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Interactive comment on "Modeling the annual cycle of daily Antarctic sea ice extent" *by* Mark S. Handcock and Marilyn N. Raphael

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Summary:
This paper analyzes the seasonal cycle and interannual variability of Antarctic sea ice extent (SIE) using various statistically approaches. Different annual cycles are defined based on amplitude and phase. Variation in phase is found to explain more of the SIE variability, but combining both amplitude and phase explains substantially more variation than traditional methods. The approach shows that the low SIE extremes in 2016 were due mainly to a shift in phase.

General Comment:
This paper makes an interesting contribution to Antarctic SIE analyses. Two lingering questions with Antarctic SIE is the small positive trend that has been seen over the long-term satellite timeseries and the whiplash in recent years going from record highs to record lows within just a couple years. The analysis presented in this paper is unique for SIE and the paper brings to light many relevant characteristics of the SIE timeseries that provide insights into both short-term and long-term variability. For example, the idea that phase plays a more important role in the seasonal cycle than amplitude is revealing and seemingly important in better understanding the character and variability of Antarctic SIE. I have a few minor comments on various aspects. I recommend acceptance after minor revision to address these.

Specific Comments (by line number):
1: "troughing", while technically correct, reads awkwardly to me. Why not just say "reaches its minimum"? This occurs in a few other places in the text.

Author's response:
We will modify the text to say "reaches its minimum"

Author's changes in manuscript:

23: "peaking in September. . .and troughing in late February. . .on average." Though you say on average, which is accurate, that masks a lot of variability. The minimum does sometimes occur in October and ranges from early Sept (even late Aug one year) through early Oct. The maximum can occur in March and ranges over 3 weeks. It might be worth providing a range along with the average to give a better sense of the variability, which as is shown later in the paper is important

Author's response:
To keep it simple in the Introduction we supply the median Julian days.

Author's changes in manuscript:
We added: "In Julian days, the median minimum day is 50 and the median maximum is 255."

29: Some of the day-to-day variation is also due to land-spillover (coastal effect of mixed land/water grid cells). It's not as variable as weather or changes in the ice cover, but I think it is important enough to warrant mention. (This is less of an issue in Antarctica because of the land ice along the coast, but still worth noting I think.)

Author's response:

We will include mention of this contribution to the variation.

Author's changes in manuscript: We will add:

"land-spillover (coastal effect of mixed land/water grid cells),"

61-63: The data reference is a little confusing. You say use the SMMR-SSMI-SSMIS Bootstrap Version 3 product, but reference Comiso (2017), which is the correct ref-erence. But you also reference Peng et al. (2013), and Meier et al. (2017), which refers to the NSIDC/NOAA Climate Data Record product. I understand the confusion here because the NSIDC/NOAA CDR does include the Bootstrap V3 concentrations

within the product. My assumption is that you used the Bootstrap V3 field within the NOAA/NSIDC CDR. So, I think all three references are warranted, but this could be more clearly explained, e.g., "We used the Bootstrap Version 3 concentration fields (Comiso, 2017) from the "NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 3" (Peng et al., 2013; Meier et al., 2017)." Or some- thing like that.

Author's changes in manuscript:

We will change the text to:

"We used the Bootstrap Version 3 concentration fields (Comiso, 2017) from the "NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 3" (Peng et al., 2013; Meier et al., 2017)."

66: You note that there are a number of days with no observations (in addition to the every-other-day SMMR). But one of those gaps is quite significant, with no data between early December 1987 and mid-January 1988. This is worth noting because it is unique in the record in terms of the length of the gap. Did you fill this in at all or leave the gap? Since the method doesn't require complete data, I assume not, but that should be made clear.

Author's response:

We will include mention of this contribution to the variation.

Author's changes in manuscript:

We will add: "In particular, there are no data between early December 1987 and mid-January 1988."

and later:

"As such we do not impute the missing days."

69: Day 0 is the minimum day of the year and then you just plot the next 364 days after that for each year. But of course, the date of the minimum differs from year to year. So, it seems like some years could have a gap – if the minimum of one year occurs before the minimum of the next year (i.e., >365 days between minimums) – where some data is not plotted, or conversely, you could have some data duplicated – if the minimum of one year occurs later than the minimum of the

next year (i.e., <365 days between minimums). Is this correct? Are these "missed" or "duplicated" accounted for in any way? Or does that potentially skew results at all?

Author's response:

In Fig. 1 the record for each year starts on Julian day 50 (the median minimum day). This is to address the length-of-cycle issue you raise (i.e., there are no missing or duplicated days in the plot). This choice is for ease of interpretation of Fig. 1. We will clarify in the text.

This also relates to a comment by Reviewer #2.

Author's changes in manuscript:

We will change the middle two sentences of this paragraph from "In this figure, day 0 on the horizontal axis represents the lowest SIE for the year, typically occurring around Julian day 50. We employ this convention for all of the time-series figures used in this paper."

to

"In this figure, day 0 on the horizontal axis represents the typical lowest SIE for the year, Julian day 50."

Figure 3: A few suggestions. First, the Day-to-day change is in Figure 4 (as noted in the Figure 3 caption). It seems like it is discussed in the context of Figure 4. So, is it necessary to include that line in Figure 3? Simpler is always better in my view, so one less line is helpful. And that would allow the y-axis to cover a smaller interval, which would more clearly show the variability lines. One thing that would be useful would be to label the max and min days (e.g., text with an arrow pointing to each). The day-to- day change does provide this, but it may not be immediately clear that the max occurs when the change turns from positive to negative. So, I think labeling would be helpful even if the day-to-day line is kept (but if labeling is included, then that line isn't really needed). The fonts on these figures are quite small – in the final version, they should be much better. Also, while the units are noted in the caption, it my view it is always better to include them with the axis labels. Similarly, for Figure 4.

Author's response:

We have chosen to retain the day-to-day line as it provides a detailed comparison with the variability. We have improved the figure in the other ways suggested.

Author's changes in manuscript:

We will add the arrows, increase the fonts size and add the units to the vertical axis.

Figure 4: There is an interesting feature in the traditional (orange) plot right around day 200, where the curve is less dense. All the other places have thin lines, highly varying day to day. But around day 200, there seems to be a period where the line just peaks and then declines over several days. Is that related to anything? Or is that just a quirk in the data, or just an optical illusion?

Author's response:

The region where the curve is less dense has two reasons. One is due to a quirk in the data. However, part of it is real and related to the relative stability of the ice extent in the region of the SIE maximum.

Author's changes in manuscript:

We will add a note in the text.

206-214: Why is the volatility higher for SMMR than for DMSP? Is it simply the every- other-day sampling? But there could also be an effect due to the sensor resolution (sensor footprint), which is actually smaller (higher resolution) in SMMR. I'm curious if the volatility of DMSP would match SMMR if every-other-day values were used from DMSP? Another, smaller aspect, is whether volatility changes from SSMI to SSMIS? If it's simply the temporal sampling, then I would expect there wouldn't be a change. But if there is a resolution component, then there might be a small effect since the sensor footprints are slightly different. While I think looking at that could be interesting, I guess it's not the main focus of the paper, so I can see not doing that. However, I think it is worth at least noting that the differences in volatility are due to temporal sampling (and maybe some resolution effect?), just to make that clear.

Author's response:

The model for the volatility is adjusted for the every-other-day sampling. We do not know the reason for the minor differences, but now add your speculation that they are due to the sensor resolution.

Author's changes in manuscript:

We will add a note in the text speculating on the sensor resolution change.

244: There is also more volatility at/near the maximum because there is more ice edge to vary. At the maximum, the perimeter of the ice cover is also at or near its maximum, which allows more areas to be affected by winds, currents, storms, etc.

Authors' response:
Thank you for this suggestion. We will include it in our discussion on page 244.

Authors' changes in manuscript:
We include in point 3, the suggestion that part of the increase in volatility at maximum may be due to the fact that the ice edge is larger.

Figure 5: What are the anomalies relative to – i.e., what is the base period? Likewise, for earlier figures, the y-axis should be labels with units.

Author's response:

The anomalies are relative to the annual cycles (in the legend) as defined in equation (14).

Author's changes in manuscript:

We will add a label to the vertical axis.

281-291: I understand the rationale for using the daily values over monthly values, but the advantage of monthly values is that you capture roughly the same period in the cycle – so you can look at trends near the maximum or near the minimum, which can be quite different than over a full year. But I also wonder is something is lost? – you're taking something with a big annual cycle and then just fitting trend lines through the entire 40 years. Would it make sense to do a Figure 6 for the max and min? Perhaps using the amplitude and phase

adjusted? Also, how does the curvilinear trend handle the endpoints – i.e., how does it calculate a trend from the beginning? In other words, how does the function (Eq. 15) calculate a smooth trend at the beginning of the time series? I assume that there is an endpoint fitting/smoothing, which may be in the equation. But some plain English explanation would be helpful as well.

Author's response:

It would make sense to do a Fig. 6 for the max and min. Indeed, it is natural to fit a non-parametric *quantile* regression curve for each quantile of the annual SIE distribution. The max and min curves are the extremes of this distribution. However, the analysis of these sets of curves would add substantial length and we will leave it for a subsequent paper.

A strength of Eq. 15 is that it directly incorporates the beginning and end of the time series into the smoothness equation.

Author's changes in manuscript:

We will add a note that in Eq. 15 "The last term also captures the beginning and end times smoothing."

Figure 6: What are the thin pink dashed lines? Are these just the beginning and end dates of the two periods? And the dashed line around the curvilinear trend?

Author's response:

The thin pink dashed lines demarcated the data segments (as Version 3 is cumulative). They were there for debugging purposes and will be removed.

The dashed lines are the 95% pointwise confidence bands for the smooth curvilinear trend equation.

Author's changes in manuscript:

We will remove the thin pink dashed lines and add a note on the confidence band.

288: The trend standard deviation (+/-) values should be included with the linear trend and maybe the trend significance.

Author's response:

We did not include the +/- value for the linear trend as they are not valid. They require the trend to be linear and the data indicate that it is curvilinear. Similarly, the trend is nominally significant.

Author's changes in manuscript:

We will add the text: “Were the trends linear they would be statistically significantly positive.”

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