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

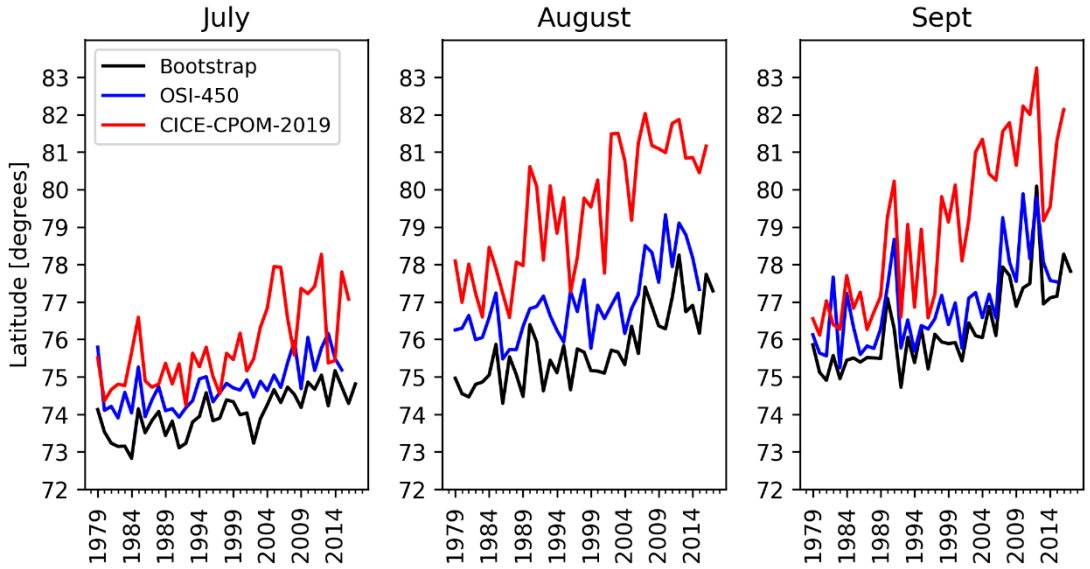

Figure 2. Timeseries of MIZ width

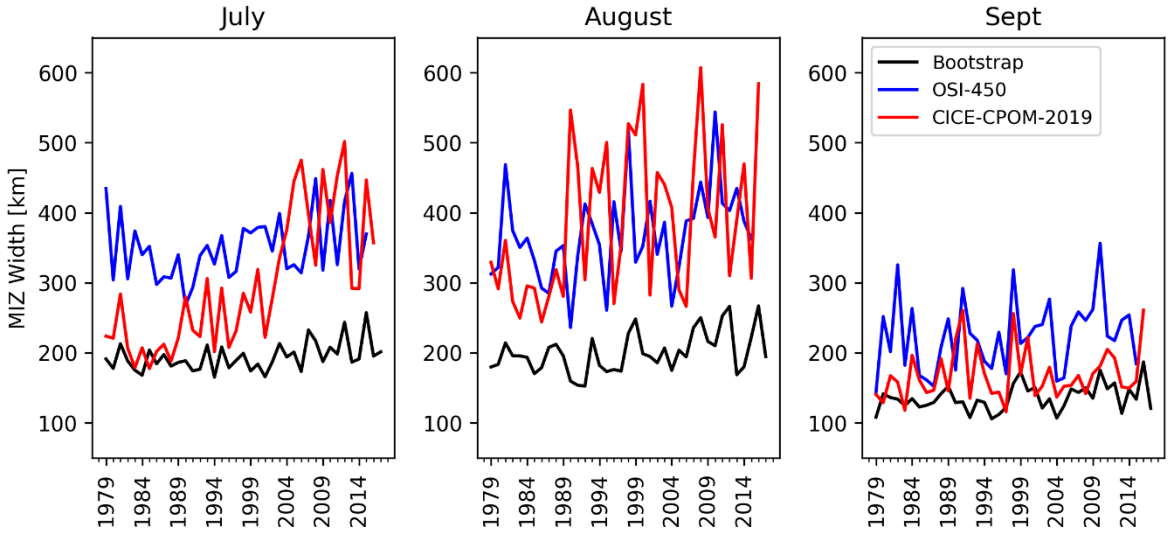

Table 1. Trends of MIZ latitude and width change based on monthly means of sea ice concentration for July, August, and September. Only significant trends at a 95% confidence level are shown. RMS values of the detrended timeseries are given in parenthesis. Timeseries of latitudes and widths from where 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		
ΔMIZ latitude [deg/year]	Bootstrap	OSI-450	CICE-CPOM-2019	0.068	0.065	0.122	0.074	0.069	0.159
	0.039	0.036	0.069						
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.