

1 **Interannual SAM modulation of Antarctic sea ice**
2 **extent does not account for its long-term trends,**
3 **pointing to a limited role for ozone depletion**

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21 **Key Points:**

- 22 • Many CMIP5 models are able to capture the observed seasonal correlation between
23 summertime SAM and Antarctic sea ice extent
- 24 • The SAM, however, only explains 15% of the year-to-year SIE variability in the
25 fall, in both models and observations
- 26 • SAM trends, and ozone depletion, are not the primary drivers of the observed Antarc-
27 tic sea ice expansion in the last four decades

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Abstract

The expansion of Antarctic sea ice since 1979 in the presence of increasing greenhouse gases remains one of the most puzzling features of current climate change. Some studies have proposed that the formation of the ozone hole, via the Southern Annular Mode, might explain that expansion, and a recent study highlighted a robust causal link between summertime Southern Annular Mode (SAM) anomalies and sea ice anomalies in the subsequent autumn. Here we show that many models are able to capture this relationship between the SAM and sea ice, but also emphasize that the SAM only explains a small fraction of the year-to-year variability. Finally, examining multidecadal trends, in models and observations, we confirm the findings of several previous studies and conclude that the SAM – and thus the ozone hole – are not the primary drivers of the sea ice expansion around Antarctica in recent decades.

Plain Language Summary

Unlike its Arctic counterpart, sea ice around Antarctica has been growing since 1979, even as the levels of carbon dioxide in the atmosphere have increased. Given that the ozone hole formed over the South Pole around the same time, one is led to ask whether the ozone hole may be responsible for the growth of Antarctic sea ice (recall that there is no ozone hole over the North Pole). In this study, looking at both models and observations, we show that the ozone hole is capable of affecting the surface winds and these, in turn, can make sea ice expand. However, the magnitude of this effect is small. Also since the ozone hole started healing after the year 2000, while Antarctic sea ice kept expanding, we conclude that ozone depletion is not the main reason for the expansion of Antarctic sea ice in recent decades.

1 Introduction

The expansion of Antarctic sea ice over the last four decades (Turner et al., 2015; Jones et al., 2016), while small and not linear (Handcock & Raphael, 2020), remains one of the most surprising aspects of recent climate change, given the robust and monotonic increase in the atmospheric concentration of anthropogenic greenhouse gases. As the Arctic has rapidly warmed (Stroeve, Serreze, et al., 2012), the sea surface has cooled around Antarctica, and this has been accompanied by an increasing area of sea ice (Fan et al., 2014; Parkinson, 2019). Furthermore, while climate models are now able to capture the strong melting of Arctic sea ice (Stroeve, Kattsov, et al., 2012; SIMIP, 2020), they remain unable to simulate the multidecadal expansion of Antarctic sea ice (Arzel et al., 2006; Turner et al., 2013; Roach et al., 2020).

62 In terms of climate forcings, one key difference between the two hemispheres is the
63 formation of the ozone hole over the South Pole in the late 20th century. This has had
64 profound impacts on many aspects of the Southern Hemisphere climate system (see Pre-
65 vidi & Polvani, 2014, for a comprehensive review), largely mediated by the Southern An-
66 nular Mode (SAM). It is now accepted that the positive trend in the summertime SAM
67 from 1960 to 2000 (approximately) was largely forced by stratospheric ozone depletion
68 (Thompson & Solomon, 2002; Gillett & Thompson, 2003; Polvani et al., 2011; Baner-
69 jee et al., 2020; Fogt & Marshall, 2020), although increasing greenhouse gases and in-
70 ternal variability have also likely contributed (Thomas et al., 2015).

71 Since positive interannual SAM anomalies induce (via Ekman drift) colder sea sur-
72 face temperatures and increased sea ice concentration (Hall & Visbeck, 2002; Liu et al.,
73 2004; Ciasto & Thompson, 2008; Simpkins et al., 2012), one is immediately led to ask
74 whether positive Antarctic sea ice extent (SIE) trends have been caused by ozone de-
75 pletion. Many studies have addressed this question reaching, unfortunately, often con-
76 tradictory conclusions. To help clarify a somewhat confused situation, we start with a
77 brief summary of the extant literature.

78 A few early studies (Goosse et al., 2009; Turner et al., 2009) using simplified model
79 configurations suggested that, indeed, ozone via the SAM might explain the observed
80 positive SIE trends. However, several subsequent studies with comprehensive earth-system
81 models (Sigmond & Fyfe, 2010; Smith et al., 2012; Bitz & Polvani, 2012; Sigmond & Fyfe,
82 2014; A. Solomon et al., 2015) found the opposite: they demonstrated that ozone deple-
83 tion in the second half of the 20th century causes a robust melting of Antarctic sea ice.
84 However, since these studies were based on models, and since current-generation mod-
85 els are unable to simulate the multidecadal growth of Antarctic SIE, doubts lingered.

86 A new modeling approach was proposed by Ferreira et al. (2015). They advocated
87 studying the response to ozone depletion using an idealized “step-like” ozone forcing, rather
88 than to a transient and realistic historical ozone forcing, in order to obtain the so-called
89 Climate Response Function (CRF, as detailed in Marshall et al., 2014). That method
90 emphasized that, over the Southern Ocean, the SST response occurs in two distinct phases:
91 a “fast” cooling phase, dominated by Ekman transport of cold waters away from the Antarc-
92 tic continent, and a “slow” warming phase, caused by the upwelling of warmer water from
93 below. This approach was pursued in a number of subsequent studies (Kostov et al., 2017;
94 Seviour et al., 2016; Holland et al., 2017), who examined a large number of climate mod-
95 els and found that SSTs over the Southern Ocean do indeed respond with a early cool-
96 ing and later warming phase. However, the cooling phase was *not* found in the response

97 of Antarctic sea ice in models subjected to impulsive ozone forcing: all CMIP-class¹ mod-
98 els showed a continuous melting of sea ice following the impulsive ozone forcing (see Fig. 9
99 of Seviour et al., 2019).

100 Although the *modeling* evidence showing that ozone depletion melts Antarctic sea
101 ice is now overwhelming, the possibility that ozone – forcing SAM trends – could nonethe-
102 less be responsible for the observed expansion of Antarctic sea ice has remained tanta-
103 lizing, because the seasonal cooling phase of the SST response to the SAM rests on a well-
104 tested physical mechanism which was shown to be operative in observations. Specifically,
105 confirming earlier studies (Liu et al., 2004; Simpkins et al., 2012), Doddridge and Mar-
106 shall (2017, hereafter DM17) recently analyzed the observed interannual relationship be-
107 tween SAM and SIE over the period 1979-2017, and demonstrated how positive summer-
108 time SAM anomalies are followed by colder sea surface temperatures (SST) leading to
109 anomalous SIE in the fall, with the largest effect occurring in April. Since the largest
110 SAM trends over that period are observed in the summer, DM17 conclude that “*The re-*
111 *sults presented in this paper suggest that anthropogenic ozone depletion, by forcing the*
112 *atmosphere toward a positive SAM state in DJF, may have contributed to a seasonal*
113 *cooling of SST near Antarctica and an increase in Antarctic sea ice extent during the*
114 *austral autumn.*”

115 The goal of the present study is to determine whether this suggestion is actually
116 borne out in reality. Building on the findings of DM17, we here address two simple ques-
117 tions:

- 118 1. Are climate models able to simulate the observed interannual lagged relationship
119 between summer SAM and fall SIE?
- 120 2. Given the SAM trends, does this interannual relationship explain the multidecadal
121 fall SIE trends, in the models and in the observations?

122 After a brief exposition of the models and the methods used herein, we show that
123 the answer to the first question is “yes”, and to the second question is “no”. We con-
124 clude with a discussion on the implications of these findings for the role of ozone deple-
125 tion on Antarctic SIE.

¹ The only exception was the MITgcm, which showed a 20-year-long initial phase of Antarctic sea ice growth, before the sea ice melting phase appears. It should be noted that MITgcm is not a CMIP-class model: it consists of an idealized “double-Drake” ocean model, coupled to a 5-level aqua-planet atmospheric model with highly simplified physical parameterizations, and a purely thermodynamic sea ice component. See the Appendix of Ferreira et al. (2015).

2 Methods

Since this paper is a direct follow-up of DM17, all methods are identical to theirs, except where explicitly noted. In addition to the observations, we here analyze two sets of climate models. The first set is the CMIP5 multimodel ensemble: we here combine the Historical and RCP8.5 integrations, analyzing all the available runs from 25 different models, for a total of 55 members. The second set is Community Earth System Model “Large Ensemble” (Kay et al., 2015, hereafter CESM-LE), for which 40 members are available. All runs are forced identically as, per the CMIP5 protocol. The CMIP5 ensemble allows us to estimate the robustness of the correlations across many models; the CESM ensemble allows us estimate how internal variability might affect the conclusions. All fields are regridded to a common resolution of 1° longitude by 0.5° latitude resolution before performing any analysis.

Updating the study of DM17, we here analyze the entire 1979-2020 period, and explore the correlation between the time series of the December-February (DJF) SAM and both SST and SIE in the subsequent months. The DJF months are chosen because it is in the summer that SAM trends have been the largest and statistically significant (see, e.g., Swart & Fyfe, 2012) and, as many modeling studies have shown, those summer trends are due primarily to stratospheric ozone depletion.

The DJF SAM index is computed as the difference between zonal mean, seasonal mean (DJF) and standardized sea level pressures at 45°S and 60°S : the standardization period is 1971- 2000 following Marshall (2003). For the observations, we obtain DJF-average, standardized zonal mean sea level pressure at 45°S and 60°S based on station-based measurements from British Antarctic Survey (<https://legacy.bas.ac.uk/met/gjma/sam.html>). For the model output, we use the variables “psl” for CMIP5, and “PSL” for CESM-LE. The results presented below are nearly identical if the observed SAM from station data is replaced by a SAM computed from zonal means using ERA5 reanalyses (not shown).

Finally, monthly Antarctic SIE time series are computed as follows. For the observations, we employ a satellite-based data set for sea ice concentration available at the National Snow and Ice Data Center (NSDIC, Fetterer et al., 2017). For the models, SIE is calculated from sea ice concentration (using the variables “sic” in CMIP5 and “ICE-FRAC” in CESM-LE), as the total area of cells with a sea ice cover greater than 15%.

Following DM17, the timeseries of the DJF SAM index and monthly SIE are detrended by simply removing the linear trend, and the SAM-SIE relationship is then investigated over the period 1979-2020. For clarity, we index the data corresponding to the SIE values, so the first year is 1980 (corresponding to a SAM in December 1979, and Jan-

161 uary and February 1980) and the last year is 2020; this gives a total of 41 years. We also
162 perform a regression of the detrended DJF SAM timeseries versus the following year’s
163 detrended values of SST and SIE for every calendar month (e.g.the 2000-2001 DJF SAM
164 is regressed against the 2001 monthly SST and SIE values).

165 **3 Results**

166 We start by validating the key observational finding of DM17, shown by the black
167 line in Figure 1a: positive summer SAM anomalies result in increased Antarctic SIE in
168 the following fall, with the maximum occurring in April, when an additional 0.18 mil-
169 lion km² of sea ice is observed after one unit increase the summer SAM index. Next, in
170 Figure 1b, we demonstrate that the CESM-LE model is capable of simulating this re-
171 lationship: nearly all CESM-LE runs show increased fall SIE following positive summer
172 SAM anomalies (the ensemble mean is shown in panel a).

173 Unfortunately, not all CMIP5 runs are able to capture the observed impact of the
174 summer SAM onto the fall SIE. We examine each individual model run, and test whether
175 the observed SAM-SIE connection is present. For simplicity we separate the CMIP5 model
176 runs in two sets, based on the correlation r between the SAM-SIE relationship in the model
177 and in the observations. Runs which accurately simulate the annual pattern of SIE re-
178 sponse to the SAM ($r > 0.5$) are shown in Figure 1c, and those with a poor simulation
179 ($r < 0.5$) in Figure 1d. Interestingly, for a few models, some runs fall in one category
180 and some in the other. For reference, 35 of the 40 CESM-LE runs show a good corre-
181 lation with observations. The ensemble mean of the CMIP5 runs with $r > 0.5$ is shown
182 in green in Figure 1a, for direct comparison with observations. The key point of that fig-
183 ure is that many CMIP5 model runs are able to capture the observed impact of the sum-
184 mer SAM on Antarctic SIE in the following months, with the largest impact in the fall.

185 At this point, therefore, we are ready to answer the first question posed in the In-
186 troduction: many CMIP5 historical runs (roughly one third of the CMIP5 historical runs,
187 and nearly all the CESM-LE runs) are indeed capable of capturing the “short-time” scale
188 response of Antarctic sea ice to the summertime SAM, in the terminology of Ferreira et
189 al. (2015), most notably the peak response in the fall. Notice however, that the relation-
190 ship between these two quantities is somewhat tenuous because, as one can see in Fig-
191 ures 1c and d, for several model runs can be found in both panels.

192 Nonetheless, we are now ready to turn our attention to the second question: does
193 the physical mechanism connecting the DJF SAM to the fall sea ice extent operate on
194 multidecadal time scales, and help us explain the long-term trends? To answer that ques-

195 tion, let us start by considering the amount of monthly SIE variance that is explained
196 by the preceding DJF SAM. This is shown in Figure 2, for the observations, the CMIP5
197 models, and the CESM-LE, respectively. Notice first the good agreement across the three
198 panels: all agree the strongest linkage is in MAM, and are quantitatively close (between
199 0.10 and 0.15). This confirms that many models are capturing the physics of the SAM-
200 SIE relationship correctly. The CESM-LE (panel) Figure 2c, provides an excellent ex-
201 ample.

202 Next, however, consider the actual values on the ordinate axis: the largest values,
203 which are found in MAM, are very small. The peak, in April, is a mere 0.15. This means
204 that the bulk (i.e. 85%) of the interannual variability in fall SIE around Antarctica is
205 *not* due to SAM anomalies in the preceding summer.

206 Given the small variance explained by the SAM on a year-to-year basis, even in the
207 peak months (i.e. in MAM), it is difficult to imagine how the SAM would be able to ex-
208 plain the long-term trends. This is illustrated in Fig. 3 where, in each panel, the SAM-
209 regressed SIE trends in MAM are plotted against the corresponding actual SIE trends
210 in MAM, both for the model runs and for the observations (the SAM in DJF is used to
211 compute the SAM-regressed SIE trends in each month). In each panel, the one-to-one
212 line is shown, for reference, by the dashed blue line.

213 Let us first discuss the modeled trends, shown by the colored dots. One might start
214 by naively computing linear trends over the entire 1980-2020 period, shown in Fig. 3a.
215 It is immediately clear that the actual modeled trends are much larger (in magnitude)
216 than the SAM-regressed trends, by nearly an order of magnitude (note the different scales
217 on the ordinate and the abscissa). This is to be expected, as the SAM only explains 15%
218 of the variance, as we have just shown, and suggests that other drivers or longer-period
219 variability dominate the modeled trends over this timescale.

220 However, taking linear trends at Southern high latitudes over the entire 1980-2020
221 period is highly problematic. It has now been well-established that the formation of the
222 ozone hole was the main driver of SAM trends in DJF in the late 20th century (Polvani
223 et al., 2011). Moreover, since the onset of ozone recovery as a consequence of the Mon-
224 treal Protocol (S. Solomon et al., 2016) SAM trends in DJF are no longer increasing, as
225 reported in Banerjee et al. (2020). This is illustrated in Fig. 4: note how the SAM (red
226 line) was increasing until the year 2000, but has been relatively constant since (we read-
227 ily admit that the interannual variability is very large).

228 Thus, to account for the non-monotonic forcing from stratospheric ozone (the main
229 driver of SAM trends in DJF prior to 2000), it is more meaningful to separate the 1980-

230 2020 period into an ozone depletion period (1980-2000) and an ozone recovery period
231 (2000-2020), and then compute separate linear trends (as, e.g., in Banerjee et al., 2020).
232 The actual and SAM-regressed trends in these earlier and later periods are plotted in
233 Fig. 3b and c, respectively.

234 Again, focusing on the modeled trends in those panels, we see that the SAM-regressed
235 trends in MAM are much smaller than the actual SIE trends in that season, indicating
236 that the summer SAM trends have very little predictive power over the modeled SIE in
237 the subsequent fall over decadal timescales. Also, note that the models runs that cap-
238 ture the internannual SAM/SIE relationship (green and purple) do not show a superior
239 relationship between the long-term SAM-regressed and actual SIE trends than the mod-
240 els that do not capture the internannual SAM/SIE relationship (orange), again demon-
241 strating that the SAM is not the major driver of the modeled SIE trends. Nonetheless,
242 contrasting panels b and c, one can see that models runs which capture the internan-
243 nual SAM/SIE relationship show slightly positive trends over the ozone-depletion pe-
244 riod (panel b), and that these disappear in the ozone-recovery period (panel c: compare
245 the means, shown in the larger dots).

246 More worrisome, however, is the fact that in the same ozone-depletion period, when
247 one might expect the SAM to have the largest impact, SIE trends in the models are mostly
248 negative, unlike the positive trends in the observations. It is important to appreciate that
249 the CMIP5 model capture well the observed SAM trends in DJF (see, for instance, Fig
250 9 of Holland et al., 2017). However, the models warm excessively, resulting in substan-
251 tial sea ice loss, not seen in the observations (Arzel et al., 2006; Turner et al., 2013; Zunz
252 et al., 2013; Roach et al., 2020). Many ideas have been proposed to explain the cause
253 of the models' bias: the introductory section of Sun and Eisenman (2021) succinctly re-
254 views the relevant literature (see also Chemke & Polvani, 2020, not included there).

255 So, let us now leave the model simulations aside, and turn our attention to the ob-
256 served SIE trends. Focusing uniquely on prescribed periods is problematic, as the large
257 internal variability makes such trends highly sensitive to the endpoints. For instance, the
258 observed and SAM-regressed SIE trends in MAM over the entire 1980-2020 period (shown
259 by the black cross in Fig. 3a), appear to fall close to the one-to-one line, and might lead
260 one to believe that the SAM is a good predictor of SIE (the SAM-regressed trends is 63%
261 of observed trend). However, as one can see in Fig. 3b and c, the observations are not close
262 to the one-to-one line in either of the two sub-periods. So, one is easily deceived by such
263 trend computations with fixed endpoints.

264 It is more instructive to examine the entire 1980-2020 time series of SAM (in DJF)
265 and SIE (in MAM), shown by the red and blue lines, respectively, in Fig. 4. While there
266 is some correlation between the two time series (0.44), one would be hard pressed to claim
267 that the SAM in DJF is the dominant driver of SIE in MAM. In the ozone-depletion pe-
268 riod the regression analysis indicates that the SAM explains 40% of the observed trends
269 over that period. However, that result is based on having detrended the SAM index us-
270 ing the entire 1980-2020 period (see Methods), which was done to be consistent with DM17.
271 If, in contrast, one detrends the two periods separately, as one should to be consistent
272 with the ozone forcing, only 14% of the observed SIE trend over the ozone depletion pe-
273 riod is explained by the corresponding SAM trends in DJF, in good agreement with the
274 interannual regression in Fig. 2 (which shows values between 10% and 15% in MAM).
275 But even that is only a correlation: note how SAM basically stops trending after the year
276 2000 (as ozone depletion was largely halted by the Montreal Protocol) whereas SIE keeps
277 growing until 2016 (when a strong and sudden reduction occurred; see, e.g., Turner et
278 al., 2017; Stuecker et al., 2017). Why would the SIE keep growing past the year 2000 if
279 it were driven by the SAM via Ekman transport?

280 One might also be tempted to ascribe the strong 2017 reduction to the SAM, as
281 suggested in DM17. Note, however the following year showed a strong *positive* SAM while
282 SIE remained *very low*. This, coupled with the small interannual SIE variance explained
283 by the SAM (see above) indicates that the concurrent 2017 minimum in SAM and SIE
284 is likely to be a coincidence. Other major mismatches can be seen, such as the year 1999
285 which show the peak SAM in the time series while the SIE that year was unremarkable,
286 or the period 1983 and 1985 where the SAM was at its lowest values but with no cor-
287 responding minima in SIE. In the end, we submit, upon simple inspection of the two time
288 series in Fig. 4 one would be hard pressed to conclude that the DJF SAM is the primary
289 driver SIE in MAM, both interannually and multidecadally.

290 **4 Summary and Discussion**

291 Building on the observational study of DM17, we have here explored whether the
292 Ekman mechanism whereby positive SAM anomalies in summer (DJF) cause positive
293 SIE anomalies in the fall (MAM) is actually captured by state-of-the-art coupled climate
294 models; the rationale is that the potential lack of such a mechanism in models may be
295 responsible for the poor agreement between modeled and observed SIE over the last four
296 decades. Our analysis has revealed that many (though not most) models are able to sim-
297 ulate the observed interannual SAM/SIE relationship. However, it has also shown that
298 their ability to capture that relationship has basically no influence of a model's ability

299 to capture the observed trends, as most models show sea ice melting over the last four
300 decades, irrespective of whether or not the SAM/SIE relationship is accurately modeled.

301 The reason for this, which is also a major finding of our analysis, is that the SAM/SIE
302 relationship is tenuous. It explains a mere 15% of the year-to-year SIE variability in the
303 fall. Splitting the last four decades into two halves – an ozone depletion and an ozone
304 recovery period – one finds that the SAM may be able to explain as much as 14% of the
305 trends during the earlier period. Even that, however, may be partially accidental, as the
306 SIE trends appear mismatched from the SAM trends: SIE kept growing until 2016, whereas
307 the SAM stopped increasing after the year 2000. Our study, therefore, largely confirms
308 the findings of several earlier observational studies (Liu et al., 2004; Lefebvre et al., 2004;
309 Simpkins et al., 2012; Kohyama & Hartmann, 2016) which also concluded that the SAM
310 is not the primary driver of sea ice trends around Antarctica.

311 Further evidence in support of this conclusion is offered by the strong longitudi-
312 nal asymmetry of the recent Antarctic sea ice trends. It is widely appreciated that the
313 polar-cap-averaged SIE trends discussed above are relatively small compared to the re-
314 gional trends, owing to large cancellations between different sectors, notably the Ross,
315 Amundsen-Bellinghshausen, and Weddell seas (Turner et al., 2015; Parkinson, 2019). Be-
316 cause the SAM is, by definition *annular*, one would expect its impact to be similar at
317 all longitudes. Thus, the simple fact that trends of opposite sign are observed at differ-
318 ent longitudes is a strong indication that the SAM is unlikely to be the main driver of
319 those trends. We stress that this argument is based solely on observational evidence, and
320 does not suffer from any potential or actual model deficiencies.

321 Our findings have implications for the role of ozone depletion on Antarctic sea ice.
322 Contradictory claims are found in the literature, with some studies suggesting that ozone
323 depletion may be responsible for positive trends in SIE (e.g., Turner et al., 2009; Fer-
324 reira et al., 2015), and others arguing that ozone depletion leads to negative SIE trends
325 (e.g., Sigmond & Fyfe, 2014; Landrum et al., 2017). The results presented here lead us
326 to conclude that stratospheric ozone depletion has not been the primary driver of SIE
327 trends although, acting via the SAM, it may have contributed a fraction of the SIE trends
328 before the year 2000. That fraction, however, may not be very large, if one keeps in mind
329 that the observed SAM trends are not due to ozone depletion alone, but also to increas-
330 ing greenhouse gases and, very likely, to internal variability (Thomas et al., 2015).

331 In fact, the idea that multidecadal internal variability may suffice to explain the
332 growth of SIE around Antarctica was proposed by Polvani and Smith (2013), and inde-
333 pendently suggested by Zunz et al. (2013), with additional evidence later provided by

334 Gagné et al. (2015) and Singh et al. (2019). As to the source of variability, the tropical
335 Pacific has been highlighted in several studies (see, e.g., Schneider et al., 2012, 2015; Purich
336 et al., 2016; Meehl et al., 2016, among others). More importantly, however, we draw the
337 reader’s attention to the entirely observational study of Fan et al. (2014), who noted that
338 trends at high Southern latitudes in several variables – sea ice extent, sea surface tem-
339 perature, zonal wind, sea level pressure and surface atmospheric temperature – changed
340 sign *simultaneously* around 1978-1979: this clearly points to internal variability, as no
341 anthropogenic or natural forcing is known to have reversed trends so as to cause surface
342 cooling and sea ice growth after those years.

343 A number of other studies have also explored the possibility that freshwater influx
344 from the retreat of the Antarctic ice sheet might be the cause of sea ice increase around
345 the Antarctic continent. The early work of Bintanja et al. (2013) suggested a consider-
346 able effect of ice-shelf melt on sea ice growth, and more recently Rye et al. (2020) have
347 shown that inclusion of meltwater helps brings models closer to observations. Unfortu-
348 nately these results were not confirmed by other modeling studies (Swart & Fyfe, 2012;
349 Pauling et al., 2016), who found the meltwater contribution to be too small to explain
350 the observed trends. Hence the role freshwater flux remains an open question, and the
351 inclusion of interactive ice-shelf models into climate models remains to be explored.

352 Finally, returning to the formation of the ozone hole and the resulting SAM trends,
353 we wish to emphasize that stratospheric ozone depletion was accompanied by increas-
354 ing levels of ozone-depleting substances in the troposphere. These are potent – and well-
355 mixed – greenhouse gases, which act to warm the ocean and thus melt sea ice not just
356 in the Antarctic (A. Solomon et al., 2015), but also in the Arctic (Polvani et al., 2020):
357 as such, ozone-depleting substances cannot possibly have contributed to the observed
358 expansion of Antarctic sea ice since 1979. Indeed, whatever is responsible for the expan-
359 sion must have been able overcome not only the increasing atmospheric concentrations
360 of carbon dioxide, but also increasing concentrations of ozone-depleting substances. Ul-
361 timately, given these anthropogenic forcing, the surprising trends in Antarctic sea ice in
362 the last four decades remain mysterious, as the attractive and physically-based mech-
363 anism linking ozone depletion to positive SAM anomalies to northward Ekman drift to
364 increased SIE is, at this point, clearly unable to account for the observed trends.

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369 and the CESM LE at <http://www.cesm.ucar.edu/>

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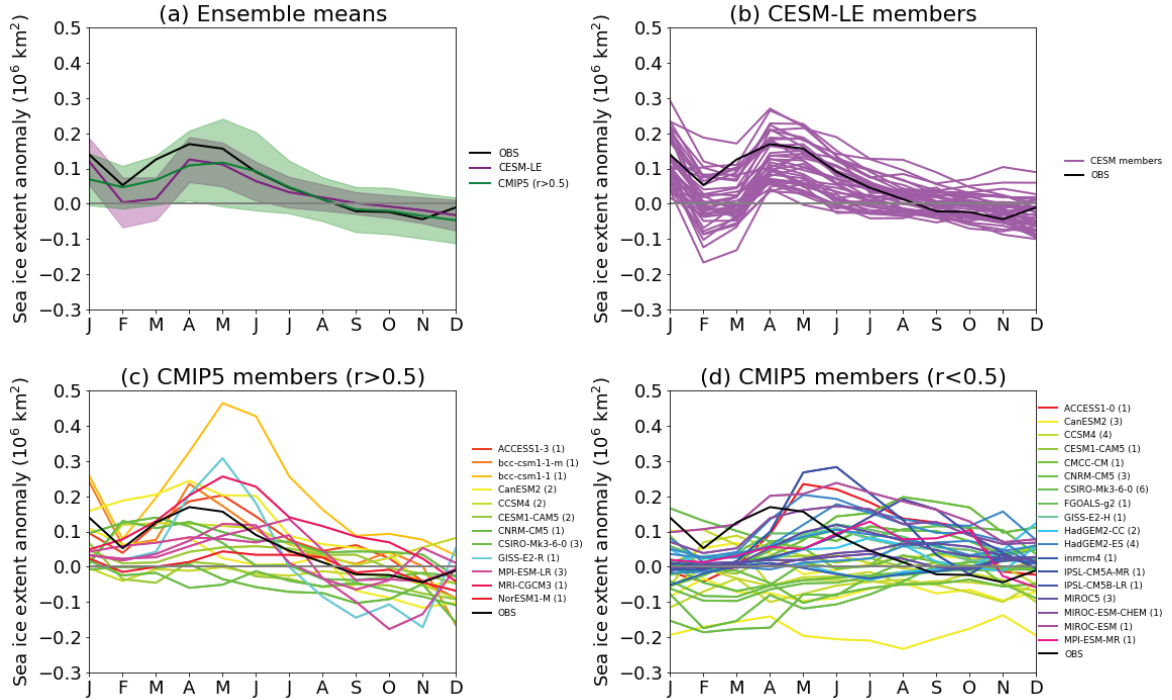


Figure 1. Monthly anomalies in Antarctic sea ice extent (SIE), in millions of km^2 , following one unit of DJF SAM anomaly, from the detrended regression analysis. (a) The observations (black), the multi-model CMIP5 ensemble mean (green, from the runs in panel c), and the CESM-LE ensemble mean (purple); the shading indicates the $1\text{-}\sigma$ spread across the respective ensembles. (b) The 40 members of the CESM-LE. (c) The 20 CMIP5 runs with good correlation with the observations ($r > 0.5$), and (d) the 35 CMIP5 runs with poor correlation ($r < 0.5$). In panels c and d, the numbers in parentheses next to each model’s name in the legend indicate the number of runs with that models in the corresponding panel.

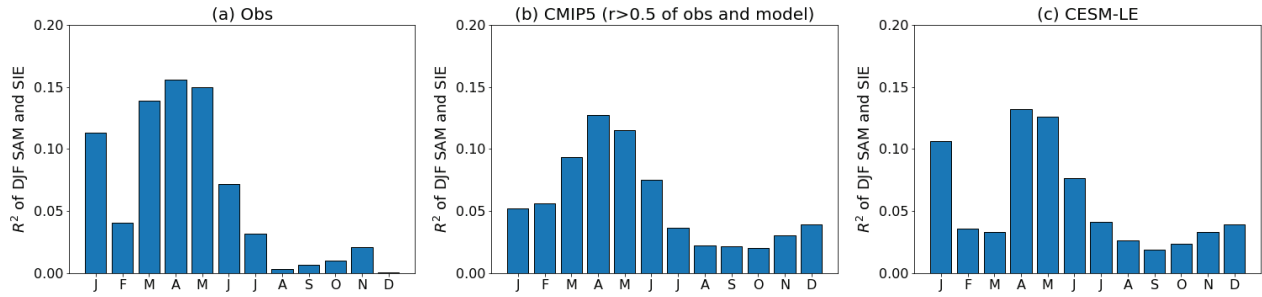


Figure 2. Monthly variance (R^2) in SIE explained by the SAM in the previous DJF months for (a) the observations, (b) the CMIP5 model runs shown in Fig. 1c, and (c) the CESM-LE runs.

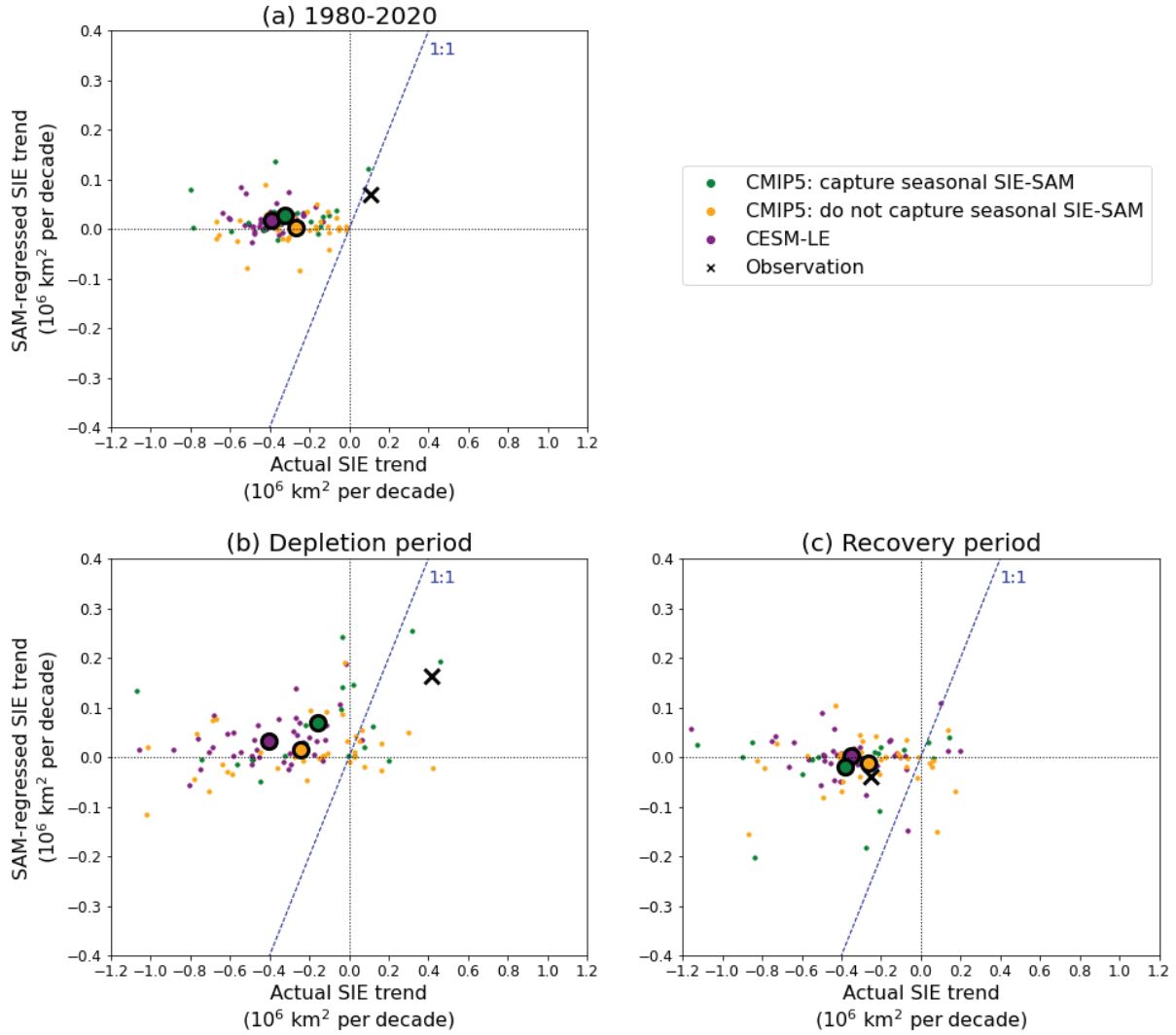


Figure 3. SAM-regressed vs actual SIE in MAM trends for (a) the entire 1980-2020 period, (b) the ozone depletion period 1980-2000, and (c) the ozone recovery period 2000-2020, in millions of km^2 per decade. The large encircled dots show the model average, by color, as indicated in the legend. The one-to-one line is in blue (dashed). The back crosses show the observations. The SAM-regressed SIE trends are computed using the SAM trends in DJF.

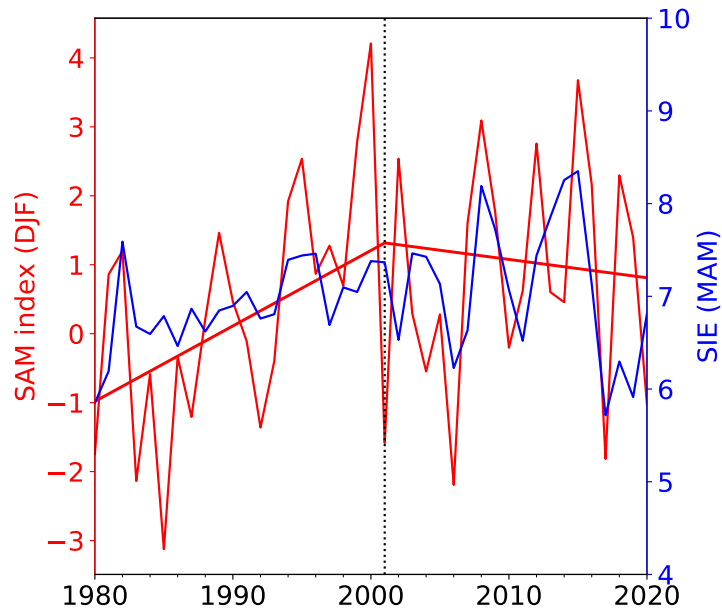


Figure 4. Time series of the observed SAM (in DJF, red) and SIE (in MAM, blue) from 1980 to 2020. The SAM values are shifted by one year from the convention adopted in DM17; e.g. the SAM value for the three month average December 1980, January 1981 and February 1981 is shown at the 1981 value on the abscissa, together with the SIE in MAM of 1981. The solid red lines are linear trends before and after the year 2000.