cover in our calculations". Will the results from this analysis differ for different MIZ definitions?

- Yes, we would expect that the MIZ extent would change if the MIZ definition were to change. The reason that the sea ice concentration was used is that the MIZ is readily calculable due to the fact that sea ice concentration data is available.
- Another common definition of the MIZ is that region where ocean waves can influence the ice cover, but this requires data that is not readily available on a pan-Arctic scale in comparison to sea ice concentration. There are benefits and drawbacks to the definition of the MIZ as the region of partially-ice covered ocean that is impacted by ocean waves.
- We have added a Discussion Section 5.1 starting at line 293: 'Differing definitions of MIZ extent':
  'Similar to sea ice extent, the MIZ extent is also defined by sea ice concentration thresholds. Another definition of the MIZ in common usage is that the MIZ (e.g. Squire, 2020) is that region of partially-ice covered ocean that is impacted by ocean waves. One drawback of this definition is that it necessitates further definition of where the ice-covered ocean is deemed to be 'impacted by ocean waves'. This could be problematic because different applications (e.g. shipping, climate studies) could require different thresholds of when they consider waves important. There are also significant uncertainties with both observing and forecasting waves within the sea ice and this is an ongoing field of study (Roach et al., 2019; Stopa et al., 2018). For instance, it has been shown that ocean waves can penetrate deeper into the ice pack than previously thought (Kohout et al., 2014). Although the definition of the MIZ using ocean wave penetration can be very useful for other studies (for example, boundary layer air-sea interaction or wave-action studies), we argue that comparisons of purely MIZ extent from different observational datasets and models should be done through sea ice concentration thresholds. This is especially true for model comparisons given the unknowns in wave-sea ice interaction (Squire, 2020). Some techniques used to analyse total sea ice extent such as geographical muting (Eisenman, 2010) only apply to those months where sea ice extends beyond the limit of the land, if the land was not present. During the summer months, the geographical muting would not well explain why the MIZ extent remains constant. '

p. 2, line 58. The timeframe could be indicated following "March, July, August, and September".

- Yes, thank you, agreed; the phrase 'for the period from 1979-2017' has been added after these month names. And this now appears at lines 62-63.

Methods

p. 6, lines 167 – 170. Perhaps the MIZ area could be examined in addition to MIZ extent, and results compared to characterize changes relative to total SIE and area over the past 40 years.

- Yes, the MIZ area (sea ice area within the MIZ) has now been calculated for all of the datasets evaluated in this manuscript, and the results are presented in Figure 1 above as well as added to the revised manuscript as a new figure (Figure 4) . Please see also the response to the 'General Comments' section).
- We have added a statement in the Methods section to include that this analysis has been done (lines 174-175, Section 3.2).
- A statement has also been added to Results Section 4.3 starting at line 280: "Although the MIZ is trending northwards, the observations do not support any trend in its overall sea ice area, with the exception of March for Bootstrap at -0.0025 x 10^6 km^2 per year (Figure 4). The modelled sea ice area within the MIZ did not show a trend except for July and September at 0.027 x 10^6 km^2 per year and -0.0092 km^2 per year, respectively (Figure 4)."
- Given that there is a lack of trend in the sea ice area within the MIZ, consistent with the lack of trend in the MIZ extent, further comparison to the decline in the sea ice extent we feel will not give important new insights.
- In the Discussion Section 5.2, we have added these statements at line 327: However, we have found no trend in the observations of sea ice area in the MIZ except for the slight negative trend in March in the Bootstrap data, but the spread of the sea ice area within the MIZ across the observational datasets is large (Figure 4). Due to this, there could possibly be a trend in the MIZ sea ice area which we are not able to resolve. For example, the slight significant trends of sea ice area in the MIZ shown by the model are still within the range of observations. Since there is no trend in sea ice area within the MIZ and no trend in the MIZ extent, there is no significant change of sea ice concentration within the MIZ based on observations. It follows that the pan-Arctic averaged sea ice concentration is not declining in concert with its declining extent. This suggests that changes to the extent of the MIZ depend strongly on the sea ice thickness distribution.
- We have also added a new statement in the Conclusions section pertaining to sea ice area, starting at line 399-400.

p. 6, lines 176 – 177. "…an error of 10%..." Does this uncertainty vary seasonally?

- Yes, this is a good point, and although we have applied an error of 10% for our observations, our results clearly show there is an uncertainty in the sea ice concentration that varies seasonally. Although the existing literature also support that the uncertainty varies seasonally, there are no robust uncertainty values to apply to our data.
- We added a statement in the Discussion section 5.4 (lines 381-382) that states: 'It is clear from the differences in the observations that the uncertainty varies seasonally and often exceeds 10%, with the greatest uncertainty in August (Figures 2 and 3).'

p. 6, lines 177 – 178. Perhaps conduct the same analysis for sea ice area, MIZ area, and relative MIZ area.

- We have now expanded the analysis of the manuscript to include the sea ice area within the MIZ (Figure 1 above and new Figure 4 in the revised manuscript). Since both the sea ice area within the MIZ and the MIZ extent do not show a trend, the sea

ice area within the MIZ relative to the MIZ extent will also not show a trend. Please see also the end of the new Section 5.2.

Results

p. 7, line 195, and p. 8, line 230. Absence of trend in MIZ sea ice extent and northward migration in MIZ. The absence of statistically significant trends in MIZ extent suggests poleward migration of the southern and northernmost MIZ boundaries at comparable rates. Application of the zonal-mean sea ice edge concept outlined in Eisenman (2010) to the northernmost and southernmost boundaries (in a sense converse to the SIE analysis, since with a deteriorated sea ice cover the northern boundary is less stable and muting less pronounced) would illustrate rates of change for each, as well as regional variability. Also of interest is the transition to lower sea ice concentrations in the MIZ over the past 40 years, documented by MIZ area. Please see also comments pertaining to the Discussion.

- We have shown that the MIZ extent is not showing a significant trend and, since it is trending northward (causing its perimeter to shrink on a spherical earth), the MIZ must be widening. This means that the southernmost and northernmost MIZ boundaries cannot be moving northwards at the same rate. Strong et al. (2017) found that it is the interior pack ice declining faster than the ice edge that causes the widening in summer. This detail has now been added to Discussion Section 5.3, lines 339: 'More specifically, the inner pack ice area is outpacing the decline of total ice area, causing a widening trend (Strong et al., 2017).'
- Since we have found no robust trend in the sea ice area within the MIZ (the observations show no trend but at the same time provide room for a trend within their spread), and there is no trend in MIZ extent, it follows that the average sea ice concentration within the MIZ is not changing over the past 40 years. Please see the paragraph starting at line 326 in Section 5.2. Please see also our response to this reviewer's first comment about the Methods section.
- Although we agree that a thorough re-analysis of the metrics presented in this paper using the Eisenman (2010) geographical-muting technique would be interesting, it would have little impact on results for the summer months where the ice is northward of land mass. Perhaps more importantly, it is difficult to interpret due to the large regional variability in the location of the MIZ (in comparison to the sea ice extent) according to the different observational products (please also see our last paragraph in the response to 'General Comments' above and the response to the comment about p. 9 L262 below).

Discussion

p. 9, line 256. Perhaps include the phrase 'due to decreasing total SIE' following "slightly decreasing".

This phrase has been added, and now falls at line 323 in the revised manuscript.

p. 9, line 262. Northward migration in the poleward MIZ boundary and area-weighted latitude of the MIZ. Also of interest is the study by Eisenman (2010) describing the role of zonal mean ice edge latitudes in describing asymmetry in winter and summer decline in SIE, in addition to the study by Stroeve et al. (2016) implementing a similar concept to define Antarctic MIZ boundaries according to zonal mean latitudes based also on the approach outlined in Strong and Rigor (2013). It would be interesting to see how evolution in the i) northern and ii) southern latitude MIZ boundaries/edges and iii) area (rather than extent,

based on discussions outlined in Notz; 2014) bounded by each, compares with results from the present analysis based on MIZ extent, and whether this approach captures asymmetry in the seasonal cycle as well as rates of poleward migration in the northern and southern MIZ boundaries. Evaluation of MIZ area might also illustrate the nature of transition to a lower sea ice concentration regime in the MIZ over the past 40 years.

- The responses above, and the newly introduced figures and sentences in the manuscript identified, address the evolution of the MIZ boundaries, extent, ice area within the MIZ and sea ice concentration.
- The suggestions regarding asymmetry in the summer and winter trends using the Eisenman approach are an interesting extension of our manuscript, but would be a significant undertaking out of scope of our manuscript. Moreover, we have found large discrepancies in the zonal location of the MIZ (e.g. Figures 3 and 5 of the revised manuscript) and these discrepancies would hamper a regional analysis of MIZ change in sea ice area and extent to the extent that they are unlikely to provide verifiable results.
- We have added the mean latitudes of the MIZ edge for the months of July, August, and September to the manuscript (new Figure 3 in manuscript) for the datasets Bootstrap, OSI-450, and CICE-CPOM-2019. The mean July through September trends are significant, and the observational trends are consistent with those found in Strong and Rigor (2013) at 0.060, 0.056, and 0.059 degrees latitude per year for the Bootstrap, OSI-450, and Strong and Rigor (2013) datasets respectively.
- This trend information has been added in Results section 4.3 starting at line 261. Please see also the discussion and Table 1 of the response to Major Comment #1 by Reviewer #2 (Court Strong).
- We have added a new Methods section 3.3. At the beginning of this new subsection, we have included statements describing how that the analysis of changes in MIZ latitude has been done.
- Also relevant is the last paragraph in our response to the 'General comments' above.

Conclusions
p. 10, lines 300-303. "Due to the spread of the observations in MIZ extent…" As previously noted, context for the phrase 'rapidly changing' should be provided (i.e. extent and/or other MIZ aspects including northern and southern MIZ boundaries and area).

We could not find the phrase 'rapidly changing' in the Conclusions section. However, we do agree with the reviewer's previous comment that context for this phrase in its previous appearances should have been added to the manuscript. We have therefore added (to the last sentence of the abstract): '… definition of both the MIZ itself and also the property of the MIZ that is changing '

Technical corrections

p. 8, line 237. Please remove 'is'.

This have been removed.

p. 10, line 295. Perhaps replace 'big' with 'large'.

This has been replaced.

References

Eisenman, I., 2010: Geographic muting of changes in the Arctic sea ice cover, *Geophys. Res. Lett.*, 37, L16501, doi:10/1029/2010GL043741.

Notz, D., 2014: Sea-ice extent and its trend provide limited metrics of model performance, *The Cryosphere*, 8, 229–243, https://doi.org/10.5194/tc-8-229-2014.

Stroeve, J. C., Jenouvrier, S., Campbell, G. G., Barbraud, C., and Delord, K., 2016: Mapping and assessing variability in the Antarctic marginal ice zone, pack ice and coastal polynyas in two sea ice algorithms with implications on breeding success of snow petrels, *The Cryosphere*, 10, 1823–1843, https://doi.org/10.5194/tc-10-1823-2016.

Thank you for the opportunity to review this manuscript.