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Inter-annual to multi-decadal Arctic sea ice extent trends in a warming world

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[1] A climate model (CCSM4) is used to investigate the influence of anthropogenic forcing on late 20th century and early 21st century Arctic sea ice extent trends. On all timescales examined (2–50+ years), the most extreme negative observed late 20th century trends cannot be explained by modeled natural variability alone. Modeled late 20th century ice extent loss also cannot be explained by natural causes alone, but the six available CCSM4 ensemble members exhibit a large spread in their late 20th century ice extent loss. Comparing trends from the CCSM4 ensemble to observed trends suggests that internal variability explains approximately half of the observed 1979–2005 September Arctic sea ice extent loss. In a warming world, CCSM4 shows that multi-decadal negative trends increase in frequency and magnitude, and that trend variability on 2–10 year timescales increases. Furthermore, when internal variability counteracts anthropogenic forcing, positive trends on 2–20 year timescales occur until the middle of the 21st century. **Citation:** Kay, J. E., M. M. Holland, and A. Jahn (2011), Inter-annual to multi-decadal Arctic sea ice extent trends in a warming world, *Geophys. Res. Lett.*, *38*, L15708, doi:10.1029/2011GL048008.

1. Motivation

[2] The influence of anthropogenic forcing on observed 20th century Arctic sea ice extent declines remains an active research topic [e.g., *Winton et al.*, 2011; *Zhang et al.*, 2008; *Maslanik et al.*, 2007; *Serreze et al.*, 2007]. Based on *Vinnikov et al.* [1999] and *Gregory et al.* [2002], the Intergovernmental Panel on Climate Change (IPCC) Assessment Report 4 (AR4) concluded "the decline in Arctic sea ice extent and its thinning appears to be largely, but not wholly, due to greenhouse gas forcing" [*Intergovernmental Panel on Climate Change* (*IPCC*), 2007]. Since AR4, *Stroeve et al.* [2007] reported that observed Arctic sea ice declines have been "faster than forecasted" by AR4 climate models. Both internal variability (variability intrinsic to a climate state) and climate model biases were offered as explanations for this under-prediction of the observed loss, but their relative contributions could not be quantified. *Min et al.* [2008] compared observed 1953–2006 trends with AR4 models and found a detectable anthropogenic influence on trends since the early 1990s. *Winton* [2011, hereafter W11], found substantial internal variability was required to reconcile climate model (AR4 models, Climate Model 3 (CM3)) and observed sea ice sensitivity, defined as the amount of sea ice loss per degree global warming. Interestingly, W11 could not rule out the possibility that the discrepancy between models and observations resulted from internal variability alone.

[3] Both anthropogenic forcing and internal variability have influenced observed sea ice loss, but quantifying their relative importance requires multiple realizations, something only models can provide. Depending on the analyzed climate variable and timescale, ensembles of various sizes are needed to isolate a forced trend. Analyzing epoch differences (2051–2060 minus 2005–2014), *Deser et al.* [2010, hereafter D10], found that more than 25 ensemble members were needed to detect forced Arctic sea level pressure (SLP) trends, while less than 3 ensemble members were needed to detect forced Arctic temperature trends. The number of ensemble members required to detect a forced Arctic sea ice extent trend has not been assessed.

[4] Analyzing climate model ensemble members with different physical parameterizations and biases obscures the influence of internal variability on modeled sea ice trends. Thus, using a single credible climate model to produce multiple 20th century ensemble members and multiple realizations of trends influenced by natural processes alone will improve our understanding of the relative contributions of anthropogenic forcing and internal variability to observed sea ice trends.

[5] Conclusions based on climate models are only as reliable as the underlying model's representation of key processes. The Community Climate System Model version 4 (CCSM4 [*Gent et al.*, 2011]) contains more sophisticated processes and is run at higher resolution (0.9° × 1.25° atmosphere, 1° ocean and sea ice) than almost all the models used for previous Arctic detection and attribution studies. In addition, CCSM4's representation of late 20th century Arctic atmospheric and sea ice processes has been thoroughly evaluated with observations (G. de Boer et al., A characterization of the present-day Arctic atmosphere in CCSM4, submitted to *Journal of Climate*, 2011; A. Jahn et al., Late 20th century simulation of Arctic sea-ice and ocean properties in the CCSM4, submitted to *Journal of Climate*, 2011), and is remarkably good. Despite having a weaker-than-observed Beaufort High and cloud and radiative flux biases, deBoer et al. (submitted manuscript, 2011) report that CCSM4's late 20th century monthly average Arctic surface temperatures biases are small (<2 K). Jahn et al. (submitted manuscript, 2011) find excellent agreement between the observed and CCSM4-modeled seasonal evolution of sea ice extent and spatial ice thickness pattern. Of particular relevance here, observed late 20th century sea ice loss is not "faster than forecasted" by some CCSM4 20th century ensemble members (Figure 1).

[6] We are by no means suggesting CCSM4 is bias free. For example, transient CCSM4 runs have excessive late

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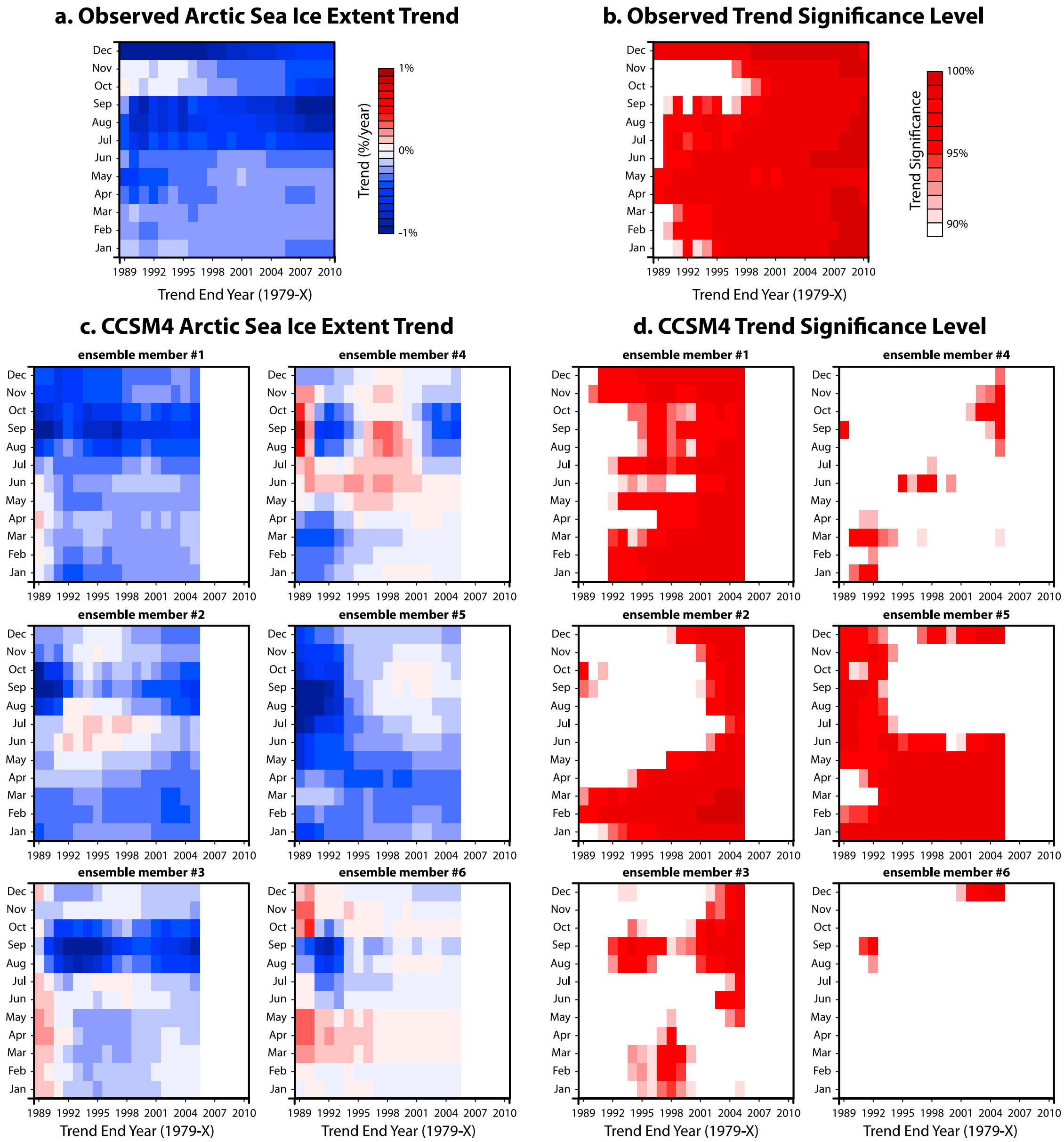

Figure 1. Arctic sea ice extent trends and trend significance level: (a and b) satellite observations and (c and d) six 20th century CCSM4 ensemble members. Trends in each month are calculated over an increasing trend length starting at the beginning of the satellite record (1979) and ending with trend end years ranging from 1990 to 2010. Trend significance level is calculated using the p value from a two-sided student t-test. CCSM4 case names are included in the auxiliary material.

20th century global warming when compared to observations. Thus, like models analyzed by W11, CCSM4 has a smaller decline in Arctic sea ice extent per degree global warming than has been observed. But, CCSM4 offers substantial improvements over models used in previous studies [e.g., see *Moritz and Bitz*, 2000; *IPCC*, 2007], and thus, we argue is a credible modeling tool for this study.

[7] Previous studies imply a long trend is needed to detect a non-natural influence on Arctic sea ice extent trends [e.g., *Min et al.*, 2008; *Vinnikov et al.*, 1999], but the recent record-breaking 2007–2010 observed sea ice loss may have changed this. Increased inter-annual variability has been associated with a thinning ice pack [*Holland et al.*, 2008; *Goosse et al.*, 2009], but no published study has examined trend variability as a function of trend length in a warming world.

[8] Motivated by the above, we use CCSM4 and observations to address the following questions: 1) What is the contribution of internal variability to observed late 20th century Arctic sea ice extent declines?; 2) Is it possible to reproduce modeled and observed late 20th century Arctic sea ice extent trends with natural variability alone?; and 3) How do Arctic sea ice extent trends with lengths ranging from 2 to 40 years change in a warming climate?. An important distinction is made between internal variability, herein defined as variability intrinsic to a climate state, and natural vari-

Table 1. September Arctic Sea Ice Extent Trend Statistics[a]

	Satellite Observations (1979–2010)					Late 20th Century CCSM4 (1979–2005, 20THC_6)			1850 CCSM4 (1300 Years, 1850CNT)			20th Century CCSM4 (1950–2005, 20THC_6)			21st Century CCSM4 (2006–2061, 21STC_6 RCP8.5)		
Trend Length	Min (Before 2005)	Min (Before 2007)	Min	Max	%Pos	Min	Max	%Pos	Min	Max	%Pos	Min	Max	%Pos	Min	Max	%Pos
40 yrs									−0.2	0.2	48%	−0.9	−0.2	0%	−2.6	−0.8	0%
30 yrs			−1.3	−1.2	0%				−0.3	0.4	48%	−1.0	0.1	7%	−3.9	−0.2	0%
20 yrs	*−0.9*	*−1.1*	−2.0	−0.6	0%	−0.9	0.7	14%	−0.7	0.9	49%	−1.4	0.4	57%	−5.1	0.3	5%
10 yrs	*−1.6*	*−2.6*	−3.6	0.2	4%	−4.0	2.5	24%	−1.7	1.8	52%	−4.0	2.5	55%	−13.3	4.7	45%
5 yrs	*−5.4*	*−5.4*	−7.6	2.7	30%	−7.8	7.4	36%	−5.3	4.4	53%	−7.8	7.4	46%	−21.5	16.4	46%
2 yrs	*−15.8*	*−15.8*	−31.7	25.0	48%	−25.6	20.7	58%	−18.4	18.6	47%	−21.9	20.7	49%	−65.0	120.0	49%

[a] All trends are reported in percent/year. Reported values are the most extreme minimum trend (min), the most extreme positive trend (max), and the percentage of all trends that are positive (%pos).

ability, herein defined as variability resulting from internal variability and external forcing during the pre-industrial era (1000–1850). During the 20th and 21st centuries, internal variability is not entirely natural because anthropogenic forcing alters the sea ice mean state and thus, the sea ice extent variability.

2. Methods

[9] All reported trends are linear trends in units of percent per year, where the percent is relative to the mean value of the data used to compute the trend. The implications for reporting trends in units of million square km per decade are also assessed in the text (see also auxiliary material).[1] While we examined trends in all months, we focus on September, the month during which the Arctic is predicted to first become seasonally ice-free. We calculated observed trends using satellite-derived monthly Arctic sea ice extents from 1979 to 2010 [*Meier et al.*, 2006]. Hemispheric sea ice extent observations prior to the satellite period (1979–present) are limited [*Polyak et al.*, 2010; *Johannessen et al.*, 2004]. We estimated the observed 1953–2006 September ice extent decline using HadISST1 data [*Rayner et al.*, 2003] and *Meier et al.*'s [2007] data for one trend comparison, but we emphasize that this trend is more uncertain than trends from the satellite period.

[10] Over 4000 years of CCSM4 integrations were used to calculate trends for this study. Natural trends were derived from a 1300-year long control run with constant 1850 forcing (1850CNT) and from an 850-year long last millennium run with transient forcings applied from 1000 to 1850 (LM) (L. Landrum et al., Last millennium climate and its variability in CCSM4, submitted to *Journal of Climate*, 2011). We found similar September trend variability in 1850CNT and LM. Late 20th century trends were calculated from a 6-member 20th century ensemble with all transient forcings applied from 1850 to 2005 (20THC_6), the same ensemble analyzed by Jahn et al. (submitted manuscript, 2011). We also examined late 20th century trends from 2-member ensembles with a subset of the transient forcing applied from 1850 to 2005: a natural (volcano and solar) forcing only ensemble (20THC_NAT_2), and an anthropogenic (greenhouse gas, ozone, and aerosol) forcing only ensemble (20THC_ANTHRO_2). Finally, we examined 21st century trends in a 6-member ensemble with the Representative Concentration Pathway (RCP) scenario RCP8.5 (21STC_6). The RCP8.5 scenario has a top-of-atmosphere radiative forcing of 8.5 $\mathrm{Wm^{-2}}$ at 2100, and was selected because it is the only RCP scenario that projects continued greenhouse gas increases with no mitigation. 21st century trends were calculated through 2061, the year when the first CCSM4 ensemble member became seasonally ice-free (<1 million $\mathrm{km^2}$ in September).

[11] To evaluate CCSM4's representation of sea ice extent variability, we compared observed and CCSM4 September trends during the late 20th century (Table 1). Though individual 20THC_6 ensemble members have trends of comparable magnitude and significance to the observations, most do not (Figure 1). It is therefore not surprising that CCSM4 has positive 20-year trends during 1979–2005, while all of the observed 20-year trends during 1979–2010 are negative. Similarly, both CCSM4 and the observations have positive 5-year and 10-year trends during the late 20th century, but the positive CCSM4 trends are larger and occur more frequently than the positive observed trends. Finally, interannual variability is similar in CCSM4 and the observations. Given the short observational record and the spread in CCSM4 ensemble member trends, it is hard to draw strong conclusions, especially about multi-decadal variability, but CCSM4 does appear to have reasonable trend variability when compared to available observations.

3. Results

[12] We begin with contour plots of observed monthly Arctic sea ice extent trends starting in 1979 with variable end years ranging from 1990 to 2010 (Figure 1). Observed extent declines occur in all months and are robust to trend end year (Figure 1a). The observed negative trends are highly statistically significant as indicated by the large p values from two-sided student t-tests (Figure 1b). The corresponding 20THC_6 contour plots reveal a large spread in CCSM4-projected late 20th century trends and individual trend significance (Figures 1c and 1d). Ensemble member #1 has sea ice extent loss approaching the observed magnitude and sustained trend statistical significance, but most ensemble members have less sea ice extent loss than the observations. A strong influence of decadal variability on the modeled trend sign and strength is apparent. Assuming this 6-member CCSM4 ensemble provides a robust assessment of the plausible spread in late 20th century trends, Figure 1 suggests

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL048008.

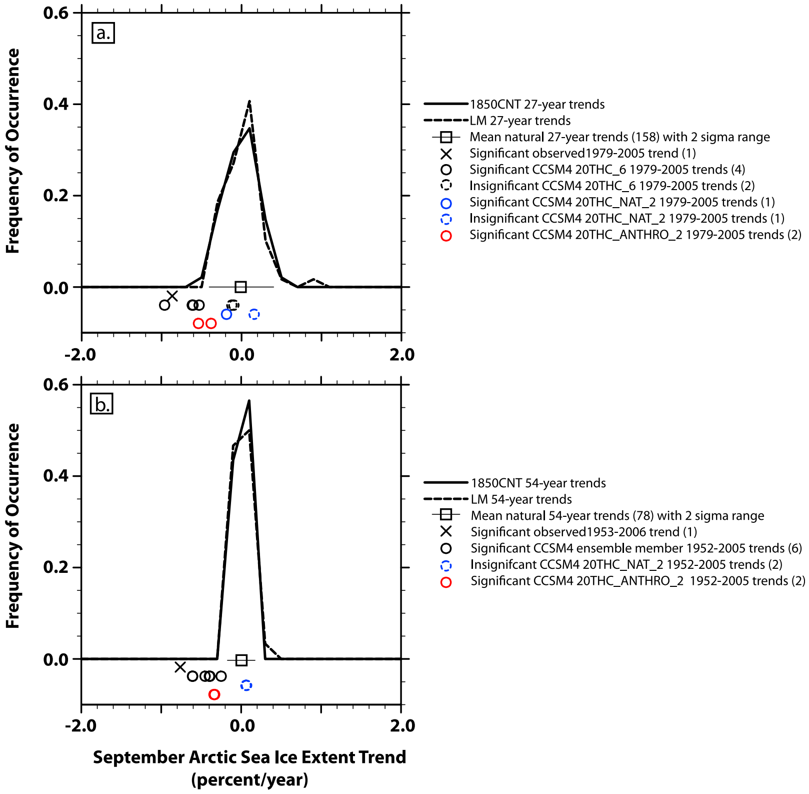

Figure 2. Observed and CCSM4 September Arctic sea ice extent trend occurrence: (a) 27-year trends and (b) 54-year trends. The trend sign significance reported in the labels is based on a student t-test with a 95% confidence level. The number of trends is indicated in parentheses. The observed 1979–2005 trends are from *Meier et al.* [2006]. The observed 1953–2006 trends measured in percent per year from *Meier et al.'s* [2007] and *Rayner et al.'s* [2003] datasets are similar, −0.75 and −0.76 respectively.

that observed Arctic sea ice extent loss has been enhanced by internal variability.

[13] For the remainder of this study, we focus exclusively on September Arctic sea ice extent trends and we use a 95% confidence level for all statistical significance tests. We first address if the observed and modeled late 20th century trends are statistically different than trends produced by modeled natural variability alone. This analysis provides a more robust test of the statistical significance than t-tests based on individual trends (e.g., as in Figure 1) because it uses a physical model to statistically discriminate between trend populations. To estimate natural trend variability, we use independent trend samples from 1850CNT and LM.

[14] We first compare 27-year trends. For the late 20th century, we calculate 1979–2005 trends because the 20th century CCSM4 runs end in 2005 and because 2005 predates the 2007–2010 acceleration in observed ice extent loss. Figure 2a shows that the observed 1979–2005 27-year trend (−0.87%/year) is outside the two standard deviation (sigma) range of the natural trend distribution. In other words, the observed 1979–2005 September ice extent trend cannot be explained by modeled natural 27-year trend variability.

[15] Consistent with Figure 1c, the September 1979–2005 trends in 20THC_6 are all negative, but have a large spread in their absolute magnitude. Following D10 and not assuming a trend sign, four ensemble members are required to detect a forced 1979–2005 trend. Thus, even though two of the six ensemble members have statistically insignificant trends, the 20THC_6 ensemble is consistent with the detection of a forced negative 1979–2005 trend. Along the same lines, even though the 20THC_NAT_2 trends bracket zero, and the 20THC_ANTHRO_2 trends are negative, the two-member single-forcing ensembles are insufficient to detect a forced 1979–2005 trend. Using the natural variability as a guide to the approximate magnitude of the 20th century internal variability, it is clear that the two-member single forcing ensembles under-sample the 20th century internal variability. In contrast, comparison of 20THC_6 and natural trend spread shows that 20THC_6 provides a plausible, albeit minimal, estimate of the 20th century internal variability.

[16] Division of the ensemble mean CCSM4 1979–2005 trend (−0.49%/year) by the observed 1979–2005 trend (−0.87%/year) implies that approximately half (56%) of the observed September trend is externally forced and approximately half results from internal variability. Though the forced contribution is similar to the 47–57% range reported by *Stroeve et al.* [2007] for 1979–2006 September trends, our estimate relies on an ensemble from a single vetted model instead of an ad hoc mix of AR4 models that have varying skill at simulating present-day Arctic sea ice conditions, and sample trend uncertainty due to both model physics and internal variability. Based on the spread in the CCSM4 20th century trends resulting from internal variability, it is plausible that if internal variability had counteracted the anthropogenic forcing, we would have seen

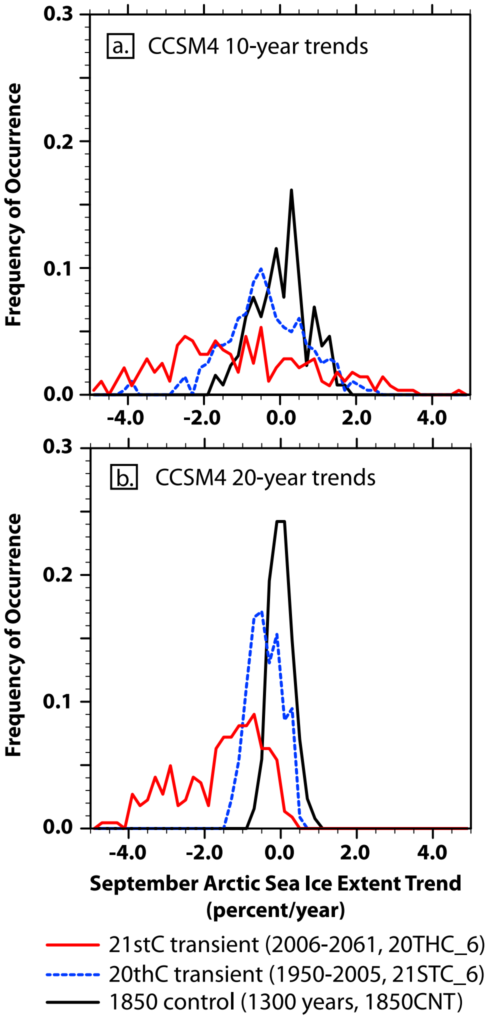

Figure 3. Changing CCSM4 September Arctic sea ice extent trend distributions as the climate warms from the 19th century through the 21st century: (a) 10-year trends and (b) 20-year trends. 20th and 21st century trends are calculated from 6 CCSM4 ensemble members using a moving trend window. Independent 1850 trends are calculated from a 1300-year long control run with constant 1850 forcing.

little or no 27-year trends in Arctic sea ice over the satellite era (e.g., ensemble member #6 in Figure 1).

[17] We next double the trend length and examine 54-year long trends in Figure 2b. While we have less confidence in the observed 1953–2006 trend, it is well outside any model-simulated natural 54-year trend variability. A t-test applied to the individual trends shows that all six 20THC_6 ensemble members have statistically significant negative 1952–2005 trends. Applying the more robust test of comparing the late 20th century trends to the trends produced by natural variability alone, all of the ensemble members in 20THC_ANTHRO_2 and 20THC_6 have negative trends that exceed the two sigma range of modeled natural 54-year trends. Individual 20THC_NAT_2 trends are not statistically significant and are within the modeled natural 54-year trend variability. Not making an assumption about trend sign, only one ensemble member is required to detect a forced 54-year trend. Figure 2 demonstrates that the anthropogenic influence on observed and modeled sea ice trends is stronger for 54-year trends than it is for 27-year trends.

[18] In summary, our detection and attribution analysis with CCSM4 reaffirms the IPCC AR4 assessment. It is impossible to reproduce *observed* and *modeled* multi-decadal 20th century declines in Arctic sea ice with modeled natural variability alone. But, we find a strong influence of internal variability on *modeled* late 20th century trends, especially as the trend length decreases.

[19] To understand trend variability as a function of trend length, we further compare 1979–2010 observed and CCSM4 trends. Because trend start and end dates are often selected for comparison with a specific dataset (e.g., as we have done in Figure 2), we compute 20th and 21st century trends over all possible permutations of start and end year.

[20] Table 1 compares observed and modeled trends ranging in length from 2 to 40 years. As trend length decreases, trend variability increases. Regardless of trend length, the most extreme observed negative trends exceed the modeled natural trend variability. The most extreme observed trends result from the 2005–2010 ice loss. Before 2007 (2005), a 10-year trend (20-year trend) was needed to exceed the modeled natural trend variability.

[21] Finally, to assess how trend variability changes in a warming world, we compare pre-industrial, 20th century, and 21st century CCSM4 trend variability for trends ranging in length from 2 to 40 years (Table 1 and Figure 3). As the climate warms from the 19th through the 21st century, negative trends of all lengths increase in magnitude. In addition, variability in 2-year, 5-year, and 10-year September Arctic sea ice extent trends increases. In other words, both positive and negative sub-decadal trend magnitude increases in a warming world. During the second half of the 20th century, negative trends are more common than positive trends once trend length exceeds 20 years. During the first half of the 21st century, positive trends lasting longer than 10 years are rare (<5% of all 20-year trends).

[22] When trends are reported in million sq. km per decade, the described results are robust with two exceptions: 1) increasing trend variability on a 2–10 year timescale in a warming climate is muted, and 2) observed negative trends during 1979–2010 on 2-5 year timescales are not outside the natural variability (see auxiliary material). These exceptions occur because the same absolute change produces a larger percent change for less extensive ice than for more extensive ice.

4. Discussion and Summary

[23] Consistent with AR4, this analysis demonstrates that observed and modeled late 20th century Arctic sea ice loss cannot result from natural variability alone. Indeed, an anthropogenic influence on the most extreme observed 1979–2010 negative trends is now evident for all trend lengths examined (2–54 years). While CCSM4 can reproduce the observed ice loss, it also shows that internal variability exerts a strong influence on sea ice trends, especially on sub-20 year timescales. Comparing a six-member CCSM4 ensemble to observed trends suggests that internal variability has enhanced observed ice loss and facilitated detection of an anthropogenic influence on observed trends during the satellite era (1979-present). In a warming world, multi-decadal negative trends increase in frequency and magnitude, trend

variability on 2–10 year timescales increases, and when internal variability counteracts anthropogenic forcing, positive trends frequently occur on 2–20 year timescales in the second half of the 20th century, and on 2–10 year timescales in the first half of the 21st century.

[24] Climate models are the primary tools we have to quantify the contribution of internal variability to observed trends, and to assess if observed trends are outside the natural variability. The conclusions we draw are only as reliable as the underlying climate model processes. Only four ensemble members were needed to detect a forced September sea ice extent trend over the satellite period with CCSM4 (1979–2005), but going beyond detecting a forced trend to quantify the relative contributions of internal variability and anthropogenic forcing requires as many ensemble members as possible. The six ensemble members analyzed here are more than have been analyzed in previous studies, but we do not know if they are statistically representative. As large ensembles from credible models become available, the robustness of results presented here should be further evaluated.

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