

Due December 5

Referee 1:

The revised version of this manuscript is certainly improved. This includes the overall quality of writing and presentation, as well as how the novel aspects of the present findings are highlighted and the discussion of how this study fits in with the existing literature. However, I still have a couple of major concerns (and several more minor ones) that I would like to see addressed. These are detailed below:

Major comments:

1) Even though the authors mention the recent study by Massonnet et al (2018) in the introduction, they basically dismiss it as having no bearing on the present study since Massonnet et al primarily consider sea ice volume, not area. However, volume and area are closely related (through thickness of course), and both Massonnet et al and the present study consider the role of ice thickness in some detail, as well as the main driver of changes in thickness: thermodynamic processes. I therefore believe the present findings should be put in context with those of Massonnet et al. Furthermore, I similarly believe it at least worth a cursory discussion of why Massonnet et al would find sea ice volume variability to decrease monotonically, while sea ice area variability increases initially.

Upon further reflection, we better understand the reviewer's point that the Massonnet et al. study has more relevance for our findings than we originally supposed. Therefore, we have added new material to the Discussion and Conclusions (Section 4) that compares our results with those of Massonnet et al. First, we added the Massonnet et al. reference to the existing Holland et al. (2006) reference for the statement that a higher efficiency of open water formation occurs in conjunction with thinning sea ice [Line 379], which was one of the key findings of the Massonnet et al. analysis. Second, the original final paragraph has been split into two parts to allow elaboration of how and why Massonnet et al.'s findings of decreasing sea ice *thickness* variability with a thinning ice pack contrast with ours that sea ice *area* variability will increase (at least transiently). This new structure offers an interesting contrast and a warning that expectations of future Arctic sea ice variability depend critically on whether ice area or thickness is being considered. [Lines 427-436]:

"Interestingly, another recent study (Massonnet et al. 2018) revealed that CESM-LE simulates a future *decrease* in interannual variability of sea ice *volume*, due to the dominance of the sea ice thickness term. Contrary to the behavior of ice area variability analyzed here, their analysis showed that interannual variability of ice thickness consistently declines when the ice pack thins. This relationship is a robust thermodynamic consequence of a strengthened "ice-formation efficiency", indicative of an enhanced stabilizing ice thickness-ice growth feedback (Notz and Bitz 2015) caused by greater wintertime vertical ice growth following summers with pronounced ice thinning. Therefore, it is important to distinguish which term (area or thickness) is being considered when assessing future changes in the variability of the ice pack."

2) Each time I read the manuscript I struggle to assess how much the differences in the variability evolution between months are just due to the winter months starting at much larger ice cover? I just realized (and apologize that I didn't earlier) that the plot I would really like to see is a scatterplot of standard deviation vs retreat rate, with different symbols for different months (and maybe color coded by time?). How good is the correlation for the individual months (a correlation that is a main finding highlighted in the abstract, L37)? Do all months fall on the same curve?

We thank the reviewer for this helpful suggestion. To elucidate the relationship among months and time periods, we have added two supplementary figures that illustrate the evolution of sea ice variability vs. sea ice loss. Figure S1 plots the time-evolving relationship by color-coding the smoothed annual data from Figure 2 across successive 30-year time periods in all months from 1920-2100. These graphs indicate that the positive correlation between ice variability and ice loss emerges clearly during the 21st century---even to some degree during the spring months---but the precise relationship is somewhat muddled by the large number of data points. To help clarify the relationship, Figure S2 (top) displays the average value of the data points from Figure S1 within each 30-year interval for every month. Again, the emergence of a positive correlation between ice variability and ice loss is apparent in most months, but this relationship is very muted during the spring (and eventually disappears when the ice pack melts off in certain months). To synthesize all of these individual monthly relationships, Figure S2 (bottom) shows all of the monthly data points on a single graph. This plot indicates that there is very little relationship between the two variables during the early-middle 20th century (dark blue and aqua points), before the warming signal takes hold, but the correlation is very evident starting in the late 20th century. From that time onward, the strength of the relationship is very stable among time periods (excluding the three points in the late 21st century when the ice pack has disappeared in August-October), as reflected by the similar magnitude of the regression among time periods.

This additional analysis supports our conclusion the correlation between ice variability and ice loss is robust, once sufficient warming occurs to manifest the relationship. Most months clearly reach this condition sometime during the 21st century, but April and May are exceptions, presumably because the simulation has not run long enough to achieve this state.

The reviewer correctly notes, however, that the statement in the abstract was too sweeping, because it didn't account for the springtime exception. We have reworded that sentence accordingly, so that it now reads, "The variability generally correlates 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." [Line 39] In addition, we have referred readers to these supplemental figures in Section 3.1 [Line 200].

Minor comments:

L43 I would feel more comfortable if this statement was qualified somewhat. Maybe something like "Our findings suggest that thermodynamic..." or "Our results agree with previous findings that thermodynamic ..."

We have modified the wording as suggested. It now reads, "Our findings suggest that thermodynamic melting . . . " [Line 45]

L72 Please rephrase: this sounds like there won't be more trade routes opening until the end of the century, where in fact the Northeastern Passage was just travelled by a MAERSK container ship a couple of weeks ago.

We have clarified by changing "by" to "throughout" in that sentence. It now reads, ". . . even more trade routes associated with the increased ice-free season are expected throughout the 21st century." [Line 77]

L83 Thin sea ice is not only more vulnerable to atmospheric forcing because of thermodynamics - it is also more easily deformed dynamically (e.g., ridged or opening leads).

Good point. We have incorporated this suggestion into the revised sentence. It now reads, ". . .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) <and deform the ice dynamically (Hibler 1979)>." [Line 90]

L87 "... sea ice EXTENT have been ..."

We thank the reviewer for catching this typo. The sentence now reads, "Changes in the interannual variability of sea ice <coverage> have been studied only in a limited capacity. . . ". [Line 94] We prefer "coverage" over "extent", because some studies we cite have used sea ice area and others have used sea ice extent.

L100 "... much coarser ..." Coarser than who? The present study? Please clarify.

We have clarified this comparison. The sentence now reads, ". . . [the Olonscheck and Notz (2017)] analysis was much coarser temporally and seasonally <than our study>, . . . " [Line 108]

L101 "... between entire blocks of time ..." change to "... between two discrete time periods ..."

Good suggestion. The sentence has been changed accordingly. [Line 109]

Fig 4 and associated text, in particular L206-217: I must admit that after reading and re-reading the text multiply times and staring at the figure for a while, I still don't quite understand what is being said/shown. Maybe this can be rewritten more clearly. At this point my understanding is

something like "The increase and decrease in variability in September is matched most closely by the increase and decrease in ice that is 30 cm thick". Is that correct?

We apologize for the confusion surrounding this figure, which admittedly is complicated and challenging to explain. What Figure 4 shows is the strength of the relationship between the variability of interannual changes in basin-wide ice area (same as the standard deviation curves in Figure 2) and "the total area of grid cells with mean ice thickness within a given [thickness] range". In other words, the interpretation of Figure 4 for September would be, "The magnitude of year-to-year variations in basin-wide ice area in September is matched most closely by the amount of ice cover around 30 cm thickness (or between 25-40 cm, as stated in the text)." Early in the simulation, the ice pack during September is so thick that there is very little ice this thin, whereas near the end of the simulation there is virtually no ice of any thickness remaining in that month. However, during the interval of maximum September ice variability in the 2020s-2030s, there is a considerable amount of sea ice within this favorable thickness range.

To clarify this point, we have added wording at the end of the existing sentence: " This peak is associated with the thinnest ice of 0.1 m to 0.2 m from October to January <, indicating that the greatest year-to-year variability of basin-wide ice area in these months occurs when there is the greatest coverage of thin sea ice between 0.1 to 0.2 m thickness.>" [Lines 215-216]

Fig 7: I find it makes the figure harder to read that the ice concentration (in %) and concentration trend (in %/day) are plotted on essentially the same axis, even though they represent very different quantities. I personally think it would be easier to interpret 7a,b if the ice concentration had its own axis for the bottom third of each panel. As it is it suggests that there is a relevant link in the magnitude of how the concentration changes and how the concentration trends change.

We have modified Figure 7 as suggested.

Referee 2:

Thanks for the careful response to the reviewer comments on „Past and future interannual variability of Arctic sea ice in coupled climate models“. While the authors mainly explain the approaches used in their initial submission, I would have wished to see some additional research to elaborate on the new aspects of the study, as well as a more elaborated comparison of their results to CMIP5. Although I feel that some chances are missed for a high impact study, I find the detailed response sufficiently conclusive to recommend publication in TC.

I have two minor recommendations that the authors may want to consider before publication:

1. Please be consistent with the terminology by using either „bottom melt“ or „basal melt“ throughout the manuscript.

We have changed “basal” to “bottom” [melt] for consistency. [Line 280]

2. Please cite the mentioned original studies in addition to Perovich et al (2007). [ll.83-84]

We have added the original studies of Grenfell and Maykut (1977), Maykut (1982), Ebert and Curry (1993), and Hunke and Lipscomb (2010). [Lines 87-88]

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

John R. Mioduszewski¹, Stephen Vavrus¹, Muyin Wang^{2, 3}, Marika Holland⁴, and Laura Landrum⁴

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

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

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

⁴National Center for Atmospheric Research, Boulder, Colorado.

Corresponding author: Steve Vavrus, sjvavrus@wisc.edu

26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49

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 generally correlates 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. Our findings suggest that 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.

Steve Vavrus 11/19/2018 10:15 AM

Deleted: in every month is directly

Steve Vavrus 11/19/2018 10:15 AM

Deleted: correlated

Steve Vavrus 11/16/2018 9:45 AM

Deleted: Thermodynamic

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).

Output from many climate models suggests 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; Massonnet 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 throughout 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 interannual 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 (Grenfell and Maykut 1977, Maykut 1982, Ebert and Curry 1993, Perovich et al. 2007, Hunke and Lipscomb 2010), 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) and deform the ice dynamically (Hibler 1979). 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 coverage have 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 km². This increased variability may occur due to increased prevalence of RILEs and periods

Steve Vavrus 11/16/2018 9:48 AM

Deleted: by the end of

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, Massonnet et al. (2018) analyzed the projected variability of sea ice *volume* and its projected future change in the CMIP5 ensemble, which suggested 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 *than our study*, in that it only compared changes between *two discrete time periods* (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 we link enhanced future variability to optimal ice thicknesses and to 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 isolate 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

Steve Vavrus 11/16/2018 10:13 AM

Deleted: entire blocks of time

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: 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 use the same sea ice model as CESM-LE (CICE, Hunke and Lipscomb 2010) or a variation of it. If a GCM provided multiple ensemble members, we only kept up to 5 realizations, so that the total ensemble numbers is close to that used in CESM-LE. There are a total of 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 variables 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

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.

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 direct relationship between the rate of sea ice retreat and the magnitude of variability is evident in nearly all months in CESM-LE and CMIP5: the standard deviation is generally highest when ice declines the fastest (Figs. 1, 2 and S1, S2). 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 $1 \times 10^6 \text{ km}^2$, 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 coverage.

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, indicating that the greatest year-to-year variability of basin-wide ice area in these months occurs when there is the greatest coverage of thin sea ice between 0.1 m to 0.2 m thickness. 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.

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

Steve Vavrus 11/19/2018 10:33 AM

Deleted: s

Steve Vavrus 11/19/2018 10:37 AM

Deleted: present

Steve Vavrus 11/19/2018 10:37 AM

Deleted: across

Steve Vavrus 11/19/2018 10:40 AM

Deleted: and

Steve Vavrus 11/16/2018 9:19 AM

Formatted: Font:(Default) Times New Roman, 12 pt

Steve Vavrus 11/16/2018 9:19 AM

Formatted: Font:(Default) Times New Roman, 12 pt

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).

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 ($\% \text{ day}^{-1}$) from thermodynamics and dynamics in the regions where the decadal standard deviation of ice concentration exceeds 30% within the grid cell (Fig. S3) 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, bottom, 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. S3), though this region displays net ice expansion in July–September in the 20th century (Fig. 7a) due to rapid ice growth in September. Thermo-

Steve Vavrus 11/29/2018 9:09 AM

Deleted: 1

Steve Vavrus 11/16/2018 9:22 AM

Deleted: basal

Steve Vavrus 11/29/2018 9:10 AM

Deleted: 1a

dynamic 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).

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. 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. S3). 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.

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.

Steve Vavrus 11/29/2018 9:12 AM
Deleted: 1b

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 results 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 [state](#). 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. 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. Support for this interpretation comes from our calculation of Eisenman's equivalent ice area applied to Fig. 1 (not shown), which resulted in the largest absolute decline in sea ice during the winter-spring months, though summer-autumn ice loss was still greater in relative terms. While useful for approximating potential sea ice extent in the absence of geographic constraints, equivalent ice area is still a theoretical construct; our purpose is to assess the variability of ice cover that actually exists. 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, [Massonnet et al. 2018](#)) 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

Steve Vavrus 11/29/2018 9:26 AM

Deleted: one

Steve Vavrus 11/19/2018 9:02 PM

Deleted: ,

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 **result** 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, their magnitudes exceed those 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, 2, S1, S2) 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 **area** 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 **interannual** 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. **Interestingly, another recent study (Massonnet et al. 2018) revealed that CESM-LE simulates a future decrease in interannual variability of sea ice volume, due to the**

Steve Vavrus 11/29/2018 9:31 AM

Deleted: and

Stephen Vavrus 11/20/2018 11:13 AM

Formatted: Font:Italic

Stephen Vavrus 11/20/2018 11:12 AM

Formatted: Font:Italic

dominance of the sea ice thickness term. Contrary to the behavior of ice area variability analyzed here, their analysis showed that interannual variability of ice thickness consistently declines when the ice pack thins. This relationship is a robust thermodynamic consequence of a strengthened “ice-formation efficiency”, indicative of an enhanced stabilizing ice thickness-ice growth feedback (Notz and Bitz 2015) caused by greater wintertime vertical ice growth following summers with pronounced ice thinning. Therefore, it is important to distinguish which term (area or thickness) is being considered when assessing future changes in the variability of the ice pack.

Increased inter-annual variability of sea ice area 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, indicating that the otherwise auspicious transition to diminished sea ice in every month may be accompanied by a confounding increase in inter-annual variability of the ice cover before the ice disappears completely.

Acknowledgements

We thank two anonymous reviewers for their helpful comments. Support was provided by the NOAA Climate Program Office under Climate Variability and Predictability Program grant NA15OAR4310166. This project is partially funded by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) under NOAA Cooperative Agreement NA10OAR4320148, contribution number 2017-087, the Pacific Marine Environmental Laboratory contribution number 4671. We would like to acknowledge high-performance computing support from Yellowstone (ark:/85065/d7wd3xhc) provided by NCAR's Computational and Information Systems Laboratory, sponsored by the National Science Foundation.

Steve Vavrus 11/19/2018 9:07 PM

Deleted:

References

- Aksenov, Y., E. E. Popova, A. Yool, A. J. G. Nurser, T. D. Williams, L. Bertino, and J. Bergh: On the future navigability of Arctic sea routes: High-resolution projections of the Arctic Ocean and sea ice, *Mar. Policy*, 1–18, doi:10.1016/j.marpol.2015.12.027, 2015.
- Bathiany, S., B. van der Bolt, M. S. Williamson, T. M. Lenton, M. Scheffer, E. H. van Nes, and D. Notz: Statistical indicators of Arctic sea-ice stability – prospects and limitations, *Cryosph.*, 10(4), 1631–1645, doi:10.5194/tc-10-1631-2016, 2016.
- Bitz, C. M., and G. H. Roe: A mechanism for the high rate of sea ice thinning in the Arctic Ocean, *J. Clim.*, 17(18), 3623–3632, doi:10.1175/1520-0442(2004)017, 2004.
- Cavalieri, D. J., and C. L. Parkinson: Arctic sea ice variability and trends, 1979–2010, *Cryosph.*, 6(4), 881–889, doi:10.5194/tc-6-881-2012, 2012.
- Collins, M. et al.: Long-term Climate Change: Projections, Commitments and Irreversibility. Intergovernmental Panel on Climate Change, 108, 2013.
- Comiso, J. C., W. N. Meier, and R. Gersten: Variability and trends in the Arctic Sea ice cover: Results from different techniques, *J. Geophys. Res. Ocean.*, 122, 1–22, doi:10.1002/2017JC012768, 2017.
- Ding, Q., et al., Influence of high-latitude atmospheric circulation changes on summertime Arctic sea ice, *Nat. Clim. Chang.*, 7, 289–295, doi:10.1038/nclimate3241, 2017.
- Döscher, R., and T. Koenigk: Arctic rapid sea ice loss events in regional coupled climate scenario experiments, *Ocean Sci. Discuss.*, 9(4), 2327–2373, doi:10.5194/osd-9-2327-2012, 2012.
- [Ebert, E. E. and J. A. Curry: An intermediate one-dimensional thermodynamic sea ice model for investigating ice-atmosphere interactions. *J. Geophys. Res.*, 98, 10085-10109, doi:10.1029/93JC00656, 1993.](#)
- Goosse, H., O. Arzel., C.M. Bitz, A. de Montety, and M. Vancoppenolle: Increased variability of the Arctic summer ice extent in a warmer climate, *Geophys. Res. Lett.*, 36, L23702, doi :10.1029/2009GL040546, 2009.
- [Grenfell, T. C., and G. A. Maykut: The optical properties of ice and snow in the Arctic Basin, *J. Glaciol.*, 18, 445-463, doi:10.3189/S0022143000021122, 1977.](#)
- Holland, M. M., C. M. Bitz, and B. Tremblay: Future abrupt reductions in the summer Arctic sea ice, *Geophys. Res. Lett.*, 33(23), 1–5, doi:10.1029/2006GL028024, 2006.
- Holland, M. M., C. M. Bitz, L. B. Tremblay, and D. A. Bailey: The role of natural versus forced change in future rapid summer Arctic ice loss. Arctic sea ice decline: Observations, projections, mechanisms, and implications, E.T. DeWeaver, C.M. Bitz, and L.B. Tremblay, Eds., *Geophysical Monograph Series*, American Geophysical Union, Washington, 133-150 doi:10.1029/180GM10, 2008.
- Holland, M. M., and J. Stroeve: Changing seasonal sea ice predictor relationships in a changing Arctic climate, *Geophys. Res. Lett.*, 38, L18501, doi:10.1029/2011GL049303, 2011.
- Jahn, A., J. E. Kay, M. M. Holland, and D. M. Hall: How predictable is the timing of a summer ice-free Arctic?, *Geophys. Res. Lett.*, 1–8, doi:10.1002/2016GL070067, 2016.
- [Hunke, E. C., and W. H. Lipscomb: CICE: the Los Alamos sea ice model documentation and software user’s manual, version 4.1. LA-CC-06-012, 2010.](#)
- Eguíluz, V. M., J. Fernández-Gracia, X. Irigoien, and C. M. Duarte: A quantitative assessment of Arctic shipping in 2010–2014, *Sci. Rep.*, 6(August), 30682, doi:10.1038/srep30682, 2016.

513 Eisenman, I.: Geographic muting of changes in the Arctic sea ice cover, *Geophys. Res. Lett.*,
 514 37(16), doi:10.1029/2010GL043741, 2010.
 515 [Hibler, W. D.: A dynamic thermodynamic sea ice model. *J. Phys. Oceanogr.*, 9, 815-846, 1979.](#)
 516 Hunke, E. C., and W. H. Lipscomb: CICE: The Los Alamos sea ice model, documentation and
 517 software user's manual, version 4.1. Los Alamos National Laboratory Tech. Rep. LACC-
 518 06-012, 76 pp., 2010.
 519 Kay, J. E. et al.: The Community Earth System Model (CESM) Large Ensemble Project: A
 520 Community Resource for Studying Climate Change in the Presence of Internal Climate
 521 Variability, *Bull. Am. Meteorol. Soc.*, 96(8), 1333–1349, doi:10.1175/BAMS-D-13-
 522 00255.1, 2015.
 523 Kay, J. E., M. M. Holland, and A. Jahn: Inter-annual to multi-decadal Arctic sea ice extent trends
 524 in a warming world. *Geophys. Res. Lett.*, 38, L15708, doi:10.1029/2011GL048008,
 525 2011.
 526 Kelleher, M., and J. Screen: Atmospheric precursors of and response to anomalous Arctic sea ice
 527 in CMIP5 models, *Adv. Atmos. Sci.*, 35(27), doi.org/10.1007/s00376-017-7039-9.
 528 Khon, V. C., I. I. Mokhov, M. Latif, V. A. Semenov, and W. Park: Perspectives of Northern Sea
 529 Route and Northwest Passage in the twenty-first century, *Clim. Change*, 100(3), 757–
 530 768, doi:10.1007/s10584-009-9683-2, 2010.
 531 Kwok, R., and D. A. Rothrock: Decline in Arctic sea ice thickness from submarine and ICESat
 532 records: 1958–2008, *Geophys. Res. Lett.*, 36(15), doi:10.1029/2009GL039035.
 533 Kwok, R., G. F. Cunningham, M. Wensnahan, I. Rigor, H. J. Zwally, and D. Yi: Thinning and
 534 volume loss of the Arctic Ocean sea ice cover: 2003–2008, *J. Geophys. Res. Ocean.*,
 535 114(7), 2003–2008, doi:10.1029/2009JC005312, 2009.
 536 Kwok, R., L. T. Pedersen, P. Gudmandsen, and S. S. Pang: Large sea ice outflow into the Nares
 537 strait in 2007, *geophys. Res. Lett.*, 37, L03502, DOI:10.1029/2009GL041872, 2010.
 538 Labe, Z., Magnusdottir, G., and H. Stern: Variability of Arctic Sea Ice Thickness Using
 539 PIOMAS and the CESM Large Ensemble, *J. Climate*, 31, 3233–3247,
 540 [DOI.ORG/10.1175/JCLI-D-17-0436.1](#), 2018.
 541 Lang, A., S. Yang, and E. Kaas: Sea ice thickness and recent Arctic warming, *Geophys. Res.*
 542 *Lett.*, 44, doi:10.1002/2016GL071274, 2017.
 543 Li, D., R. Zhang, and T. Knutson: Comparison of Mechanisms for Low-Frequency Variability of
 544 Summer Arctic Sea Ice in Three Coupled Models, *J. Climate*, 31, 1205–
 545 1226, [DOI.ORG/10.1175/JCLI-D-16-0617.1](#), 2018.
 546 Maslanik, J. A., M. C. Serreze, and R. G. Barry: Recent decreases in Arctic summer ice cover
 547 and linkages to atmospheric circulation anomalies, *Geophys. Res. Lett.*, 23(13), 1677–
 548 1680, doi:10.1029/96GL01426, 1996.
 549 Maslanik, J., S. Drobot, C. Fowler, W. Emery, and R. Barry: On the Arctic climate paradox and
 550 the continuing role of atmospheric circulation in affecting sea ice conditions, *Geophys.*
 551 *Res. Lett.*, 34(3), 2–5, doi:10.1029/2006GL028269, 2007a.
 552 Maslanik, J. A., C. Fowler, J. Stroeve, S. Drobot, J. Zwally, D. Yi, and W. Emery: A younger,
 553 thinner Arctic ice cover: Increased potential for rapid, extensive sea-ice loss, *Geophys.*
 554 *Res. Lett.*, 34(24), 2004–2008, doi:10.1029/2007GL032043, 2007b.
 555 Maslanik, J., J. Stroeve, C. Fowler, and W. Emery: Distribution and trends in Arctic sea ice age
 556 through spring 2011, *Geophys. Res. Lett.*, 38(13), 2–7, doi:10.1029/2011GL047735,
 557 2011.

558 Massonnet, F., T. Fichefet, H. Goosse, C. M. Bitz, G. Philippon-Berthier, M. M. Holland, and P.
 559 Y. Barriat: Constraining projections of summer Arctic sea ice, *Cryosphere*, 6(6), 1383–
 560 1394, doi:10.5194/tc-6-1383-2012, 2012.
 561 Massonnet, F., M. Vancoppenolle, H. Goosse, D. Docquier, T. Fichefet, and E. Blanchard-
 562 Wrigglesworth: Arctic sea-ice change tied to its mean state through thermodynamic
 563 processes. *Nat. Clim. Change*, 8, 599–603, 2018.
 564 Maykut, G. A.: Energy exchange over young sea ice in the central Arctic, *J. Geophys. Res.*,
 565 83(C7), 3646–3658, doi:10.1029/JC083iC07p03646, 1978.
 566 [Maykut, G. A.: Large-scale heat exchange and ice production in the central Arctic. *J. Geophys.*](#)
 567 [Res., 87, 7971–7984, doi:10.1029/JC087iC10p07971, 1982.](#)
 568 Melia, N., K. Haines, and E. Hawkins: Sea ice decline and 21st century trans-Arctic shipping
 569 routes, *Geophys. Res. Lett.*, 43(18), 9720–9728, doi:10.1002/2016GL069315, 2016.
 570 Moore, G. W. K., Schweiger, A., Zhang, J., and M. Steele: Collapse of the 2017 winter Beaufort
 571 High: A response to thinning sea ice? *Geophysical Research Letters*, 45, 2860–2869,
 572 [doi.org/10.1002/2017GL076446](#), 2018.
 573 Nghiem, S. V., I. G. Rigor, D. K. Perovich, P. Clemente-Colón, J. W. Weatherly, and G. Neu-
 574 mann: Rapid reduction of Arctic perennial sea ice, *Geophys. Res. Lett.*, 34(19), 1–6,
 575 doi:10.1029/2007GL031138, 2007.
 576 Notz, D.: The future of ice sheets and sea ice: between reversible retreat and unstoppable loss.,
 577 *Proc. Natl. Acad. Sci. U. S. A.*, 106(49), 20590–5, doi:10.1073/pnas.0902356106, 2009.
 578 [Notz, D., and C. M. Bitz: *Sea ice in Earth system models* \(ed. Thomas, D. N.\). John Wiley &
 579 \[Sons, Chichester, 2017.\]\(#\)
 580 Notz, D., and J. Marotzke: Observations reveal external driver for Arctic sea-ice retreat,
 581 *Geophys. Res. Lett.*, 39\(8\), 1–6, doi:10.1029/2012GL051094, 2012.
 582 Notz, D., and J. Stroeve: Observed Arctic sea-ice loss directly follows anthropogenic CO₂
 583 emission, *Science*, 354\(6313\), 747–750, doi:10.1126/science.aag2345, 2016.
 584 Olonscheck, D., and D. Notz: Consistently estimating internal variability from climate model
 585 simulations. *J. Clim.*, 30, 9555–9573, 2017.
 586 Overland, J. E., and M. Wang: When will the summer Arctic be nearly sea ice free?, *Geophys.*
 587 *Res. Lett.*, 40\(10\), 2097–2101, doi:10.1002/grl.50316, 2013.
 588 Perovich, D. K., B. Light, H. Eicken, K. F. Jones, K. Runciman, and S. V. Nghiem: Increasing
 589 solar heating of the Arctic Ocean and adjacent seas, 1979–2005: Attribution and role in
 590 the ice-albedo feedback, *Geophys. Res. Lett.*, 34\(19\), 1–5, doi:10.1029/2007GL031480,
 591 2007.
 592 Petty, A. A.: A possible link between winter Arctic sea ice decline and a collapse of the Beaufort
 593 High? *Geophysical Research Letters*, 45, 2879–2882,
 594 \[DOI.ORG/10.1002/2018GL077704\]\(#\), 2018.
 595 Ridley, J. K., R. A. Wood, A. B. Keen, E. Blockley, and J. A. Lowe: Brief Communication:
 596 Does it matter exactly when the Arctic will become ice-free?, *Cryosph. Discuss.*,
 597 \(March\), 1–4, doi:10.5194/tc-2016-28, 2016.
 598 Sanderson, B. M., Xu, Y., Tebaldi, C., Wehner, M., O'Neill, B., Jahn, A., Pendergrass, A. G.,
 599 Lehner, F., Strand, W. G., Lin, L., Knutti, R., and Lamarque, J. F.: Community climate
 600 simulations to assess avoided impacts in 1.5 and 2 °C futures, *Earth Syst. Dynam.*, 8,
 601 827–847, \[https://doi.org/10.5194/esd-8-827-2017\]\(#\), 2017.](#)

Steve Vavrus 11/19/2018 9:41 PM
 Formatted: Font:Italic

Sanderson, B. M., K. W. Oleson, W. G. Strand, F. Lehner, and B. C. O'Neill: A new ensemble of GCM simulations to assess avoided impacts in a climate mitigation scenario. *Clim. Change*, 146(3-4), 303-318, 2018.

Serreze, M. C., and J. C. Stroeve: Arctic sea ice trends, variability and implications for seasonal ice forecasting, *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, 373(2045), 20140159, doi:10.1098/rsta.2014.0159, 2015.

Stephenson, S. R., L. C. Smith, L. W. Bringham, and J. A. Agnew: Projected 21st-century changes to Arctic marine access, *Clim. Change*, 118(3-4), 885-899, doi:10.1007/s10584-012-0685-0, 2013.

Stammerjohn, S., R. Massom, D. Rind, and D. Martinson: Regions of rapid sea ice change: An inter-hemispheric seasonal comparison, *Geophys. Res. Lett.*, 39(6), L06501, doi:10.1029/2012GL050874, 2012.

Stroeve, J. C., M. C. Serreze, M. M. Holland, J. E. Kay, J. Malanik, and A. P. Barrett: The Arctic's rapidly shrinking sea ice cover: a research synthesis, *Clim. Change*, 110(3-4), 1005-1027, doi:10.1007/s10584-011-0101-1, 2012.

Stroeve, J., M. M. Holland, W. Meier, T. Scambos, and M. Serreze: Arctic sea ice decline: Faster than forecast, *Geophys. Res. Lett.*, 34(9), 1-5, doi:10.1029/2007GL029703, 2007.

Swart, N. C., J. C. Fyfe, E. Hawkins, J. E. Kay, and A. Jahn: Influence of internal variability on Arctic sea-ice trends, *Nat. Clim. Chang.*, 5(2), 86-89, doi:10.1038/nclimate2483, 2015.

Tietsche, S., D. Notz, J. H. Jungclauss, and J. Marotzke: Recovery mechanisms of Arctic summer sea ice, *Geophys. Res. Lett.*, 38(2), 1-4, doi:10.1029/2010GL045698, 2011.

Wang, M., and J. E. Overland: A sea ice free summer Arctic within 30 years? *Geophys. Res. Lett.*, 36, L07502, doi:10.1029/2009GL037820, 2009.

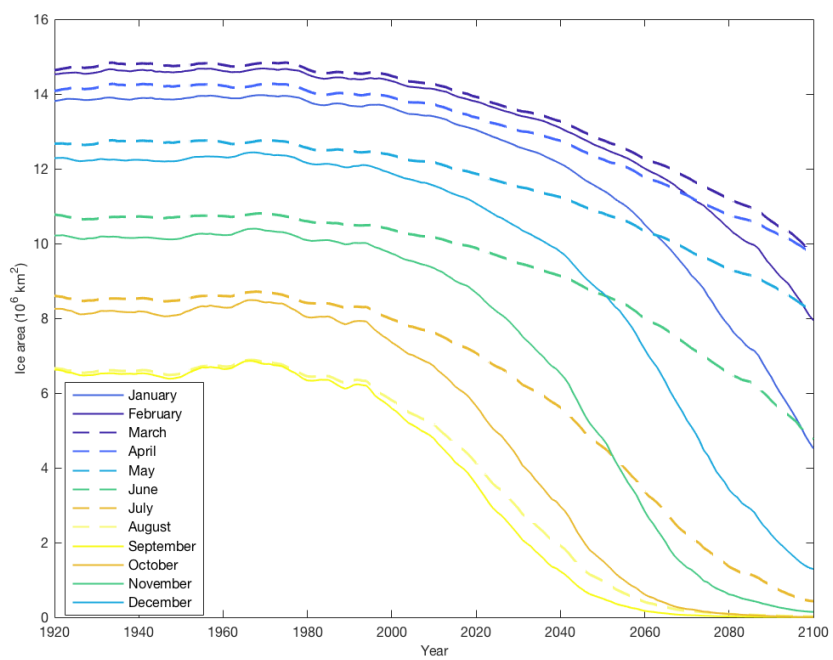
Wang, M., and J. E. Overland: A sea ice free summer Arctic within 30 years: An update from CMIP5 models, *Geophys. Res. Lett.*, 39(18), doi:10.1029/2012GL052868, 2012.

Wang, M., and J. E. Overland: Projected future duration of the sea-ice-free season in the Alaskan Arctic, *Prog. Oceanogr.*, 136, 50-59, doi:10.1016/j.pocean.2015.01.001, 2015.

Wernli, H., and L. Papritz: Role of polar anticyclones and mid-latitude cyclones for Arctic summertime sea-ice melting, *Nat. Geos.*, 11, 108-113, doi:10.1038/s41561-017-0041-0, 2018.

Woodgate, R. A., T. J. Weingartner, and R. Lindsay: Observed increases in Bering Strait oceanic fluxes from the Pacific to the Arctic from 2001 to 2011 and their impacts on the Arctic Ocean water column, *Geophys. Res. Lett.*, 39, L24603, doi:10.1029/2012GL054092, 2012.

Zhao, J., D. Barber, S. Zhang, Q. Yang, X. Wang, and H. Xie: Record Low Sea-Ice Concentration in the Central Arctic during Summer 2010, *Adv. Atmos. Sci.*, 35(January), 106-115, doi:10.1007/s00376-017-7066-6, 2018.



639 **Figure 1:** The CESM-LE ensemble mean time series of monthly sea ice area ($\text{km}^2 \times 10^6$).
 640
 641
 642

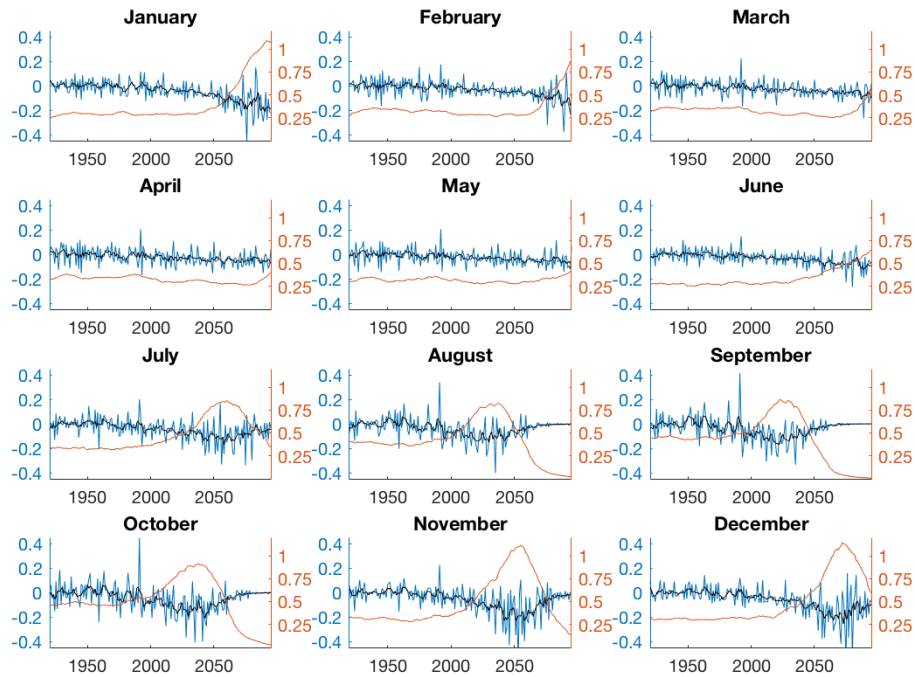


Figure 2: The CESM-LE ensemble mean of the 1-year differences in sea ice area (blue; million km²) with their 5-year running mean overlaid (black) and the running standard deviation of the interannual change in sea ice area (gold; million km²).

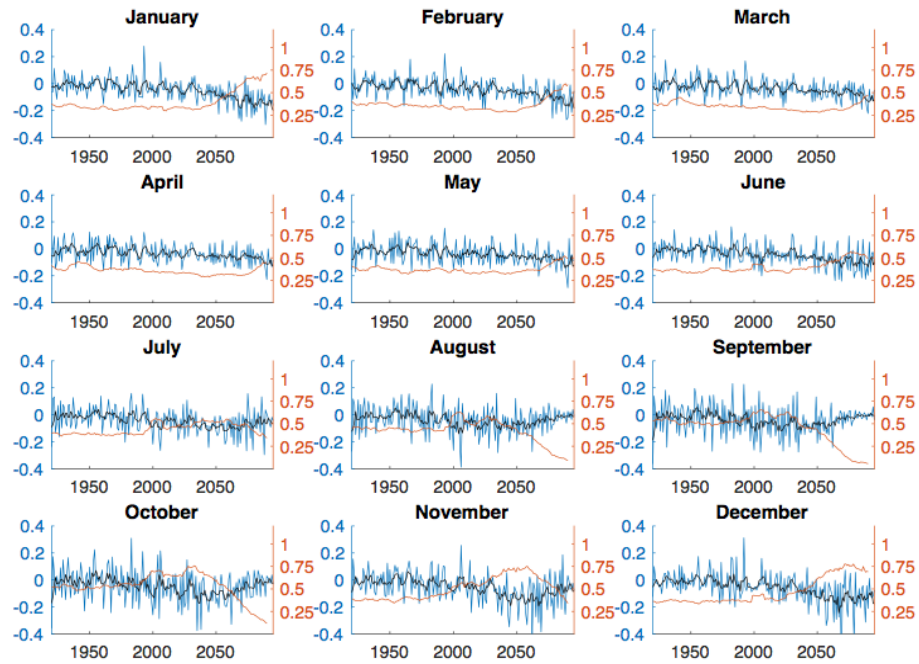


Figure 3: As in Fig. 2, but for the ensemble mean from 12 CMIP5 models' sea ice area.

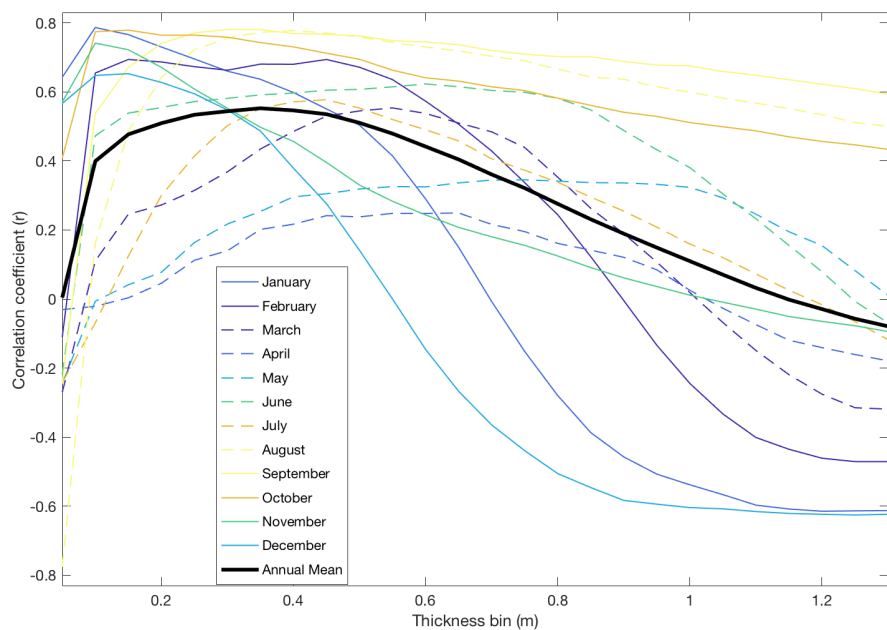


Figure 4: Monthly correlation coefficient (r) of the 2000-2100 10-year running standard deviation of 1-year difference in sea ice area with mean grid cell ice thickness binned every 0.05 m of thickness.

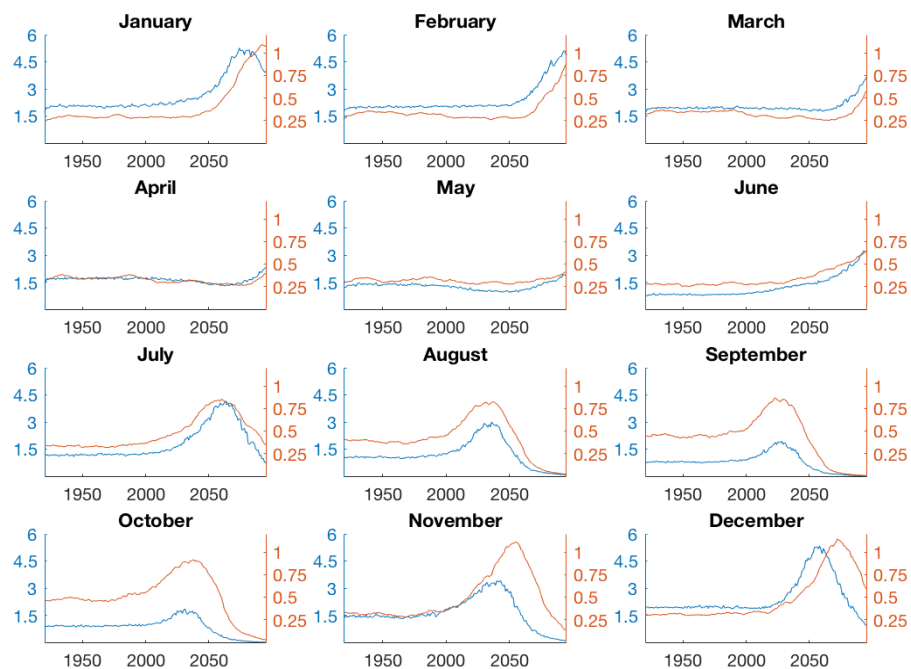
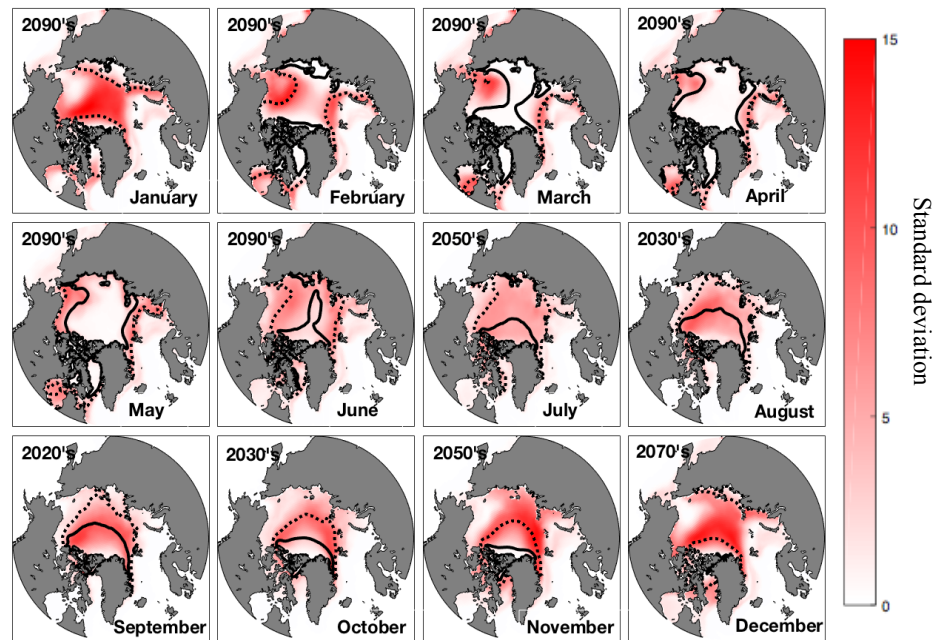


Figure 5: The CESM-LE ensemble mean of the 10-year running standard deviation of 1-year difference in sea ice area from Figure 1 (gold; million km²) and the ensemble mean total area of grid cells with mean ice thickness between 0.2 m and 0.6 m (blue; million km²).

773
774
775
776
777
778



779
780
781
782
783
784
785
786
787
788
789
790
791
792
793
794
795

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.

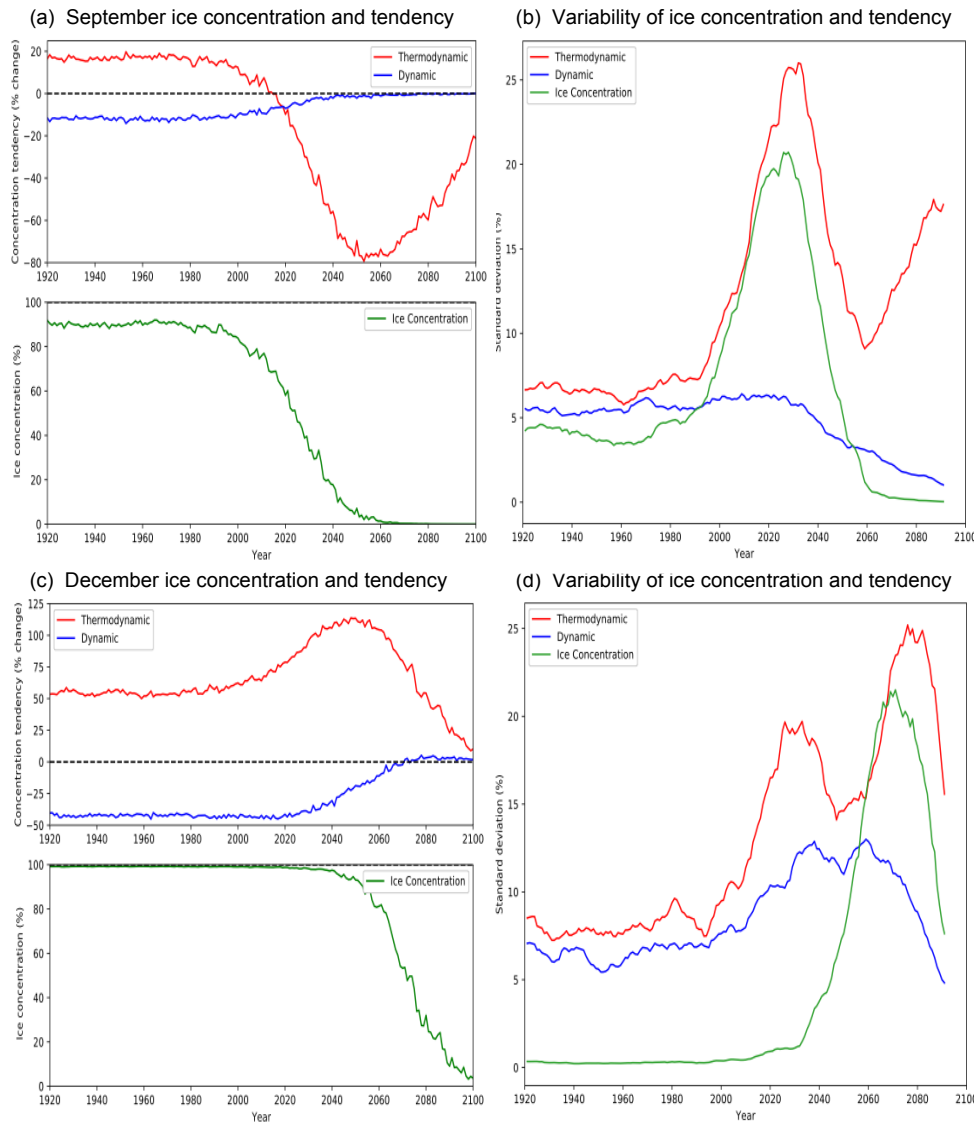


Figure 7: Time series of ensemble-mean a) September ice concentration (%) and July-September averaged concentration tendency ($\% \text{ day}^{-1}$) from dynamics and thermodynamics, and b) the 10-year running standard deviation of: the inter-annual difference in ice concentration (%), and July-September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

Steve Vavrus 11/16/2018 10:27 AM

Deleted: -

... [1]