Anonymous Referee #1

general comments:

This is an interesting study addressing the evolution of the interannual variability of Arctic sea ice area and its causes. The study is based on analyzing historical and RCP8.5 simulations of CESM-LE and, in part, 12 CMIP5 models. The study primarily finds an inverse relationship between the rate of sea ice retreat and the magnitude of variability. The authors further show that a sufficiently thin ice cover fosters the variability and that thermodynamical processes dominate over dynamical processes in causing this variability. Although I find the study relevant, well written and structured, I have some major concerns about the novelty of the findings, some methodological aspects and the robustness of their conclusions. I recommend publication in TC only if these major concerns will be addressed.

Thank you for the thoughtful evaluation. In this revised version, we have addressed all three of the reviewer's concerns regarding novelty, methodology, and robustness.

specific comments:

Title: The paper does not only address the future interannual variability but also the past.

Good point. The title has been changed to "Past and future interannual variability of Arctic sea ice in coupled climate models".

#1 ll. 47-48 The "important physical and societal consequences" could be given more specific.

Although there isn't room in the abstract to explain the physical and societal consequences of short-term variations in sea ice as the pack diminishes, some of these impacts are covered in the Introduction. These include enhanced marine navigation through the Arctic, amplified positive ice-albedo feedback, and increased sea ice sensitivity to ocean heat transport initiated upon short-term declines in ice cover. The components of the surrounding ecosystem will also adjust as the physical environment changes.

#2 ll. 60-62 It is not clear from the abstract what "thermodynamic processes" exactly mean. I would like to have this more specific (e.g., open water formation efficiency), especially because you specifically name the dynamic processes, which you find to be less important, but not the important thermodynamic ones.

We have added more specificity by clarifying that the thermodynamic processes involve melting (top, bottom, lateral) and growth (frazil, congelation). There is no more space to get into additional details within the short abstract.

#3 l. 106 Where does the judging statement "likely“ comes from? Is this justified in the given references according to IPCC language. As you mention, the likelihood of summer ice-free conditions strongly depends on the emission scenario. For RCP8.5, it might be rather certain, for RCP2.6 it is not. "Likely“ is vague here.

To avoid bogging down in the spread and plausibility of the various RCP scenarios, we have changed the sentence to read that that the Arctic “may” become seasonally ice-free within a few decades.

#4 l. 117 To me, there is no logical link between the reduction in sea-ice extent and the loss of multi-year ice. The reduction in sea-ice extent is not obviously the cause for the loss of multi-year ice. Please rephrase.

Although the reduction of sea-ice extent does not directly cause a loss of multi-year ice, past studies do show that a large portion of the reduction of sea-ice extent in the past decade is associated with the loss of multi-year ice (Kwok et al., 2010). That reference is now added. We have rephrased the sentence, “As the Arctic sea ice pack thins and retreats, multi-year ice is being lost and there is consequently a larger proportion of seasonal, first year ice.”

#5 ll. 122-123 How does decreased ice thickness amplifies the ice-albedo feedback? Please explain.

As demonstrated by observations (e. g., Grenfell and Maykut 1977) and applied in various parameterizations and models (e. g., Maykut 1982, Ebert and Curry 1993), the albedo of thin, first year sea ice is lower than that of thick, multiyear ice. The CICE sea ice model used in CESM-LE also lowers the surface albedo for thin ice floes (Hunke and Lipscomb 2010).

Grenfell, T. C., and G. A. Maykut, 1977: The optical properties of ice and snow in the Arctic Basin. J. Glaciol., 18, 445-463.

Maykut, G. A., 1982: Large-scale heat exchange and ice production in the central Arctic. J. Geophys. Res., 87, 7971-7984.

Ebert, E. E., and J. A. Curry, 1993: An intermediate one-dimensional thermodynamic sea ice model for investigating ice-atmosphere interactions. J. Geophys. Res., 98, 10085-10109.

Hunke, E. C., and W. H. Lipscomb, 2010: CICE: the Los Alamos sea ice model documentation and software user’s manual, version 4.1. LA-CC-06-012.

#6 ll. 141-142 I appreciate that you specifically mention the novel aspects of your study. However, I find these aspects only partly novel. The first aspect is not truly novel. Olonscheck and Notz, 2017 (Consistently Estimating Internal Climate Variability from Climate Model Simulations. Journal of Climate) distinguish changes in the variability of winter and summer Arctic sea ice area. The second aspect is also touched by Olonscheck and Notz, 2017 but your study goes beyond this by investigating the underlying processes for the model-simulated changes in CESM-LE. However, the very recent study by Massonnet et al., 2018 (Arctic sea-ice change tied to its mean state through thermodynamic processes. Nature Climate Change) covers parts of your findings. I recommend to more clearly work out the novel aspect of your study, to distinguish your results from the mentioned studies, and to discuss your results in the context of their findings.

Thank you for pointing us to these very recent papers, which are relevant for and complementary to our study. The Massonet et al. (2018) analysis only addressed sea ice volume variability and its projected future change, which is to be a monotonic decrease, unlike the more complicated time-dependent response of ice area variability that is our focus. Our findings help resolve the findings in Olonscheck and Notz (2017), whose analysis is of future changes in sea ice variability is much coarser temporally and seasonally (the 2006-2100 time block for JAS and JFM), and less conclusive: (a) "the future internal variability of summer Arctic sea ice area possibly increases. . . ", and (b) ". . . winter and summer Arctic sea ice area show inconsistent model responses" [in CMIP5]. They also identify a decrease in future sea ice volume variability, like Massonet et al., but that is not directly pertinent to our findings.

We have added these two new studies to the introductory material, where we highlight previous findings on this topic and distinguished our focus from their work. In addition, we now compare and contrast our results with those of Olonscheck and Notz in the final section.

#7 ll. 147-148 I don't believe that the internal variability is robustly characterized from just one model. The internal variability largely differs between the CMIP5 models. How do we know that CESM-LE is representative? I assume you mean that 40 ensemble members allow to robustly quantify the internal variability WITHIN THAT MODEL, but I don't believe that your statement is correct as it is now. Please be more precise here.

We agree that the sentence needed refining, so we have modified it to address the reviewer's point. The sentence now reads, "We analyze a large 40-member ensemble from a single GCM, which allows us to isolate internal variability, which is otherwise muddled with inter-model variability in multi-model comparisons."

#8 ll. 162 A medium ensemble of 15 members for RCP4.5 described in Sanderson et al., 2015 (A new ensemble of GCM simulations to assess avoided impacts in a climate mitigation scenario. Climatic Change) and recent ensembles, e.g., for RCP2.6 described in Sanderson et al., 2017 (Community climate simulations to assess avoided impacts in 1.5 and 2C futures. Earth System Dynamics) also exist.

We have added the two Sanderson et al. papers, as suggested.

#9 ll. 170-172 For two reasons, I am not convinced by the usefulness of this selection criteria. First, because the threshold of 20-percent error seems arbitrary to me. How is this justified? Second and more importantly, there is no reason to believe that models that fit the observations comparatively well are better than others because of the large influence of internal variability. When taking model-specific internal variability into account the sea-ice simulations of most CMIP5 models are plausible. I would like to see whether or not your basic conclusions change when using the full set of CMIP5 models. Also, as a reader I would like to know which CMIP5 models you used without having to look this up in Wang and Overland, 2015.

The model selection criteria was introduced by Wang and Overland 2009 (GRL) and then gradually accepted by the community, not only for sea ice but also for other variables. We want to use trustworthy models, which can capture the corrected physics and dynamics. This is especially important for a sea-ice model, because we are dealing with the absolute value (the sea-ice extent) instead of anomalies (e.g. global mean temperature). The systematic biases in a model can significantly contaminate the ensemble means. Besides, as Massonet et al., (2018) pointed out, models far outside the observed base state should be omitted, because they won't capture the correct physics of thermodynamic processes in the future. Then how do we define "far outside", and which ones should be omitted? The 20% threshold was chosen because it can remove the outliers yet keep a reasonable number of models for a proper ensemble size. We also tested other selection criteria and determined that 20% is a good choice for this purpose. In IPCC AR5, this model selection method was adapted with a variation for the first time in IPCC history (IPCC, 2013, Chapter12). The 20% cut-off was also followed in their modified selection scheme.

Model names have been added into the text.

#10 ll. 176-177 To calculate the statistics for each of the 33 ensemble members and to then average them gives a biased estimate, because models with more ensemble members have a larger weight than models with only few (or even one) members. Again, I would like to see whether your basic conclusions would change when you always use e.g. three ensemble members from a model. As it is, I don't find the approach convincing.

We use no more than 5 ensemble members from each model, even if there are more ensemble members available, to avoid overweighting certain models. In addition, we tried to make the total ensemble number as close as possible to that used in the CESM-LE. This sentence is now added to the text. It is unfortunate that some models only provided one single realization. If we had only kept one member each, then the total ensemble numbers would be too small (12).

#11 ll. 212-217 I find the analysis of the CMIP5 models rather weak. To me, it is no proof that the variability is indeed increasing as shown by e.g., Goosse et al. 2009. This is because I see no logic behind simply averaging the CMIP5 models. As you write, the timing of ice retreat is very different in the different models, so averaging them will smooth out possible signals. For instance, one could normalize the timing of sea ice retreat before doing the analysis. I think that more analysis of the robustness of the results based on the CMIP5 models is needed.

We appreciate this suggestion and recognize that there is no ideal way to assess the collective response of the CMIP5 models. We are not sure how to normalize the timing of sea ice retreat before doing the analysis. The paper acknowledges that multi-model averaging leads to smoothing, but this procedure is standard in analyses of CMIP5 (e.g., the IPCC AR5 report Chapters 9 to 12). The purpose for presenting the CMIP5 models is to supplement our more detailed analysis of CESM-LE by showing that their first-order features are similar and therefore that our major conclusions are not model-specific. That this resemblance emerges despite the timing differences among the models is evidence that our primary conclusions are robust.

#12 ll. 230-232 Related to the previous comment, I would like to know which of the two reasons is more relevant.

The discussion in the original manuscript is a little confusing, when we say “CMIP5 model spread could also be responsible for inflated variance as models diverge in their timing of the downward trend and its rate of decline”. We were trying to explain two different things in one sentence. Here is the revised portion:

“Near the end of the 21st century, the running standard deviation also shows an increase in the CMIP5 ensembles from December to June (Fig. 2), very similar behavior to that displayed by CESM-LE. However the magnitude of the increase in the running standard deviation in the CMIP5 ensemble mean is smaller than that in CESM-LE. This is not surprising, as the timing of ice retreat varies among models, so averaging them will smooth out the possible signals. The CMIP5 models therefore provide additional evidence that increased variability is associated with decreasing sea ice cover. “

#13 ll. 219-220 See again Olonscheck and Notz, 2017.

We have added comparison of our findings to Olonscheck and Notz in a couple of places, but their analysis of the difference in sea ice area variability averaged between entire time blocks (1850-2005 vs. 2006-2100) doesn’t lend itself to a direct comparison with the time series presented in Figures 1 and 2.

#14 ll. 304-322 It is not very clear to me how exactly you calculate the thermodynamic and dynamic component. For instance, do you sum up top, basal and lateral melt for the thermodynamic melt component? I think I can guess what you did, but it is not written down precisely.

The thermodynamic component is a sum of these three terms, as we have clarified in the text.

#15 l. 373 I recommend one or two introductory sentences here to guide the reader. This would also help to improve the structure of the discussion section.

Good suggestion. We have added some introductory sentences that summarize the overall study and segue to the bullet points in the rest of the section describing our major findings.

#16 l. 443 This should be "projected", instead of "predicted".

Text has been changed to "projected."

#17 ll. 448-449 I very much appreciate that your work includes the analysis of CMIP5 models. But I question that the presented analysis is sufficiently well done to justify this statement on robustness. Especially, because the CMIP5 models are only used for section 3.1 and not in the later sections that deal with the mechanisms. The questionable (see comment #11) and generally weak inverse relationship between variability and rate of retreat that you show for the CMIP5 models does NOT necessarily imply (and also does not suggest) that the same mechanisms are at work like the ones you describe for CESM-LE. This statement is too strong. I recommend to either extend your analysis of the mechanisms to the CMIP5 models (if possible) or further weaken or delete this statement.

We have softened this sentence by stating that the physical mechanisms identified in CESM "may apply more generally" [to CMIP5 models]. We agree with the reviewer that our conclusions derived from CESM don't demonstrate robustness across all models, but we think that other simulations should exhibit a similar non-linear (parabolic) ice variability response, based on the geographic dependencies described in Goosse et al. (2009) and Eisenmann (2010).

technical corrections:

l. 331 I prefer "the variability in the thermodynamic term", rather than "the thermodynamic term variability"

The text has been changed as suggested.

Figures: I suggest to make the figures look more consistently, i.e. Figures 3 and 6 like Figures 1, 2 and 4. Also, I find the different axis labeling in Figure 6a and 6c confusing. For Figure 6, a title for each panel would increase the readability and lines at 0 percent and 100 percent in panels a and c, too.

We have made these modification to Figure 6, though it is unclear otherwise how the figures look inconsistent. The former Fig. 3 and S1 were adjusted to have matching sequential color schemes, while Fig. 6 is displaying the data in a different way than the other figures and is presented as best as possible. These three figures are included in this discussion comment.

l. 345 frazil = frazil ice?

Yes, frazil “ice” has been added.

References: Comiso et al ... The year of publication is missing. Zhao et al., 2018 ... This reference appears twice.

These two references have been corrected. Thanks for catching these oversights.

Anonymous Referee #2

This study by Mioduszewski and co-authors is concerned with the future (and to some degree past and present) variability of the Arctic sea ice cover in GCMs. The article focuses on seasonal aspects of the variability in sea ice area, and on potential drivers of such variability. The authors find a strong correlation between ice area variability and ice thickness, and argue that thermodynamic processes have a stronger impact on variability than dynamic processes.

The study is concerned with an important topic that fits well within the scope of The Cryosphere. I agree by-and-large with the comments of the other reviewer, and would hope to see some substantial revisions of the manuscript. Furthermore, several parts of the manuscript are marked by a somewhat disappointing standard of language and presentation, in particular given the experience and seniority of the co-authors. Below I will detail concerns that I have in addition to those voiced by the other reviewer.

<u>General comments</u>:

1. The abstract and introduction should be thoroughly revised (see specific comments below). The writing improves from Section 2 onward.

See our responses below to the reviewer’s specific comments.

2. Please consider the geographic muting effect of Eisenman (2010) in more detail. i.e. what do analogues to Fig S1 and Fig 1 look like when using Eisenman’s "equivalent ice extent"? This would help quantify the role that the distribution of land around the Arctic basin plays in this context.

We have attached this analysis to this discussion comment. The adjustment for geographic constraints does result in some of the expected changes, as there are steeper declines in some of the winter and spring months which result in greater peaks in their variability. However, it shouldn’t change the main results shown in the monthly time series of ice variability in Figure 1. Furthermore, while this alternative metric does produce much larger reductions in future ice cover during winter-spring, it's not clear how this result should affect our existing interpretations. It is a theoretical construct and our purpose is to assess the variability of ice cover that actually exists and that has practical implications for societal impacts such as marine navigation.

We believe it is worth noting how the calculation of equivalent ice extent compares with our analysis since this is a relatively well-known concept in the field and some others will likely have the same question, and have made these modifications to the discussion.

3. I share the concerns of the other reviewer in that the discussion of the CMIP5 analysis is somewhat vague and incomplete. It also should be put more clearly in context with other recent work on the subject.

Please see our responses to Reviewer 1 about their points #9 and 10, copied below:

The model selection criteria was introduced by Wang and Overland 2009 (GRL) and then gradually accepted by the community, not only for sea ice but also for other variables. We want to use trustworthy models, which can capture the corrected physics and dynamics. This is especially important for a sea-ice model, because we are dealing with the absolute value (the sea-ice extent) instead of anomalies (e.g. global mean temperature). The systematic biases in a model can significantly contaminate the ensemble means. Besides, as Massonet et al., (2018) pointed out, models far outside the observed base state should be omitted, because they won't capture the correct physics of thermodynamic processes in the future. Then how do we define "far outside", and which ones should be omitted? The 20% threshold was chosen because it can remove the outliers yet keep a reasonable number of models for a proper ensemble size. We also tested other selection criteria and determined that 20% is a good choice for this purpose. In IPCC AR5, this model selection method was adapted with a variation for the first time in IPCC history (IPCC, 2013, Chapter12). The 20% cut-off was also followed in their modified selection scheme.

We use no more than 5 ensemble members from each model, even if there are more ensemble members available, to avoid overweighting certain models. In addition, we tried to make the total ensemble number as close as possible to that used in the CESM-LE. This sentence is now added to the text. It is unfortunate that some models only provided one single realization. If we had only kept one member each, then the total ensemble numbers would be too small (12).

4. In Sec 3.3 it seems odd to choose Sept and Dec as months to study the roles of ice retreat and expansion, respectively. First, the sea ice minimum occurs typically in mid-Sept, which means that there's substantial ice expansion in the 2nd half of the month (as remarked in L.314). Thus, if the authors want a fully retreating month, why not choose August? December, on the other hand, is fairly early in the ice expansion

phase, so if the aim is to capture as much as possible of the preceding expansion, why not choose February? Or January? To that point, in the conclusions (L.413-414) the authors relate Fig 6c,d to "Nov-Jan" variability (rather than to Oct-Dec, as used in the analysis).

We understand why the reviewer questions our choices of representative months, but we tried to balance various considerations in selecting September and December. Because there has been so much interest in September sea ice coverage as the annual minimum and previous work on interannual variability in that month (e. g., Goosse et al. 2009, Swart et al. 2015), we felt that a focus on September would be of interest to readers. In addition, our choices for selected months had to strike a balance between conditions in the present climate---in which there is some ice expansion during late September---and future conditions, when September becomes ice-free and therefore no longer has any ice expansion.

December is of particular interest because that is a month of ice expansion exhibiting the distinct three-phase evolution of interannual ice variability described in the text: essentially flat, then a pronounced peak, followed by a decline (see Figure 1). By contrast, other ice-expansion months we could have chosen, such as January-March, do not show this three-phase evolution, and March has only a modest increase in interannual variability at the tail end of the simulation (Figure 1). A benefit of choosing September and December in Figure 6 is that the analysis sheds light on the physical mechanisms responsible for the three-phase evolution in months with very different thermodynamic and dynamic processes operating.

We're sorry about the confusion regarding "November-January" in the original lines 413-414. This range of months was in reference to the slightly lower mean thicknesses coinciding with the peak in interannual ice variability in these months, as shown in Figure 4. To clarify this point in the revised text, we have added that the behavior of Nov-Jan is taken to be explained by our findings for December in Figure 6c,d as a representative month.

5. As pointed out by the other reviewer, this work needs to be put carefully in context with the very recent paper by Massonnet et al ("Arctic sea-ice change tied to its mean state through thermodynamic processes", Nature Climate Change, 2018). I appreciate that the latter study was published after this one was submitted.

We thank both reviewers for bringing the Massonnet et al. study to our attention, and we point the our response above to comment #6 of Reviewer 1 for how we put our work into that context. While sharing thematic similarities with our paper, Massonnet et al. focused exclusively on sea ice volume, rather than ice area, which is the focus of our analysis. This distinction is very important, because Massonnet et al. found that the interannual variability of Arctic sea ice volume has already peaked and that it will decline in accordance with the thinning ice pack in the future. By contrast, our study reveals a more complicated behavior in the future interannual variability of sea ice area, such that it exhibits a two-to-three phase evolution in each month: relatively steady during the thick-ice regime of the past, a pronounced increase when the ice packs thins sufficiently, and then a decline if the ice cover diminishes sufficiently in a particular month (July-December).

Specific comments:

I would suggest moving Fig S1 to the main text as Fig 1. I'd also suggest color-coding the different months sequentially in this figure so that the seasonal cycle becomes more visible.

This is a good suggestion. We have incorporated this figure into the text as Fig. 1 and changed the color scheme as suggested, which now matches Fig. 3.

L.49: I would suggest deleting "independent".

We appreciate the suggestion but feel that this term is a useful reminder to readers that the differences among the 40 CESM-LE realizations express purely internal variability within the climate system.

L.52-54: This sentence is somewhat confusing. Some months see an essentially monotonic increase and it's not immediately clear what part of the sentence refers to CESM-LE and what to CMIP5. I suggest rephrasing and/or splitting into 2 sentences.

We realize that this sentence may be ambiguous, so we have reworded into two sentences. The text now states, "Both CESM-LE and CMIP5 models project that ice area variability will indeed grow substantially, but not monotonically in every month. There is also a strong seasonal dependence in the magnitude and timing of future variability increases that is robust among CESM ensemble members."

L.55: "inversely" correlated. This is used at several points in the ms. Unless I'm mistaken, isn't the rate of retreat "directly" correlated with the variability? In other words, the larger the rate of retreat, the larger the variability (?). At L.428 the authors talk about the rate of change. Here I can see the inverse relation: the more negative the rate of change, the larger the variability.

Good point. The reviewer is correct that the variability is directly correlated with the ice retreat rate, so the text has been modified accordingly. We had been thinking in terms of the rate of <u>change</u> in the ice area, which is inversely correlated with the variability.

L.58: "...indicating that [for most of the years (?)] substantial future thinning ..."

We think that a qualifier is unnecessary in this sentence, because we are really just making a general statement that the ice pack needs to thin substantially before a peak in ice variability can be expected.

L.59-60 "... depends on the season, primarily due to whether ..." This could be written more clearly.

That phrasing has been reworded to “. . . depends on the season, especially whether. . . “.

L.98 "... reduces the [mean] thickness of the basin ice back …"

Sentence changed as suggested

L.100 " ... the [estimated] negative trend ..."

Sentence changed as suggested

L.103 "[Output from] many climate models suggest[s] ..."

Sentence changed as suggested

L.113-114 rephrase

The sentence has been rephrased as follows: “Nonetheless, navigation through the Arctic has already increased in frequency as a result of this decline (Melia 2016; Eguíluz et al. 2016), and even more trade routes associated with the increased ice-free season are expected by the end of the 21st century (Aksenov et al. 2015; Stephenson and Smith 2013).”

L.117 I agree with the other reviewer that the implied causality between reduced extent and loss of multi-year ice is misleading.

As noted above, we have rephrased this sentence: “As the Arctic sea ice pack thins and retreats, multi-year ice is being lost and there is consequently a larger proportion of seasonal, first year ice.”

L.118 "Increased thin ice ...". Replace with "Overall thinner ice ..."

Sentence changed as suggested

L.121 "... ice growth and retreat rates ..." I’d argue this should either be "expansion and retreat" or "growth and melt"

The sentence has been changed to, “. . . , at least partially due to enhanced ice growth and melt.”

L.129 "relationship between ice area and its variability". Do the authors mean the "mean ice area" and the "variability in ice area"?

The wording of this topic sentence has been revised for simplicity and to accommodate the broader investigation of sea ice volume variability cited later in the paragraph. This sentence has become, “Changes in the interannual variability of sea ice have been studied only in a limited capacity, likely because they are only beginning to become visible in September in the present day.”

L.130 "... it is only beginning to become visible ..." The relationship is becoming visible? Does this mean that we are starting to observe a correlation between the mean ice area and the variability of ice area? Please clarify.

See the comment above.

L.143 "... monthly differences are [societally/economically?] important ..."

We have altered the text to read “societally important”

L.148 "... characterize internal variability [of CESM]" (see other reviewer’s comment)

This sentence has been modified as suggested: “We analyze a large 40-member ensemble from a single GCM, which allows us to isolate internal variability, which is otherwise muddled with inter-model variability in multi-model comparisons.”

L.198 "... follows [an analogous] three-phase progression ..."

Sentence changed as suggested

L.222 "inverse" see comment at L.55

Sentence changed as described above

Fig.3 I find it hard to decipher the individual curves here. What about splitting the figure into 2 panels, with panel (a) showing spring/summer months and (b) showing fall/winter months. The missing curves in each panel could shown as faint gray in the background for reference. Again, I would use a sequential color map.

We have modified Figure 3 by using a sequential color map to help readers discern the individual monthly curves, while still allowing for a direct comparison of the curves on a single graph.

L.240 "... between ice thickness and [ice area] variability ... " Otherwise it might be read as "ice thickness and ice thickness variability"

Sentence changed as suggested

L.267-272 Would it be worth showing another thickness curve (<0.2 m) in Fig 4 to illustrate the phase dependence (and different area coverage) for different ice thicknesses?

We appreciate this suggestion and have tried overlaying another thickness curve on Figure 4, but this ended up cluttering the figure and distracted from the main point we're making with these graphs.

Fig 5: The left hand side of the bounding boxes was cut off. Also, the resolution of the figure was low (jpg? Better to use png with resolution > 150 dpi). It'd be nice to add the respective decade in the top left corner of each panel.

We have resized Figure 5, so that the left-hand side doesn't get truncated during the online pdf conversion of figures, and we added the decade to each panel.

L.275: Please mention CESM-LE in the caption.

Caption changed as suggested

L.287: "... thin ice and [the variability of] inter-annual ice coverage ... "

Sentence changed as suggested

L.280-282: How much of this difference is simply due to the limited run length of the simulations? In other words, once the ice retreats further in winter and spring after 2100, would one then also see the horse-shoe pattern in those seasons? Conversely, in the summer, are the regions of high variability restricted to the Arctic boundaries during earlier decades in the simulations?

Presumably, the horse-shoe pattern of maximum ice variability would shift to the winter-spring months after 2100 if the model had been run longer, but we can't prove that with the existing simulations. We have confirmed that the regions of highest variability during summer in the earlier decades of the simulation occur along the periphery of the ice pack, where the thinnest ice exists.

L.293 "expanding" rather than growing

Sentence changed as suggested

L.304 Why is a different method used here to calculate the standard deviation?

We have clarified that the method is not actually different, but the decadal average of the running standard deviation is used in Figure 5, which results in a slightly lower amplitude of standard deviation when comparing to the time series.

L.337-340 delete "rather than melt". Split into two sentences?

As suggested, we have deleted that phrase and split into two sentences: "From the 20th century well into the 21st century, ice growth occurs in the October-December period in a similar region of maximum interannual variability as September, except slightly equatorward (Fig. S2b). Ice export plays a relatively larger role in the regions of interest in December than in September (Fig. 6c)."

L.342 "[mid] 21st century"

Sentence has been changed to "early-mid 21st century".

L.345 "frazil [ice]"

Sentence changed as suggested

Fig 6: The (a)-(d) labels are too big and bold, and the rest of the text in the figure is too small.

This figure has been modified to improve readability.

L.376 Isn't the smaller magnitude of spring variability just a result of the time series ending in 2100 (before the ice edge retreats into the Arctic basin in spring)?

Presumably, although we can't prove that. We have modified the sentence by adding "by the time the simulation ends in 2100" to avoid implying that future variability during spring will necessarily be less than in other seasons.

L.415 "... ice area variability [in winter] also coincides ..."

The sentence has been altered nearly as suggested, but we use the phrase "in these months" to refer to the Nov-Jan period cited in the previous sentence (since November isn't a winter month).

Past and future interannual variability of Arctic sea ice in coupled climate models

John R. Mioduszewski[1], Stephen Vavrus[1], Muyin Wang[2, 3], Marika Holland[4], and Laura Landrum[4]

[1]Nelson Institute Center for Climatic Research, University of Wisconsin—Madison, Madison, Wisconsin.

[2]Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle, Washington.

[3]Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, Seattle, Washington.

[4]National Center for Atmospheric Research, Boulder, Colorado.

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Corresponding author: Steve Vavrus, sjvavrus@wisc.edu

Abstract

The diminishing Arctic sea ice pack has been widely studied, but mostly focused on time-mean changes in sea ice rather than on short-term variations that also have important physical and societal consequences. In this study we test the hypothesis that future interannual Arctic sea ice area variability will increase by utilizing 40 independent simulations from the Community Earth System Model's Large Ensemble (CESM-LE) for the 1920-2100 period, and augment this with simulations from 12 models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5). Both CESM-LE and CMIP5 models project that ice area variability will indeed grow substantially, but not monotonically in every month . There is also a strong seasonal dependence in the magnitude and timing of future variability increases that is robust among CESM ensemble members. The variability in every month is directly correlated with the average ice retreat rate before there is an eventual disappearance in both terms as the ice pack becomes seasonal in summer and autumn by late century. The peak in variability correlates best with the total area of ice between 0.2 - 0.6 m monthly thickness, indicating that substantial future thinning of the ice pack is required before variability maximizes. Within this range, the most favorable thickness for high areal variability depends on the season, especially whether ice growth or ice retreat processes dominate. Thermodynamic melting (top, bottom, lateral) and growth (frazil, congelation) processes are more important than dynamical mechanisms, namely ice export and ridging, in controlling ice area variability.

1. Introduction

Arctic sea ice extent has declined by more than 40% since 1979 during summer (e.g. Stroeve et al. 2012; Serreze and Stroeve 2015; Comiso et al. 2017), primarily as a consequence of greenhouse gas forcing (Notz and Marotzke 2012) but also internal variability (Ding et al. 2017). While this trend is greatest in summer, substantial losses are observed throughout the year (Cavalieri and Parkinson 2012) resulting in an ice season duration that is up to 3 months shorter in some regions (Stammerjohn et al. 2012). Reduced ice area is accompanied by a greater fraction of younger ice (Nghiem et al. 2006; Maslanik et al. 2007a, 2011), which reduces the mean thickness of the basin ice pack (Kwok and Rothrock 2009; Kwok et al. 2009; Lang et al. 2017). As a result, the estimated negative trend in sea ice volume (-27.9% per decade) is about twice as large as the trend in sea ice area (-14.2% per decade; Overland and Wang 2013).

Outputs from many climate models suggest that the Arctic sea ice cover will not retreat in a steady manner, but will likely fluctuate more as it diminishes, punctuated by occasional Rapid Ice Loss Events (RILEs; Holland et al. 2006; Döscher and Koenigk 2013). The overall decline in ice cover is expected to continue (Collins et al. 2013), and the Arctic may become seasonally ice-free within a few decades, depending on emissions pathway (Stroeve et al. 2007; Wang and Overland 2009; 2012; Massonet et al. 2012; Wang and Overland 2012; Overland and Wang 2013; Jahn et al. 2016; Notz and Stroeve 2016). However, internal variability confounds prediction of this timing (Stocker et al. 2013; Swart et al. 2015; Jahn et al. 2016; Labe et al. 2018), and even the definition of ice-free differs among Arctic stakeholders (Ridley et al. 2016). Nonetheless, navigation through the Arctic has already increased in frequency as a result of this decline (Melia 2016; Eguíluz et al. 2016), and even more trade routes associated with the increased ice-free season are expected by the end of the 21st century (Aksenov et al. 2015; Stephenson and Smith 2013).

As the Arctic sea ice pack thins and retreats, multi-year ice is being lost and there is consequently a larger proportion of seasonal, thin first-year ice (Kwok et al., 2010, Maykut 1978; Holland et al. 2006). Overall thinner ice may result in an ice pack that exhibits greater inter-annual variability (Maslanik et al. 2007b; Goosse et al. 2009; Notz 2009; Kay et al. 2011; Holland and Stroeve 2011; Döscher and Koenigk 2013), at least partially due to enhanced ice growth and melt (Maykut 1978; Holland et al. 2006; Bathiany et al. 2016a). Decreased ice thickness promotes amplification of a positive ice-albedo feedback, which can magnify sea ice anomalies (Perovich et al. 2007), and thin ice is more vulnerable to anomalous atmospheric forcing and oceanic transport due to the smaller amount of energy required to completely melt the ice (Maslanik et al. 1996, Zhao et al. 2018). For example, pulse-like increases in oceanic heat transport can trigger abrupt ice-loss events in sufficiently thin ice (Woodgate et al. 2012).

Changes in the interannual variability of sea ice ehave been studied only in a limited capacity, likely because they are only beginning to become visible in September in the present day. Both Goosse et al. (2009) and Swart et al. (2015; their Fig. S6) reported that maximum ice area variability during September occurs once the mean ice extent declines to 3-4 million km^2. This increased variability may occur due to increased prevalence of RILEs and periods of rapid recovery during this timeframe (Döscher and Koenigk 2013). The thickness distribution during these periods skews toward thinner ice, which is conducive to both rapid ice loss and rapid recovery processes (Tietsche et al. 2011; Döscher and Koenigk 2013). Holland et al. (2008) considered a critical ice thickness that can serve as a precursor to RILEs, but found it more likely that intrinsic variability played the primary role in the particular RILEs that were studied. More recently, Massonet et al. (2018) analyzed the projected variability of sea ice *volume* and its projected future change in the CMIP5 ensemble, which suggests a monotonic future decrease. The corresponding variability of sea ice area was investigated by Olonscheck and Notz (2017), but their analysis was much coarser temporally and seasonally, in that it only compared changes between entire blocks of time (the historical 1850-2005 period vs. the future 2006-2100 interval) and was further restricted to the summer and winter seasons.

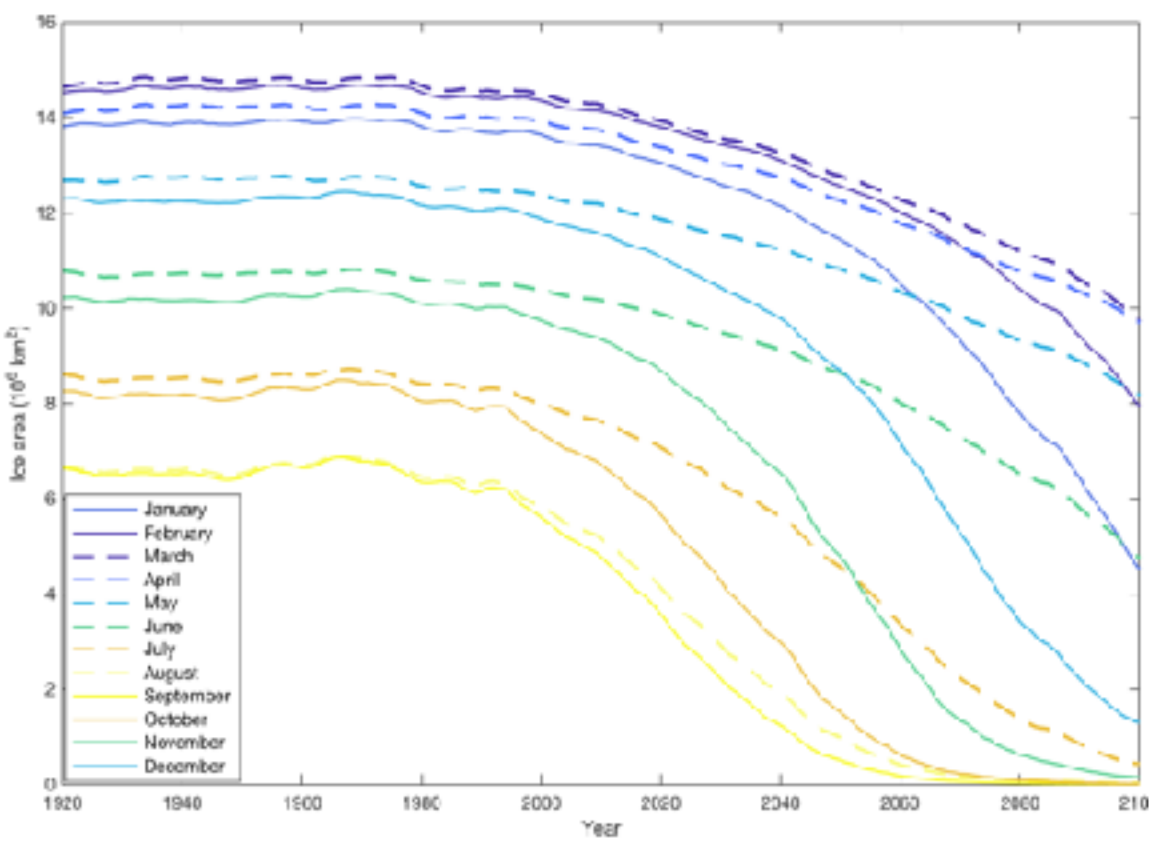
Building on these previous studies, our paper has two novel aspects. First, we analyze the transient interannual variability of sea ice area over the course of the year from the early 20th century through the entire 21st century and find very different behavior across the four seasons. These monthly differences are societally important, because marine access to the Arctic will likely expand beyond late summer as the ice pack shrinks. Second, we detail how interannual sea ice area variability changes as the ice pack retreats and link enhanced future variability to optimal ice thicknesses as well as the various thermodynamic and dynamic processes that control ice area variability. We analyze a large 40-member ensemble from a single GCM, which allows us to eisolate internal variability, which is otherwise muddled with inter-model variability in multi-model comparisons. This allows us to test the hypothesis that inter-annual Arctic sea ice cover variability will increase throughout the year in the future as the ice pack diminishes.

2. Data and Methods

Ice thickness, concentration, and area were obtained from simulations of the Community Earth System Model Large Ensemble Project (CESM-LE). Ice concentration refers to the percentage of a given grid cell that is covered by ice, while ice area in this study refers specifically to this percent coverage multiplied by the area of the grid cell yielding a total Arctic ice-covered area. The CESM-LE was designed to enable an assessment of projected change in the climate system while incorporating a wide range of internal climate variability (Kay et al. 2015). It consists of 40 ensemble members simulating the period 1920-2100 under historical and projected (RCP8.5 emissions scenario only) external forcing. The ensemble members are produced by introducing a small, random round-off level difference in the initial air temperature field for each member. This then generates a consequent ensemble spread that is purely due to simulated internal climate variability. A full description of the CESM-LE is given in Kay et al. (2015), and similar ensembles using the weaker RCP4.5 and RCP2.6 scenarios can be found in Sanderson et al. (2017, 2018).

Another data set used in the current study is the model simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5). Although more than 40 models submitted their simulation results to the Program for Climate Model Diagnosis and Intercomparison (PCMDI), only 12 of them simulated the Arctic sea ice extent both of the monthly means (each individual month) and the magnitude of the seasonal cycle (March minus September sea-ice extent) within 20-percent error when compared with observations (Wang and Overland, 2012, Wang and Overland 2015). Therefore, we used only these 12 models identified by Wang and Overland (2015) in this study. The 12 models are: ACCESS1.0, ACCESS1.3, CCSM4, CESM1(CAM5.1), EC-EARTH, HadGEM2-AO, HadGEM2-CC, HadGEM2-ES, MIROC-ESM, MIROC-ESM-CHEM, MPI-ESM-LR, and MPI-ESM-MR. Among the 12 models, half of them are using CICE (?need the name) or a variation of CICE as their sea-ice model component. When model has more ensemble members provided, we only kept up to 5 ensemble members from each model so that the total ensemble numbers are close to the CESM-LE. There are total 33 ensemble members from these 12 models in the RCP8.5 emissions scenario. Sea ice area, rather than ice extent, is computed from these 12 CMIP5 models to be consistent with CESM-LE results.

One of our primary analysis datasets is the time series of monthly ice variables. The ensemble mean of all statistics is taken after the statistics are calculated for each ensemble member. 1-year differences in ice area are calculated for each month separately to remove the confounding effect of amplified variability resulting from a downward trend. Finally, a 10-year running standard deviation is applied to the time series of 1-year differences in monthly ice area, centered on a given year. Ten years was chosen to quantify variability over decadal-scale intervals and to provide an adequate number of years for a standard deviation calculation. The timing and magnitude of variability is generally insensitive to the standard deviation window, however, and whether the 1-year difference in ice area or its raw time series is used.



3. Results

3.1 Sea ice area and its variability

Figure 1: The CESM-LE ensemble mean time series of monthly sea ice area (km^2 x 10^6).

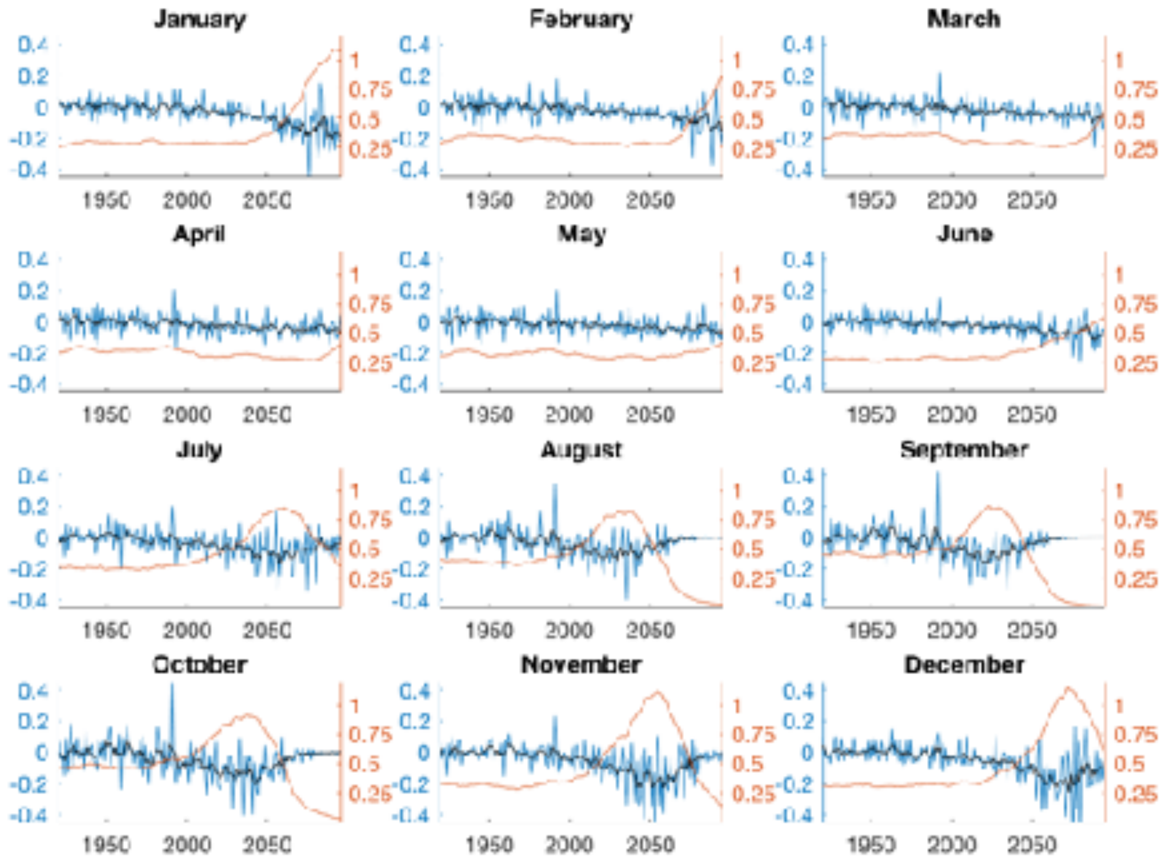


Figure 2: The CESM-LE ensemble mean of the 1-year differences in sea ice area (blue; million km^2) with their 5-year running mean overlaid (black) and the running standard deviation of the interannual change in sea ice area (gold; million km^2).

Sea ice area in the CESM-LE is projected to decline in all months in the 21st century, proceeding in three phases: a fairly stable regime of extensive coverage in the 20th century, then a decline, followed by virtually no ice remaining in summer and autumn months (Fig. 1). Sea ice area variability follows an analogous three-phase progression in months spanning mid-summer to early winter (Fig. 2). For example, in September this includes a period of modest variability during the 20th century, then a distinct variability peak in the late 2020s and 2030s that coincides with the maximum rate of ice retreat, and finally negligible variability in the late 21st century as the Arctic reaches near ice-free conditions (Fig. 2). The first two phases of this progression in variability occur for months in late winter to early summer (January-June), and suppressed variability would likely emerge beyond the end of the century, assuming that ice cover in these months would continue to retreat. The maximum rate of ice retreat (negative values of the derivative) occurs at a different time in the 21st century in each month, occurring presently in September but not until the end of the century in spring.

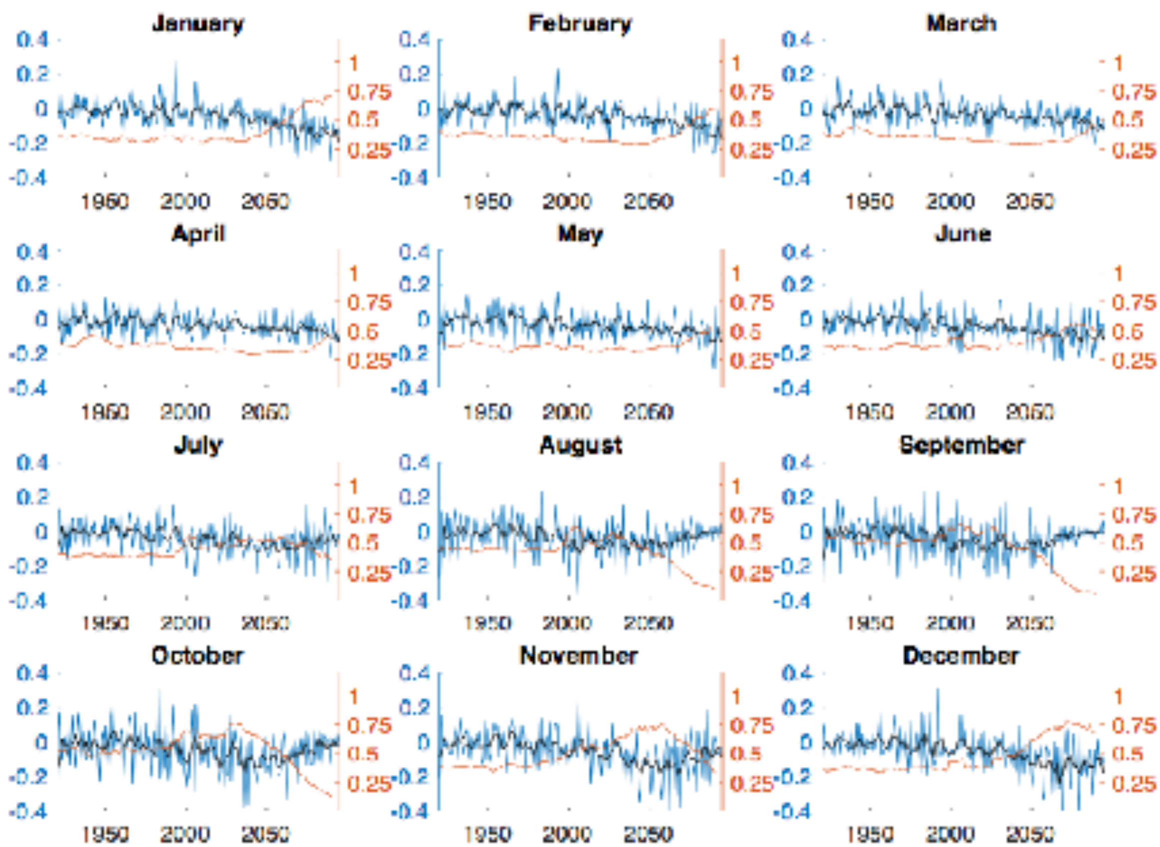


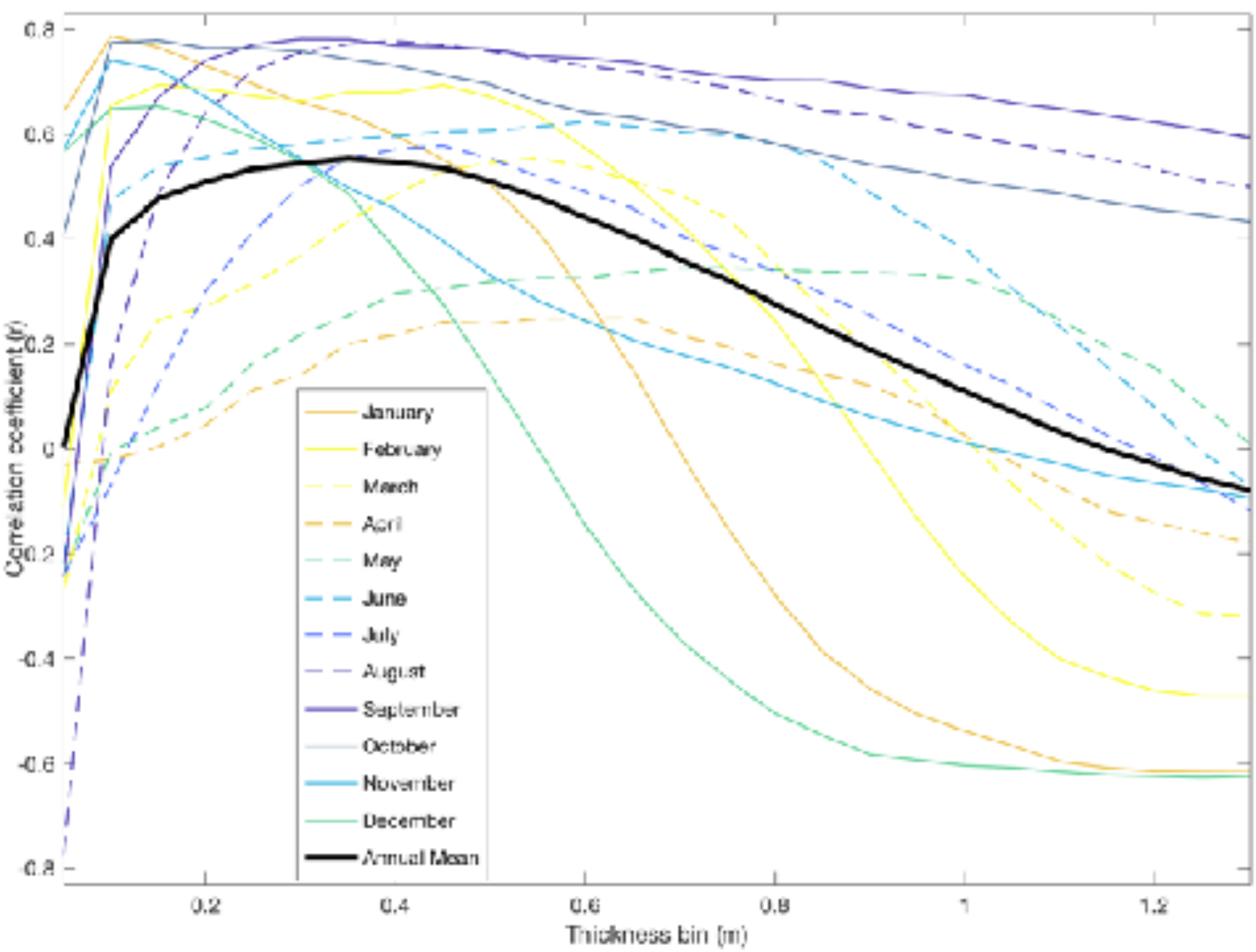
Figure 3: As in Fig. 2, but for the ensemble mean from 12 CMIP5 models' sea ice area.

The same relationship between ice area and its variability is maintained across CMIP5 models, though with more noise resulting from the aggregation of many different models rather than ensemble members from a single model (Fig. 3). This is most notable in the sea ice area (1-year difference) time series (Fig. 3, blue), indicating that there is considerable spread in when and how the downward trend proceeds each month as found in Massonnet et al. (2012), but good agreement that variability increases in this timeframe.

The analysis of ice area variability in Fig. 2 and Fig. 3 follows that of Goosse et al. (2009) and Swart et al. (2015), but we extend their findings for September to all months and confirm that the variability in ice area is maximized as its total basin area decline is well underway in both CESM-LE ensembles and across CMIP5 models. A directs relationship between the rate of sea ice retreat and the magnitude of variability is present across all months in CESM-LE and CMIP5: the standard deviation is highest when ice declines the fastest (Figs. 1 and 2). Furthermore, the magnitude and timing of peak ice area variability in both sets of experiments differs greatly by season. The peak in magnitude in CESM-LE is most pronounced from November-January when the running standard deviation of ice area exceeds 1 x 10^6 km^2, while the lowest magnitudes occur in April and May, when the downward trend in ice area does not peak prior to 2100 (Fig. 2). Near the end of the 21st century, the running standard deviation also shows an increase in the CMIP5 ensembles from December to June (Fig. 3), very similar behavior to that displayed by CESM-LE. However the magnitude of the increase in the running standard deviation in the CMIP5 ensemble mean is smaller than that in CESM-LE. This is not surprising, as the timing of ice retreat varies among models, so averaging them will smooth out the possible signals. The CMIP5 models therefore provide additional evidence that increased variability is associated with decreasing sea ice cover.

Figure 4: Monthly correlation coefficient (r) of the 2000-2100 10-year running standard deviation of 1-year difference in sea ice area with mean grid cell ice thickness binned every 0.05 m of thickness.

3.2 Relationship between ice area variability and thickness



Because increasing future concentrations of thin ice are likely a primary factor in increased ice area variability, we next consider the relationship between ice thickness and ice area variability in CESM-LE. This is done by correlating the standard deviation of basin-wide ice area (Fig. 2) with the total area of grid cells with mean ice thickness within a given range for an aggregation of all years and ensemble members, binned at 0.05 m intervals (Fig. 4). 20th century data are omitted because both variables are largely stationary for this period. There is a large difference in the maximum correlation coefficient across seasons, but in most months it peaks between r = 0.6 and r = 0.8. This peak is associated with the thinnest ice of 0.1 m to 0.2 m from October to January. There is a broad peak in the correlation coefficient between 0.25 m and 0.40 m in August and September, while July peaks near 0.45 m thickness but with a weaker maximum correlation coefficient (r = 0.6). In June, r = 0.6 for most ice thicknesses below 0.8 m, and there is only a weak correlation between these variables in April and May.

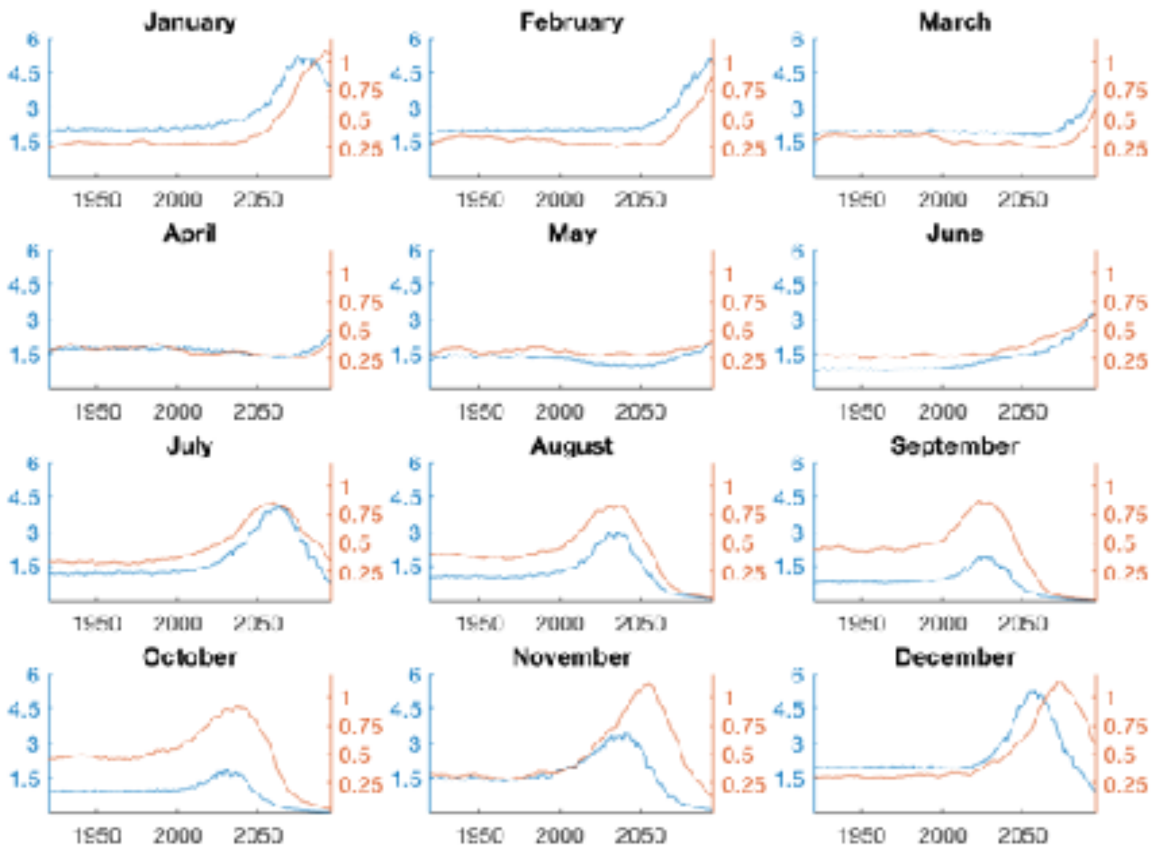
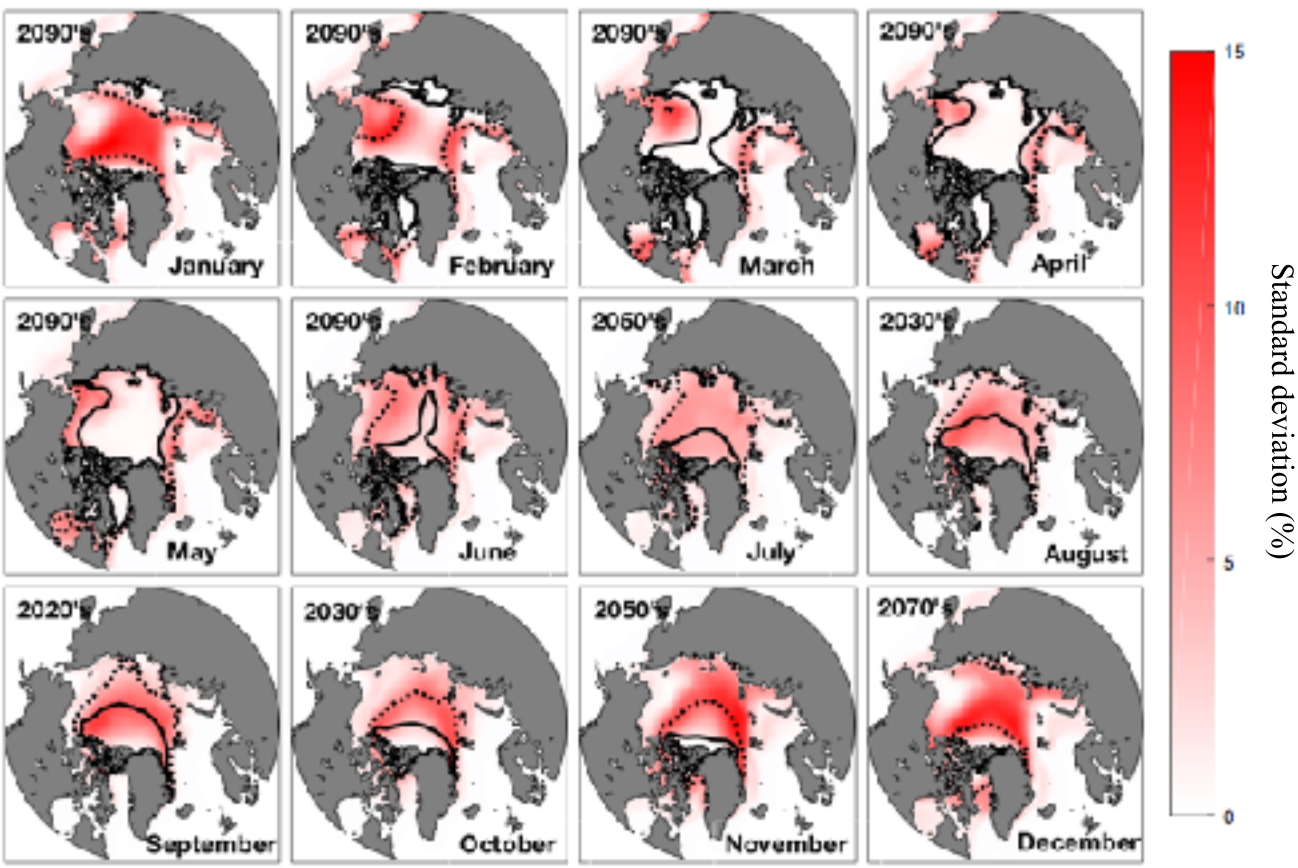


Figure 5: The CESM-LE ensemble mean of the 10-year running standard deviation of 1-year difference in sea ice area from Figure 1 (gold; million km²) and the ensemble mean total area of grid cells with mean ice thickness between 0.2 m and 0.6 m (blue; million km²).

The analysis in Fig. 4 allows us to identify a common range of ice thicknesses when ice area variability generally peaks regardless of the month, which we approximate as 0.2 m to 0.6

m. We next track the temporal evolution of this thin ice throughout the basin by calculating the total area of ice that falls within that range. The time-transgressive nature of when the peak in thin ice cover occurs (earliest in September, latest in winter-spring) is consistent with the corresponding timing of the peak future sea ice area variability, suggesting that the emergence of a sufficiently thin and contracted ice pack is a primary factor for enhanced ice cover variability (Fig. 5). Both curves match each other in shape, with a steady state early, increasing to a peak and dropping to zero as the Arctic becomes ice-free. The exception is in the spring and early summer when neither increases until the end of the 21st century, when ice begins to decline more rapidly. The two curves are largely in phase as well, with one preceding the other by no more than 10-20 years in July, August, and November–January. The phase difference is due to the chosen range of ice thicknesses, since the best relationship varies by month (Fig. 4). The two curves are in phase from August-October (Fig. 5) when the 0.2 m to 0.6 m range approximates the best relationship between thickness and variability (Fig. 4). However, ice area variability maximizes



after the peak in 0.2 m – 0.6 m thickness area in November–January, because variability is more highly correlated with ice slightly thinner than 0.2 m in these months (Fig. 4; Fig. 5).

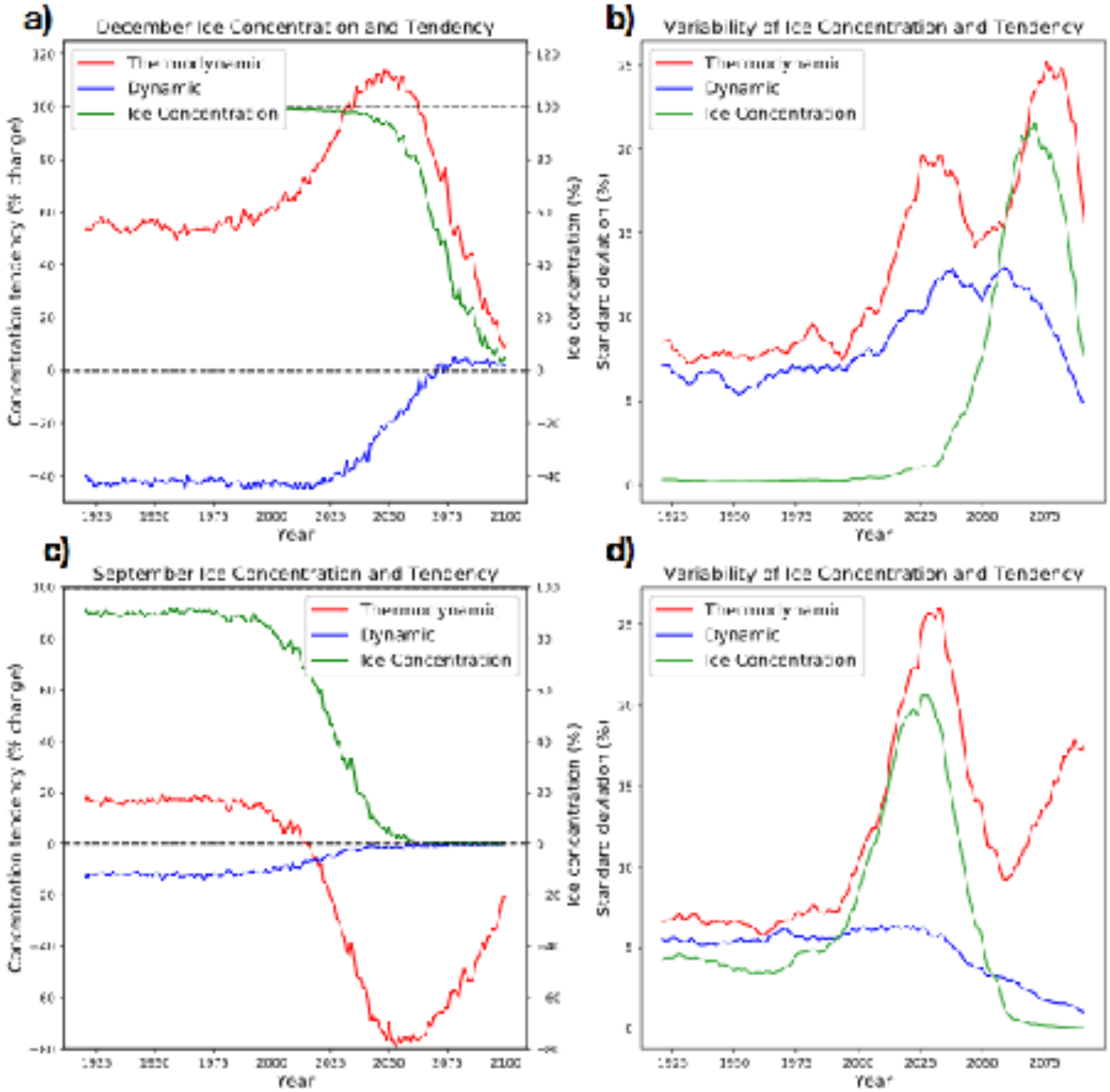


Figure 6: Monthly ensemble average in CESM-LE of the 10-year running standard deviation of ice concentration (%) in the decade when ice area variability is maximum. Mean 0.2 m and 0.6 m ice thicknesses are indicated by the dotted and solid contours, respectively.

There are also notable seasonal differences in the spatial pattern of variability during the decade when variability in ice concentration peaks in CESM-LE (Fig. 6). The largest fluctuations occur in a horseshoe-shaped pattern across the Arctic Ocean in autumn, but they are restricted to the boundaries of the Atlantic and Pacific Oceans in late winter and spring. The result is a larger area of high variability in the second half of the year and into January. The mean 0.2 m (dotted) and 0.6 m (solid) ice thickness contours are overlaid for reference (Fig. 6). The contours correspond closely to the boundary of maximum variability in ice coverage in most months, which is consistent with results from Fig. 4 and Fig. 5. This demonstrates the first-order relationship between thin ice and the variability of inter-annual ice coverage within a given region.

3.3 Ice concentration tendency

The strong relationship between thin ice coverage and high concentration variability occurs primarily due to the differing underlying mechanisms controlling ice concentration variability at a given time, namely whether ice is expanding or retreating. To illustrate this, we chose two months representative of these processes, September and December, to conduct an in-depth analysis of the physical mechanisms involved in the time difference in the two curves in Fig. 5. September is the end of the melt season, and therefore the ice concentration over the entire basin in this month reflects the cumulative impact of melt processes throughout the summer. By contrast, December is a time of ice growth, particularly in the future, and thus the ice concentration in this month is largely regulated by cumulative growth processes during the autumn. Using available model output, we calculate the ice concentration tendency (% day^{-1}) from thermodynamics and dynamics in the regions where the decadal standard deviation of ice concentration exceeds 30% within the grid cell (Fig. S1) to evaluate the mean ice budget. These regions of maximum variability in September and December closely match those in Fig. 6, though the magnitude is smaller in Fig. 6 due to the standard deviation being a decadal mean. The daily change in ice concentration is a function of dynamic contributions (ice import/export and ridging), thermodynamic melt processes (the sum of top, basal, and lateral), and thermodynamic growth (frazil and congelation). Because antecedent conditions of the icepack can be an important factor for determining ice concentration in the month of interest, we sum these terms over the preceding months (July-September or October-December) and report the net 3-month change in ice concentration resulting from each component.

The most interannually variable ice cover during September occurs primarily in the 2020s and is centered across the central Arctic (Fig. S1a), though this region displays net ice expansion in July-September in the 20th century (Fig. 7a) due to rapid ice growth in September. Thermodynamic processes dominate over dynamics and are of opposing sign during the 20th century, and thermodynamic processes add an average of 20% to the ice concentration of each grid cell in the region by the end of September, compared with a loss of only 10% from dynamical processes (Fig. 7a). Ice growth diminishes and melt processes accelerate in the early-mid 21st century when the melt processes reduce ice concentration by more than 75% and the dynamic processes essentially disappear with less ice to export (Fig. 7a). After 2060, September ice free conditions occur, and the thermodynamic term becomes less negative due to reduced areal coverage of ice in June and hence less ice area to melt over the summer (Fig. 7a).

Figure 7: Time series of ensemble-mean a) September ice concentration (%) and July-September averaged concentration tendency (% day^{-1}) from dynamics and thermodynamics, and b) the 10-year running standard deviation of: the inter-annual difference in ice concentration (%), and July-September ice concentration tendency from dynamics and thermodynamics (% day^{-1}). The same information is presented in c) and d) for December concentration and October-December ice concentration tendency terms.

Because thermodynamic processes dominate in controlling ice concentration in the future, they should also be the first-order forcing explaining future ice concentration variability, particularly given that the magnitude of the dynamic contribution approaches zero by the 2020s when ice cover is rapidly diminishing. As shown in Figure 7b, the peak interannual variability in the thermodynamic term (red curve) is indeed several times larger than peak variability of the dynamic term (blue curve), and the variability in the thermodynamic term maximizes during the late 2020s in phase with the variability of the ice concentration (green curve) when the thermodynamic term is declining most rapidly in Figure 7a. The variability likely also reflects the influence of the surface albedo feedback in amplifying summer ice area variations as well. There is a secondary rise in the variability of the thermodynamic term after 2060 (Figure 7b), coinciding with its rapid rise toward zero in Figure 7a, but ice coverage by this point is confined to a diminishing area.

From the 20th century well into the 21st century, ice growth occurs in the October-December period in a similar region of maximum interannual variability as September, except slightly equatorward (Fig. S1b). d Ice export plays a relatively larger role in the regions of interest in December than in September (Fig. 7c). However, the thermodynamic tendency is still the dominant term controlling ice concentration within this region of maximum interannual variability, and this term increases in the early-mid 21st century to a total of nearly 120%, some of which is offset by ice export that contributes to a 40% decrease in mean ice concentration in the 20th and early 21st centuries (Fig. 7c). The increased net ice growth occurs at this time primarily because there is more initial open water on which frazil ice can form.

aas.

Figure 7d shows that the standard deviation of December ice concentration (green curve) peaks around 2070 and is accompanied by a peak in the variability of the thermodynamic tendency (red curve) of more than double the magnitude of its dynamic tendency (blue curve). A smaller first peak in thermodynamic tendency occurs in the 2020s, when ice growth in this region increases due to increased frazil growth as this region's waters become more open on average in October. This initial peak may be smaller due to the anti-correlation between dynamic and thermodynamic tendency which reduces the effect of the latter. The rapid subsequent decline in ice growth occurs as conditions become too warm for ice growth over much of the October–December period in the 2050s and 2060s (Fig. 7c). This is reflected in the peak in variability of the thermodynamic tendency (red curve) approximately corresponding to the timing of the peak in the ice area variability (green curve) in 2070 (Fig. 7d). The coincidence in their peak variability is similar to that in Figure 7b and underscores the dominance of thermodynamics over dynamics in regulating the variability of ice area.

4. Discussion and Conclusions

This study has assessed the behavior of interannual Arctic sea ice area variability in the past and future, using a large set of independent realizations from the CESM-LE and simulations from 12 models participating in CMIP5. The demonstrate the complex, time-varying response of the ice pack as it transitions from a relatively stable state during the 20th century to a more volatile one. A few of our most important findings are summarized below.

1) Inter-annual variability of Arctic sea ice cover increases (at least transiently) in all months in the future as sea ice area and thickness decline, but there is a strong seasonal dependence. There is also a strong seasonal dependence of the magnitude of the maximum ice area variability in the future, with the greatest magnitude occurring during autumn and winter and smallest during spring by the time the simulation ends in 2100 (Fig. 2-3). The future peak in variability emerges soonest in late-summer months and latest during spring months, and the magnitude of this peak is positively correlated with the rate of ice loss in every month.

It is possible that the seasonal differences in ice area variability are partially a construction of the geography of the Arctic Basin, as evident in Fig. 6: when the ice margin is geographically constrained and unable to expand and contract due to a coastline early in the simulation, there is a smaller area subject to high ice variability. This explanation was offered by Goosse et al. (2009) for the same relationship in summer ice area variability, as well as by Eisenman (2010) to explain retreat rate differences between summer and winter. Our calculation of equivalent ice area applied to Fig. 1 (not shown) resulted in the expected larger drop in sea ice during the winter-spring months which result in greater peaks in their variability, though autumn and winter ice loss and variability were still greater. However, equivalent ice area is a theoretical construct and our purpose is to assess the variability of ice cover that actually exists. In the future, the ice in the central Arctic Ocean becomes thin enough to expand and contract extensively each season, leading to an increase in variability. Therefore, variability could be considered to be limited particularly in the first phase of its time series (Fig. 2) by the inability of ice to spread across a large open area. Furthermore, results from Fig. 4 and Fig. 5 suggest that the amount of thin ice alone can explain the evolution of ice variability in every month, though differences in the optimal ice thickness by month may require a partial geographical explanation in addition to one incorporating the components of the thermodynamic tendency of ice area from Fig. 7.

2) Ice needs to be sufficiently thin before areal variability maximizes, and in CESM-LE the optimal thickness range is generally between 0.2 m to 0.6 m but with some seasonal dependence resulting from the ice melt or ice growth processes that dominate in a given season (Fig. 4-5). The mean ice thickness in late summer and autumn is close to 0.6 m when ice area variability is highest, but is 0.2 m or less for a grid cell average in the winter.

Increased ice area variability in summer and fall is partly attributable to a higher efficiency of open water formation with the thinning sea ice (Holland et al., 2006) and the fact that smaller heating anomalies are required to completely melt through vast areas of the thin ice pack (Bitz and Roe, 2004). We find that the total area of thin ice between the range 0.2 m to 0.6 m is closely related to how soon and how strongly the peak variability in basin-wide ice area emerges, and this is primarily a function of variability in ice area's thermodynamic tendency. This is consistent with a physical understanding of this relationship, since ice that is too thin tends to be seasonal and melt off every year, whereas thick ice is more likely to survive the melt season. Seasonal forecasting of September sea ice coverage takes advantage of this concept, with the forecast skill improved when initializing ice thickness up to 8 months in advance (Chevallier et al., 2012; Day et al., 2014).

In contrast, ice area variability in November-January arises primarily from inter-annual variability in ice growth (as represented by December in Fig. 7c,d), which is dependent on existing open water conditions and temperature anomalies. The peak in ice area variability in these months also coincides with a slightly lower mean ice thickness of 0.2 m, though it is unclear whether that is due to these ice growth rather than melt processes at work during the winter.

3) Interannual variability in ice concentration is driven primarily by thermodynamic mechanisms, which are primarily comprised of either ice growth or ice melt depending on the season. Despite being opposing processes, they both exceed in magnitude that of dynamic ice processes (Fig. 7).

The thermodynamic tendency in ice concentration is of much greater magnitude than its dynamic counterpart at both the end of the melt season and start of the growth season, and the maximum interannual variability of the thermodynamic term is mostly in phase with that of ice concentration. The inverse relationship between ice area's interannual variability and its interannual rate of change (Figs. 1 and 2) is also found between the thermodynamic tendency and its rate of change (not shown, but inferred from Fig. 7). This is further evidence that ice area variability is primarily driven by thermodynamic processes in the icepack.

The dominance of the thermodynamic tendency is unsurprising and has been established as the relatively more important set of processes controlling sea ice variability, primarily via transport of mid-latitude eddy heat flux anomalies (Kelleher and Screen, 2018), anticyclone passage (Wernli and Lukas, 2018), and increased ocean heat transport (Li et al., 2018). However, the dynamic contribution to changes in ice concentration can likely be substantial in the absence of regional and monthly averaging, and numerous mechanisms have been described that can generate increased ice transport. Recent examples include divergent ice drift events connected to anomalous circulation patterns (Zhao et al., 2018) as well as the collapse of the Beaufort High (Petty, 2018; Moore et al., 2018), both of which may become more common in the future due to preconditioning of the icepack and further intrusion of mid-latitude cyclones into the Arctic.

This study offers a unique contribution by focusing on the projected transient evolution of Arctic sea ice variability throughout the year, as characterized by its response to external greenhouse forcing superimposed on short-term internal variability. A recent study (Olonscheck and Notz, 2017) also identified an overall increase in projected variability of summertime sea ice area in CMIP5, but this conclusion was not consistent across all models, possibly because the analysis did not incorporate the pronounced changes in variability over time as the ice pack diminishes. Increased inter-annual variability in the CESM Large Ensemble as sea ice declines most rapidly is an important result that needs to be accounted for as the ice-free season expands and the timing of maximum variability shifts from September. We also confirm that this relationship is maintained across CMIP5 models, suggesting that the responsible mechanisms reported here may apply more generally. These results have important implications for marine navigation going forward, suggesting that the otherwise auspicious transition to diminished sea ice in every month will be accompanied by a confounding increase in inter-annual variability of the ice cover before the ice disappears completely.

Acknowledgements

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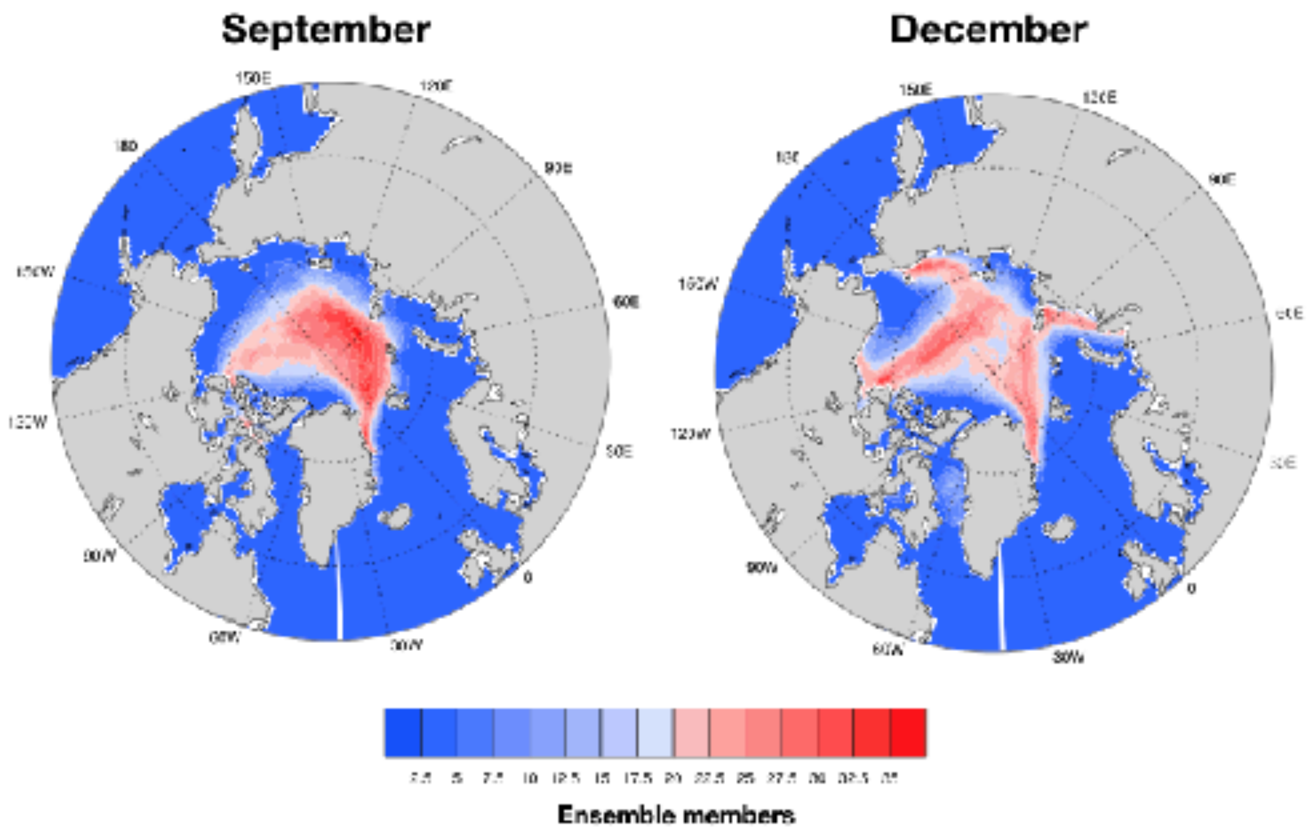

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Figure S1: Map of the total number of ensemble members where the standard deviation of the 10-year time series of ice area within each grid cell exceeds 30% within a) September and b) December's decade of maximum variability.