Reviewer 1.

We thank the reviewer for their comments and provide our response below in blue.

This paper shows that there is no trend in the areal extent of the marginal ice zone (MIZ), an increase in the fractional area that the MIZ covers in the total sea ice extent, and that the CICE-CPOM model fails to reproduce these observations. I think the observation that the total areal extent of the MIZ hasn't changed is an interesting way to reconsider the dramatic changes in Arctic sea ice, but this isn't really a new insight. For example, Strong and Rigor (2013) and other studies have shown that the MIZ moved northward and its width has increased.

It is true that Strong and Rigor (2013) showed that the width of the MIZ was increasing and moving north. However, our manuscript shows, for the first time and within the bounds of observation error, that there is no trend in the MIZ extent. This is a new insight, as noted by the other reviewers, including the first author of the Strong and Rigor paper.

Rolph et al. is simply arguing that the glass is half full (no change in MIZ extent), rather than half empty (MIZ width is increasing). While I think this is an interesting way to look at the changes in Arctic sea ice, does this different perspective provide any new scientific advances?

Our analysis indicates that the MIZ extent is both not changing in extent *and* is increasing in width, in contrast to the reviewer's description of our results. It is not our intention to speak in sweeping terms about a 'glass half-full' or 'half-empty' situation in relation to climate change and sea ice, but rather to present the first historical analysis of the marginal ice zone extent, which is a vital part of the Arctic climate and biology, e.g. Barber et al. (2015).

The authors also need to consider that the sea ice concentration data has larger errors during summer than they assume. As this paper currently stands, I don't think it provides enough compelling reason to warrant publication.

Naturally, the error in summer sea ice concentration is larger than the 10% error bar we applied. This is evident from the fact that the different observation products do not agree within 10%. We have now made this point more explicitly (see below). However, the true error associated with each observation product is not a known quantity. There are complexities in the processing chain for each observation product produced and, while errors may be quoted for each step in the analysis chain, the true error in representation of sea ice concentration may be subject to systematic or random errors that are not fully accounted for. It is for this reason that we followed precedent and used the 10% error previously introduced in Spreen et al (2008). Increasing the uncertainty of the sea ice concentration datasets would not lead to a known trend, given that the lower uncertainty we used does not show significant trends in MIZ extent.

Major Comments:
1) Why is it important to consider that the areal extent of the MIZ hasn't changed? The authors need to beef up their case that it is important to think of the changes in the MIZ this way. Can the authors show how this perspective provides new insights that the many physical process studies of changes in the fractional area of young ice versus old ice do not? Or new insight into some biological process?

- The Arctic sea ice area is declining with the strongest rate during summer. This can be described by either of the following two extreme scenarios: 1) sea ice concentration is reducing everywhere, so the whole Arctic will become MIZ before it will be free of ice, or 2) the sea ice concentration remains between 80-100% (our definition of pack ice), but the total sea ice extent is reducing until all of the ice is gone. There is no MIZ in the second scenario. We have shown that reality is somewhere in the middle. This is important to know because both of these extreme scenarios are physically very different. In the second scenario, sea ice thickness is homogenous within a grid cell, but in the first scenario, there is a wide sub-grid cell ice thickness distribution, with the thinner ice melting and thicker ice surviving. The changes to the extent of the MIZ depend strongly on the sea ice thickness distribution and provide insights to how sea ice can be expected to melt in the future. We have added a statement to the Discussion section 5.2, at line 324: 'The lack of trend in the MIZ extent gives an indication about how the sea ice is melting. Given that the sea ice area is declining, it could be (and is often assumed) that the sea ice concentration is declining everywhere.

- The Arctic MIZ extent is an indicator for the extent of habitat for extremely important biological activity in the Arctic. This is the first study that provides this metric/indicator. While width might be a proxy for extent, it becomes an indirect indicator of extent due to the retracting northward movement of the MIZ.

- Examples of biological activity dependent on the extent of the marginal ice zone have been added in Section 5.3, starting at line 355. Please see also the response to Specific Comment #1 from Reviewer #3.

- Because the MIZ has been shown to be important also in the physical Arctic climate, the timeseries of the extent metric for the MIZ is interesting for a wide variety of Arctic fields of study.

2) The errors in the sea ice concentration retrievals from passive microwave satellites during summer are large. For example, in their figure 3 they show wildly varying estimates of where the northern edge of the MIZ is. Some (Walt Meier and/or others at NSIDC or NASA may have a paper on this) have estimated the summer SIC error to be higher than 40% during summer, and most of this error and differences between the retrieval methods is related to how they filter weather. Rolph et al. need to provide a more thorough error analysis than assuming an overall 10% error estimate since the errors in the SIC retrievals affect how robust their conclusions are.

- We agree and show in our results that the generally applied 10% error is for retrieval of sea ice concentration is not valid for the summer period. Indeed, our analysis demonstrates that MIZ quantities based on current sea ice concentration retrievals are not accurate enough to constrain model results. To avoid misinterpretation, we have added to the manuscript in the Discussion Section 5.5 at lines 381-382: '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).'

- Increasing the uncertainty of the sea ice concentration will not change the main result of the paper that the MIZ is not exhibiting a significant trend in extent. For this reason, the robustness of the conclusion still stands without increasing the error in summer to 40% for example.

- Spreen et al (2008) gave an error between 10-12% between the sea ice concentration observations from a summer expedition with the German icebreaker Polarstern and three separate algorithms used to process AMSR-E satellite data.

3) The fact that models don't reproduce these observations isn't surprising. There are already many papers that show that various models don't reproduce some observation. But as with any tool, does simply showing that a tool doesn't work for this job warrant publication? If Rolph et al. could pin down what needs to be improved in the models, that would advance science and the inclusion of the model study would be interesting.

- We included the model experiment in order to understand how the MIZ extent, as calculated from satellite-derived sea ice concentrations, compares with the range of MIZ extent as calculated from the model results. We found that modelled MIZ extent does lie within the range/uncertainty of the observations (please see dashed lines in Figure 1).

- Please note we do not conclude that the model does not reproduce observations, but that the observations of the MIZ are not accurate enough to constrain model results.

Minor Suggestions:
4) Be consistent in your use of units. E.g. in lines 194-195 you switch between meters squared to kilometers squared. I suggest sticking with kilometers squared.

Yes, this has been changed now to kilometers squared.

5) Need to note 10ˆ7 in the label for the Y axes in Fig. 1 rather than "1e7" on the top corner of the plots.

Yes, thanks, this has been changed to 10^7 in Figure 1.

6) Provide a short section 3.3 discussing how statistical significance was estimated. Maybe just move this from caption of table 1.

We have moved this from the caption of Table 1 to the end of Section 3.2.

7) Caption of Fig. 1: Change "…is defined at…" to "…is defined as…".

Thanks, changed.

Reviewer 2 (Court Strong)

Authors responses in blue.

The authors present an analysis of historical MIZ extent using available satellite products and the CICE-CPOM model. They find no historical trend in extent but an increase in the fraction of the total ice that is MIZ. MIZ extent provides an interesting perspective which is complementary to the previously published trends in MIZ position and width. Within the scope of the present study, an explanation for the lack of trend drawing on MIZ geometry and prior results could strengthen and contextualize the findings.

We would like to thank Court Strong for his thorough review of our manuscript and his helpful suggestions to improve our manuscript. Following his advice, we added time series showing the poleward movement and widening of the MIZ resulting in a constant MIZ extent due to the geometry of the earth.

Major comments:

1. A poleward trending and widening MIZ does not necessarily need to conserve area, so the lack of trend reported here is potentially interesting. The manuscript would be strengthened by explaining how this result follows from the magnitude and direction of changes in MIZ width and position. One could, for example, simplify the geometry by approximating the MIZ as an annulus and then plug in the latitude rate of change (as a radius) and width rate of change from Table 1 of Strong and Rigor 2013). Over the satellite record, this gives changes in warm-season MIZ extent which are small relative to interannual variability.

    - Simplifying the MIZ shape to an annulus presented problems because we found that certain months (especially March) had pack or landfast ice south of the MIZ, and so it was difficult to determine true MIZ area in this way. Instead, we approximated the MIZ area by first finding the average of latitudes over all the grid cells that were defined as MIZ. Using this latitude and assuming a spherical earth and no land, we found the average MIZ perimeter. Because we assumed no land when calculating the average perimeter of the MIZ, we focused on the months when the ice is, in general, north of the main northern hemisphere landmass. Following this, further analysis of the summer months (which show the most change in relative MIZ fraction) is shown below. The changes in average MIZ latitude and MIZ width are shown in Figures 1 and 2, respectively.
    - Since we had previously found the extent of the MIZ (Figure 1 in the manuscript), the MIZ width could be found from Width = Extent / Perimeter.
    - For each month, the change in width and change in perimeter were both calculated from the slope of each yearly timeseries. These methods have been added as a new section in the manuscript (Section 3.3)

Figure 1. Timeseries of average MIZ latitude

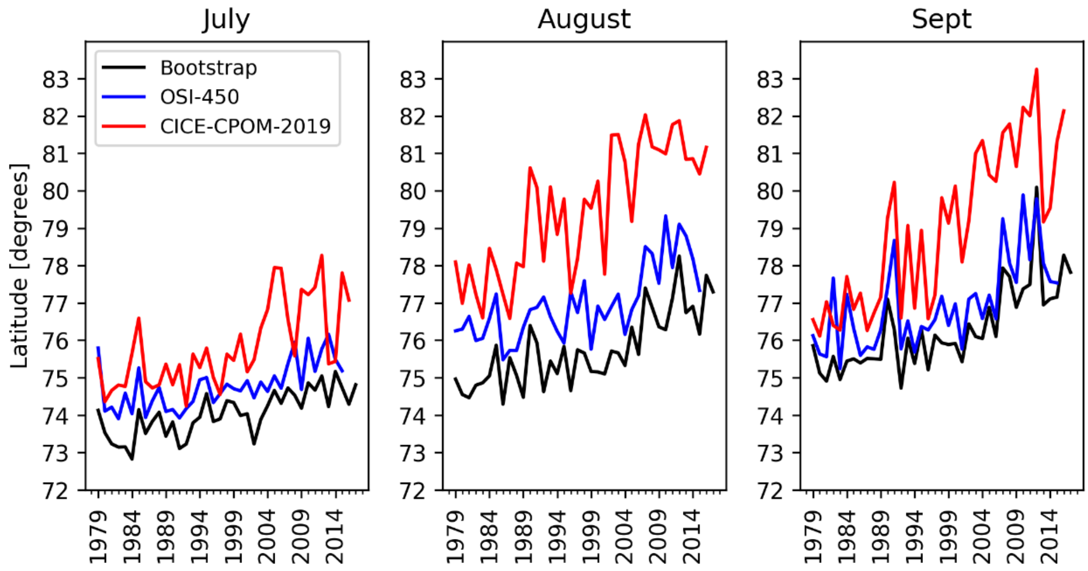


Figure 2. Timeseries of MIZ width

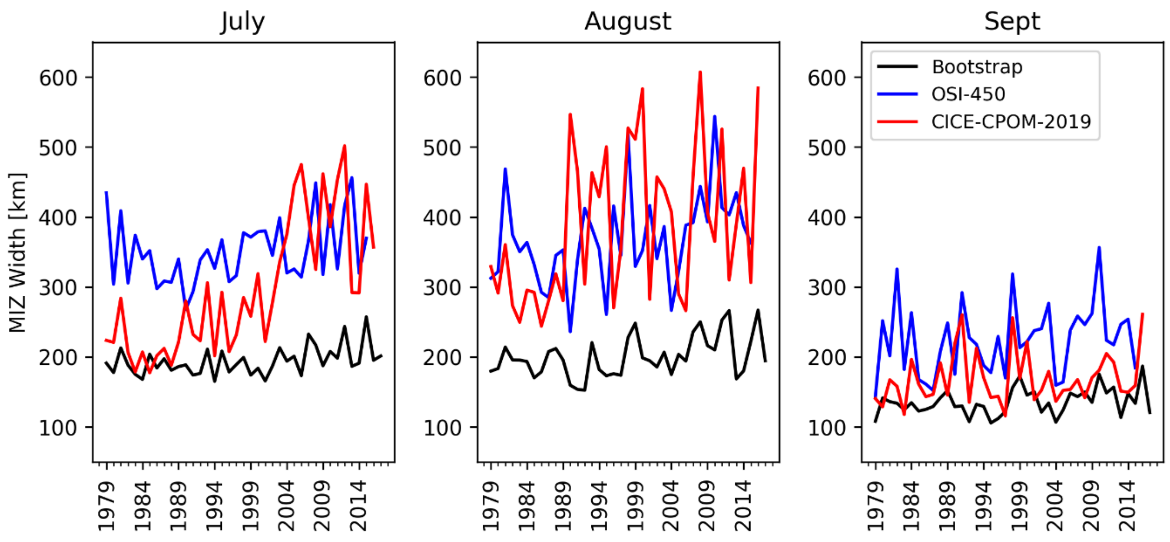


Table 1. Trends of MIZ latitude and width change based on monthly means of sea ice concentration for July, August, and September. Only significant trends at a 95% confidence level are shown. RMS values of the detrended timeseries are given in parenthesis. Timeseries of latitudes and widths from where these trends originate for Bootstrap (black), OSI-450 (blue), and CICE-CPOM-2019 (red) are shown in Figures 1 and 2 respectively. AMSR timeseries were excluded due to the limited number of years in those datasets.

	July			August			September		
	Bootstrap	OSI-450	CICE-CPOM-2019						
ΔMIZ latitude [deg/year]	0.039	0.036	0.069	0.068	0.065	0.122	0.074	0.069	0.159
RMS for ΔMIZ latitude	0.387	0.484	0.806	0.607	0.667	0.998	0.708	0.896	1.13
ΔMIZ width [km/year] (RMS)	0.720	Insignif.	6.50	1.11	2.19	4.06	0.55	Insignif.	Insigif.
RMS for ΔMIZ width	18.3	--	59.7	26.3	59.6	96.9	17.5	--	--

- We show, in agreement with Strong and Rigor (2013), that the interannual variability (RMS values in Table 1 above) of both the mean latitude of the MIZ and the mean width is roughly 10 to 30 times larger than annual trends. Since the MIZ extent is a function of latitude and perimeter, it also shows that the change in MIZ extent is small relative to interannual variability.

- We have summarized the latitude trends given above in Table 1 to the Results Section 4.3, starting at line 267.

- We also compared these changes of the MIZ width and latitude calculated from the Bootstrap, OSI-450, and CICE-CPOM-2019 model output with the values of the MIZ width and latitude changes found in Table 1 of Strong and Rigor (2013). The average latitude change in the observational datasets (Bootstrap and OSI-450) agree well with the results from Strong and Rigor (2013), as seen in the bottom rows of Table 2 below (0.0603, 0.0564, and 0.059 degrees/year respectively). The model overestimates the latitude change at 0.117 degrees/year. This has been added to the Results Section 4.3, starting at line 261.

- Compared to the 1.3 km/year trend in MIZ width as found in Strong and Rigor (2013), Bootstrap shows a lower trend (0.793 km/year), OSI-450 a comparable trend at 1.49 km/year, and the model has a much higher trend at 3.72 km/year (Table 2). It should be noted that the datasets cover different temporal ranges, with the Strong and Rigor from 1979-2011 and the other datasets covering through 2017, 2015, and 2016 for Bootstrap, OSI-450, and CICE-CPOM-2019 respectively. The OSI-450 trends in MIZ width and latitude are closer to that of Strong and Rigor (2013), compared to the NASA Bootstrap. This can be attributed in part to the differences in the Bootstrap and OSI-450 algorithms.

Table 2. Comparison of MIZ width and latitude change with Strong and Rigor (2013). Only significant trends (95% confidence level) are shown for Bootstrap, OSI-450, and model data.

	July- Sept			July – Sept from Strong and Rigor (2013)
Average width change [km/year]	Bootstrap (1979-2017)	OSI-450 (1979 – 2015)	CICE-CPOM-2019 (1979-2016)	(1979-2011) 1.3
	0.793	1.49	3.72	
Average latitude change [deg per year]	0.0603	0.0564	0.117	0.059

2. Related to above, the authors touch on the concept of perimeter briefly in their remarks on lines 1 and 260, but this can be made more quantitative and also contextualized by prior related work. For example, Strong et al. (2017) calculated pan-Arctic MIZ extent in the bootstrap data, denoted by A in their equation (15), and used this time series in conjunction with MIZ perimeter (L) to study the width trend. They also concluded that the widening is consistent with the decline in the inner pack ice area outpacing the decline in total ice area (expressed as effective radii; trends reported at the end of their Section 4a and Fig 8b).

- This is a good suggestion, and we now have quantitatively compared the necessary changes in width for the MIZ extent to remain constant.
- We calculated how much the MIZ width needs to change in order to keep its area constant, using the equation Area = Perimeter * Width, and set dA/dt = 0. The trend of the latitude was used to find the fraction change of the perimeter. The approximated perimeter of the MIZ (P_{MIZ}) using the average latitude of the MIZ (Θ_{MIZ}) is found with the following steps, where $\theta_{initial}$ is the initial latitude taken from the trendline and θ_{final} is the final latitude taken from the trendline.

- $R_{MIZ} = R_{Earth} * \cos(\Theta_{MIZ})$
- Plugging this radius into the perimeter equation for a circle: $P_{MIZ} = 2\pi * R_{earth} * \cos(\Theta)$
- Finding the fraction of how much the MIZ extent is reduced if the MIZ was only moving northward with no change in width can be approximated by:

$$\frac{P_{MIZ\ (final)}}{P_{MIZ\ (initial)}} = \frac{2\pi\ R_{MIZ\ (final)}}{2\pi\ R_{MIZ\ (initial)}}$$

$$= \frac{2\pi\ R_{Earth} * \cos(\theta_{final})}{2\pi\ R_{Earth} * \cos(\theta_{initial})} = \frac{\cos(\theta_{final})}{\cos(\theta_{initial})}$$

- The above gives the fraction that the MIZ extent has decreased due to the decreased perimeter from the MIZ moving northwards. Since the MIZ area remains constant (as we have shown in the manuscript), the width must increase by the inverse of the above fraction, or:

$$\text{Fraction that MIZ width must increase for area to remain constant} = \frac{\cos(\theta_{initial})}{\cos(\theta_{final})}$$

  These results are given in the first row of Table 3. The second row of Table 3 compares the fraction change of the MIZ width as given from the trends calculated from the sea ice concentration data (Figure 2 above). With the exception of the model and given the simplifications of our MIZ geometry, the fractions are relatively consistent in that they support the MIZ is widening enough to keep the area constant as the MIZ trends northwards. This point has been added in a new subsection in the Discussion (Section 5.4).

- The methods described here have also been added in a new Methods subsection (Section 3.3)

- The results of Table 3 below have been summarized in the Results (Section 4.3, renamed to 'Changes in MIZ location and geometry') starting at line 368. Table 3 has also been also added to the manuscript.

Table 3. Fraction changes of MIZ width needed for the MIZ area to remain constant compared with calculated trends in MIZ width assuming an averaged perimeter

	July			August			September		
Required fraction change of MIZ width for MIZ area to remain constant	Bootstrap	OSI-450	CICE-CPOM-2019	1.20	1.20	1.56	1.23	1.21	1.75
	1.10	1.09	1.20						
Calculated fraction change from MIZ width trends	1.16	Insig.	2.42	1.24	1.25	1.49	1.17	Insig.	Insig.

- The widening trend found in Section 4a of Strong et al. (2017) with the l_{per} definition is 40% for the period of 1979-2015 in July through September. This is slightly more than the 37% widening in the 1979-2012 period as reported in Strong and Rigor (2013). Our data show lower widening trends (order of 20%, Table 3) but we think still roughly comparable given the simplifications used in the above approach compared to those methods in Strong et al. (2017). This has been added to the new Discussion Subsection 5.4 'Increase in width compensates for decrease in perimeter'.
- We have also added a statement in the Discussion Section 5.3 of the revised manuscript at lines 339-340 that the inner pack ice is outpacing the decline in total ice area with the reference to Strong et al. (2017).

3. Section 3.1: For model validation, the interpolation of concentration onto the model grid makes sense. However, to provide a definitive statement on MIZ extent trends, why not use the native 25-km NSIDC grid? I think the nominal resolution around the pole in the 1-degree tripolar grid is about 85 km, although line 100 in Section 2.2. mentions _40 km. Either way, potential artifacts of the regridding and interpolation should be considered because MIZ width ranges from about 50 to 150 km.

   - The nominal resolution of our 1 degree tripolar grid is 40-km in the Arctic (as stated in the manuscript). The regridding from a 25-km grid to our 40-km grid has no significant impact.
   - We have shown in our response to Comment #1 (please see Table 2 above) that our latitude trend data is consistent with that of Strong and Rigor (2013)

4. The abstract states that the MIZ is "trending northwards" and Section 4.3 is titled "MIZ trending northwards," but the presented results seem restricted to maps of August 1993 and August 2013. I did not see the record-length analysis to support the statement in the abstract "The MIZ is trending northwards, consistent with other studies" (line14).

   - Yes, we agree with the reviewer's comment, and that the quantified latitude and width trends add support to this statement. Please also refer to our answer to Comment #1.
   - We have added the figure showing the timeseries of MIZ latitudes as Figure 3 to the revised manuscript and have added a description of the latitude trends given above to the Results Section 4.3, starting at line 260. We have also added a reference to the Figure 3 in Discussion Section 5.3 at line 355.

5. The MIZ fraction change is reported as "small" in the abstract, and a quantitative value would be informative here. Also, is it really small? If I understand the units correctly, a 0.003 / year trend would amount to an increase of 0.117 MIZ fraction over the record. For a quantity starting round 0.2, increasing to 0.3 would be a 50% increase.

   - Yes, this is a great point, and for all of the datasets, the change has now been calculated in terms of % increase, in addition to the previously stated fraction per year units. A column was added to Table 1 of the revised manuscript, and is also shown below.
   - The statement in the abstract (starting at line 16) that had indicated the relative MIZ change is small has now been changed to the following: 'We find a large and significant increase (>50%) in the August and September MIZ fraction (MIZ extent divided by sea ice extent) for the Bootstrap and OSI-450 observational datasets, which can be attributed to the reduction in total sea ice extent.'

Table 1. Added column of % increase of MIZ cover compared to total ice extent. Other columns are trends of total ice extent, MIZ extent, and extent of MIZ relative to total ice extent.

$\alpha = 0.05$

Trend in 10^{10} m^2 per year (r^2)			Relative MIZ	Total change
March	Total ice extent	MIZ extent	(MIZ extent/total ice extent) [1/year]	Relative MIZ (%)
OSI 450	-2.42 (0.74)	Insig.	Insig.	Insig.*
Bootstrap	-2.76 (0.78)	-0.520	Insig.	Insig.*
AMSR	-3.04 (0.43)*	Insig.*	Insig.*	Insig.*
CICE-CPOM-2019	Insig.	Insig.	Insig.	Insig.*
July				
OSI 450	-5.27 (0.84)	Insig.	+0.003 (0.375)	27%
Bootstrap	-5.85 (0.87)	Insig.	+0.002 (0.450)	38%
AMSR	-7.55 (0.67)*	Insig.*	Insig.*	Insig.*
CICE-CPOM-2019	-4.29 (0.70)	Insig.	+0.009 (0.636)	124%
August				
OSI 450	-6.52 (0.78)	Insig.	+0.005 (0.479)	50%
Bootstrap	-7.19 (0.81)	Insig.	+0.003 (0.444)	56%
AMSR	-7.96 (0.47)*	Insig.*	+0.008 (0.672)*	60%
CICE-CPOM-2019	-9.61 (0.71)	Insig.	+0.010 (0.557)	91%
September				
OSI 450	-7.80 (0.75)	Insig.	+0.004 (0.392)	79%
Bootstrap	-8.07 (0.75)	Insig.	+0.003 (0.479)	66%
AMSR	-9.72 (0.50)*	Insig.*	Insig.*	Insig.*
CICE-CPOM-2019	-9.02 (0.79)	-1.37 (0.31)	+0.003 (0.293)	57%

- We have also amended a similar statement in the conclusion so that it now reads (starting at line 397): 'Due to the decrease in Arctic sea ice extent, there is a significant increase (> 50%) in the relative MIZ extent (MIZ extent divided by sea ice extent) during August and September for the Bootstrap and OSI-450 observational datasets. During July and August, the positive trend is 2 to 4 times stronger in our model simulation than these observations.'

6. We see that the model performance varies through the year as discussed in Section 4.1, but it is difficult to interpret the discrepancy from the warm-season observations because the spatial pattern is left implicit. Does the total extent error signal that the model MIZ has a position error, width error, or both? A more spatially explicit treatment of the model performance would help the reader to understand the purpose of including the model, and its intended role and weight in the suite of results.

- We have included a model to examine the extent to which the observed changes could constrain models and the extent to which the model represents observations. But this can only be indicative without a much larger study. This is particularly interesting in considerations of future projections of changes of the MIZ (e.g. Aksenov et al, 2017).
- Figure 5 in the revised manuscript (previously Figure 3) gives an indication of the spatial discrepancy between the model and the observations. This is especially true during the summer months.
- Our primary purpose is to examine changes in the observed marginal ice zone, and we have shown that any further analysis of the spatial patterns of MIZ in model output will be very poorly constrained by the observations. We have added a statement in Section 4.3, lines 284-285 to make this more clear: 'The spatial variability of the MIZ is poorly constrained by observations' with a reference to Figure 5.

7. Suggest including a paragraph somewhere in main text to detail the statistical methods (assumed degrees of freedom, tests were parametric versus bootstrap, etc.).

    - The following statement regarding the statistical method has been removed from the caption of Table 1 and added at the end of Section 3.2: ‘’A linear least-squares regression was used to calculate the trends, using a 95% confidence level.’’

8. The title is very general. To more precisely reflect the presented analysis, suggest something like: Historical analysis of Arctic marginal ice zone extent”.

    - Agreed, the title has been changed to ‘Changes of the marginal ice zone during the satellite era.’

Minor comments:

1. Line 11 in abstract: I did not see an extrapolation of the results forward in time in the paper. If this remark just follows from the report of no trend, suggest removing to avoid implying that a supporting extrapolation with uncertainty analysis was performed.

    Yes, this statement has been removed.

2. Lines 14-16 recommends that future authors “provide a specific and clear definition when stating that the MIZ is rapidly changing.” Suggest an edit here to clarify if future authors are being asked to specify the MIZ definition or to specify the particular MIZ property that is changing (width, area, latitude, etc.).

    The sentence has been changed 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.’

3. Lines 22-24 state that the cited studies “tend to assume that marginal ice zone (MIZ) extent is increasing.” I am familiar with these studies and looking back through a few of them as a sample, found no assumption that MIZ extent is increasing. Instead, the remarks about MIZ change were literature-based and referred to specific properties.

    Some statements in the above references that gave the authors this impression that the MIZ is increasing in extent are listed below. We realize that other specific properties are what might have been referred to here, but one of the suggestions of this work is to clearly indicate which property of the MIZ is expanding. This way, to say ‘the MIZ is expanding’ will not be interpreted as the MIZ extent is increasing (which, as we have presented in this paper, is not what the satellite data show).

    - ‘The Arctic Marginal Ice Zone … is expanding as the result of on-going sea ice retreat ‘ (The first statement of the abstract in Boutin et al (2019).)
    - A new reference (under review) has also been added to this line, which states in the first statement of the abstract: ‘The decrease in Arctic sea ice extent is associated with an increase of the area where sea ice and open ocean interact, commonly referred to as the Marginal Ice Zone (MIZ).’ (Boutin et al 2020a).

- 'The most dramatic intra-annual variability in sea-ice cover is found in the MIZ … As summer sea-ice cover becomes thinner and more fractured, these regions will become larger' . (A statement in the introduction of Horvat and Tziperman (2015))
- 'Summertime opening of the Beaufort and Chukchi Seas has amplified the extent … of the seasonal MIZ, the region of fractional ice cover that forms the transition between open water and pack ice' (Lee and Thomson 2017).
- 'These changes in Arctic sea ice extent suggest scientifically important changes in the position, width, and area of the marginal ice zone' (Strong et al 2017) Width and position are also referred to in this statement, but this study shows that area should not be assumed to also change.
- After searching again through the other references in this statement, the authors removed those references where this assumption couldn't be clearly identified.
- These statements appear at lines 25-26 in the Introduction.

4. Why was the NSIDC Climate Data Record not used? I think one of the motivations for CDR was to develop a consistent record suitable for trend analysis.

   Our selection of satellite products OSI-450 (EUMETSAT), NASA Bootstrap, AMSR-E and AMSR-2 provide an adequate representation. Differences between NSIDC CDR and OSI-450 are small with respect to shown discrepancies as shown in our results.

5. Line 202: It's not clear what is meant by "The interannual variability of the MIZ … varies more than the sea ice extent." A more precise statement referencing specific variance statistics could clarify.

   We have provided variance statistics of the detrended MIZ width and latitude timeseries for 3 datasets and these are given in Table 1 above. We have changed this statement (now at line 232 of the revised manuscript) so it now refers to the spread of the MIZ observations being larger than the spread of the observations for sea ice extent, especially in the summer months.

6. Line 212 and thereafter. Suggest using a consistent format when referring to the MIZ fraction trends. Something like "0.003 per year" as in the Table seems less likely to confuse than 0.3% the latter could be interpreted as a percent change rather than change in percent).

   Yes, we agree. The text starting at line 241 in Section 4.2 has been changed so the numbers match the same format as the table. (0.3% has been changed to 0.003 per year, etc) in the text.

7. Line 238: "Our results are robust" – not clear which specific results are referred to here.

   The sentence has been rephrased to 'The lack of trend in MIZ extent is robust given changes in the upper and lower bounds of the sea ice concentration in the MIZ definition'. This statement now appears at lines 290-291.

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.

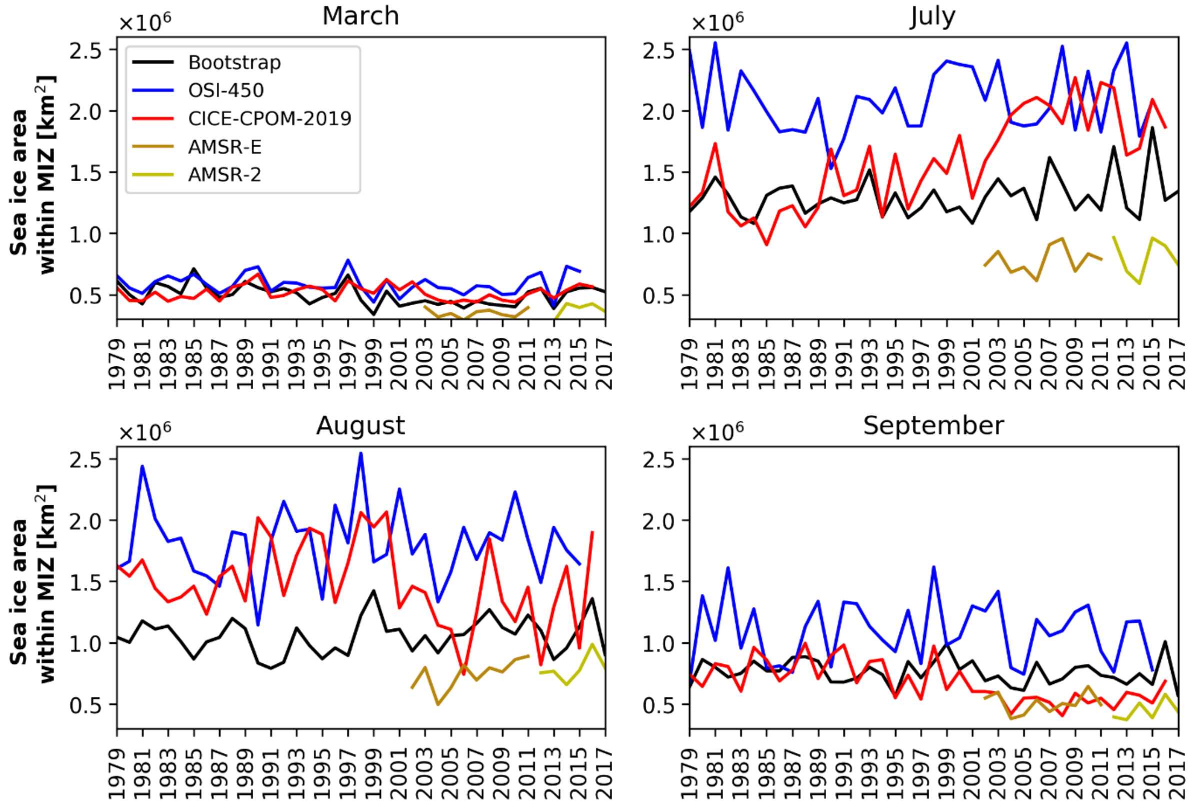
Also of interest however is the sensitivity of this analysis to the mathematical and physical definition for the MIZ; investigation of additional techniques used to analyse total SIE (i.e. geographic muting described in Eisenman, 2010) applied to the MIZ that could perhaps explain the absence of statistically 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.

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Thank you for the opportunity to review this manuscript.

Changes of the Arctic marginal ice zone during the satellite era

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Abstract. Many studies have shown a decrease in Arctic sea ice extent. 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. 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. Here, we present, for the first time, an analysis of satellite observations of pan-Arctic averaged MIZ extent. We find no trend in the MIZ extent during the last 40 years from observations. Our results indicate that the constancy of the MIZ extent is the result of an observed increase in width of the MIZ being compensated by a decrease in the perimeter of the MIZ as it moves further north. We present simulations from a coupled sea ice-ocean mixed layer model using a prognostic floe size distribution which we find is consistent with, but poorly constrained by, existing satellite observations of pan-Arctic MIZ extent. We provide seasonal upper and lower bounds on MIZ extent based on the 4 satellite-derived sea ice concentration datasets used. ~~An extrapolation of the observations shows the MIZ extent as remaining relatively constant in the coming decades, at least until the Arctic is completely covered by seasonal ice.~~ We find a ~~small~~ large and significant increase (>50%) in the ~~summer~~ August and September MIZ fraction (MIZ extent divided by sea ice extent) for the Bootstrap and OSI-450 observational datasets, which can be attributed to the reduction in total sea ice extent. ~~The MIZ location is trending northwards, consistent with other studies.~~ Given the results of this study, we suggest that references to 'rapid changes' in the MIZ should ~~future studies need to~~ remain cautious and provide a specific and clear definition of both the MIZ itself and also the property of the MIZ that is changing ~~when stating the MIZ is 'rapidly changing'.~~.

1 Introduction

Arctic sea ice extent has been declining rapidly during the last 40 years (Comiso et al., 2008; Onarheim et al., 2018; Serreze et al., 2007; Stroeve et al., 2007). The MIZ has been variously defined as where ocean wind-generated waves interact with the sea ice (e.g. Dumont et al., 2011) or as the area of ocean covered with 15-80% sea ice (e.g. Aksenov et al., 2017; Strong and Rigor, 2013). Due to its utility and the wealth of sea ice concentration data available, we use the latter operational definition of the MIZ extent being the total area of ocean capped by 15-80% sea ice cover. Given the rapid decline of sea ice extent in the Arctic, associated studies consequently tend to assume that the marginal ice zone (MIZ) extent is increasing (Boutin et al., 2020a~~19~~; Boutin et al., 2020b; ~~Flocco et al., 2010;~~ ~~Horvat and Tziperman, 2015;~~ Lee and Thomson, 2017; Strong et al., 2017;

Horvat and Tziperman, 2015; Tsamados et al., 2015). The purpose of this paper is to show whether the extent of MIZ is actually changing. While there are significant regional changes happening in the Arctic MIZ such as increased light penetration (e.g. PAR), open water, and gas exchange (Barber et al., 2015), it is important to keep in mind that these changes are not necessarily a result of a change in the coverage of the total MIZ, but rather more likely the change in its location. As the Arctic MIZ moves northwards (Aksenov et al., 2017) the increased southward area of open ocean subsequently allows for increased wind-wave generation which can break up the ice (Collins et al., 2015; Thomson and Rogers, 2014). Thinner ice cover (Kwok, 2018) in combination with an increase in wind-wave action may result in smaller floes that melt faster due to an increased lateral melt rate (Tsamados et al., 2015). The MIZ can also contribute to Arctic amplification because it is an area for Arctic cyclogenesis which is important for northward meridional heat transport (Inoue and Hori, 2011). The MIZ supports many important processes such as Arctic marine primary production (Alexander and Niebauer, 1981), delivery of nutrients to the euphotic zone, air-sea gas exchange, and carbon exchange across the air-sea interface (Barber et al., 2015; Hansen et al., 1996). Monitoring changes of the MIZ environment in which these processes occur can help us understand the associated changes in the climate system.

It has been found that the width of the MIZ has increased in the summer and decreased in winter from 1979-2011 (Aksenov et al., 2017; Strong and Rigor, 2013). However, it was also found that there is a positive (northward) trend in the area-weighted latitude of the MIZ during the same time period (Strong and Rigor, 2013). A northward trend of the MIZ and an increase of its (summer) width does not necessarily imply that the MIZ extent is increasing as the effective perimeter of the MIZ may be decreasing. A decrease of total sea ice extent combined with a widening of the MIZ does imply, however, that the central pack ice will occupy less area. This could ease Arctic access for ships (Aksenov et al., 2017). While the Arctic is projected to have entirely seasonal ice cover by mid-century (Notz and Stroeve, 2018; IPCC, 2014), a study of specific trends in MIZ extent is lacking, such as quantification of the MIZ extent relative to the total sea ice extent. Thus, we need to remain cautious and provide a specific and clear definition of the property of the MIZ when stating the MIZ is 'rapidly changing'. 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. This paper aims to fill that gap.

We use a state-of-the-art sea ice-ocean model to better understand how well simulations can capture the satellite-observed MIZ. Due to the nature of the operational MIZ extent definition used here, this study can also be viewed as a test of model performance concerning how well sea ice concentrations are simulated on a pan-Arctic scale. Winter, summer, and autumn months were selected to illuminate how well observations and simulation agree on a seasonal timescale. The bulk of the model set-up follows Schröder et al. (2019) and can be seen as representative of how well other models simulate sea ice concentration.

The paper set-up is as follows. In Section 2, we introduce the satellite observational datasets and model set-up we used. In Section 3, we describe the methods of applying our satellite data to our model grid, and subsequent analysis of the results.

Here we also describe how we defined the MIZ and sea ice cover in our calculations. Section 4 presents our analysis of the extent of the total sea ice cover and MIZ as monthly averages for March, July, August, and September for the period from 1979-2017. It also includes trends and statistical analysis of the total MIZ extent relative to the total ice extent. Section 4 discusses the apparent change of location in the MIZ. The subsequent discussion (Section 5) outlines possible implications of the trends we observe, and what this could mean for future projections of the MIZ.

2 Model set-up and Data

2.1 Observational datasets

The satellite products used in this study are: OSI-450 (EUMETSAT), NASA Bootstrap (Comiso, 2017), AMSR-E and AMSR-2 (Spreen et al., 2008). OSI-450 is the second version of a processing of the EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI SAF) team Sea-Ice Concentration (SIC) Climate Data Record (CDR). Sea ice concentration is provided over the polar regions at 25 km resolution and derived from passive microwave satellite data SSMR, SSM/I and SSMIS for years 1979 through 2015 (every other day from January 1, 1979 to August 20, 1987 and daily from August 21, 1987 through December 31, 2015). This processing includes using Numerical Weather Prediction re-analysis atmospheric data to correct brightness temperature, dynamic tie-points, and state-of-the-art algorithms which are described in detail in (Lavergne et al., 2016). The NASA Bootstrap sea ice concentration product has a 25 km resolution and is derived from SSMR, SSM/I, and SSMIS sensors and generated using the AMSR-E Bootstrap Algorithm (Comiso, 2017) with daily data available from November 1978 through 2018. The AMSR-E Bootstrap algorithm uses daily varying tie-points, three frequency channels which are available continuously from SSMR, through SSM/I and to AMSR-E. All three of these channels have vertical polarization and two of those have horizontal polarization. A basic assumption of the Bootstrap algorithm is that a certain observational area is covered by entirely ice or water, which can lead to data smearing at the ice-ocean edge or in areas where the contrast of emissivity between ice and water are not so strong. A higher resolution in general gives better chances to distinguish the correct location of the ice edge and characterize the MIZ (Comiso, 2012).

AMSR-E v5 and AMSR-2 v5.4 are datasets processed using the ASI-algorithm (Spreen et al., 2008) and are the highest resolution observational datasets used in this study with a grid spacing of 6.25 km. The time frame for available data for the Japanese AMSR-E sensor onboard the EOS/Aqua satellite is from 1 June 2002 to 4 October 2011 and for the AMSR-2 sensor onboard the GCOM-W satellite is from July 2012 to 17 November 2018. The ice concentration is calculated from the difference of brightness temperatures in the vertical and horizontal polarization, which is a result of emissivity differences. At 90 GHz, the emissivity of open water is much smaller than that of all ice types and so water can be distinguished from the ice. An atmospheric correction is applied to account for the influence of the atmosphere on the upwelling polarization (Spreen et al., 2008). This correction assumes a horizontally stratified Arctic atmosphere with an effective temperature to replace the vertical temperature profile and a diffusely reflecting surface viewed under a 50º incidence angle (Svendsen et al., 1987). The ice concentration then becomes a function of the polarization difference and the atmospheric correction term which is in general also a function of ice concentration (Svendsen, 1983; Svendsen et al., 1987). Atmospheric influence is assumed to be a smooth function of ice concentration and a third order polynomial for ice concentration is solved as a function of polarization difference. Fixed tie points, which provide necessary values for unknowns, are found by comparing ice concentration from the Svendsen algorithm and an ice concentration reference from an independent source that has been well validated (Spreen et al., 2008). A weather filter is applied due to the disadvantage of the brightness temperatures from 89 GHz channels being influenced by the atmospheric cloud liquid water and water vapor. Some sources of error include water vapor and wind roughening of the ocean influencing the polarization difference. Values for error between the different data products used in this study are given in Section 5.5~~3~~.

2.2 Model set-up (CICE-CPOM-2019)

We use a dynamic-thermodynamic sea ice model, CICE-CPOM-2019, which is designed to be included in global climate models. CICE-CPOM-2019 is based on the existing CICE model version 5.1.2, but with some additions. We perform a stand-alone (fully forced) simulation for the pan-Arctic region (~40 km grid resolution) with a spin-up of 10 years from 1979, and then restarted at 1979 and run through 2016. The CICE model solves 1-D vertical heat balance equations for 5 ice thickness categories. The momentum balance equation which provides the sea ice velocity includes air and ocean drag, the Coriolis force, sea surface tilt, and internal ice stresses. Hunke et al., (2015) gives a detailed description of the CICE model. Since we did not use a coupled ocean model to calculate heat transport in the ocean or ocean currents, the temperature and salinity in the layer below the ocean mixed layer are restored every 20 days to climatological monthly means from MYO-WP4-PUM-GLOBAL-REANALYSIS-PHYS-001-004 (Ferry et al., 2011). Ocean currents are restored on the same timescale and from the same reanalysis dataset. For the atmospheric forcing, NCEP Reanalysis-2 (NCEP2) is used (Kanamitsu et al., 2002, updated 2017).

Some of the default CICE configurations used in this study include: seven vertical ice layers, one snow layer, thermodynamics of Bitz and Lipscomb (1999), Maykut and Untersteiner (1971) conductivity, the Rothrock (1975) ridging scheme with a Cf value of 12 (an empirical parameter that accounts for dissipation of frictional energy), the delta-Eddington radiation scheme (Briegleb and Light, 2007), and linear remapping ITD approximation (Lipscomb and Hunke, 2004). For CICE-CPOM-2019, we switched on a prognostic melt pond model (Flocco et al., 2010, 2012), used an elastic anisotropic plastic rheology (Heorton et al., 2018; Tsamados et al., 2014; Wilchinsky and Feltham, 2006), a prognostic oceanic mixed layer (Petty et al., 2014) and a prognostic floe size distribution (Roach et al., 2018). Demonstrated use of CICE-CPOM-2019 including the above additions, with the exception of the prognostic mixed layer and floe size distribution, is provided as the reference simulation in Schröder et al. (2019). The prognostic mixed layer allows the ocean below the mixed layer to be relaxed toward observations so that the mixed layer can calculate its salinity, temperature, and depth based on the fluxes from the deeper ocean (Petty et al., 2014).

The prognostic floe size distribution is a new development (Roach et al., 2018) and warrants more detailed description which is provided in the next section.

2.2.1 Prognostic floe size distribution

A sea ice floe size distribution is a probability distribution function (Thorndike et al., 1975) that characterizes the extensive variability (centimeters to hundreds of kilometers) in the range of sea ice floe sizes. Imposing a subgrid-scale floe size distribution (e.g. Bennetts et al., 2017; Zhang et al., 2016) does not account for physical processes acting on individual floes. However, here we have added the recent development by Roach et al., (2018) into CICE-CPOM-2019, which accounts for ice formation, welding of floes, lateral freeze/melt, and fracture by ocean surface waves. Particularly important processes which determine the floe size evolution are lateral melt of floes and floes welding together, as well as wave fracture. When floes are smaller, the lateral melt becomes more important, and this can lead to a significant reduction in sea ice concentration in summer (Roach et al., 2018). CICE simulates an ice thickness distribution and the sea ice concentration is calculated by integrating over all ice thickness categories. The change in the ice thickness distribution depends on growth/melt at a melting/freezing rate, ice advection, and redistribution of thickness categories caused by sea ice deformation. When the heat available from the surface of the ocean is enough to melt the ice, basal melting will occur by balancing the conductive heat flux from the bottom and downward heat flux from the ice to the ocean. Lateral melt is obtained as a function of floe size. CICE uses a constant floe size of 300 m, but in CICE-CPOM-2019 a joint floe-size thickness distribution (FSTD) is used which has been developed by Roach et al. (2018) following the ice thickness distribution of Horvat and Tziperman, (2015).

The thermodynamic changes in the FSTD not included in the standard CICE model include a welding parameter for newly formed floes to freeze together and a ‘lead region’ which is part of the open water fraction where lateral growth of existing floes can occur around non-circular floes. Mechanical breaking of sea ice floes by ocean surface waves is determined by a critical strain and minimum floe size (10 m) which can be impacted by wave fracture. The fractures that would occur if the waves enter an entirely ice-covered region defined in the 1-dimensional direction of propagation are calculated and then the outcome is applied proportionally to each grid cell’s ice-covered fraction. Swell from hindcast wave data coming from the equatorward meridional direction are used to select the significant wave height and mean period. This is then used to construct the wave spectrum (Bennetts et al., 2017; Horvat and Tziperman, 2015) which is attenuated exponentially given the number of floes in the grid cell, and is a function of ice thickness and wave period. With the assumption that sea ice flexes with the sea surface height field, the strain of the ice is calculated and the floe will fracture if this crosses a threshold. New floe radii are put into a histogram which depend on the local sea surface height field only.

3 Methods

3.1 Applying satellite-derived sea ice data to model grid

All available OSI-450, NASA Bootstrap, and AMSR data through 2017 (2015 for OSI-450) were interpolated onto the ORCA tripolar 1º grid. A tripolar grid allows a construct of a global orthogonal curvilinear ocean mesh that has no singularity point inside the computational domain because two north mesh poles are placed on land (Madec and Imbard, 1996). The ORCA tripolar grid is used by CICE and so will hereafter be referred to as the 'CICE grid' for simplicity. We use about a 40 km resolution mesh, with the CICE land mask also applied. For NASA Bootstrap, AMSR-E, and AMSR2, a data gap at the pole exists in the downloaded product we filled in. To do this, after interpolating the daily satellite data to the CICE grid, we marked which grid cells at the pole were missing sea ice concentration data. Then, we re-gridded each daily file onto a lower-resolution grid such that the missing values near the pole could no longer be resolved. We then applied this output back to the original higher resolution CICE grid. However, only the values of those grid cells which had previously been missing data on the CICE grid were kept from this method. One exception to this pole-filling method includes the years of 1979 through 1987 in the Bootstrap data, where the pole gap was larger than the rest of the Bootstrap data and the interpolation to the coarser grid still resolved some of the pole gap. Based on the high surrounding summer ice concentration (>80%) for these early years, the sea ice concentration within the pole gap is expected to be over 80%, so this was assumed for these years. The rest of the values in the CICE grid were taken via direct interpolation of the satellite data.

3.2 Calculating the marginal ice zone and sea ice extent

The MIZ extent was calculated as the total area of all grid cells between the thresholds of 15% and 80% sea ice cover, as the MIZ is also defined by other studies (e.g. Strong and Rigor (2013), Aksenov et al., (2017)). The daily values of MIZ extent were calculated for each of the observational datasets after they had been re-gridded to the model grid (and model land mask applied). The daily values of model MIZ extent were ~~also~~ calculated ~~for~~ from the model output. The sea ice area within the MIZ was also calculated for all observational datasets in this study (Bootstrap, OSI-450, AMSR-E, AMSR-2) as well as the model. The daily total sea ice extent was ~~also~~ found for each dataset, which is defined as the total area of those grid cells which are covered by at least 15% sea ice. The daily MIZ extent was divided by the daily sea ice extent to get the daily relative MIZ extent. The monthly means of all these daily metrics were then calculated, and the main further analysis has used these monthly means. AMSR-E and AMSR-2 were combined into one time series, labelled AMSR, for the purpose of cross-correlating with the other datasets. We were unable to derive the error associated with these total measures of extent from the satellite products themselves due to uncertainties in the processing chains that prevent clear statements of error bounds. Following Spreen et al. (2008), we apply an error of 10%, based on systematic differences of monthly satellite products, to our calculated monthly means of the sea ice extent, MIZ extent, as well as the relative MIZ extent. The r^2 values are calculated using a linear least-squares regression and alpha represents a 95% confidence level.

3.3 Approximating changes in MIZ geometry

We next investigated how the changes in MIZ width and position (latitude) impact its extent. The monthly means of the latitudes of all MIZ grid cells were quantified for Bootstrap, OSI-450, and CICE-CPOM-2019. The timeseries of the latitudes for the MIZ found in the AMSR datasets was not calculated due to the relatively shorter temporal coverage compared to the other datasets. The trendlines of the yearly timeseries of the monthly MIZ latitude means were calculated with the associated RMS values. The radius of the MIZ was approximated by $R_{MIZ} = R_{Earth} * \cos(\Theta_{MIZ})$ where Θ_{MIZ} is the monthly-averaged MIZ latitude and R_{Earth} is the radius of the earth. The MIZ perimeter (P_{MIZ}) was then approximated from the average latitude of all MIZ grid cells while assuming a spherical earth and no land. This was done by substituting R_{MIZ} for the radius in the perimeter equation for a circle: $P_{MIZ} = 2*\pi*R_{Earth} * \cos(\Theta_{MIZ})$. Because we assumed no land when calculating the average perimeter of the MIZ, we focused on the summer months when the ice is, in general, north of the main northern hemisphere landmass. Since we had previously found the extent of the MIZ (Section 3.2), the MIZ width could be approximated using the simple formula: MIZ Width = MIZ Extent / MIZ Perimeter. For July, August, and September, the change in MIZ width and MIZ perimeter with associated RMS values were calculated from the slope of each yearly timeseries, while setting the change in MIZ extent to zero. The fraction of the MIZ extent that must be reduced as the MIZ trends northward, given no change in width, was approximated using Equation 1 below where the initial and final values for each variable are taken from the trendlines of the respective yearly timeseries of each July, August, and September month.

$$\frac{P_{MIZ\,(final)}}{P_{MIZ\,(initial)}} = \frac{2\pi\, R_{MIZ\,(final)}}{2\pi\, R_{MIZ\,(initial)}} = \frac{2\pi\, R_{Earth} * \cos(\theta_{final})}{2\pi\, R_{Earth} * \cos(\theta_{initial})} = \frac{\cos(\theta_{final})}{\cos(\theta_{initial})} \quad \text{(Eq. 1)}$$

Equation 1 gives the fraction of the MIZ extent which has decreased due to the decreased perimeter caused by the MIZ moving northwards. The inverse of Equation 1 was calculated to find the fraction of the MIZ width that must increase for the extent to remain constant. The fractions that the MIZ width must increase for the extent to remain constant using the approximation as given in Equation 1 are compared with the fraction change of the MIZ width found from the trends of the average latitudes of MIZ grid cells in the Bootstrap, OSI-450, and CICE-CPOM-2019 products.

4 Results

4.1 Extent of marginal ice zone and total sea ice

The sea ice extent across the observational products do agree within their range of uncertainty. The model simulation agrees with the observations during winter, but slightly underestimates the summer ice extent (solid lines in Figure 1). The sea ice extent as calculated by the model still falls within the error range through July (solid lines in Figure 1b) and is underestimated starting in August (solid lines in Figure 1c) and September (solid lines in Figure 1d). However, by October, the ice extent is again within the 10% error range within the observational products. The March, July, August and September trends of declining total sea ice extent (Table 1) are significant with the exception of the modelled trend in the March sea ice extent. September shows the fastest rate of decline compared to the other months examined, consistent with other studies (Boé et al., 2009). There is also a significant high correlation between the inter-annual variability of sea ice extent observations for all months examined, with values greater than 0.957 in March and greater than 0.987 for July, August and September (Table 2). The lowest correlations occur in March between the model and OSI-450 (0.448), the model and Bootstrap (0.587), and also in July between the model and AMSR (0.575).

In contrast with the sea ice extent, there is no significant trend in the MIZ extent in any of the observational datasets, with the exception of a small negative trend in Bootstrap in March of -0.52% or -0.520 x 10^{4}~~^{10}~~ km^2 per year (Figure 1, Table 1). There is also no significant trend in the modelled MIZ extent except for September (roughly 1.1% or -1.37x10^{4}~~^{10}~~ km^2, $r^2 = 0.31$, Figure 1, Table 1). For most of the summer months, the spread of observations of MIZ extent is greater than the 10% error placed on each of the observations themselves (Figures 1b-d). This indicates that the observational error for the MIZ is larger than our assumed value of 10% based on Spreen et al. (2008). The modelled MIZ extent generally lies within the spread of the observations. The observations taken together provide lower and upper bounds for MIZ extent of between roughly 5-15 x10^5 km^2 for March, 15-50 x10^5 km^2 for July, 15-45 x10^5 km^2 for August, and 10-30 x10^5 km^2 for September (Figure 1).

The ~~interannual variability~~spread of the MIZ ~~(dashed lines in Figure 1) varies~~ is larger~~more~~ than the sea ice extent in the observations ~~as well as in the model results~~ (~~Table~~ Figure 1~~2~~). In the winter months (e.g. dashed lines in Figure 1a), the MIZ extent is more consistent across the datasets. In March, there are significant correlations between the MIZ extent observations (>0.889, Table 2) as well as for the model results. From July through August, the differences in the absolute MIZ extent become very pronounced (dashed lines in Figures 1b-d). In July, the AMSR and Bootstrap are the most highly correlated (0.869), with lower or insignificant values between the other datasets. In September, the AMSR is well correlated with the other observations of MIZ extent (0.805 with OSI-450 and 0.852 with Bootstrap, Table 1).

4.2 Fraction of MIZ relative to total sea ice extent

The trends for the MIZ fraction, i.e. MIZ extent divided by the sea ice extent, for all of the observations are insignificant for March, but slightly positive for July, August, and September with the exception of AMSR, which is insignificant for July and September (Figure 2, Table 1). The trends per year for July are +0.003~~%~~ for OSI-450 and +0.002~~%~~ for Bootstrap. In August, there is an increase in MIZ fraction per year of 0.005~~%~~ for OSI-450, 0.003~~%~~ for Bootstrap, and 0.008~~%~~ for AMSR. In September, the positive significant trends per year are 0.004~~%~~ for OSI-450 and 0.003~~%~~ for Bootstrap. The positive trend in MIZ fraction is given by the stable MIZ extent and decline in sea ice extent (compare dashed and solid lines in Figure 1). The

MIZ fraction for OSI-450 is consistently higher compared to the other observational datasets (Figure 2). The Bootstrap MIZ extent (absolute) is lower than OSI-450, which is the main reason for its lower MIZ fraction. The MIZ fraction for the model is insignificant for March, but slightly positive for July, August and September at +0.009~~%~~, +0.01~~.~~0~~%~~ and +0.00~~.~~3~~%~~ per year, respectively. In July, CICE-CPOM-2019 model shows a trend in MIZ fraction three times that of the OSI-450 and over four times that of the Bootstrap dataset. In August, the model shows a trend two times that of OSI-450 and over three times that of Bootstrap. In September, the trends of MIZ fraction become roughly the same in the model and observations, and this remains so during the winter months (Table 1).

The modelled MIZ fraction generally lies within the spread of the observations with the exception of August, where it is overestimated (Figure 2). The observations taken together provide lower and upper bounds for the MIZ fraction of roughly 0.050-0.10 for March, 0.17-0.52 for July, 0.21-0.57 for August, and 0.4-0.15 for September. The correlations between the model and observations tend to be lower than the correlations between the observations themselves (Table 2). High correlations (>0.843) exist between the Bootstrap and AMSR relative MIZ extent values for all months examined, with generally lower values in July and August between Bootstrap and OSI-450.

4.3 ~~MIZ trending northwards~~Changes in MIZ location and geometry

There is no trend in the absolute MIZ extent (dashed lines in Figure 1), but the location of the MIZ in the more recent years is further northwards, towards the pole (Figure 3). The observational trends averaged over July, August, and September 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. The model overestimates the latitude change at 0.117 degrees per year. There is close agreement in the average latitude change across the observations despite the fact that each timeseries cover slightly different temporal ranges, with the Strong and Rigor (2013) dataset covering the period from 1979-2011, and the other datasets covering from 1979 through 2017, 2015, and 2016 for the Bootstrap, OSI-450, and CICE-CPOM-2019 datasets, respectively. The individual trends (and RMS) in latitude for Bootstrap, OSI-450, and CICE-CPOM-2019, respectively (in degrees per year) are for July: 0.039 (0.387), 0.036 (0.484), 0.069 (0.806); August: 0.068 (0.607), 0.065 (0.667), 0.122 (0.998); September: 0.074 (0.708), 0.069 (0.896), 0.159 (1.13) degrees per year. The interannual variability of the mean latitude of the MIZ is roughly 10 to 30 times larger than the annual trends. The fractional changes in MIZ width required for the MIZ extent to remain constant have been calculated as described in Section 3.3 and show similarity to the fractional change in MIZ width as derived from sea ice concentration (Table 3). This is with the exception of the model which overestimates the MIZ width. In July, the required increase in the MIZ width for the approximated extent to remain constant is 10% for Bootstrap (over the period 1979-2017) and 9% for OSI-450 (1979-2015). This is compared to the fractional change in width of the MIZ based on average latitudes of the MIZ grid cells for Bootstrap and OSI-450 of 16% and an insignificant value respectively. In August, both the Bootstrap and OSI-450 datasets require a 20% increase in width to maintain MIZ extent as it moves northwards given our geometrical simplification, and have an average 24% and 25% increase in width from the observed average latitudes of their respective MIZ grid cells.

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). To further illustrate the discrepancy of MIZ location between the observational datasets, we give the example of August 1993 (~~Figure 3~~Figure 5a) and August 2013 (~~Figure~~ Figure 5~~3~~b) ~~illustrate~~ spatial maps of MIZ contours. The spatial variability of the MIZ is poorly constrained by observations (Figure 5). ~~that i~~In 20 years the MIZ has shifted northwards, and the ice pack has become separated by stretches of MIZ. The similar ice extent contours (15% sea ice concentration, given by the solid lines in ~~Figure 3~~Figure 5) illustrate that the similar magnitude of ice extent (Figure 1) are also consistent with ice location. The pack ice contours (dashed lines in ~~Figure 3~~Figure 5) show differences between the datasets, accounting for the variability and differences in the MIZ extent (Figure 1, Table 2). In 1993, the pack ice is not separated by areas of partial ice cover (~~Figure 3~~Figure 5a) as it is in 2013 (~~Figure 3~~Figure 5b). The MIZ ~~is~~ covers more of the central Arctic in the more recent year (2013) than it does in 1993. ~~Our results are~~The lack of trend in MIZ extent is robust given changes in the upper and lower bounds of the sea ice concentration thresholds in the MIZ definition.

5 Discussion

5.1 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.

5.2~~1~~ Trends and correlations between observations and model

The lack of trend in the MIZ extent contrasts with the significant decline in total sea ice extent (Figure 1, Table 1). While September is a common month to examine for projecting future sea ice extent since it is the month of the year where sea ice reaches its annual minimum (Comiso et al., 2008), it is interesting to note that for studies of the MIZ, it is July and August which may be more informative because these months show the greatest differences in trends of MIZ fraction between the observational and model results (Table 1). These seasonal differences in observations of the MIZ fraction and model result will have consequences for any future projections of the MIZ, and one must be wary of monthly extrapolation in particular during the summer months.

The size of the MIZ is poorly defined by observations, and it follows that models of the MIZ can only be constrained within these observational values. There have been recent developments in modelling of the MIZ, such as how waves break up the ice (Meylan and Bennetts, 2018), the simulation of the floe size distribution and changes of sea ice floe size (Roach et al., 2018), and how sea ice floe size information is important for accurately capturing the seasonality of sea ice concentration in climate models (Bateson et al., 2020~~19~~). However, the results in this study highlight the fact that attention must also be given to improving observations of the MIZ location and extent in order to validate such models. It is important to note that while the relative MIZ extent is slightly increasing due to decreasing total sea ice extent, it does not necessarily follow that the MIZ extent itself is also increasing. The lack of trend in the MIZ extent gives an indication about how the sea ice is melting.

Given that the sea ice area is declining, it could be (and is often assumed) that the sea ice concentration is declining everywhere. 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 (where sea ice concentration in the MIZ is given as the ratio of the area of sea ice in the MIZ and the extent of the MIZ). Similarly, there would not be any trend of sea ice area within the MIZ relative to the MIZ extent. Since there is also no observed change in MIZ extent, 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.

5.3~~2~~ MIZ trending northward

Since the MIZ extent remains constant, it then follows that the central pack ice extent is decreasing because the total ice extent is decreasing (Figure 1). More specifically, the inner pack ice area is outpacing the decline of total ice area, causing a widening trend (Strong et al., 2017). Because the width of the MIZ is increasing in summer (Strong and Rigor, 2013) while the total extent remains constant then the perimeter around the MIZ must be decreasing, forcing a northward movement (Figures 3, 4). This is consistent with the positive trend in the area-weighted latitude of the MIZ found for the same months with the same MIZ definition in Strong and Rigor (2013). This northward migration of the MIZ has broad implications for changes in the coupled bio-geo-physical climate system.

A declining sea ice cover in summer is a main contributor to the amplification of increasing temperatures in the Arctic (Screen and Simmonds, 2010). The MIZ is also a potential area for Arctic cyclogenesis, which allows for significant heat release from the ocean to the atmosphere (Inoue and Hori, 2011), thus contributing to the temperature amplification. With a northward shifting storm track (Sepp and Jaagus, 2011), a northward shift of meridional heat transport is also expected. In addition, changes in MIZ location will have regional implications for total momentum transfer from the atmosphere to the ocean through the ice, because maximum momentum transfer occurs at moderate ice concentrations (~70-90%), full ice cover, and low ice concentrations (~10-30%) (Cole et al., 2017; Tsamados et al., 2014) and is also impacted with varying surface roughness (Martin et al., 2016).

From a biological perspective, it has already been established that sea ice receding further from the coastline, followed by the MIZ (Figure 3), is a problem for marine mammals who use the sea ice as a platform for resting, hunting and breeding (Hamilton et al., 2015; Kovacs et al., 2011). When there is no ice to rest on, there have been increasing accounts of animals changing their behaviour to use land as a refuge. For example, walrus have been increasingly observed in mass haul-outs (Jay et al., 2012) resulting in premature death due to overcrowding. Other important impacts of the northward-trending MIZ on sea ice-associated biota have been explored. For instance, the northward movement of the MIZ has an impact on primary productivity of sea ice algae due to changes in light availability (Tedesco et al., 2019). Ice algae grow on the underside of (and within) the sea ice and are an early important food source for zooplankton and ice fauna (Hegseth, 1998; Horner et al., 1992; Søreide et al., 2013). However, one aspect that could be further explored is the impact of an unchanging MIZ extent in combination with the northward movement of the MIZ. The extent provides a metric about the range of the habitat for MIZ-dependent animals. For example, 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 ice for animals such as seals, polar bears, and seabirds (Hamilton et al., 2017).

5.4 Increase in width compensates for decrease in perimeter

Given our simplifications for MIZ geometry, the fractions of the required changes in MIZ width in order for the MIZ extent to remain unchanged (first row of Table 3) are relatively consistent with the calculated fraction change of MIZ width from sea ice concentration data (second row of Table 3), with the exception of the model. The model is showing a greater increase in MIZ width than the observations, with the greatest overestimation of MIZ width occurring in July. This monthly variation in how much the model overestimates MIZ width could lead to other overestimations that would then also vary by month, such as an overestimated atmosphere-ocean heat transfer in July. The similarities of the observed fraction change in MIZ width and necessary fraction change for a constant MIZ extent from the observational datasets (Table 3) provide support that the MIZ is widening enough to maintain its extent as it travels northwards and its perimeter decreases.

5.5~~3~~ Sources of error

Observational uncertainty is one factor among others which must be considered when assessing the accuracy of any model (Notz, 2015), including the CICE-CPOM-2019 model used here. An error of 10% applied to the observational products in this study is consistent with other studies, as noted in Section 3.2. The error of 10% has been chosen because it is consistent with the systematic differences between the ASI algorithm used to generate the AMSR data and other observational products (NASA Team 2 and Bootstrap) are approximately 10% (Spreen et al., 2008). 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). Comiso and Steffen, (2001) found an error range between visible/infrared-derived ice concentrations (e.g. AVHRR) of 5-20%. The error between AVHRR products and other SSM/I products ranging from 0.7 and 10.5% (with 5.3% error between AVHRR and Bootstrap) (Meier, 2005). A source of error for SSM/I concentrations is the use of hemispheric tie-points, which are unchanging and may not agree on conditions at a specific time and place (Meier, 2005). As well, since SSM/I concentrations are calculated based on daily composites of brightness temperatures and then averaged onto a 25-km resolution grid, it will result in errors stemming from spatial and temporal averaging (Meier, 2005). Our study reveals that the systematic error in deriving the MIZ from these satellite products must be larger than 10% as documented by differences in monthly mean MIZ values of up to 300% (Figure 1).

6 Conclusions

We have analyzed the evolution of the absolute and relative marginal ice zone from 1979 through 2017 based on four satellite retrievals (OSI-450, Bootstrap, AMSR-E, and AMSR-2) and simulations with a stand-alone sea ice model CICE-CPOM-2019 including a floe size distribution model. While all products agree within their uncertainties during winter, ~~big~~ large discrepancies occur during summer between the satellite products. We have found no significant trend in the MIZ extent across any of the observational datasets examined here (OSI-450, Bootstrap, and AMSR), with the exception of a small negative trend in March for Bootstrap. Due to the decrease in Arctic sea ice extent, there is a ~~small~~ significant increase (> 50%) in ~~positive trend for~~ the relative MIZ extent (MIZ extent divided by sea ice extent) ~~at +0.2-0.3%/y in July, 0.3-0.8%/y in August, and 0.3-0.4%/y in September.~~ during August and September for the Bootstrap and OSI-450 observational datasets. During July and August, the positive trend is 2 to 4 times stronger in our model simulation than these observations. We found no observed trend in the sea ice area within the MIZ (except for a slight negative trend in March for the Bootstrap dataset), but the observed spread of sea ice area within the MIZ is too great such that the significant trend of the modelled sea ice area in the MIZ still lies within the spread of observations. Due to the also large spread inof the observations in MIZ extent, we should be cautious about what conclusions we make about whether or not there is a true trend in the MIZ extent, and how well we can validate our MIZ models. Given this uncertainty, the fact that climate model projections show the Arctic becoming seasonally ice free by the mid-century (Notz and Stroeve, 2018) does not mean we will have an increased area of the ocean covered by marginal ice as defined by the 15-80% ice cover threshold definition. Only at the point when there is a completely seasonal ice cover in conjunction with no pack ice, would our results suggest that further ice loss will result in decreases in MIZ extent.

Author contribution: RR performed the model simulations and wrote the code for analysis. RR wrote the manuscript with contributions from DF and DS.

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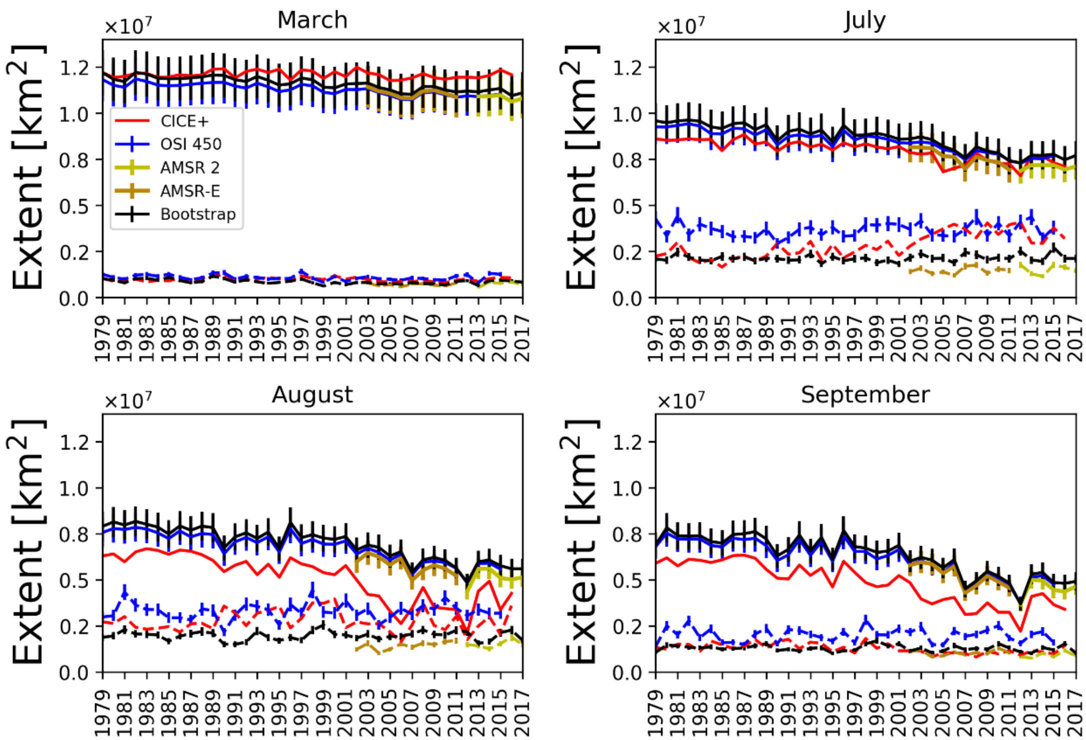

Figure 1: Arctic sea ice extent (solid lines) and marginal ice zone extent (dashed lines) from our CICE simulation CICE-CPOM-2019 and four remote sensing products for (a) March (b) July (c) August (d) September. Marginal ice zone extent is defined a~~t~~s the area where sea ice concentration is between 15-80%. Sea ice extent is the area of ice coverage above 15%. An error bar of 10% has been applied to the observational output.

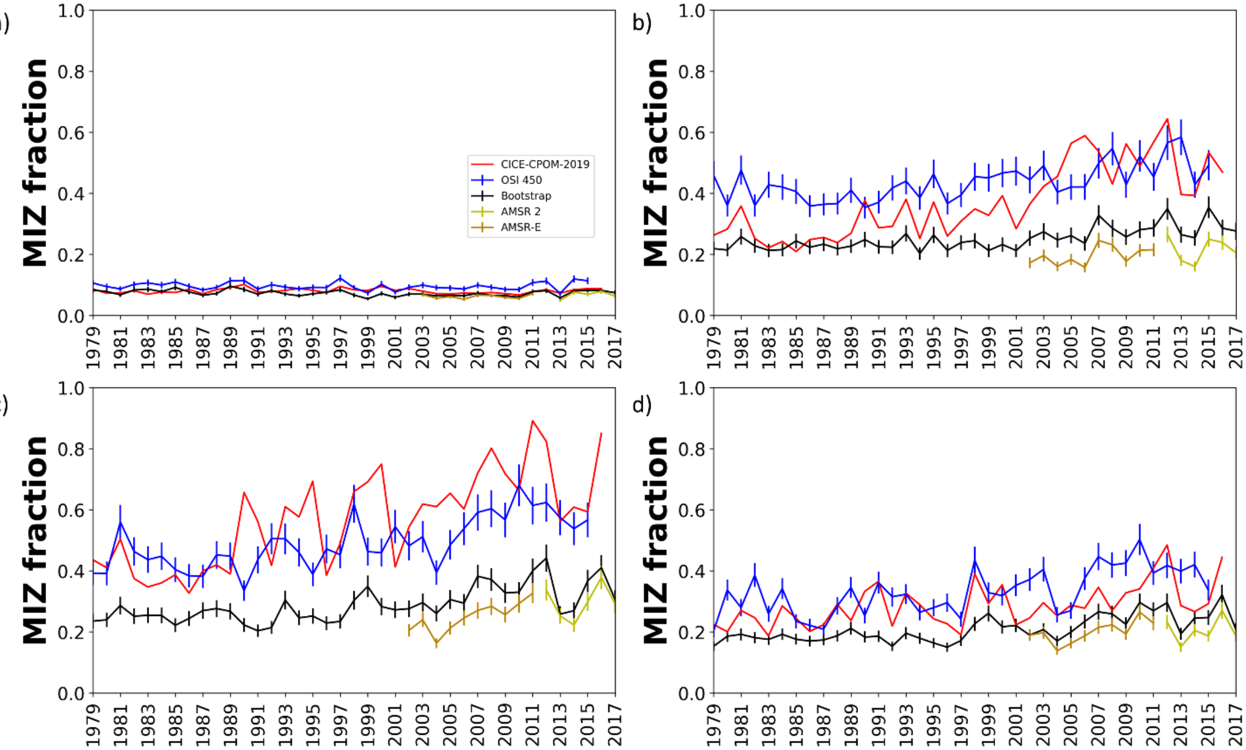

Figure 2: As Figure 1, but MIZ fraction for (a) March (b) July (c) August (d) September. Marginal ice zone extent is defined at the area where sea ice concentration is between 15-80%. Sea ice extent is the area of ice coverage above 15%. An error bar of 10% has been applied to the observational output.

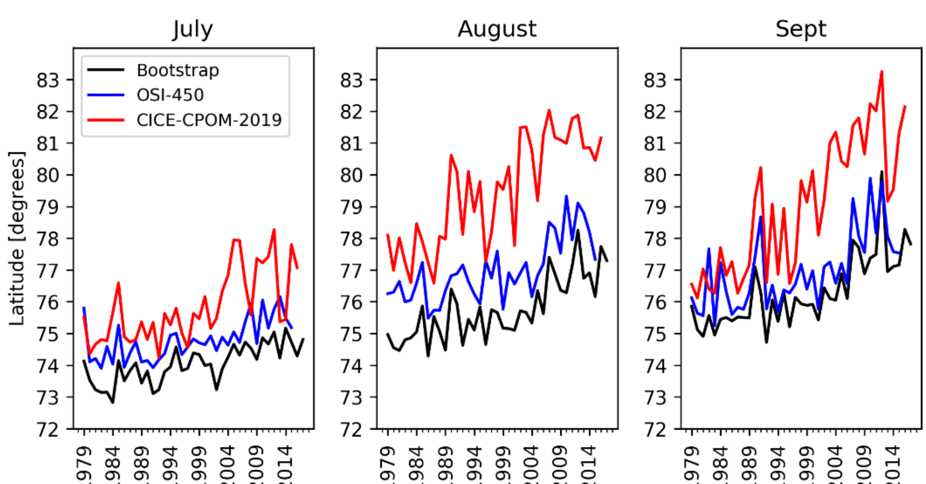

Figure 3: Timeseries of monthly-averaged latitudes of MIZ for Bootstrap (black), OSI-450 (blue) and model CICE-CPOM-2019 (red).

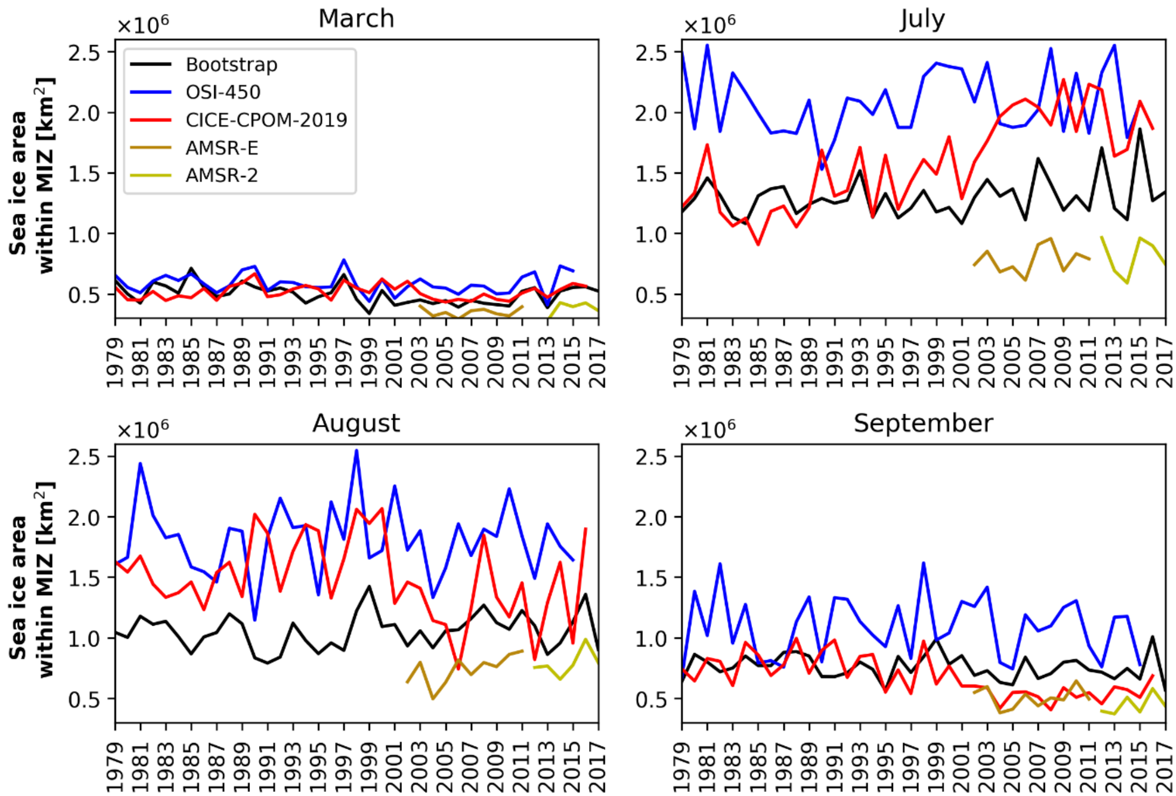

Figure 4: Timeseries of sea ice area within the MIZ, monthly-averages from daily data.

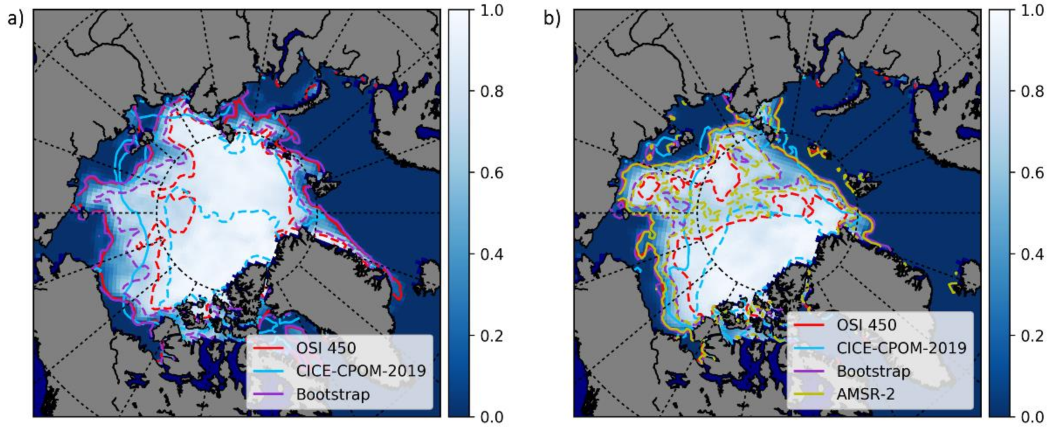

Figure 53: The location of the MIZ for August 1993 (a) and August 2013 (b). The MIZ seems to beis trending northwards in recent years (See also Figure 3 for timeseries of latitudes). Dashed and solid lines represent the 80% and 15% sea ice concentration levels, respectively. AMSR data is not available prior to 2002. Underlying sea ice concentration is from the OSI-450 satellite product.

$\alpha = 0.05$

Trend in 10^{10} m^2 per year (r^2)		MIZ extent	Relative MIZ (MIZ extent/total ice extent) [1/year]	Total change Relative MIZ (%)
March	**Total ice extent**			
OSI 450	-2.42 (0.74)	Insig.	Insig.	Insig.*
Bootstrap	-2.76 (0.78)	-0.520	Insig.	Insig.*
AMSR	-3.04 (0.43)*	Insig.*	Insig.*	Insig.*
CICE-CPOM-2019	Insig.	Insig.	Insig.	Insig.*
July				
OSI 450	-5.27 (0.84)	Insig.	+0.003 (0.375)	27%
Bootstrap	-5.85 (0.87)	Insig.	+0.002 (0.450)	38%
AMSR	-7.55 (0.67)*	Insig.*	Insig.*	Insig.*
CICE-CPOM-2019	-4.29 (0.70)	Insig.	+0.009 (0.636)	124%
August				
OSI 450	-6.52 (0.78)	Insig.	+0.005 (0.479)	50%
Bootstrap	-7.19 (0.81)	Insig.	+0.003 (0.444)	56%
AMSR	-7.96 (0.47)*	Insig.*	+0.008 (0.672)*	60%
CICE-CPOM-2019	-9.61 (0.71)	Insig.	+0.010 (0.557)	91%
September				
OSI 450	-7.80 (0.75)	Insig.	+0.004 (0.392)	79%
Bootstrap	-8.07 (0.75)	Insig.	+0.003 (0.479)	66%
AMSR	-9.72 (0.50)*	Insig.*	Insig.*	Insig.*
CICE-CPOM-2019	-9.02 (0.79)	-1.37 (0.31)	+0.003 (0.293)	57%

Table 1: Trends with r^2 values in brackets for total sea ice extent, MIZ extent, and extent of the MIZ relative to the total sea ice extent (also as a total % change) for the model run and all observational datasets examined. Note that the periods between above datasets are not the same: OSI-450 (1979-2015), CICE-CPOM-2019 (1979-2017), Bootstrap (1979-2017), and AMSR (June 2002 – 4 Oct 2011 AMSR-E, July 2012 – 2017 AMSR2). The AMSR trends are denoted with * to clearly indicate the shortened time coverage

of those observations in comparison with the rest. ~~**The r^2 values are calculated using a linear least squares regression and alpha represents a 95% confidence level.**~~

α = 0.05

Correlations	Total ice extent			MIZ extent			Relative MIZ extent		
March	**OSI 450**	**CICE19**	**Bootstrap**	**OSI 450**	**CICE19**	**Bootstrap**	**OSI 450**	**CICE19**	**Bootstrap**
CICE-CPOM-2019	0.448			0.548			0.502		
Bootstrap	0.998	0.440		0.894	0.415		0.876	0.392	
AMSR*	0.957	Insig.	0.962	0.922	0.759	0.889	0.932	0.792	0.902
July	**OSI 450**	**CICE19**	**Bootstrap**	**OSI 450**	**CICE19**	**Bootstrap**	**OSI 450**	**CICE19**	**Bootstrap**
CICE-CPOM-2019	0.896			Insig.			0.547		
Bootstrap	0.996	0.913		0.362	0.414		0.655	0.778	
AMSR*	0.989	0.575	0.990	0.595	Insig.	0.869	0.645	Insig.	0.922
August	**OSI 450**	**CICE19**	**Bootstrap**	**OSI 450**	**CICE19**	**Bootstrap**	**OSI 450**	**CICE19**	**Bootstrap**
CICE-CPOM-2019	0.902			Insig.			0.539		
Bootstrap	0.998	0.900		0.472	Insig.		0.719	0.749	
AMSR*	0.991	Insig.	0.987	0.826	Insig.	0.637	0.886	0.755	0.843
September	**OSI 450**	**CICE19**	**Bootstrap**	**OSI 450**	**CICE19**	**Bootstrap**	**OSI 450**	**CICE19**	**Bootstrap**
CICE-CPOM-2019	0.957			Insig.			0.552		
Bootstrap	0.998	0.955		0.577	Insig.		0.755	0.719	
AMSR*	0.990	0.778	0.989	0.805	Insig.	0.852	0.780	0.675	0.927

Table 2: Correlations of the inter-annual variability for the total sea ice extent, MIZ extent, and extent of the MIZ relative to the total sea ice extent for the model run and all observational datasets examined. The AMSR trends are denoted with * to clearly indicate the shortened time coverage of those observations in comparison with the rest.

	July			**August**			**September**		
	Bootstrap	**OSI-450**	**CICE-CPOM-2019**						
Required fraction change of MIZ width for MIZ area to remain constant	1.10	1.09	1.20	1.20	1.20	1.56	1.23	1.21	1.75
Calculated fraction change from MIZ width trends	1.16	Insig.	2.42	1.24	1.25	1.49	1.17	Insig.	Insig.

Table 3: Fraction changes of MIZ width needed for the MIZ area to remain constant compared with the calculated trends in MIZ width assuming an averaged perimeter