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Key Points:
- Internal variability can drive Antarctic sea ice area expansion, even as atmospheric CO_2 rises
- Such Antarctic sea ice expansion can occur when a global climate model is started from a warm Southern Ocean state
- Over interannual to (short) multidecadal time scales, regional trends in Antarctic sea ice area are dominated by internal variability

Supporting Information:
- Supporting Information S1

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Antarctic Sea Ice Expansion, Driven by Internal Variability, in the Presence of Increasing Atmospheric CO_2

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Abstract A number of physically based hypotheses have been proposed to explain the surprising expansion of Antarctic sea ice area (SIA) over the satellite era (1979 to 2015). Here, we use a fully coupled state-of-the-art global climate model to show that internal variability alone can produce such multidecadal periods of Antarctic SIA expansion even as atmospheric CO_2 increases at observed rates and the planet warms. When our model is started from a relatively warm Southern Ocean state, Antarctic SIA sometimes (in one of three ensemble members) expands over multidecadal time scales at a rate comparable to that over the satellite era. SIA expansion occurs concurrently with rising atmospheric CO_2 and warming global surface temperatures, and SIA trends by region and sector resemble those over the satellite era. Our results suggest that internal variability over long time scales in the Southern Ocean region may suffice to explain Antarctic SIA expansion over the satellite era.

1. Introduction

As rising atmospheric CO_2 warms the planet, polar sea ice is expected to retreat as global surface temperatures increase. This expected outcome has been observed in the Arctic, where sea ice has declined rapidly (in both area and volume) over the last 40 years (Stroeve et al., 2012). In the Antarctic, on the other hand, sea ice area (SIA) has been expanding at the modest, but statistically significant, rate of 0.2 million km^2 per decade over much of the observational era (Jones et al., 2016; Parkinson & Cavalieri, 2012; Simmonds, 2015). This observed increase in Antarctic SIA—in defiance of expectations given the rise in radiative forcing from increased atmospheric CO_2—has triggered a flurry of research activity to identify a plausible mechanism for such a paradoxical phenomenon.

Several hypotheses have been proposed to explain this paradox. Stratospheric ozone loss over the Antarctic was initially posited to drive SIA expansion by strengthening of the surface westerlies over the Southern Ocean (Turner et al., 2009); later modeling work, however, showed that stratospheric ozone loss causes SIA decline, not expansion, by augmenting poleward heat convergence by upwelling and oceanic eddies (Bitz & Polvani, 2012; Sigmond & Fyfe, 2010; Solomon et al., 2015). Others posited that increased freshwater input over the Southern Ocean (caused by increased ice shelf melt, for example) could instigate SIA expansion by stabilizing the water column (Bintanja et al., 2013); follow-up studies, however, demonstrated that the amount of freshwater input required for such water column stabilization is at least an order of magnitude greater than that estimated to arise from hydrological cycle amplification and ice shelf melt over the observational period (Pauling et al., 2016; Swart and Fyfe, 2013).

Because such mechanistic hypotheses do not appear viable, an appealing alternative is to attribute observed Antarctic SIA expansion to internal variability in the Earth system. Long preindustrial control integrations of many state-of-the-art global climate models (GCMs) contain multiple multidecadal time periods over which Antarctic SIA expands at a rate comparable to that in the observations, suggesting that such observed SIA expansion could arise through internal variability (Polvani & Smith, 2013). However, analyses of historical (1850 to 2005) runs from Phase 5 of the Climate Model Intercomparison Project show that multidecadal Antarctic SIA expansion occurs only rarely during the past few decades (Zunz et al., 2013) and even the few model runs that simulate expanding SIA do not correctly reproduce the seasonal spatial patterns of sea ice trends found in the observations (Turner et al., 2015). Furthermore, one of the largest single model initial condition historical ensembles, the 40-member Community Earth System Model (CESM1) Large Ensemble, did not produce a single member with expanding Antarctic SIA over the observational period (Kay et al., 2015; Rosenblum & Eisenman, 2017).

While initial condition ensembles might be expected to sample the full range of shorter time scale internal variability in a GCM, variability over longer time scales may plausibly be undersampled, particularly in models that display ocean-driven multidecadal fluctuations in the SH (see, e.g., Martin et al., 2013). Recently, Zhang et al. (2019) proposed that such oceanic variability may provide a reasonable explanation for observed Antarctic SIA expansion. They found that when subjected to historical forcings, the fate of Antarctic SIA over the observational period in their GCM depended sensitively on the initial state of the ocean from which the run was initialized: Model runs that were initialized from ocean states with weak or average Southern Ocean convection experienced Antarctic SIA decline (as would be expected with increasing radiative forcing over the historical period), while model runs that were initialized from ocean states with strong Southern Ocean convection experienced vigorous Antarctic SIA expansion. Seasonal and spatial trends in Antarctic SIA from the latter runs resembled those seen in the observational era.

While the hypothesis of Zhang et al. (2019) is compelling, their GCM runs were initiated from extreme Southern Ocean convective states, with overturning in the oceanic Deep Cell in the range of 3 to 20 Sv in their ensemble members. Regardless of whether such variability in Southern Ocean convection is realistic, indirect assessments of Antarctic SIA prior to the observational era hint at a decline in SIA over the earlier part of the twentieth century (Fan et al., 2014), and possibly a minimum (de la Mare, 1997), suggesting that SIA expansion over the observational era may have occurred as SIA rebounded from a climatologically low state. The question then arises as to whether models with less extreme patterns of ocean variability (than the one used by Zhang et al., 2019) are capable of producing Antarctic SIA expansion concurrent with rising radiative forcing from increasing atmospheric CO_2 if they are simply started from a climate state in which sea ice is low.

In this study, we provide one such example. We use the fully coupled CESM1, a state-of-the-art GCM, to demonstrate that internal variability can drive Antarctic SIA expansion, even as atmospheric CO_2 rises and global surface temperatures increase. In a three-member ensemble initiated from a warm Southern Ocean state and subjected to rising atmospheric CO_2, we find that Antarctic SIA expands over a multidecadal time period in one out of three members. We show that internal variability in total Antarctic SIA, and over individual sectors, is very substantial, notwithstanding identically rising radiative forcing in all three ensemble members. Our results suggest that internal variability in the coupled atmosphere-ocean-ice system can overwhelm the forced response to increasing atmospheric CO_2 at present-day rates. They provide further evidence that internal variability is the most parsimonious explanation for Antarctic SIA expansion over the observational period.

2. Methods

We employed the fully coupled CESM1 (Hurrell et al., 2013) with the CAM5 atmosphere (Neale et al., 2012), fully dynamic CICE4 sea ice (Hunke and Lipscomb, 2008), the POP2 ocean (Danabasoglu et al., 2012) with parameterized subgrid ocean eddies (Gent and McWilliams, 1992), and CLM4 land (Oleson et al., 2010). All model components were nominally at 1° spatial resolution and were configured identically to those employed in the CESM1 Large Ensemble project (Kay et al., 2015).

Years 800 to 2000 of the CESM1 Large Ensemble Control run (hereafter LE Control; Kay et al., 2015, atmospheric CO_2 was fixed at 284.7 ppm) was used to assess the range of internal variability characteristic of the model preindustrial climate and to identify ocean states that preceded periods of prolonged Antarctic SIA expansion. We used linear regression to identify 40-year periods when (annual mean) Antarctic SIA expanded more rapidly than the rate estimated for the observational era (0.2 million km^2 per decade over 1979 to 2015).

To select the initial state for our CO_2-ramping three-member ensemble (hereafter "CO2Ramp"), we identified a point in the CESM1 LE Control that most closely matched the following criteria: Antarctic SIA was at a local minimum and at a near-global minimum (at least 1.5 standard deviations below its climatological value), qualitatively similar to the inferred SIA minimum prior to the satellite era (Fan et al., 2014); from

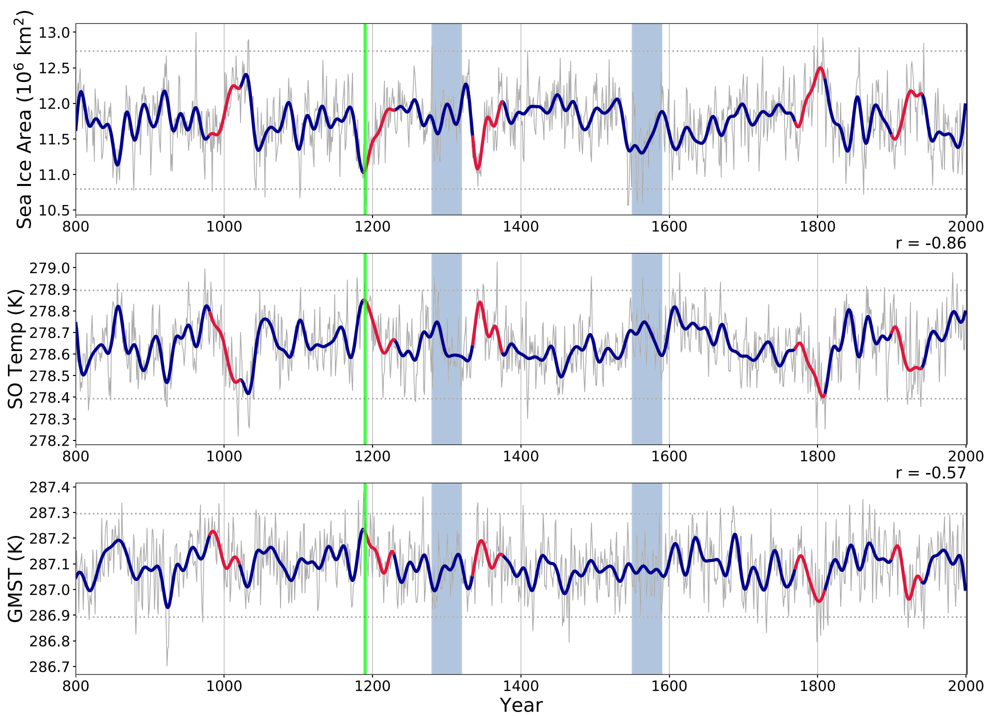

Figure 1. Internal variability over 1,200 years of the CESM1 Large Ensemble Control (LEControl): (a) annual mean Antarctic SIA (10^6 km^2); (b) annual mean Southern Ocean SST (from 45° S to 60° S; K); and (c) and annual global mean surface temperature (GMST; K). Thin gray lines show the annual mean time series, with 2 standard deviations above and below the mean indicated (dotted gray). Thick lines show the 10-year low-pass filtered time series (filtered using a ten-year Lanczos filter with 11 weights; see Duchon, 1979), with five 40-year time periods over which Antarctic SIA expands at a rate greater than that in observations (1979–2015) drawn in red. Highlighted blue areas indicate 30-year periods during which Antarctic SIA and Southern Ocean SSTs trends are in the same sense (i.e., increasing SIA and decreasing SSTs), but trends in GMST are in the opposite sense (see text). The year from which CO2Ramp ensemble members are branched, 1190, is indicated in all panels (green vertical line).

that point, Antarctic SIA expanded for 40 years at a rate greater than its expansion over the observational era; and restart files were available at that point. The year 1190 closely satisfied all three criteria, and three CO2Ramp ensemble members were branched from this initial state (with small perturbations to the atmospheric initial state using the CAM5 "pertlim" parameter) and run for 40 years. In each CO2Ramp member, atmospheric CO_2 was increased by 0.6%/year, approximately equal to the linear rate of CO_2 increase over Years 1985 to 2000 (Mauna Loa Observatory data, NOAA ESRL; Tans and Keeling, 2019).

We compared SIA evolution in our CO2Ramp runs to observations of Antarctic SIA from 1979 to 2018, collected through passive microwave satellite retrieval and processed through NASA Team and bootstrap algorithms (the merged GSFC NASA Team/Bootstrap monthly sea ice concentration dataset; Cavalieri et al., 1996, updated yearly, accessed Jan 2019). Global mean surface temperature (GMST) over the same time period was obtained from the NASA GISS Land-Ocean Temperature Index (LOTI; GISTEMP Team, 2016 Dataset accessed 2019-01-15; Hansen et al., 2010).

3. Antarctic Sea Ice Variability in the CESM1 LE Control

In the CESM1 LE Control, Antarctic SIA exhibits significant interannual fluctuations (Figure 1a, gray lines). The standard deviation of the annual mean SIA is approximately 0.5 million km^2 (for a 2.0 million km^2 2 standard deviation envelope; see dotted horizontal lines in Figure 1a). That such variability spans a range of time scales is evident in the 10-year low-pass filtered time series (Figure 1a, thick lines), which reveals several multidecadal to centennial time periods over which Antarctic SIA expands and contracts.

Over these 1,200 years of the CESM1 LE Control integration, we find five 40-year periods over which Antarctic SIA expands at a (linear) rate that exceeds that in the observations (0.2 million km^2 per decade from 1979 to 2015), an average of one 40-year period every 240 years (Figure 1a, red segments). As Antarctic SIA

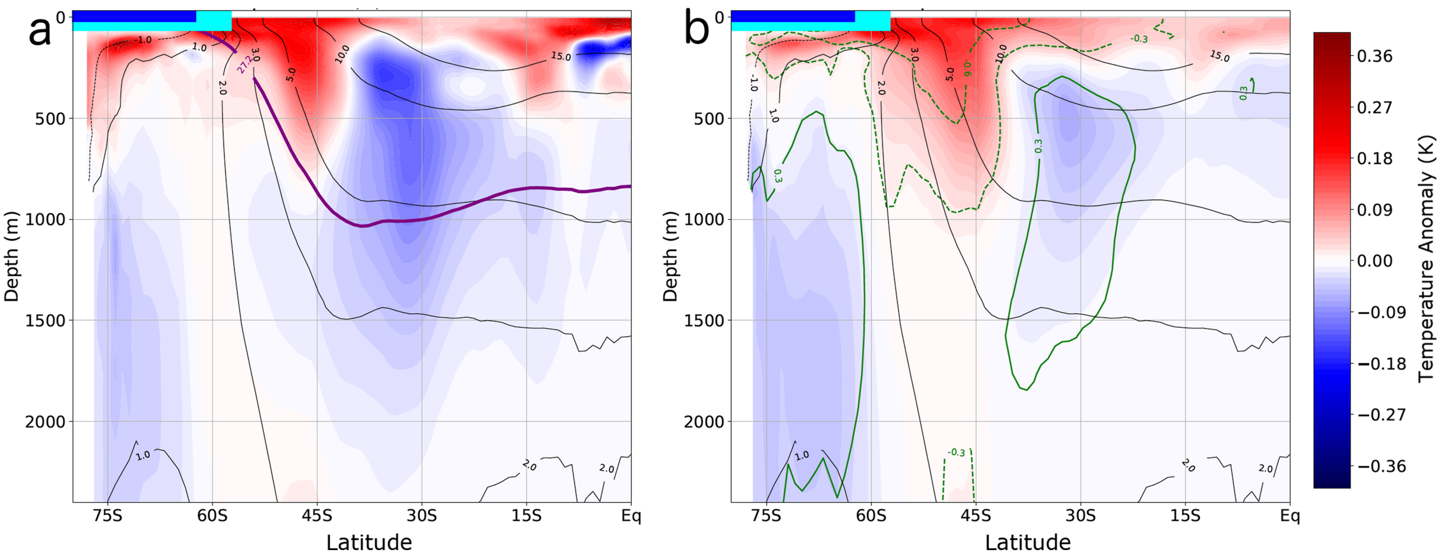

Figure 2. Ocean temperature anomaly (colors; K) when Antarctic SIA is low in the CESM1 LE Control: (a) at Year 1189 (with the 27.2σ isopycnal surface; thick purple contour) and (b) regressed on the Antarctic SIA, shown at two standard deviations below the climatological mean (the correlations for the regression are shown as green contours at $r = [-0.6, -0.3, 0.3]$). Annual mean temperatures (black contours) are shown in both panels. Sea ice extent (the mean latitude of the 0.15 ice fraction contour) in DJF (dark blue) and JJA (cyan) is shown (a) at Year 1189 in the CESM1 LE Control and (b) regressed on SIA in the CESM1 LE Control at two standard deviations below the climatological mean.

expands, Southern Ocean SSTs concurrently cool (cf. Figures 1a and 1b, red segments). The close relationship between Southern Ocean SSTs and Antarctic SIA is evident in the strong correlation between their filtered time series ($r = -0.86$).

Whereas Southern Ocean SSTs and Antarctic SIA evolve together, GMST only co-evolves with Antarctic SIA some of the time ($r = -0.57$ for the filtered time series; Figure 1c). That Antarctic SIA and GMST need not necessarily evolve together is evident in the two 30-year periods highlighted (Figure 1, light blue shading): While Antarctic SIA is expanding and Southern Ocean SSTs are cooling during both periods, GMST is either rising (first period ca. Year 1300), or holding steady (second period ca. Year 1550). The former is qualitatively similar to the observations from 1979 to 2015, when Antarctic SIA expanded with cooling Southern Ocean SSTs, but GMST rose steadily (Cavalieri et al., 1996, updated yearly; GISTEMP Team, 2016, Dataset accessed 2019-01-15).

The simplest explanation for multidecadal Antarctic sea ice variability in the CESM1 LE Control is thermal coupling between the atmosphere, ocean mixed layer, and sea ice, similar to that described by Bitz et al. (1996): Long time scales emerge in this coupled system as the sea ice and ocean mixed layer integrate high-frequency atmospheric noise. Variability in the surface westerly winds, often referred to as the Southern Annular Mode, also drives decadal variability in Antarctic SIA in the CESM1 (Holland et al., 2017). Variability in the ocean circulation can arise from (and amplify) low-frequency variability due to thermal coupling but is not necessary to initiate it (see, e.g., Barsugli & Battisti, 1998). That variability in Antarctic SIA in the CESM1 can be understood to arise primarily from the thermal coupling in the atmosphere-ocean-ice system, rather than variability in the ocean circulation, is further supported by the very weak interannual variability in Southern Ocean deep convection in the CESM1 (Behrens et al., 2016).

Indeed, significant Southern Ocean temperature anomalies always accompany Antarctic SIA extrema. To demonstrate this, we examine the Year 1189 in the CESM1 LE Control (Figure 1, green line), which precedes a multidecadal period of vigorous SIA expansion (a SIA increase of nearly 1 million km^2 from Years 1189 to 1228). In that year, Antarctic SIA is roughly 1.5 standard deviations (0.7 million km^2) below its climatological mean value, and Southern Ocean SSTs are 1.5 standard deviations (0.2 K) warmer. Warm ocean temperature anomalies extend well below the surface, with the top 200 m of the Southern Ocean (up to 40° S) at least 0.15 K warmer than climatology (Figure 2a). Warm anomalies are greatest near 60° S, and warming extends to 800-m depth into the ocean interior ≈50° S as temperature anomalies are readily transported downwards by subgrid scale eddies along sloping isopycnals (Figure 2a; 27.2σ isopycnal contour shown for reference, purple line). Cool anomalies are also evident at depths below these warm anomalies. Inspection of the 20-year period prior to Year 1189, when Antarctic SIA was declining toward its Year 1189 minimum, shows that these warm upper ocean temperature anomalies, and the accompanying cool ocean interior temperature anomalies, evolve concurrently with SIA: Warm surface anomalies appear and amplify as sea ice retreats in the years preceding 1189, while cold surface anomalies (characterizing previous periods with extensive SIA) are transported into the ocean interior by the general circulation (see Figure S1 in the supporting information).

When ocean temperatures are regressed on Antarctic SIA and are evaluated when SIA is 2 standard deviations below its mean value, a very similar pattern of ocean temperature anomalies emerges to that found at Year 1189 (Figure 2b): warm anomalies in the upper Southern Ocean and extending to depth ≈50° S and cold anomalies in the interior below. The strongest correlations between Antarctic SIA and ocean temperatures are found near the Southern Ocean surface (above 400 m, and poleward of 40° S), though statistically significant relationships extend below 2000-m depth at some latitudes (Figure 2b, green contours). Neither salinity nor density have statistically significant relationships with Antarctic SIA (see Figures S2 and S3), further suggesting that Antarctic SIA variability in the CESM1 can be understood as arising primarily through thermal coupling between the atmosphere, sea ice, and ocean mixed layer. This contrasts with the model employed by Zhang et al. (2019), in which Antarctic SIA variability was generated in the preindustrial climate by order-of-magnitude, multidecadal fluctuations in the strength of Southern Ocean deep convection.

4. Antarctic SIA Expansion in the CESM1 CO2Ramp Ensemble

We now examine how Antarctic SIA evolves in the CO2Ramp ensemble, where the CESM1 is restarted from the warm Southern Ocean state found at Year 1189 of the CESM1 LE Control and where atmospheric CO_2 is increased monotonically at historical rates (see section 2 for details). As seen in Figure 3a, in the first year, Antarctic SIA in all CO2Ramp Ensemble Members (CO2Ramp EM1, EM2, and EM3) is at least 1 standard deviation below CESM1 LE Control climatological values (three blue lines at green vertical line). Antarctic SIA subsequently recovers rapidly in CO2Ramp EM1 and EM2, rising above its CESM1 LE Control climatological value within 5 years (Figure 3a, dotted and dash-dotted blue lines). Following this initial rapid recovery, Antarctic SIA first stabilizes and then slowly begins to decline in both CO2Ramp EM1 and EM2, presumably in response to rising radiative forcing with CO_2 ramping.

In contrast to the rapid recovery of Antarctic SIA in CO2Ramp EM1 and EM2, SIA slowly expands for a period of 27 years in CO2Ramp EM3, at a rate only slightly greater than that in the CESM1 LE Control (0.25 million km^2 per decade in CO2Ramp EM3 vs. 0.21 million km^2 per decade in the CESM1 LE Control from Years 1190 to 1229; Figure 3a, compare solid blue and gray lines; dashed blue and gray lines show the respective best fit lines). The rate of Antarctic SIA expansion in CO2Ramp EM3 also exceeds the rate of SIA expansion in the observations (from 1979 to 2015, when the trend was positive; Figure 3b), though the trend in the observations lasts longer by about one decade (37 years in the observations vs. 27 years in the CO2Ramp EM3). Concomitant with Antarctic SIA expansion in CO2Ramp EM3, GMST increases at a rate of 0.15 K/decade, similar to the 0.17 K/decade rate of GMST increase in the observations (Figure 3c). Table 1 summarizes these periods of Antarctic SIA expansion in the CESM1 LE Control, CO2Ramp EM3, and observations. We are well aware that direct comparison between CO2Ramp EM3 and observations must be done with caution, as the observed evolution of sea ice and temperature may be caused, in part, by other natural and anthropogenic forcings that are not included in our CO2Ramp runs. Nonetheless, to the degree that CO_2 is the largest driver of climate change, it is not inappropriate to compare our CORamp runs with the observations.

Following this relatively long period of expansion, Antarctic SIA in CO2Ramp EM3 declines over the final decade of the run to terminate 2 standard deviations below climatological SIA in the CESM1 LE Control (Figures 3a and 3b). This decline is suggestive of the decline in Antarctic SIA in the most recent observational period (2016 to 2018; Figure 3b), though the length of the satellite record is too short to determine whether observed SIA has dropped below its preindustrial climatological mean as it has in CO2Ramp EM3. In both CO2Ramp EM3 and recent observations, the rapid decline in Antarctic SIA might be attributable to rising radiative forcing overwhelming internal variability or may represent further Antarctic SIA fluctuations with internal variability. That Antarctic SIA has dipped more than 2 standard deviations below the climatological

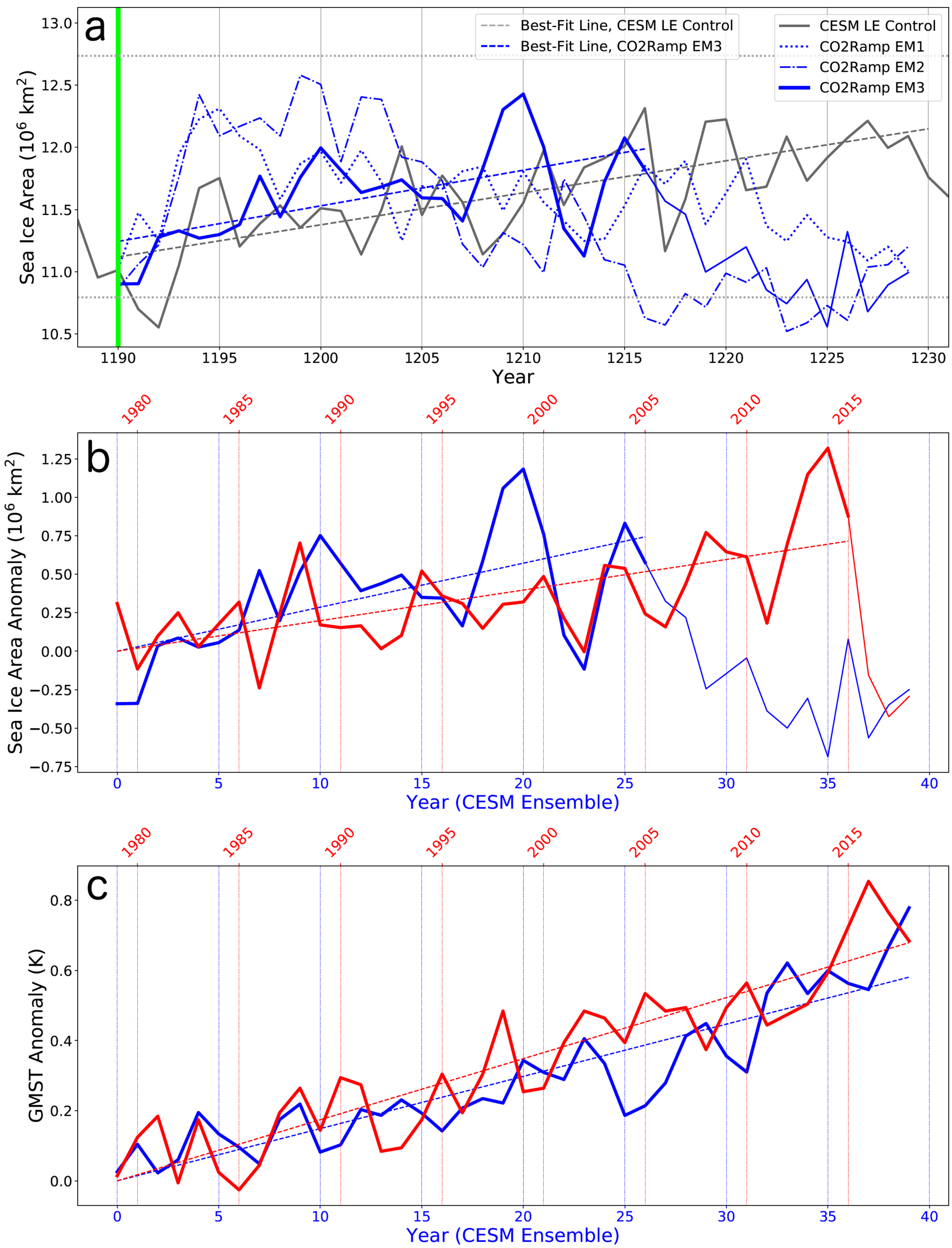

Figure 3. Antarctic ice area and GMST evolution in the CO2Ramp ensemble members: (a) Antarctic ice area in all 3 CO2Ramp ensemble members (blue lines; solid blue line is ensemble member 3, with best fit line over Years 0 to 26 shown in dashed blue) and in the CESM1 LE Control (gray; best fit line over Years 1190 to 1229 shown in dashed gray; vertical green line denotes the year from which all CO2Ramp ensemble members were branched); (b) Antarctic SIA anomaly in CO2Ramp EM3 (blue; best fit line over years 0 to 26 in dashed blue) and in the observational record (red; best fit line over 1979 to 2015 in dashed red); (c) GMST anomaly in CO2Ramp EM3 (blue; best fit line over Years 0 to 39 in dashed blue) and in observations (red; best fit line over Years 1979 to 2018 in dashed red).

Table 1
Comparison of Multidecadal Periods of SIA Expansion in the CESM1 LE Control, CESM1 CO2Ramp Ensemble Member 3, and the Observations (Years 1979 to 2015)

	Rate of CO_2 Increase (%/year)	AA SIA Trend (10^6 km^2/decade)	Period of SIA Increase (years)	GMST Trend (K/decade)
CESM1 LE Control				
Yrs 1190 - 1229	None	0.25	40	−0.03
CESM1 CO2Ramp				
Ensemble Member 3	0.6	0.29	27	0.15
Observations,				
Yrs 1979 - 2015	0.6	0.20	37	0.17

Note. Rate of CO_2 increase, trend in Antarctic sea ice area (AA SIA), length of time during which SIA expanded, and trend in global mean surface temperature (GMST).

mean in only two out of three CO2Ramp ensemble members (Figure 3a, between Years 35 and 40) suggests that internal variability continues to play a large role in Antarctic sea ice variability in the CESM1 even after atmospheric CO_2 has been rising for several decades.

Inspection of the spatial pattern of Antarctic sea ice trends in the three CO2Ramp ensemble members (Figure 4) highlights how significantly internal variability impacts Antarctic SIA evolution, even with rising radiative forcing and increasing GMST. While each of the three CO2Ramp ensemble members is forced identically with rising atmospheric CO_2, each displays a very different spatial pattern of trends in Antarctic SIA (over the first 27 years of the integration; Figures 4a–4c) with distinct seasonality (Figures 4e–4g, 4i–4k, 4m–4o, and 4q–4s). This internal variability in the CO2Ramp ensemble suggests that there are few robust spatial patterns of SIA expansion or decline that characterize the Antarctic sea ice response to increased radiative forcing over a timespan of a few decades and that differing trends in different sectors mostly arise through internal variability in the CESM1.

Surprisingly, we find that the spatial pattern of annual mean SIA trends in the observations closely resembles the spatial pattern in CO2Ramp EM3 (cf. Figures 4c and 4d). This is particularly evident in DJF (Figures 4g and 4h) and MAM (Figures 4k and 4l), where SIA expands around much of the Antarctic continent but declines in the Amundsen and Bellinghausen Seas in both the observations and CO2Ramp EM3. In JJA, SIA expands more robustly about the Antarctic continent in CO2Ramp EM3 than in the observations, but both exhibit a decline in SIA near the West Antarctic peninsula (Figures 4o and 4p). Because such regional trends in SIA are not common to all three CO2Ramp ensemble members, though all experience the same radiative forcing, these modeled trends must be due to internal variability. By extension, we deduce that observed regional trends in Antarctic SIA need not be a robust forced response to rising atmospheric greenhouse gases but may simply arise from internal variability in the coupled climate system.

5. Discussion

This study demonstrates that Antarctic SIA can expand concurrently with rising GMSTs and, most importantly, with increasing radiative forcing from atmospheric CO_2. We have shown that internal variability, particularly that associated with the ocean state, can play a key role in determining the transient evolution of Antarctic SIA under these conditions: multidecadal Antarctic SIA expansion, similar to that over the observational period (1979 to 2015) occurred in one of three ensemble members when the CESM1 evolved from a warm Southern Ocean state, notwithstanding coincident rising radiative forcing and warming GMSTs. This result stands in contrast with the evolution of Antarctic SIA in the 40-member CESM1 Large Ensemble, in which all members were started from the same (nearly climatological) ocean state and not a single member experienced Antarctic SIA expansion over the observational period and beyond. Our results imply that a GCM ensemble started from a single ocean initial state may undersample the model's internal variability, as shown by Hawkins et al. (2015) with an intermediate complexity Earth system model. Furthermore, our findings also imply that accurate ocean initialization is likely necessary for probabilistic prediction of Antarctic SIA evolution over interannual to multidecadal time scales. Of course, the results we present here

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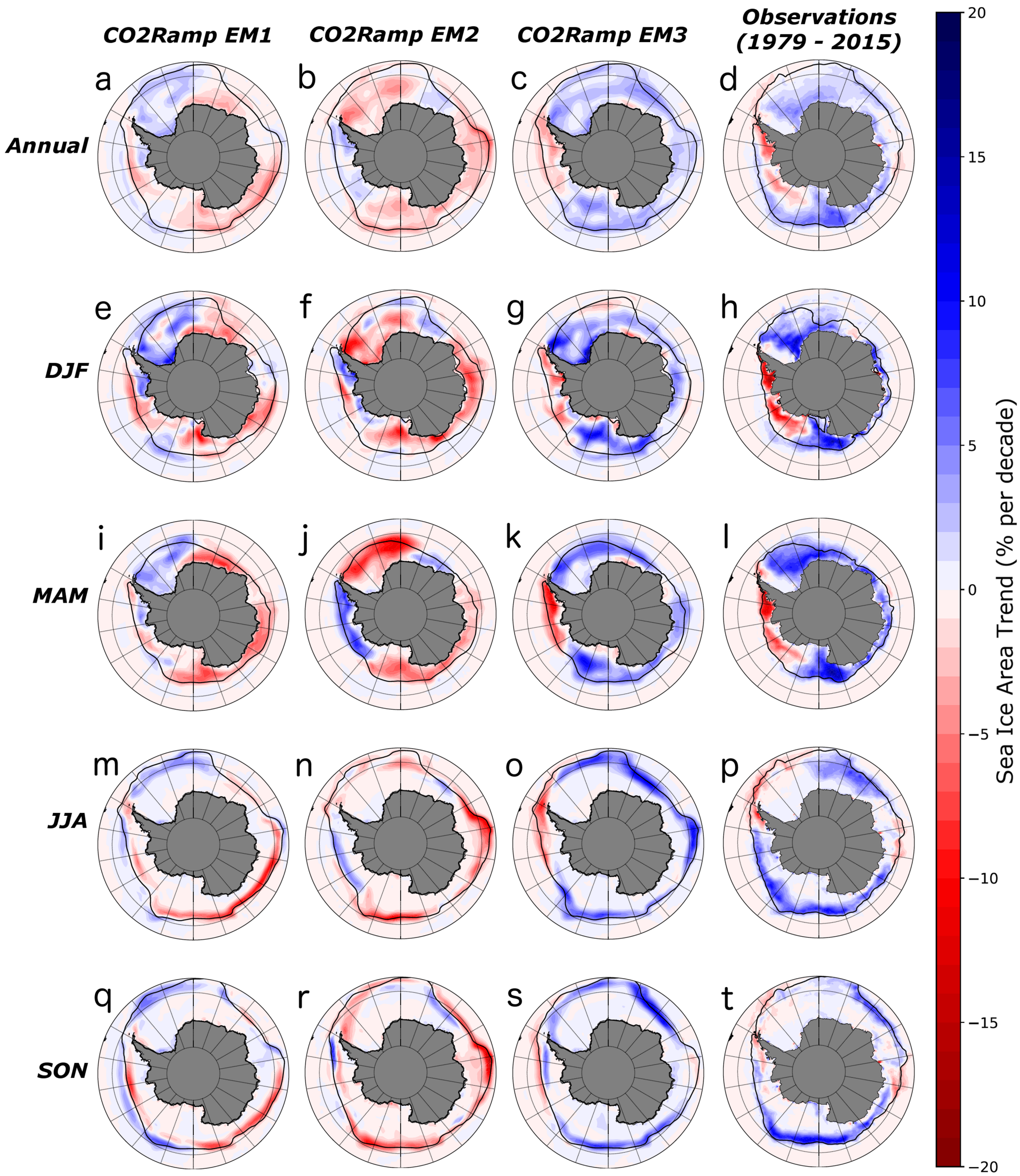

Figure 4. Regional trends in Antarctic SIA (% per decade) in the three CESM1 CO2Ramp ensemble members (Years 0 to 26) and in observations (1979 to 2015): (a–d) in the annual mean, (e–h) December-January-February (DJF), (i–l) March-April-May (MAM), (m–p) June-July-August (JJA), and (q–t) September-October-November (SON) for CO2Ramp ensemble member 1 (EM1; a, e, i, m, and q), CO2Ramp ensemble member 2 (EM2; b, f, j, n, and r), CO2Ramp ensemble member 3 (EM3; c, g, k, o, and s), and observations (d, h, l, p, and t). In all panels, the 15% sea ice fraction contour is indicated (black line).

are only suggestive, and further work with larger GCM ensembles, started from a variety of Southern Ocean states, will be necessary to carefully quantify how oceanic variability impacts Antarctic sea ice evolution.

Our results further build upon those of Zhang et al. (2019), who also demonstrated that the ocean state determines the evolution of Antarctic SIA in a GCM. Our results, however, imply that more modest variations in ocean state may produce Antarctic SIA expansion concomitant with rising atmospheric CO_2, and extrema in Southern Ocean convection are not necessary; indeed, warm Southern Ocean conditions were sufficient to trigger subsequent Antarctic SIA expansion in our three-member ensemble. Furthermore, the seasonal spatial patterns of SIA trends noted by Zhang et al. (2019), found to be similar to SIA trends over the observational period, were associated with changes in Southern Ocean deep convection in their model intrinsic to the preindustrial state as the strength of Southern Ocean deep convection fluctuated. In contrast, our results suggest that these seasonal spatial patterns of SIA trends need not be intrinsic to the preindustrial climate (see Figure S4) but can arise spontaneously in some ensemble members by mere chance.

Even in the face of a changing climate, characteristics of the Antarctic itself may render its climate state more likely to be driven by internal variability than that of other regions. The Antarctic is characterized by substantial internal variability (see, e.g., Mayewski et al., 2004), low climate sensitivity relative to the Arctic (Singh et al., 2018), and delayed surface warming (Armour et al., 2016). Furthermore, radiative forcing from greenhouse gases over the observational period has only increased gradually over the last several decades. In combination, this confluence of low sensitivity, delayed surface warming, high internal variability, and slowly ramping radiative forcing point to internal variability playing an outsized role in the transient climate response over the Antarctic. Equivalently, the time of emergence of the climate change signal is expected to be substantially longer over the Antarctic than over regions with higher sensitivity and less internal variability (Hawkins and Sutton, 2012).

Overall, our work further supports the hypothesis that Antarctic SIA expansion over the observational period (1979 to 2015) was largely driven by internal variability, and coincident processes like ice shelf melt and stratospheric ozone depletion are not necessary to produce the observed trends. However, we must emphasize that our experiments are not meant to explain, quantitatively, the observed trends in Antarctic sea ice from 1979 to 2015, as these experiments were not conceived to be a realistic simulation of Antarctic climate over that time period. First, our experiments were evolved from a preindustrial climate state, not the climate state of the late 1970s. Furthermore, our experiments were forced uniquely with increasing atmospheric CO_2, and they do not include the formation of the ozone hole, which has been shown to be an important driver of Antarctic sea ice loss (Sigmond & Fyfe, 2010; Bitz & Polvani, 2012; Solomon et al., 2015). As such, further and more realistic experiments will be necessary to determine whether these additional factors significantly alter the findings we report here.

While transient Antarctic SIA expansion concurrent with rising atmospheric CO_2 and warming global temperatures is consistent with internal variability in the coupled Earth system, our work also suggests that Antarctic SIA will eventually decline in response to ramping radiative forcing. The recent abrupt decline in Antarctic SIA (2016 to present) may have been triggered by internal variability (Stuecker et al., 2017; Meehl et al., 2019) but may also signal that we have entered such a period of forced sea ice retreat. Be that as it may, the potential impact of internal variability on future Antarctic sea ice evolution should still not be underestimated.

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