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### Title

An Assessment of the Temporal Variability in the Annual Cycle of Daily Antarctic Sea Ice in the NCAR Community Earth System Model, Version 2: A Comparison of the Historical Runs With Observations

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1 **An assessment of the temporal variability in the annual**  
2 **cycle of daily Antarctic sea ice in the NCAR**  
3 **Community Earth System Model, Version 2: A**  
4 **comparison of the historical runs with observations**

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9 **Key Points:**

- 10 • Antarctic sea ice extent variability is dominated by sub-decadal variability and  
11 that is well represented in the CESM2 simulations.  
12 • The CESM2 simulates an annual cycle of sea ice extent that is comparable in size  
13 to that observed but begins its advance and retreat later.  
14 • The later retreat of the CESM2 sea ice is potentially related to its simulation of  
15 the semi-annual oscillation of the circumpolar trough.

## Abstract

Understanding the variability of Antarctic sea ice is an ongoing challenge given the limitations of observed data. Coupled climate model simulations present the opportunity to examine this variability in Antarctic sea ice. Here, the daily sea ice extent simulated by the newly-released National Center for Atmospheric Research Community Earth System Model Version 2 (CESM2) for the historical period (1979–2014), is compared to the satellite-observed daily sea ice extent for the same period. The comparisons are made using a newly-developed suite of statistical metrics that estimates the variability of the sea ice extent on timescales ranging from the long-term decadal to the short term, intraday scales. Assessed are the annual cycle, trend, day-to-day change, and the volatility, a new statistic that estimates the variability at the daily scale. Results show that the trend in observed daily sea ice is dominated by sub-decadal variability with a weak positive linear trend superimposed. The CESM2 simulates comparable sub-decadal variability but with a strong negative linear trend superimposed. The CESM2’s annual cycle is similar in amplitude to the observed, key differences being the timing of ice advance and retreat. The sea ice begins its advance later, reaches its maximum later and begins retreat later in the CESM2. This is confirmed by the day-to-day change. Apparent in all of the sea ice regions, this behavior suggests the influence of the semi-annual oscillation of the circumpolar trough. The volatility, which is associated with smaller scale dynamics such as storms, is smaller in the CESM2 than observed.

## Plain Language Summary

Antarctic sea ice is strongly variable in space and in time. Lack of observed data makes it difficult to determine what causes this variability and limits our ability to understand the variability and to project how it might change in the future. Climate models give the opportunity to study the sea ice and to project change. We compare the sea ice simulations produced by the National Center for Atmospheric Research (NCAR) Community Earth System Model Version 2 (CESM2) with satellite-observed data for the years 1979–2014. We examine the annual cycle, trend, day-to-day change in sea ice and the volatility, a new statistic that estimates the variability at the daily scale. We show that the CESM2 is able to simulate sub-decadal variability comparable to that apparent in the observed sea ice but not the weak, positive, linear trend. The CESM2 also simulates an annual cycle of similar amplitude to that observed but the ice starts growing later and retreating later in the CESM2 than is observed. This difference in timing in the annual cycle occurs in the sea ice all around Antarctica, which suggests that it might be because of a circum-Antarctic atmospheric circulation feature called the circumpolar trough.

## 1 Introduction

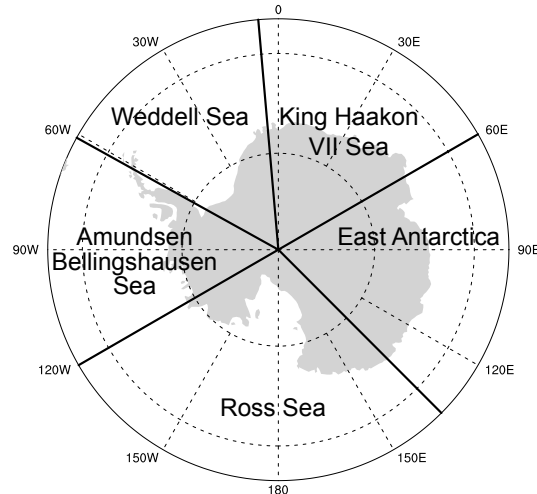
Each year, the total Antarctic sea ice extent (SIE) grows for approximately 225 days to its maximum at the end of winter and retreats for 140 days to its minimum at the end of summer (Handcock & Raphael, 2020), describing what is arguably the most pronounced annual cycle on earth. Embedded within this regularity are regional and temporal variations (e.g., Stammerjohn et al., 2012; Raphael & Hobbs, 2014; Hobbs et al., 2016) that have significance for the Antarctic and global climate. However, aspects of its large scale variability while closely observed, are still not well understood. These include the positive trend in SIE that occurred over the satellite era until 2016 when anomalously early retreat of the sea ice led to record low SIE which continued in subsequent years (Parkinson, 2019; Meehl et al., 2019; Wang et al., 2019; Schlosser et al., 2018). There is a critical need for long term data within which to place such variability into context and to provide a basis for projecting future sea ice variability because of the important role that Antarctic sea ice plays in our closely coupled climate system. In the absence of such long term data, coupled climate model simulations present the opportunity to examine this vari-

66 ability in Antarctic sea ice and also to project future sea ice climate. The models have  
67 had some success in simulating the climate. For example, in their analysis of CMIP5 cou-  
68 pled climate models Holmes et al. (2019) have identified one model that exhibits real-  
69 istic behavior. This model is able to match observations of sea ice drift. They use this  
70 to argue that the existing climate models are sophisticated enough to represent aspects  
71 of Antarctic sea ice correctly. However, while this is a significant step forward, coupled  
72 climate models have had limited success in simulating correctly fundamental aspects of  
73 the observed annual cycle and the long term trend. An assessment of the coupled cli-  
74 mate models that were contributed to the fifth phase of the Coupled Model Intercom-  
75 parison Project (CMIP5) found that many of the models had an annual SIE cycle that  
76 differed markedly from that observed over the last 30 years (Turner et al., 2013; Zunz  
77 et al., 2013). The majority of models had a SIE that was too small at the minimum in  
78 February, while several of the models exhibited much smaller SIE than observed at the  
79 September maximum. All of the models had a negative trend in SIE since the mid-twentieth  
80 century (contrary to observed) (Turner et al., 2013). For the same suite of models Roach  
81 et al. (2018) found that the sea ice concentration (SIC) from which the SIE is calculated  
82 was not well represented, for example, being too loose and low-concentration all year.  
83 They attribute this to the sea ice thermodynamics used in the models. Antarctic sea ice  
84 is intimately tied to the Antarctic climate and these biases in simulated sea ice affect the  
85 simulated climate (Bracegirdle et al., 2015). Therefore the inability of the models to sim-  
86 ulate historical sea ice correctly limits the confidence that we might have in their pro-  
87 jections of future climate.

88 In this current study we analyze the Antarctic sea ice simulated by the National  
89 Center for Atmospheric Research (NCAR) Community Earth System Model Version 2  
90 (CESM2) (Danabasoglu et al., 2020). The CESM2 is a fully-coupled, community, global  
91 climate model that provides state-of-the-art computer simulations of the Earth’s past,  
92 present, and future climate states. It is one of the coupled climate models that have been  
93 contributed to the sixth phase of the Coupled Model Intercomparison Project (CMIP6;  
94 Eyring et al., 2016). Other studies have assessed other aspects of the CESM2 Antarc-  
95 tic climate, including the influence of new sea ice physics (Bailey et al., 2020) and vari-  
96 ability characteristics in the pre-industrial climate (Singh et al., 2020). Here we focus  
97 on how this model’s simulation of Antarctic sea ice variability compares with observa-  
98 tions. Our comparisons focus on the time period 1979–2014, which represents a subset  
99 of the historical runs and which coincides with the bulk of the period of satellite record.  
100 We assess the simulations using a suite of statistical metrics developed by Handcock and  
101 Raphael (2020) that allow us to look at the variability on timescales ranging from the  
102 long-term decadal to the short term intra-day scales. We focus especially on the annual  
103 cycle and the trend, the two most significant components of variability in Antarctic sea  
104 ice, and as mentioned above, components which climate models have had difficulty re-  
105 producing. The data and method are presented in Section 2. The results are presented  
106 and discussed in Section 3 and the work is summarized and conclusions are made in Sec-  
107 tion 4.

## 108 2 Data and Method

109 Here we use a subset of the CESM2 historical (1850–2014) simulations, 1979–2014,  
110 from ten ensemble members and compare it with satellite-observed sea ice data from Nimbus-  
111 7 SMMR and DMSP SSM/I-SSMIS. Specifically, we used the Bootstrap Version 3 con-  
112 centration fields (Comiso, 2017) from the “NOAA/NSIDC Climate Data Record of Pas-  
113 sive Microwave Sea Ice Concentration, Version 3” (Peng et al., 2013; Meier et al., 2017)  
114 for the same period. The structural details of the CESM2 are elaborated upon in other  
115 papers in this CESM2 special collection (Danabasoglu et al., 2020) so are not discussed  
116 here.



**Figure 1.** Sea Ice Sectors around Antarctica. Based on Raphael and Hobbs (2014).

117 Daily sea ice extent (SIE) for the CESM2 ensemble mean as well as for the indi-  
 118 vidual ensemble members are compared with the daily SIE from the SSMI data. The SIE  
 119 is calculated using the limit of the 15% SIC isoline. Thus, it is the sum of the area of  
 120 every grid cell that is 15% or more covered with sea ice. The use of daily data here is  
 121 new as previous model comparisons have typically used monthly averaged values. How-  
 122 ever, daily data has the potential to give much added information about the sea ice vari-  
 123 ability simulated by the model at a much finer temporal resolution. Also, much of the  
 124 variability in contemporary Antarctic sea ice occurs at sub-monthly scales making the  
 125 examination of daily data particularly useful. For simplicity, most of the discussion of  
 126 the results focuses chiefly on the model ensemble means.

127 The components of variability of the SIE that are assessed are the annual cycle,  
 128 trend, day-to-day change and the *volatility*. Comparisons to the long term trends may  
 129 be challenging due to the role of internal variability (e.g., Polvani & Smith, 2013; Mahlstein  
 130 et al., 2013). However, looking across multiple ensemble members allows some insight  
 131 on whether the model can simulate a combination of external forcing and internal vari-  
 132 ability that is comparable to observations. While the annual cycle and trend are the two  
 133 components most usually assessed, the day-to-day change and the volatility are new. This  
 134 is largely because most analyses have been conducted on monthly or seasonal averages.  
 135 The volatility is a new metric developed in Handcock and Raphael (2020). The sea ice  
 136 record on any given day is the sum of a number of components of variation. These are  
 137 the inter-annual variation, the annual cycle for that day, day-to-day variation and the  
 138 volatility (or statistical error) in the observed daily value. Normally that magnitude of  
 139 the error is considered or represented as a constant over time. However, here, we allow  
 140 it to vary, explicitly representing it as a calendar time varying component. We define it  
 141 as the daily standard deviation which is the intra-day variation in the sea ice extent. The  
 142 volatility in the observed data is considered to be due largely to factors like the ephemeral  
 143 dynamic effects of storms at the ice edge and wave-ice interactions. Some, smaller, por-  
 144 tion of it may be due also to instrumentation and algorithm effects.

145 Antarctic sea ice distribution varies regionally, therefore our analysis examines the  
 146 total SIE as well as the regional SIE variability in order to get a comprehensive sense  
 147 of the model’s performance. The sea ice regions used in this analysis (Figure 1) were de-  
 148 fined by Raphael and Hobbs (2014) and are based on coherent spatial variability in the  
 149 sea ice concentration field. DuVivier et al. (2020) assesses the seasonal distribution of  
 150 sea ice concentration simulated by the CESM2. They show that the model does a cred-  
 151 ible job of simulating the distribution of sea ice concentration. Antarctic sea ice variabil-

152 ity is closely tied to the variability in sea level pressure (SLP) over the Southern Ocean  
 153 (Enomoto & Ohmura, 1990). Using SLP, taken from the ERA-Interim Reanalyses for  
 154 the period 1979–2014, we make a preliminary diagnosis of reason for the differences be-  
 155 tween the simulated and observed SIE. We compare the simulated SLP with the corre-  
 156 sponding variable in the ERA-Interim dataset.

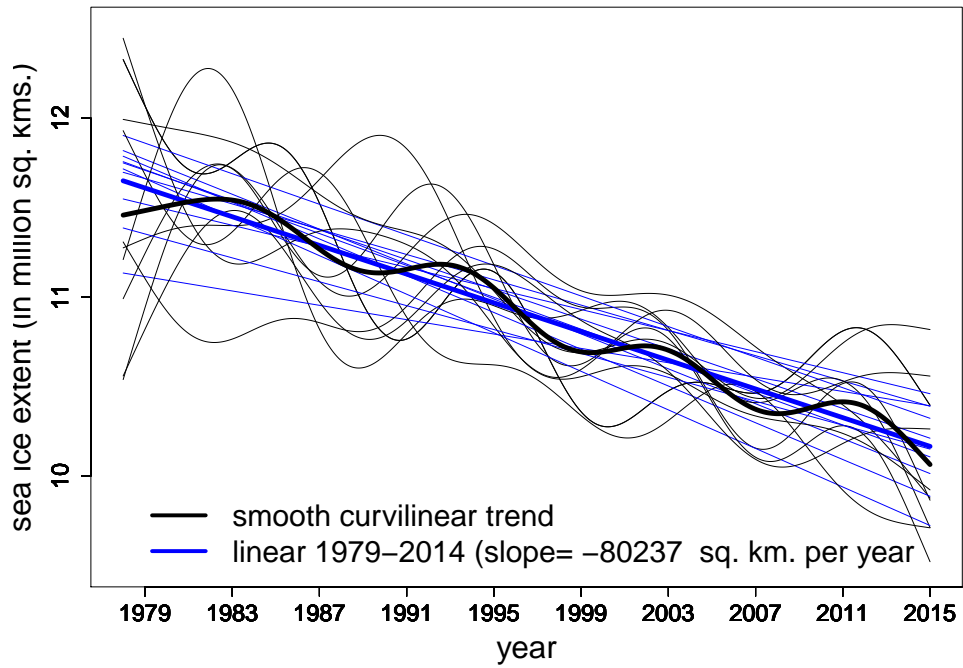
### 157 3 Results

#### 158 3.1 Trend

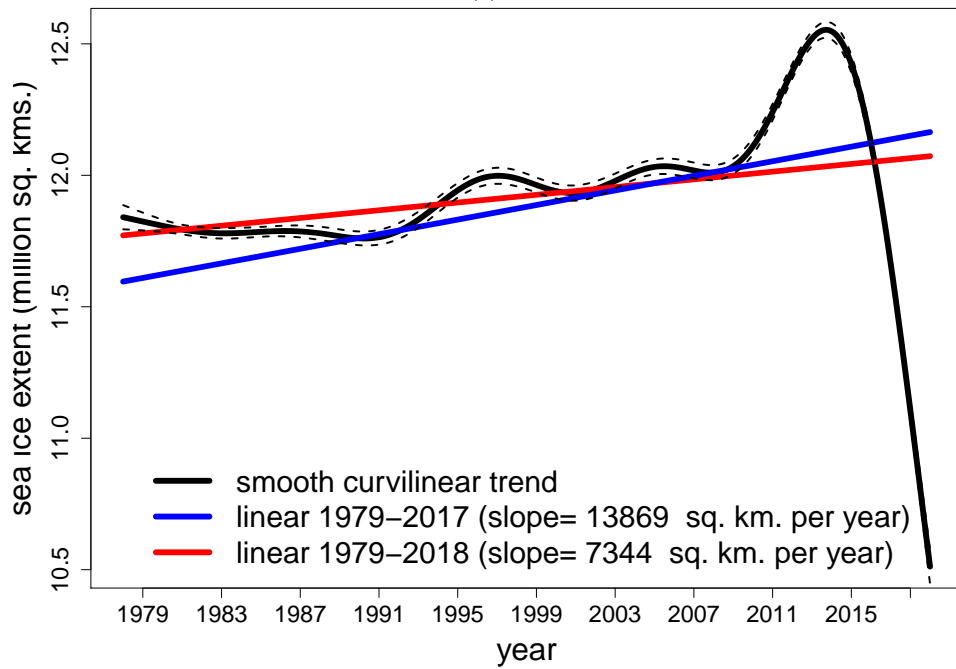
159 It is common in climate science to represent variability at sub-decadal or longer  
 160 timescales as linear functions of time. In this case the presence of a non-zero slope is ev-  
 161 idence of change. Here we expand the representation to allow non-linear functions of time,  
 162 specifically, slowly changing curvilinear functions of time. This allows more flexible and  
 163 realistic representations of change while retaining linear trends as a special case. Our trend  
 164 is explicitly defined in equation (15) of Handcock and Raphael (2020). As we show be-  
 165 low, this curvilinear trend captures variability at sub-decadal timescales.

166 Very few climate models that participated in the previous CMIPs have been able  
 167 to simulate the observed positive linear trend in Antarctic SIE that occurred from 1979–  
 168 2016 (e.g., Turner et al., 2013; Shu et al., 2015). One suggested reason for this discrep-  
 169 ancy is the possibility that the processes underlying the increase in sea ice extent are not  
 170 correctly represented in the models (e.g., Turner et al., 2013; Sigmond & Fyfe, 2014).  
 171 Another is that the observed increase in sea ice extent might be due to natural variabil-  
 172 ity rather than external forcing in the system and therefore, that the climate models do  
 173 not simulate it is not necessarily a failure of the models (e.g., Polvani & Smith, 2013;  
 174 Mahlstein et al., 2013). Figure 2a, which shows change in SIE associated with the trend,  
 175 illustrates that as was the case for the majority of the CMIP5 models, this most recent  
 176 version of CESM2 simulates a pronounced negative linear trend. This is true in the en-  
 177 semble mean (thick blue line) and also apparent in each ensemble member (thin black  
 178 lines). However, Figure 2b which shows the observed daily linear trend in total Antarc-  
 179 tic SIE demonstrates that this observed positive linear trend is quite weak and may be  
 180 strongly influenced by the record maxima which occurred from 2012–2014. Interestingly,  
 181 Figure 2b also suggests that this level of variability of daily SIE is better represented as  
 182 a curvilinear function of time rather than a linear one, suggesting variability at sub-decadal  
 183 timescales. The linear trend does not provide a good characterization of the data because  
 184 of these sub-decadal variations. The CESM2 simulates a comparable sub-decadal vari-  
 185 ability (Figure 2a, indeed the variability in the simulated version is much more pronounced  
 186 than observed). The sub-decadal variability in the daily SIE in this current analysis is  
 187 consistent with that discussed by Simpkins et al. (2013) in their analysis of changes in  
 188 the magnitudes of the sea ice trends in the Ross and Bellingshausen Seas. That the CESM2  
 189 is successful at simulating sub-decadal variability in the SIE suggests that the model may  
 190 be used for diagnosing the mechanisms that force this nonlinear behavior.

191 We also examine the simulated and observed trends by region. Shown in Figure  
 192 3 are the observed and ensemble mean simulated trends. The curvilinearity apparent in  
 193 the observed total SIE (Figure 3a) is also noted regionally as is expected. It is most pro-  
 194 nounced in the Weddell and Ross sectors, which also show the largest changes, followed  
 195 by King Haakon VII Sea, East Antarctica and the Amundsen-Bellingshausen (ABS) sec-  
 196 tors. It is interesting to note that the timing of the sub-decadal variation is not synchronous  
 197 in some regions, a fact best illustrated by the Ross and Weddell Sea sectors (Figure 3a).  
 198 This dipole of variability between the Weddell and Ross sectors is reminiscent of the Antarc-  
 199 tic Dipole, the leading mode of interannual variability in Antarctic sea ice (e.g., Yuan  
 200 & Martinson, 2000, 2001; Holland et al., 2005). Given that these two sectors contribute  
 201 most to the total SIE, such lack of synchronicity has a potentially damping effect on the  
 202 trend in total SIE. Regionally, the CESM2 captures the range of the trends in terms of

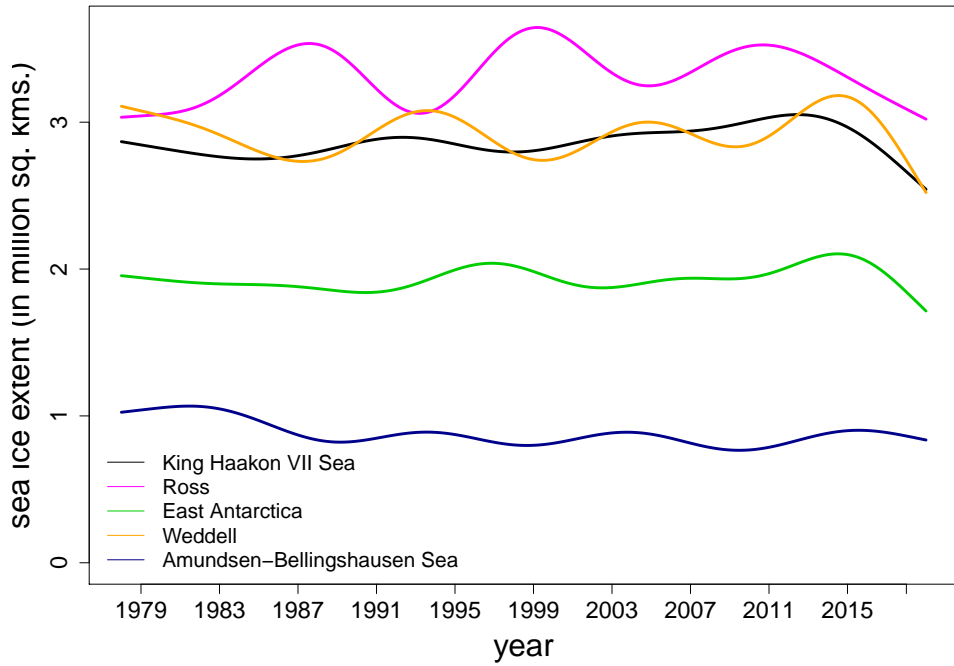


(a)

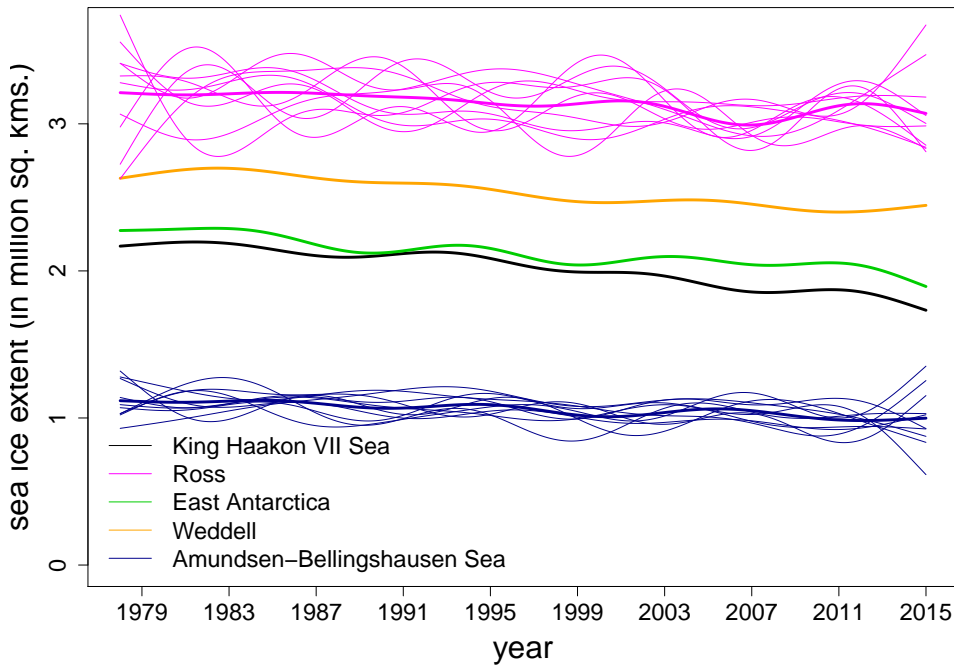


(b)

**Figure 2.** Observed and simulated trends in daily Antarctic sea ice extent represented in terms of the area of sea ice involved in the trend. a) Curvilinear (black) and linear (blue) trends simulated by the CESM2. Bold lines are the ensemble mean, thin lines are the individual ensemble members; b) Observed trends in daily Antarctic sea ice—linear trend from 1979–2017 (blue), from 1979–2018 (red); curvilinear trend (black) with 95% pointwise confidence intervals (dashed black lines).



(a)



(b)

**Figure 3.** Regional observed and simulated trends in daily Antarctic sea ice extent. a) Observed trends; b) Trends simulated by the CESM2. Regions are Amundsen-Bellingshausen sector (dark blue), East Antarctica (green), Weddell Sea (orange), King Haakon VII Sea (black); Ross Sea (magenta). The thin blue and magenta lines are the individual ensemble members for the Ross and Amundsen-Bellingshausen sectors, respectively. On the horizontal axis is time. On the vertical axis is the change in sea ice extent due to the trend.

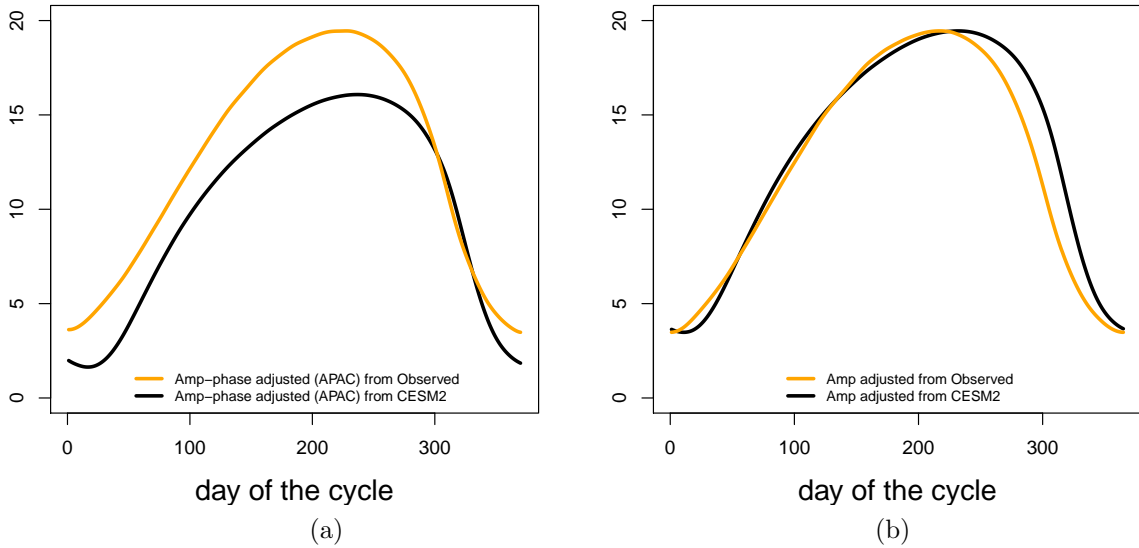


203 the area of sea ice involved. As is observed, the simulated ABS sector has the smallest  
 204 effect while the Ross sector has the largest in terms of the area of sea ice. The simulated  
 205 trend in the King Haakon VII Sea sector is weaker than observed and now comparable  
 206 to the neighboring East Antarctica sector. Both Singh et al. (2020) and DuVivier et al.  
 207 (2020), show that the SIE simulated by the CESM2 in the King Haakon VII Sea sector  
 208 is smaller than observed, particularly in winter. This can be expected to reduce the area  
 209 of sea ice involved in the trend for this sector. The curvilinearity in the ensemble mean  
 210 time-series of the CESM2’s SIE is apparent at the regional scale (Figure 3b) but much  
 211 weaker in general than observed, especially in the ABS. A good proportion of this is due  
 212 to averaging of the curvilinearity of the ensemble members. To illustrate this we show  
 213 the ensemble members for the Ross (thin, magenta lines) and the ABS (thin, dark blue  
 214 lines). It seems clear, especially for the Ross that individual ensemble members are more  
 215 variable than the mean. However, calculations of the average variance of the curvilinear-  
 216 earity of ensemble members show that the Ross, Weddell and Amundsen-Bellingshausen  
 217 Sea sectors have lower variance than the observed, while the King Haakon VII Sea and  
 218 East Antarctica exhibit more (The variance ratios are 0.66, 0.37, 0.88, 1.28, 1.25, respec-  
 219 tively).

### 220 3.2 Annual cycle

221 Here we compare the amplitude (the difference between the maximum and min-  
 222 imum extents), and phase (the timing of the advance and retreat) of the observed, daily  
 223 annual cycle of SIE with that simulated by CESM2. The amplitude and phase are the  
 224 two key characteristics of the annual cycle of sea ice. The traditional way of calculat-  
 225 ing the annual cycle is to take the average SIE for each day of the year. However, an an-  
 226 nual cycle produced in this fashion does not include the effect of the day preceding nor  
 227 the day following the averaged day, therefore it disguises the fact that the phase may be  
 228 changing slowly and that the amplitude as well as the shape of the annual cycle might  
 229 vary. Given these limitations we consider an annual cycle that allows variation for am-  
 230 plitude and phase. It assumes that the phase, which is the timing of advance and retreat  
 231 of the ice, varies continuously while the amplitude varies annually. In this way, the an-  
 232 nual cycle is not constrained to be a fixed (in time) cyclical pattern. Instead, the am-  
 233 plitude and shape of the cycle are allowed to vary, as would occur naturally. Specifically,  
 234 the annual cycle is modeled as a cyclic cubic spline function of the phase of the cycle with  
 235 an amplitude that varies annually. The phase is modeled as a slowly changing smooth  
 236 function of the day-of-the-cycle, with the smoothness estimated from the data. The math-  
 237 ematical details of the annual cycle and its estimation are given in Handcock and Raphael  
 238 (2020), Section 3.1. The outcome, averaged over the dataset period, is shown in Figure  
 239 4a and presents a more thorough if nuanced description of the annual cycle than the tra-  
 240 ditional daily climatology. For clarity, Figure 4 shows only the ensemble mean and the  
 241 observed cycles. On the horizontal axis is the day of the cycle, not the day of year. Day  
 242 1, which is the average day on which the sea ice stops retreating and begins to advance  
 243 is Julian day 50. Figure 4a shows that the simulated SIE is much smaller than the ob-  
 244 served during the period of ice advance, and especially at sea ice minimum and maxi-  
 245 mum. This result is similar to what was found in some models in the CMIP5 suite (e.g.,  
 246 Turner et al., 2013) and more recently in some of the CMIP6 suite of models (Roach et  
 247 al., 2020). Moreover, it shows clearly that the sea ice minimum in the CESM2 occurs  
 248 after ice has begun its advance in the observed cycle and that there are small differences  
 249 during the retreat phase of the ice. Given that the annual cycle in the model is start-  
 250 ing later and from a lower minimum it is possible that the model is simulating an am-  
 251 plitude, i.e a difference between the SIE at maximum and minimum, that is within range  
 252 of that observed.

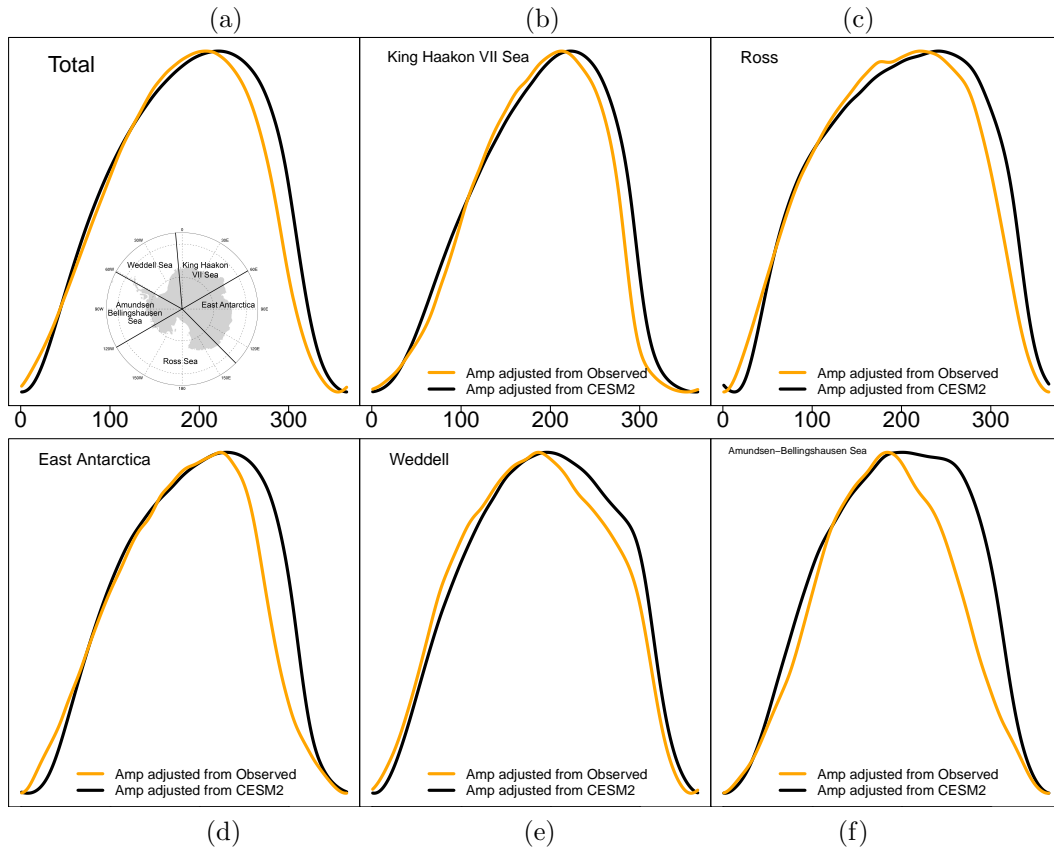
253 To examine more closely the apparent differences in amplitude and phase shown  
 254 on Figure 4a, we consider a variant of the annual cycle that allows for variation in am-  
 255 plitude while having invariant phase. This is the amplitude adjusted annual cycle, de-



**Figure 4.** Observed and simulated annual cycles. a) Amplitude and phase adjusted annual cycles (APAC); b) Amplitude adjusted annual cycles. CESM2 (black lines), Observed (orange lines). On the horizontal axis is day of cycle – day 0 is Julian Day 50. On the vertical axis is sea ice extent in millions of square kilometers. See Hancock and Raphael (2020) for more information on the annual cycles.

256 tailed in Hancock and Raphael (2020), Section 3.1. This is similar to the amplitude-  
 257 phase adjusted annual cycle (APAC), but allows the phase differences to be identified.  
 258 Figure 4b shows that the amplitude is of comparable size as suggested earlier. The ob-  
 259 vious difference is that of the phase in the retreat period. We note that this difference  
 260 in phase is hinted at in Figure 4a but is not as obvious perhaps because the apparent  
 261 amplitude difference is dominant. This phase difference also appears (but is not discussed)  
 262 in the monthly analysis carried out by DuVivier et al. (2020). They show that sea ice  
 263 retreat in the CESM2 begins in October rather than September. In the advance period  
 264 (Figure 4b), the sea ice in CESM2 begins advancing some days later than the observed  
 265 but catches up quickly and the rate of advance appears to be more or less the same for  
 266 most of the growth phase of the ice. There is however, a clear difference in phase for the  
 267 latter part of the ice cycle. During this time, the observed sea ice begins to retreat at  
 268 day of cycle 215 (Julian Day 266), 12 days earlier than the CESM2 ensemble mean sim-  
 269 ulations. To put this in recent context, the anomalously early retreat of sea ice in 2016  
 270 began approximately three weeks before the median retreat onset. This points to the ben-  
 271 efit of using daily data, as these differences would not be adequately resolved using monthly  
 272 means.

273 The amplitude adjusted annual cycles are also examined for each region alongside  
 274 the total SIE for comparison (Figure 5). The regional cycles, both simulated and observed,  
 275 exhibit marked differences in the shape and length of the annual cycles which demon-  
 276 strate why it is important to study Antarctic sea ice variability from a regional perspec-  
 277 tive. These annual cycles differ in the timing of the start and rate of advance, the time  
 278 spent at maximum and the start and rate of retreat. Some of these differences are quan-  
 279 tified in Table 1 which gives the day that SIE maximum is achieved for the observed and  
 280 CESM2 for each sector in Julian days. In the observed, the timing of maximum SIE is  
 281 quite varied. First to achieve maximum is the ABS, followed closely by the Weddell. The  
 282 King Haakon VII Sea sector achieves maximum SIE last, more than a month after the  
 283 ABS sector. The shape of the annual cycle of the ABS is unusually peaked compared  
 284 to the others because the ice grows rapidly to maximum, and spends very little time there



**Figure 5.** Total and Regional observed and simulated amplitude-adjusted annual cycles. a) Total sea ice extent. b) King Haakon VII Sea, c) Ross Sea, d) East Antarctica, e) Weddell Sea, f) Amundsen-Bellinghousen Sea. On the horizontal axis is day of cycle – day 0 is Julian Day 50. On the vertical axis is the annual cycle of the sea ice extent. Each vertical axis has the same standardized scale of 0 to 1.

285 before retreat begins. This is also true but is not as pronounced for the Weddell and King  
 286 Haakon VII Sea sectors. In the CESM2 the timing of retreat varies across the regions  
 287 similarly to the observed, except that SIE in King Haakon VII Sea sector begins its re-  
 288 treat earlier than the SIE in the Ross. Here we define the onset of retreat as the day af-  
 289 ter the SIE reaches its maximum. One measure of the delay in timing of the retreat is  
 290 the difference in the onset of retreat for the observed SIE and CESM2 SIE. The last col-  
 291 umn of Table 1 shows this delay in retreat which is also visible in Figure 5 (It is easier  
 292 to see in the day-to-day changes in Figure 6, the subject of the next section). This de-  
 293 lay is longest in the Ross which begins to retreat approximately one month after the ob-  
 294 served, and shortest in East Antarctica which experiences a delay of only six days.

295 These regional differences in the shape and length of the annual cycle are interest-  
 296 ing to explore, and indicate that there is much to learn about Antarctic sea ice variabil-  
 297 ity at the regional scale. Certainly the fact that each sea region is influenced by differ-  
 298 ent components of the large scale atmospheric circulation (Raphael & Hobbs, 2014) dur-  
 299 ing ice advance and retreat can provide some explanation here. It is also quite likely that  
 300 the state of the ocean exerts some influence. The comparison of the annual cycles of the  
 301 observed and the CESM2 yields one striking similarity; they all have in common the phase  
 302 difference seen in the total SIE. That is, sea ice begins to retreat later in the model than  
 303 observed in each of the regions. Even here there are interesting differences, notably in  
 304 the Weddell and the ABS regions. In both these regions the start of retreat is later and

**Table 1.** Days-of-the-year for Annual Cycle Events<sup>a</sup>

	Observed			CESM2			Delay
	Advance	Maximum	Retreat	Advance	Maximum	Retreat	
Total	125	266	352	103	282	3	16
King Haakon VII Sea	166	280	349	124	295	362	15
Ross	87	267	5	97	297	18	30
East Antarctica	125	277	323	102	283	364	6
Weddell	121	244	4	102	259	9	15
ABS	168	241	343	118	254	11	13

<sup>a</sup>Regional observed and simulated Julian day-of-the-year for the date of maximum SIE advance rate, maximum SIE and maximum SIE retreat rate. The last column is the number of days delay in the start of SIE retreat from observed to simulated.

305 slower than observed. The slower rate of retreat is likely linked to thicker ice that de-  
 306 velops in the ABS and Weddell sectors in winter and lingers into summer (Singh et al.,  
 307 2020). Thicker ice also develops in the Ross sector in winter but it does not last into sum-  
 308 mer which is probably why the annual cycle for the Ross is closer in shape to the observed.

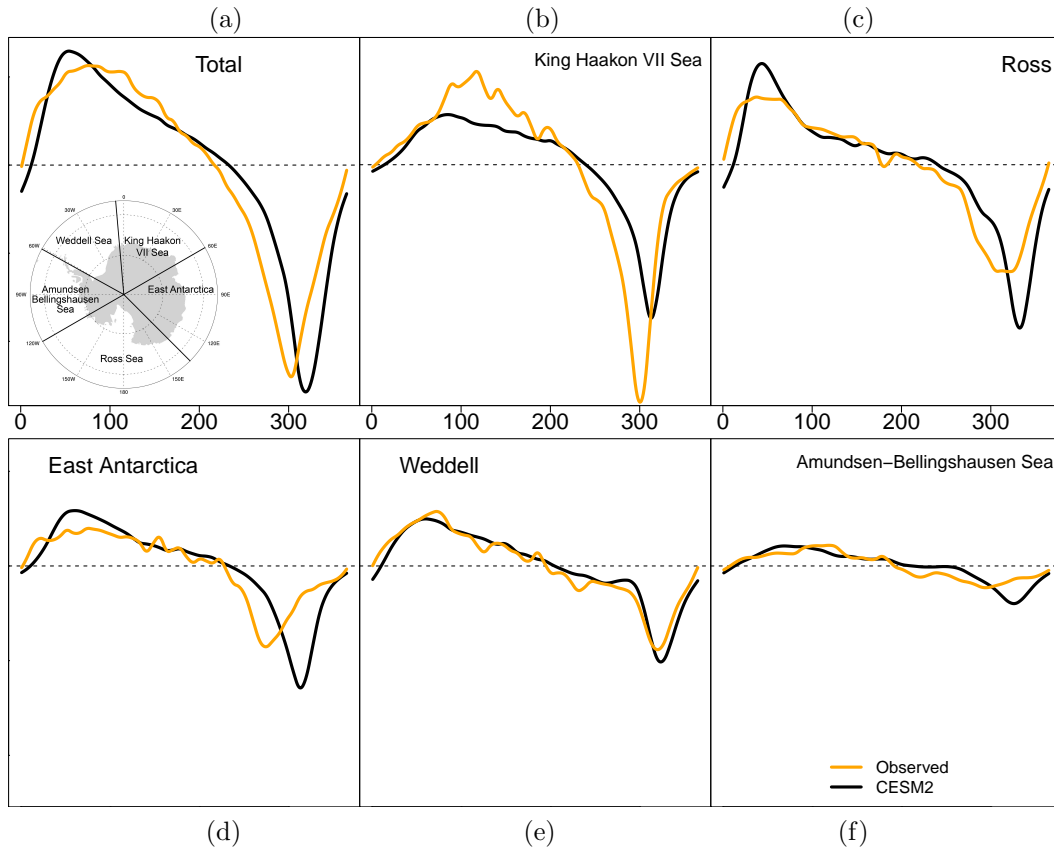
309 That the difference in phase is consistent in all of the regions around the continent  
 310 suggests that it is due to a large-scale rather than regional mechanism. A potential agent  
 311 is the semi-annual oscillation (SAO) of the circumpolar trough (CPT). Earlier studies  
 312 suggest that the SAO modulates the advance and retreat of the ice because it influences  
 313 the location of the westerly and easterly surface winds which in turn promote or limit  
 314 the spread of the ice (e.g., Enomoto & Ohmura, 1990; Stammerjohn et al., 2003). This  
 315 is explored below.

### 316 3.3 Day-to-day change in SIE

317 The simulated day-to-day change in SIE has not been compared with observed data  
 318 before. It is essentially the derivative of the annual cycle. It gives insight into the rate  
 319 of daily advance and retreat of the ice and in doing so becomes an expression of the phase.  
 320 Shown in Figure 6, positive values of the day-to-day change indicate that ice is advanc-  
 321 ing while negative values indicate that ice is retreating. Zero advance (retreat) occurs  
 322 at maximum (minimum). Growth in the observed total SIE (Figure 6a) begins quickly  
 323 before slowing to maximum near Julian day 266. The retreat is faster than the advance.  
 324 This describes a well-known characteristic of the Antarctic sea ice cycle — a relatively  
 325 slow growth to maximum followed by a rapid retreat. This daily analysis, seen in all of  
 326 the regions as well as the total SIE, shows that the rate of ice advance is not monotonic,  
 327 but the rate of retreat is monotonic both when it is increasing and decreasing.

328 As might be expected from the analysis above, there are clear regional differences  
 329 in the observed day-to-day change in SIE (Figure 6b–f). The King Haakon VII Sea sec-  
 330 tor (Figure 6b) sustains the most rapid rates of advance and retreat while the ABS sec-  
 331 tor shows the least. This latter behavior in the ABS sector might be related to the fact  
 332 that this sector has the smallest SIE. Table 1 gives the Julian days of maximum advance  
 333 and maximum retreat and of maximum SIE by region.

334 As shown by the ensemble mean (Figure 6a), the simulations capture the general  
 335 shape of the day-to-day changes in ice but there are important differences. SIE in the  
 336 CESM2 starts advancing later, from a lower value, but achieves its peak growth rate ear-  
 337 lier (see Table 1), and has a maximum growth rate that is higher than the observed. Once  
 338 its peak growth rate is achieved however, it continues to grow more slowly than the ob-  
 339 served for the rest of its advance. It begins retreat later, achieving a maximum rate of  
 340 retreat that is faster and later in the cycle than is observed (see Table 1), continuing to  
 341 retreat after the observed has begun to advance. The day-to-day change in Figure 6a is



**Figure 6.** Total and Regional observed (orange) and simulated (black) day-to-day change in Antarctic sea ice. a) Total sea ice extent. b) King Haakon VII Sea, c) Ross Sea, d) East Antarctica, e) Weddell Sea, f) Amundsen-Bellingshausen Sea. On the horizontal axis is day of cycle – day 0 is Julian Day 50. On the vertical axis is rate of change of the sea ice extent in millions of square kilometers per day. The vertical axes on panels (b)-(f) are the the same.

342 consistent with the annual cycle shown in Figure 4, especially with the phase differences  
 343 seen in Figure 4b. Additionally, it suggests that the very low minimum SIE achieved by  
 344 the CESM2 is related to the high, late stage, maximum decay rate.

345 Regionally, the day-to-day changes (Figure 6b–f) display grossly similar character-  
 346 istics to the total SIE. The sea ice retreat begins later in CESM2 in each region (typ-  
 347 ically 2 weeks; See the last column of Table 1). The maximum rate of retreat also oc-  
 348 curs later in CESM2 (typically 2 weeks; Table 1); this is most pronounced in the East  
 349 Antarctica sector (41 days), least in the Weddell Sea (5 days). The Weddell Sea sector  
 350 is most similar to the observed, achieving its maximum extent and maximum rate of re-  
 351 treat at approximately the same days, while the King Haakon VII Sea sector is the most  
 352 different. Unlike the other sectors, its advance and retreat rates are lower than observed.  
 353 This might be related to the smaller SIE simulated by the CESM2 in the King Haakon  
 354 VII Sea sector (DuVivier et al., 2020; Singh et al., 2020). In the ABS, the extended lag  
 355 noted in Figure 5f shows up as an extended period of little change at maximum in the  
 356 CESM2 while during that same period the observed SIE was retreating. The East Antarc-  
 357 tica and Ross sectors are quite similar to the observed but have later and greater max-  
 358 imum rate of decrease. Overall the regional day-to-day changes are consistent with shape  
 359 and the regional phase differences seen in the amplitude-only adjusted annual cycles in  
 360 Figure 5.

### 3.4 Volatility

The sea ice volatility, the daily standard deviation in the sea ice simulated by the coupled climate models, has not been evaluated before. However, as shown in Figure 7, it can be responsible for fluctuations at the ice edge on the order of 40,000 – 50,000 km<sup>2</sup> which, while small compared to the total SIE, becomes significant at the regional scale and when compared to the size of the sea ice grid box. The volatility is considered to be due mainly to the dynamic effects of storms, ocean circulation (eddies) and wave-ice interaction at the ice edge. Stammerjohn et al. (2003) suggest that dynamics rather than thermodynamics initiate and dominate anomalies along the ice edge. The total observed volatility (Figure 7a) is lowest during the early stages of ice advance, large at SIE maximum and achieves a second, larger maximum later in the cycle, during the days of fastest sea ice retreat. The increased volatility at SIE maximum may be associated with the peak in storm activity in the southern winter discussed by Carleton (1979) and Simmonds and Keay (2000). These storms cause fluctuations at the sea ice edge rather than within the pack where the sea ice concentration is at or close to 100%. Therefore, the apparent cycle in volatility may be due to the effect of storms at the ice edge. The second peak which occurs shortly after the maximum rate of retreat (indicated by the green line) might also be dynamically induced, which would be consistent with the finding of Kushara et al. (2018) that the retreat of Antarctic sea ice (except in the Ross Sea) is largely wind driven.

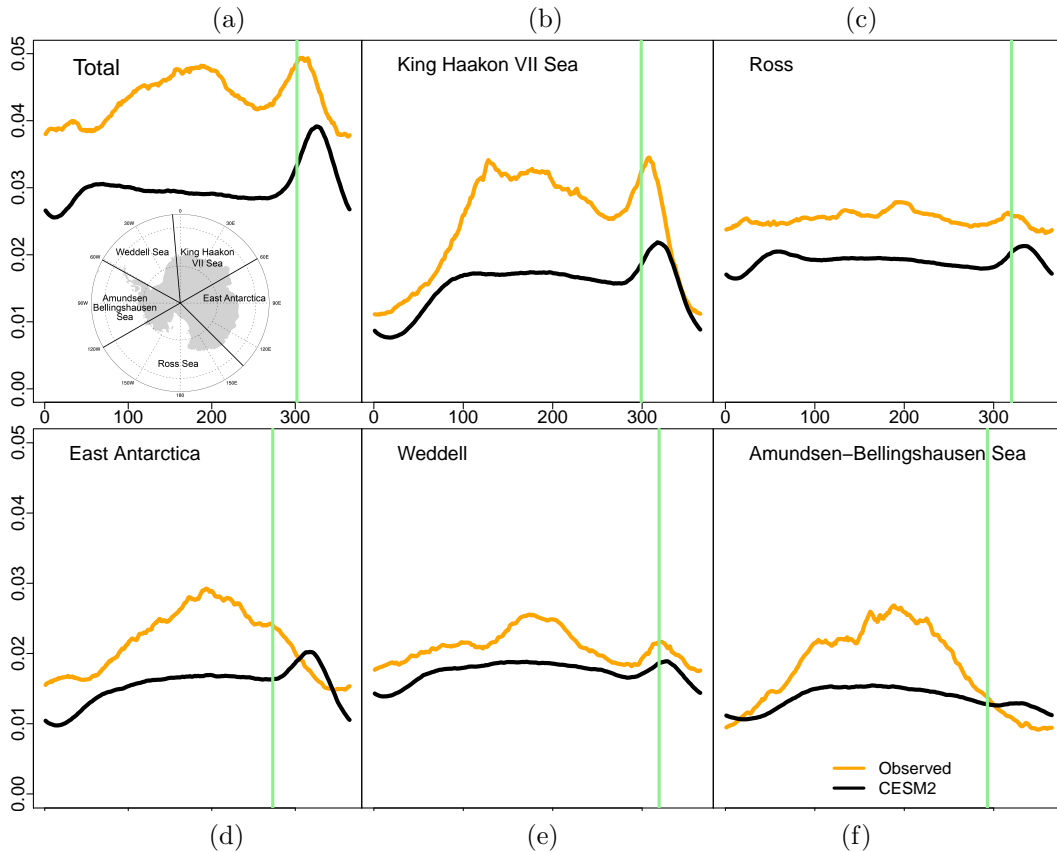
Regionally, the observed double peak is strongly apparent in the King Haakon VII Sea sector, and more weakly in the Weddell and Ross sectors. It is interesting that East Antarctica and the ABS sectors have only one, pronounced peak at the SIE maximum before shrinking quite rapidly to a minimum near the end of the cycle. This lack of a second peak in volatility in the ABS might simply be due to the lack of sea ice in those regions at that stage of the cycle.

Overall, the volatility of total SIE in the CESM2 is lower than the observed by approximately 20,000 km<sup>2</sup> per day and the cycle of volatility is also weak. The simulated volatility increases early during ice advance, but instead of climbing to a maximum, it maintains a steady state for most of the year until, like the observed, it experiences a large maximum late in the ice cycle. Regionally (Figure 7), volatility is usually lower in CESM2 except late in the retreat period in the ABS and East Antarctica. The late cycle increase in volatility occurs in all of the regions, except the ABS, and immediately follows the time of maximum decay.

The lower volatility exhibited by the CESM2 during most of the growth stage of the ice, suggests that daily dynamic forcing of ice fluctuation at the ice edge in the CESM2 is smaller than observed. This can happen if the processes that drive high frequency variability inherent in features such as storms and ocean eddies, are deficient in the model, which is a likely consequence of the relatively coarse model resolution (of about 1 degree in latitude and longitude).

### 3.5 The Potential role of the Semi-annual Oscillation

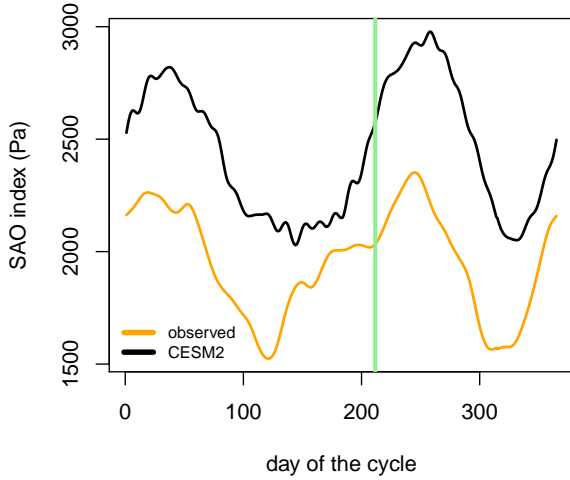
Integrating the information given by the comparison of the annual cycles, the day-to-day mean and the volatility we see that the CESM2 simulates an annual cycle with amplitude similar to that observed but with a retreat phase that begins later in the cycle. We also see that the simulated maximum decay rate is greater, occurs later in the cycle, and is associated with the late peak in volatility. We address now a factor that moderates the timing or phase of the annual cycle, the semi-annual oscillation (SAO). Although it has not been fully quantified, a number of studies suggest that the timing of advance and retreat of Antarctic sea ice is moderated by the SAO (Enomoto & Ohmura, 1990; Simmonds, 2003; Stammerjohn et al., 2003; Simmonds et al., 2005). An important characteristic of the southern hemisphere atmospheric circulation, the SAO is associated with more than 50% of the variability in SLP (van Loon & Rogers, 1984; Taschetto et



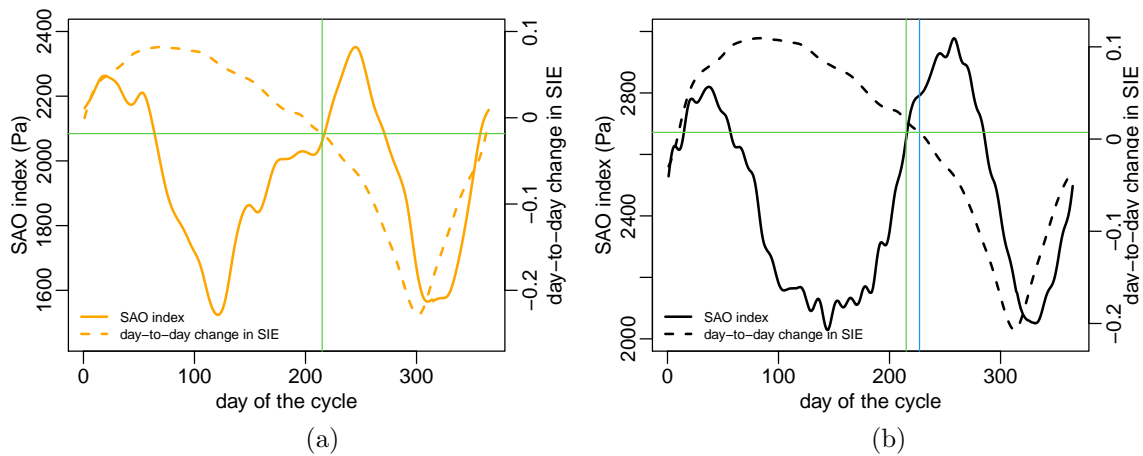
**Figure 7.** Total and Regional observed (orange) and simulated (black) volatility in Antarctic sea ice. a) Total sea ice extent. b) King Haakon VII Sea, c) Ross Sea, d) East Antarctica, e) Weddell Sea, f) Amundsen-Bellingshausen Sea. On the horizontal axis is day of cycle – day 0 is Julian Day 50. On the vertical axis is the daily standard deviation of sea ice extent. Each vertical axis has the scale 0 to 0.05 millions of square kilometers. The green vertical lines mark the day of maximal observed SIE retreat for that region or total (See Figure 6). The observed values are based on DMSP era data only.

al., 2007). It is expressed by the bi-annual changes in location and intensity of the circumpolar trough (CPT). As described in van Loon (1967), the CPT contracts, deepens and moves south in March and September and expands, weakens and moves north in June and December. Similar accompanying fluctuations of the tropospheric temperature gradients, geopotential heights, SLP and winds at middle and high latitudes in the SH occur. The changing wind directions associated with the meridional shift in the CPT in spring is thought to create divergence in the ice pack causing a reduction in sea ice concentration and priming the pack for rapid break up by wind and ocean late in the annual cycle (December) (Enomoto & Ohmura, 1990). Stammerjohn et al. (2003) show that the timing of the north/south migration of the CPT influences the timing of sea-ice advance and retreat via wind-driven sea-ice drift. A lucid discussion of the SAO and its influence on Antarctic sea ice can be found in Eayrs et al. (2019).

An in-depth evaluation of SAO simulated by the CESM2 within the context of sea ice variability is beyond the scope of this paper. However, given the hypothesized link between the SAO and the timing of sea ice advance and retreat, and its potential for explanation, we examined how well the CESM2 simulates the SAO, using the zonal mean SLP difference between latitudes 50S and 65S. It is a measure of the strength of the winds between those latitudes such that a large, positive value indicates stronger westerlies,



**Figure 8.** Semi-annual Oscillation Index: Observed (orange) and simulated (black) zonal mean SLP difference between latitudes 50S and 65S. The green line marks the observed day of onset of sea ice retreat. On the horizontal axis is day of cycle – day 0 is Julian Day 50. On the vertical axis is the zonal mean sea level pressure difference in Pa.



**Figure 9.** Observed (a) and simulated (b) day-to-day change and corresponding SAO index. The green line marks the observed day of onset of sea ice retreat. The blue line marks the simulated day of onset of sea ice retreat. On the horizontal axis is day of cycle: day 0 is Julian Day 50. On the left vertical axes are the zonal mean sea level pressure differences in Pa. On the right vertical axes are the rates of change of the sea ice extent in millions of square kilometers per day

430 and the intensity of the CPT (Hurrell & van Loon, 1994; Meehl et al., 1998; Taschetto  
 431 et al., 2007). The CESM2 (Figure 8: black line) simulates a well-defined SAO index which  
 432 is different from the observed in two ways; it is always larger, indicating stronger winds  
 433 and a deeper CPT, and it is offset in time so that the minimum and maximum merid-  
 434 ional pressure gradients are achieved later in the year than observed. This means that  
 435 the simulated CPT begins shifting southwards later, reaching its southernmost location  
 436 and greatest intensity later than the observed CPT. The significance of this temporal  
 437 offset to the timing of ice retreat becomes clearer in Figure 9a and b where the day-to-  
 438 day changes in SIE are overlaid on the observed and simulated SAO indices along with  
 439 the times of onset of retreat. The later retreat of ice in the CESM2 is tied to the slower  
 440 southward movement of the CPT.



#### 441 **4 Summary and Conclusions**

442 This study is an evaluation of the satellite-era variability in Antarctic sea ice extent  
 443 simulated by the CESM2, using some newly developed metrics from Handcock and  
 444 Raphael (2020). These metrics examine the variability from the long term trends to the  
 445 intra-day, giving a detailed picture of the temporal variability of Antarctic sea ice extent  
 446 simulated by the model. This complements work that has assessed other aspects  
 447 of the Antarctic climate in pre-industrial control conditions (Singh et al., 2020). Here,  
 448 we are able to explicitly diagnose differences between the model and observed, which may  
 449 be used to give a sense of what elements of the model need more development. Over the  
 450 historical period the trend in observed daily sea ice is dominated by a curvilinear inter-  
 451 annual component with a weak positive linear trend superimposed. As was the case for  
 452 the majority of the CMIP5 models, CESM2 simulates a strong negative trend in SIE and  
 453 therefore is still in contrast to the observations, a difference which might be due to nat-  
 454 ural variability rather than a model deficiency. Analysis of the observed daily sea ice shows  
 455 that the linear trend is weak and that the longer term variability in Antarctic sea ice is  
 456 dominated by sub-decadal variability. The CESM2 simulates a comparable sub-decadal  
 457 variability in the total SIE and well as in the individual sea ice sectors, although this is  
 458 better seen in the individual ensemble members than in the ensemble mean. That the  
 459 CESM2 is able to simulate comparable sub-decadal variability suggests that the model  
 460 may be used to diagnose and or evaluate the factors contributing to this variability.

461 With respect to the annual cycle, the total SIE at time of maximum simulated by  
 462 the CESM2 is lower than recorded. Since sea ice in the model begins advancing later and  
 463 from a much smaller minimum than observed it might never reach the size of the observed  
 464 SIE at the time of maximum. However, if the amplitude is calculated as the difference  
 465 between the minimum and maximum SIE, the CESM2 does produce an annual cycle with  
 466 similar amplitude to that observed. This apparent difference in amplitude between the  
 467 the observed annual cycle and that of the CESM2 is the result of the complex relation-  
 468 ship between amplitude and phase, the two key characteristics of the annual cycle. Sep-  
 469 aration of the variation of the amplitude and phase by using an amplitude-adjusted only  
 470 annual cycle showed that the main difference between the simulated and observed an-  
 471 nual cycles is the timing of ice retreat. The CESM2 reaches its SIE maximum later and  
 472 begins its retreat later than observed and this is apparent in both the total and the re-  
 473 gional SIE.

474 This difference in the annual cycles is echoed in the day-to-day change, a variable  
 475 that has not been examined before since most analyses focus on the monthly and sea-  
 476 sonal SIE. Here, the day-to-day change is consistent with and might be considered a proxy  
 477 for the large scale elements of the annual cycle (advance/retreat), while adding preci-  
 478 sion with respect to the exact timing of advance and retreat. While the rates of change  
 479 are generally similar (except for the peak rate of retreat in the CESM2 which is much  
 480 larger), sea ice begins its advance and retreat later in the CESM2. An additional phe-  
 481 nomenon not seen when looking at monthly averages, but perhaps known anecdotally,  
 482 is that the rate of sea ice advance is not monotonic but the rate of sea ice retreat is mono-  
 483 tonic when it is increasing and when it is decreasing (Figure 6). This knowledge is po-  
 484 tentially useful when considering thermodynamic vs dynamic effects on sea ice advance  
 485 and retreat.

486 A potential contributor to the retreat phase difference between the observed an-  
 487 nual cycle and that of the CESM2 is the simulated semi-annual oscillation (SAO). An  
 488 initial evaluation of the SAO index shows that the meridional gradient of pressure sim-  
 489 ulated by the CESM2 is larger and the maximum (and minimum) of this gradient oc-  
 490 cur later in the cycle than observed. We suggest that this is due to a deeper, slower mov-  
 491 ing Circumpolar Trough. Indeed, our analysis links the later retreat of ice in the CESM2  
 492 to the slower southward movement of the Circumpolar Trough. The influence of the SAO  
 493 on sea ice variability has long been a subject of study (e.g., van Den Broeke, 2000). The

494 differences between the CESM2 and the observed data discussed here, present an oppor-  
495 tunity to examine closely this important atmospheric mechanism and its role in the Antarc-  
496 tic sea ice climate.

497 A novel aspect of variability compared here is the daily standard deviation, named  
498 here, the volatility (Handcock & Raphael, 2020). This measure of variability is associ-  
499 ated with smaller scale dynamics, and is responsible for significant fluctuations in SIE  
500 at the grid scale. In the observed, it achieves a first maximum near the time of sea ice  
501 maximum and a second near the time of maximum rate of retreat of the ice. In general,  
502 this component of variability is lower in the CESM2 than observed. Also missing is the  
503 slow but clear growth in volatility to a maximum near the time of the sea ice maximum.  
504 However, the CESM2 does simulate the peak volatility associated with the very rapid  
505 rate of decay late in the ice cycle. As mid-winter sea ice variability is associated with  
506 the smaller scale dynamics such as storms (e.g., Stammerjohn et al., 2003), ocean ed-  
507 dies and wave-ice interaction at the ice edge, it may be that the model is not simulat-  
508 ing these processes well, something that is common across the CMIP models. We note  
509 also that the observed sea ice grid size at 25km x 25km is much smaller than that of the  
510 CESM2's (1 degree) thus might be expected to exhibit more daily volatility than the CESM  
511 which is a 1 degree model.

512 Finally, the focus of this analysis has been to determine the ability of the CESM2  
513 to simulate the key components of the variability of Antarctic sea ice and to suggest what  
514 might be the proximate cause of the differences that are seen. However, what has be-  
515 come even clearer in the process is that in-depth analysis of Antarctic sea ice variabil-  
516 ity requires a regional (or by sea ice sector) approach. Important differences in variabil-  
517 ity that are apparent by sector are muted or damped, when only the total SIE is con-  
518 sidered. The sea ice sectors differ not only in the amplitude of their sea ice extents but  
519 also in their phase (or timing) of sea ice advance and retreat, and the rates of advance  
520 and retreat of the sea ice. All of these combine to present a fairly complex picture of vari-  
521 ability. This is true of the observed as well as the simulated SIE. Raphael and Hobbs  
522 (2014) show that sea ice in each sector is influenced by different components of the large  
523 scale atmospheric circulation, both remote from, and local to, the Antarctic. The state  
524 of the ocean and the effect of the interaction between the ocean and the atmosphere on  
525 the ice must also be considered in attempts to determine the sources of these differences  
526 in Antarctic sea ice variability.

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540 Meier et al., 2017). The ERAI reanalysis data (Dee et al., 2011) are available from the  
541 Centre for Medium-Range Weather Forecasts (ECMWF).

542

**References**

- 543 Bailey, D. A., Holland, M. M., DuVivier, A. K., Hunke, E. C., & Turner, A. K.  
 544 (2020). *Impact of a new sea ice thermodynamic formulation in the CESM2*  
 545 *sea ice component*. (Manuscript submitted for publication to the *Journal of*  
 546 *Advances in Modeling Earth Systems*)
- 547 Bracegirdle, T. J., Stephenson, D. B., Turner, J., & Phillips, T. (2015). The impor-  
 548 tance of sea ice area biases in 21st century multimodel projections of antarctic  
 549 temperature and precipitation, geophys. *Geophysics Research Letters*, *42*(10),  
 550 832-839. doi: 10.1002/2015GL067055
- 551 Carleton, A. M. A. (1979). Synoptic climatology of satellite-observed extratropical  
 552 cyclone activity for the southern hemisphere winter. *Archives for meteorology,*  
 553 *geophysics, and bioclimatology*, *27*, 265-279.
- 554 Comiso, J. (2017). *Bootstrap sea ice concentrations from NIMBUS-7 SMMR and*  
 555 *DMSP SSM/I-SSMIS, Version 3*. NASA National Snow and Ice Data Center  
 556 Distributed Active Archive Center. doi: 10.5067/7Q8HCCWS4I0R
- 557 Danabasoglu, G., Lamarque, J.-F., Bacmeister, J., Bailey, D. A., DuVivier, A. K.,  
 558 Edwards, J., ... Strand, W. G. (2020). The community earth system model  
 559 Version 2 (CESM2). *Journal of Advances in Modeling Earth Systems*, *12*(2),  
 560 e2019MS001916. doi: 10.1029/2019MS001916
- 561 Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., ...  
 562 Vitart, F. (2011). The era-interim reanalysis: configuration and performance  
 563 of the data assimilation system. *Quarterly Journal of the Royal Meteorological*  
 564 *Society*, *137*(656), 553-597. doi: 10.1002/qj.828
- 565 DuVivier, A. K., Holland, M. M., Kay, J. E., Tilmes, S., Gettelman, A., & Bailey,  
 566 D. A. (2020). *Arctic and antarctic sea ice state in the community earth system*  
 567 *model version 2*. Manuscript submitted to JGR-Oceans.
- 568 Eayrs, C., Holland, D. M., Francis, D., Wagner, T. J. W., Kumar, R., & Li, X.  
 569 (2019). Understanding the seasonal cycle of antarctic sea ice extent in the  
 570 context of longer-term variability. *Reviews of Geophysics*, *57*, 1037-1064.
- 571 Enomoto, H., & Ohmura, A. (1990). The influences of atmospheric half-yearly  
 572 cycle on the sea ice extent in the antarctic. *Journal of Geophysical Research:*  
 573 *Oceans*, *95*(C6), 9497-9511. doi: 10.1029/JC095iC06p09497
- 574 Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., &  
 575 Taylor, K. E. (2016). Overview of the coupled model intercomparison project  
 576 phase 6 (cmip6) experimental design and organization. *Geoscientific Model*  
 577 *Development*, *9*(5), 1937-1958. doi: 10.5194/gmd-9-1937-2016
- 578 Handcock, M. S., & Raphael, M. N. (2020). Modeling the annual cycle of daily  
 579 antarctic sea ice extent. *The Cryosphere*, *14*(7), 2159-2172. doi: 10.5194/tc-14  
 580 -2159-2020
- 581 Hobbs, W. R., Massom, R., Stammerjohn, S., Reid, P., Williams, G., & Meier,  
 582 W. (2016, August). A review of recent changes in Southern Ocean sea ice,  
 583 their drivers and forcings. *Global and Planetary Change*, *143*, 228-250. doi:  
 584 10.1016/j.gloplacha.2016.06.008
- 585 Holland, M. M., Bitz, C. M., & Hunke, E. C. (2005). Mechanisms forcing an antarctic  
 586 dipole in simulated sea ice and surface ocean conditions. *Journal of Cli-*  
 587 *mate*, *18*(12), 2052-2066. doi: 10.1175/JCLI3396.1
- 588 Holmes, C. R., Holland, P. R., & Bracegirdle, T. J. (2019). Compensating biases  
 589 and a noteworthy success in the CMIP5 representation of antarctic sea ice  
 590 processes. *Geophysical Research Letters*, *46*, 4299-4307.
- 591 Hurrell, J. W., & van Loon, H. (1994). A modulation of the atmospheric annual cycle  
 592 in the southern hemisphere. *Tellus*, *46A*, 325-338.
- 593 Kusahara, K., Williams, G., Massom, R., Reid, P., & Hasumi, H. (2018, 07). Spa-  
 594 tiotemporal dependence of antarctic sea ice variability to dynamic and ther-  
 595 modynamic forcing: A coupled ocean-sea ice model study. *Climate Dynamics*.  
 596 doi: 10.1007/s00382-018-4348-3

- 597 Mahlstein, I., Gent, P. R., & Solomon, S. (2013). Historical antarctic mean sea ice  
598 area, sea ice trends, and winds in CMIP5 simulations. *Journal of Geophysical*  
599 *Research: Atmospheres*, *118*(11), 5105-5110. doi: 10.1002/jgrd.50443
- 600 Meehl, G. A., Arblaster, J. M., Chung, C. T. Y., Holland, M. M., DuVivier, A.,  
601 Thompson, L., ... Bitz, C. M. (2019). Sustained ocean changes contributed to  
602 sudden antarctic sea ice retreat in late 2016. *Nature Communications*, *10*(1),  
603 14. doi: 10.1038/s41467-018-07865-9
- 604 Meehl, G. A., Hurrell, J. W., & H. van Loon, A. (1998). Modulation of the mech-  
605 anism of the semiannual oscillation in the southern hemisphere. *Tellus*, *50A*,  
606 442-450.
- 607 Meier, W. N., Fetterer, F., Savoie, M., Mallory, S., Duerr, R., & Stroeve, J. (2017).  
608 NOAA/NSIDC climate data record of passive microwave sea ice concentra-  
609 tion, version 3 [Computer software manual]. Boulder, Colorado USA. doi:  
610 https://doi.org/10.7265/N59P2ZTG
- 611 Parkinson, C. L. (2019). A 40-y record reveals gradual antarctic sea ice increases fol-  
612 lowed by decreases at rates far exceeding the rates seen in the arctic. *Proceed-*  
613 *ings of the National Academy of Sciences*, *116*(29), 14414-14423. doi: 10.1073/  
614 pnas.1906556116
- 615 Peng, G., Meier, W. N., Scott, D. J., & Savoie, M. H. (2013). A long-term and  
616 reproducible passive microwave sea ice concentration data record for climate  
617 studies and monitoring. *Earth System Science Data*, *5*(2), 311-318. doi:  
618 10.5194/essd-5-311-2013
- 619 Polvani, L. M., & Smith, K. L. (2013). Can natural variability explain observed  
620 antarctic sea ice trends? new modeling evidence from CMIP5. *Geophysical Re-*  
621 *search Letters*, *40*(12), 3195-3199. doi: 10.1002/grl.50578
- 622 Raphael, M. N., & Hobbs, W. (2014). The influence of the large-scale atmospheric  
623 circulation on antarctic sea ice during ice advance and retreat seasons. *Geo-*  
624 *physical Research Letters*, *41*, 5037-5045. doi: 10.1002/2014gl060365
- 625 Roach, L. A., Dean, S. M., & Renwick, J. A. (2018). Consistent biases in antarctic  
626 sea ice concentration simulated by climate models. *The Cryosphere*, *12*, 365-  
627 383.
- 628 Roach, L. A., Dörr, J., Holmes, C. R., Massonnet, F., Blockley, E. W., Notz, D., ...  
629 Bitz, C. M. (2020). Antarctic sea ice area in cmip6. *Geophysical Research*  
630 *Letters*, *47*(9), e2019GL086729. (e2019GL086729 10.1029/2019GL086729) doi:  
631 10.1029/2019GL086729
- 632 Schlosser, E., Haumann, F. A., & Raphael, M. N. (2018). Atmospheric influences on  
633 the anomalous 2016 antarctic sea ice decay. *The Cryosphere*, *12*(3), 1103-1119.  
634 doi: 10.5194/tc-12-1103-2018
- 635 Shu, Q., Song, Z., & Qiao, F. (2015). Assessment of sea ice simulations in the  
636 CMIP5 models. *The Cryosphere*, *9*(1), 399-409. doi: 10.5194/tc-9-399-2015
- 637 Sigmond, M., & Fyfe, J. C. (2014). The antarctic sea ice response to the ozone hole  
638 in climate models. *Journal of Climate*, *27*(3), 1336-1342. doi: 10.1175/JCLI-D  
639 -13-00590.1
- 640 Simmonds, I. (2003). Modes of atmospheric variability over the southern ocean.  
641 *Journal of Geophysical Research: Oceans*, *108*(C4), SOV 5-1-SOV 5-30. doi:  
642 10.1029/2000JC000542
- 643 Simmonds, I., & Keay, K. (2000, March). Mean Southern hemisphere extratropical  
644 cyclone behavior in the 40-year NCEP-NCAR reanalysis. *Journal of Climate*,  
645 *13*, 873-885. doi: 10.1175/1520-0442(2000)013<0873:MSHECB>2.0.CO;2
- 646 Simmonds, I., Rafter, A., Cowan, T., Watkins, A. B., & Keay, K. (2005, October).  
647 Large-scale Vertical Momentum, Kinetic Energy and Moisture Fluxes in the  
648 Antarctic Sea-ice Region. *Boundary-Layer Meteorology*, *117*(1), 149-177. doi:  
649 10.1007/s10546-004-5939-6
- 650 Simpkins, G. R., Ciasto, L. M., & England, M. H. (2013). Observed variations in  
651 multidecadal antarctic sea ice trends during 1979-2012. *Geophysical Research*

- 652 *Letters*, 40(14), 3643-3648. doi: 10.1002/grl.50715
- 653 Singh, H. K. A., Landrum, L., & Holland, M. M. (2020). *An overview of antarctic*  
 654 *sea ice in the CESM2: Analysis of the seasonal cycle, predictability, and*  
 655 *atmosphere-ocean-ice interactions.* (Manuscript submitted for publication to  
 656 *the Journal of Advances in Modeling Earth Systems*)
- 657 Stammerjohn, S., Drinkwater, M. R., Smith, R. C., & Liu, X. (2003). Ice-  
 658 atmosphere interactions during sea-ice advance and retreat in the west-  
 659 ern antarctic peninsula region. *Journal of Geophysical Research: Oceans*,  
 660 108(C10). doi: 10.1029/2002JC001543
- 661 Stammerjohn, S., Massom, R., Rind, D., & Martinson, D. (2012). Regions of rapid  
 662 sea ice change: An inter-hemispheric seasonal comparison. *Geophysical Re-*  
 663 *search Letters*, 39(6). doi: 10.1029/2012GL050874
- 664 Taschetto, A., Wainer, I., & Raphael, M. (2007). Interannual variability associated  
 665 with semiannual oscillation in southern high latitudes. *Journal of Geophysical*  
 666 *Research: Atmospheres*, 112(D2). doi: 10.1029/2006JD007648
- 667 Turner, J., Bracegirdle, T. J., Phillips, T., Marshall, G. J., & Hosking, J. S. (2013).  
 668 An initial assessment of antarctic sea ice extent in the CMIP5 models. *Journal*  
 669 *of Climate*, 26(5), 1473-1484. doi: 10.1175/JCLI-D-12-00068.1
- 670 van Den Broeke, M. (2000). The semi-annual oscillation and antarctic climate.  
 671 part 4: a note on sea ice cover in the amundsen and bellingshausen seas. *In-*  
 672 *ternational Journal of Climatology*, 20(4), 455-462. doi: 10.1002/(SICI)1097  
 673 -0088(20000330)20:4<455::AID-JOC482>3.0.CO;2-M
- 674 van Loon, H. (1967). The half-yearly oscillations in middle and high southern lat-  
 675 itudes and the coreless winter. *Journal of the Atmospheric Sciences*, 24(5),  
 676 472-486. doi: 10.1175/1520-0469(1967)024<0472:THYOIM>2.0.CO;2
- 677 van Loon, H., & Rogers, J. C. (1984). Interannual variations in the half-yearly cycle  
 678 of pressure gradients and zonal wind at sea level on the southern hemisphere.  
 679 *Tellus A*, 36A(1), 76-86. doi: 10.1111/j.1600-0870.1984.tb00224.x
- 680 Wang, Z., Turner, J., Wu, Y., & Liu, C. (2019, 07). Rapid Decline of Total Antarctic  
 681 Sea Ice Extent during 2014–16 Controlled by Wind-Driven Sea Ice Drift. *Jour-*  
 682 *nal of Climate*, 32(17), 5381-5395. doi: 10.1175/JCLI-D-18-0635.1
- 683 Yuan, X., & Martinson, D. (2000, 05). Antarctic sea ice extent variability and  
 684 its global connectivity\*. *Journal of Climate*. doi: 10.1175/1520-0442(2000)  
 685 013<1697:ASIEVA>2.0.CO;2
- 686 Yuan, X., & Martinson, D. G. (2001). The antarctic dipole and its predictability.  
 687 *Geophysical Research Letters*, 28(18), 3609-3612. doi: 10.1029/2001GL012969
- 688 Zunz, V., Goosse, H., & Massonnet, F. (2013). How does internal variabil-  
 689 ity influence the ability of cmip5 models to reproduce the recent trend  
 690 in southern ocean sea ice extent? *The Cryosphere*, 7(2), 451–468. doi:  
 691 10.5194/tc-7-451-2013