

Interannual SAM modulation of Antarctic sea ice extent does not account for its long-term trends: implications for the role of ozone depletion

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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 an early cool-
96 ing and later warming phase. However, a corresponding sea ice growth phase was *never*

97 found: all CMIP-class¹ models have shown a continuous melting of sea ice following im-
 98 pulsive ozone forcing (see Fig. 9 of Seviour et al., 2019), confirming earlier modeling stud-
 99 ies with more realistic ozone forcing (e.g., Bitz & Polvani, 2012; A. Solomon et al., 2015).

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 following impulsive ozone forcing, before the sea ice melting phase appears (Ferreira et al., 2015). 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 the satellite-based data set of sea ice concentration available at the National Snow and Ice Data Center (NSIDC, Fetterer et al., 2017). For the models, SIE is calculated from sea ice concentration (using the variables “sic” in CMIP5 and “ICEFRAC” 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

161 SIE values, so the first year is 1980 (corresponding to a SAM in December 1979, and Jan-
162 uary and February 1980) and the last year is 2020; this gives a total of 41 years. We also
163 perform a regression of the detrended DJF SAM timeseries versus the following year’s
164 detrended values of SST and SIE for every calendar month (e.g.the 2000-2001 DJF SAM
165 is regressed against the 2001 monthly SST and SIE values).

166 **3 Results**

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

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

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

193 Nonetheless, we are now ready to turn our attention to the second question: does
194 the physical mechanism connecting the DJF SAM to the fall sea ice extent operate on

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

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

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

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

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

229 Thus, to account for the non-monotonic forcing from stratospheric ozone (the main
230 driver of SAM trends in DJF prior to 2000), it is more meaningful to separate the 1980-
231 2020 period into an ozone depletion period (1980-2000) and an ozone recovery period
232 (2000-2020), and then compute separate linear trends (as, e.g., in Banerjee et al., 2020).
233 The actual and SAM-regressed trends in these earlier and later periods are plotted in
234 Fig. 3b and c, respectively.

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

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

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

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

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

291 4 Summary and Discussion

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

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

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

312 Further evidence in support of this conclusion is offered by the strong longitudi-
313 nal asymmetry of the recent Antarctic sea ice trends. It is widely appreciated that the
314 polar-cap-averaged SIE trends discussed above are relatively small compared to the re-
315 gional trends, owing to large cancellations between different sectors, notably the Ross,
316 Amundsen-Bellingshausen, and Weddell seas (Turner et al., 2015; Parkinson, 2019). Be-
317 cause the SAM is, by definition *annular*, one would naively expect its impact to be sim-
318 ilar at most² longitudes. Thus, the simple fact that trends of opposite sign are observed
319 at different longitudes is a strong indication that the SAM is unlikely to be the main driver
320 of those trends. We stress that this argument is based solely on observational evidence,
321 and does not suffer from any potential or actual model deficiencies.

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

² The peninsula might be an exception, as it reaches further north than the rest of the Antarctic con-
tinent. See for instance, Fig. 7c of (Sen Gupta & England, 2006), illustrating the sea ice concentrations
regressed onto the SAM, averaged from January to March.

332 In fact, the idea that multidecadal internal variability may suffice to explain the
333 growth of SIE around Antarctica was proposed by Polvani and Smith (2013), and inde-
334 pendently suggested by Zunz et al. (2013), with additional evidence later provided by
335 Gagné et al. (2015) and Singh et al. (2019). As to the source of variability, the tropical
336 Pacific has been highlighted in several studies (see, e.g., Schneider et al., 2012, 2015; Purich
337 et al., 2016; Meehl et al., 2016, among others). More importantly, however, we draw the
338 reader’s attention to the entirely observational study of Fan et al. (2014), who noted that
339 trends at high Southern latitudes in several variables – sea ice extent, sea surface tem-
340 perature, zonal wind, sea level pressure and surface atmospheric temperature – changed
341 sign *simultaneously* around 1978-1979: this clearly points to internal variability, as no
342 anthropogenic or natural forcing is known to have reversed trends so as to cause surface
343 cooling and sea ice growth after those years.

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

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

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371 at <https://esgf-node.llnl.gov/projects/cmip5/> and the CESM LE at <http://www.cesm.ucar.edu/>

References

- Arzel, O., Fichefet, T., & Goosse, H. (2006). Sea ice evolution over the 20th and 21st centuries as simulated by current AOGCMs. *Ocean Modelling*, *12*(3-4), 401–415.
- Banerjee, A., Fyfe, J. C., Polvani, L. M., Waugh, D., & Chang, K.-L. (2020). A pause in Southern Hemisphere circulation trends due to the Montreal Protocol. *Nature*, *579*(7800), 544–548.
- Bintanja, R., van Oldenborgh, G. J., Drijfhout, S., Wouters, B., & Katsman, C. (2013). Important role for ocean warming and increased ice-shelf melt in antarctic sea-ice expansion. *Nature Geoscience*, *6*(5), 376–379.
- Bitz, C., & Polvani, L. M. (2012). Antarctic climate response to stratospheric ozone depletion in a fine resolution ocean climate model. *Geophysical Research Letters*, *39*(20).
- Chemke, R., & Polvani, L. (2020). Using multiple large ensembles to elucidate the discrepancy between the 1979–2019 modeled and observed antarctic sea ice trends. *Geophysical Research Letters*, *47*(15), e2020GL088339.
- Ciasto, L. M., & Thompson, D. W. (2008). Observations of large-scale ocean–atmosphere interaction in the Southern Hemisphere. *Journal of Climate*, *21*(6), 1244–1259.
- Doddridge, E. W., & Marshall, J. (2017). Modulation of the seasonal cycle of Antarctic sea ice extent related to the Southern Annular Mode. *Geophysical Research Letters*, *44*(19), 9761–9768.
- Fan, T., Deser, C., & Schneider, D. P. (2014). Recent Antarctic sea ice trends in the context of Southern Ocean surface climate variations since 1950. *Geophysical Research Letters*, *41*(7), 2419–2426.
- Ferreira, D., Marshall, J., Bitz, C. M., Solomon, S., & Plumb, A. (2015). Antarctic Ocean and sea ice response to ozone depletion: A two-time-scale problem. *Journal of Climate*, *28*(3), 1206–1226.
- Fetterer, F., Knowles, K., Meier, W., Savoie, M., & Windnagel, A. (2017). *Sea Ice Index, Version 3*. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. doi: <https://doi.org/10.7265/N5K072F8>
- Fogt, R. L., & Marshall, G. J. (2020). The Southern annular mode: Variability, trends, and climate impacts across the Southern Hemisphere. *Wiley Interdisciplinary Reviews: Climate Change*, *11*(4), e652.
- Gagné, M.-È., Gillett, N., & Fyfe, J. (2015). Observed and simulated changes in antarctic sea ice extent over the past 50 years. *Geophysical Research Letters*, *42*(1), 90–95.

- 409 Gillett, N. P., & Thompson, D. W. (2003). Simulation of recent southern hemisphere
410 climate change. *Science*, *302*(5643), 273–275.
- 411 Goosse, H., Lefebvre, W., de Montety, A., Crespin, E., & Orsi, A. H. (2009). Con-
412 sistent past half-century trends in the atmosphere, the sea ice and the ocean at
413 high southern latitudes. *Climate Dynamics*, *33*(7-8), 999–1016.
- 414 Hall, A., & Visbeck, M. (2002). Synchronous variability in the Southern Hemi-
415 sphere atmosphere, sea ice, and ocean resulting from the annular mode. *Jour-
416 nal of Climate*, *15*(21), 3043–3057.
- 417 Handcock, M. S., & Raphael, M. N. (2020). Modeling the annual cycle of daily
418 antarctic sea ice extent. *The Cryosphere*, *14*(7), 2159–2172.
- 419 Holland, M. M., Landrum, L., Kostov, Y., & Marshall, J. (2017). Sensitivity of
420 Antarctic sea ice to the Southern Annular Mode in coupled climate models.
421 *Climate Dynamics*, *49*(5-6), 1813–1831.
- 422 Jones, J., Gille, S., Goosse, H., Abram, N., Canziani, P., Charman, D., . . . Vance, T.
423 (2016). Assessing recent trends in high-latitude Southern Hemisphere surface
424 climate. *Nature Climate Change*, *6*(10), 917–926.
- 425 Kay, J. E., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., . . . Vertenstein,
426 M. (2015). The Community Earth System Model (CESM) Large Ensemble
427 Project: A community resource for studying climate change in the presence of
428 internal climate variability. *Bulletin of the American Meteorological Society*,
429 *96*(8), 1333–1349.
- 430 Kohyama, T., & Hartmann, D. L. (2016). Antarctic sea ice response to weather and
431 climate modes of variability. *Journal of Climate*, *29*(2), 721–741.
- 432 Kostov, Y., Marshall, J., Hausmann, U., Armour, K. C., Ferreira, D., & Holland,
433 M. M. (2017). Fast and slow responses of Southern Ocean sea surface tem-
434 perature to SAM in coupled climate models. *Climate Dynamics*, *48*(5-6),
435 1595–1609.
- 436 Landrum, L. L., Holland, M. M., Raphael, M. N., & Polvani, L. M. (2017). Strato-
437 spheric ozone depletion: An unlikely driver of the regional trends in Antarctic
438 Sea Ice in Austral fall in the late twentieth century. *Geophysical Research
439 Letters*, *44*(21), 11–062.
- 440 Lefebvre, W., Goosse, H., Timmermann, R., & Fichefet, T. (2004). Influence of the
441 Southern Annular Mode on the sea ice–ocean system. *Journal of Geophysical
442 Research: Oceans*, *109*(C9).
- 443 Liu, J., Curry, J. A., & Martinson, D. G. (2004). Interpretation of recent Antarctic
444 sea ice variability. *Geophysical Research Letters*, *31*(2).
- 445 Marshall, J., Armour, K. C., Scott, J. R., Kostov, Y., Hausmann, U., Ferreira, D.,

- 446 ... Bitz, C. M. (2014). The ocean's role in polar climate change: asymmetric
 447 Arctic and Antarctic responses to greenhouse gas and ozone forcing. *Philo-*
 448 *sophical Transactions of the Royal Society A: Mathematical, Physical and*
 449 *Engineering Sciences*, 372(2019), 20130040.
- 450 Meehl, G. A., Arblaster, J. M., Bitz, C. M., Chung, C. T., & Teng, H. (2016).
 451 Antarctic sea-ice expansion between 2000 and 2014 driven by tropical pacific
 452 decadal climate variability. *Nature Geoscience*, 9(8), 590–595.
- 453 Parkinson, C. L. (2019). A 40-y record reveals gradual antarctic sea ice increases fol-
 454 lowed by decreases at rates far exceeding the rates seen in the arctic. *Proceed-*
 455 *ings of the National Academy of Sciences*, 116(29), 14414–14423.
- 456 Pauling, A. G., Bitz, C. M., Smith, I. J., & Langhorne, P. J. (2016). The response
 457 of the southern ocean and antarctic sea ice to freshwater from ice shelves in an
 458 earth system model. *Journal of Climate*, 29(5), 1655–1672.
- 459 Polvani, L. M., Previdi, M., England, M. R., Chiodo, G., & Smith, K. L. (2020).
 460 Substantial twentieth-century Arctic warming caused by ozone-depleting sub-
 461 stances. *Nature Climate Change*, 10(2), 130–133.
- 462 Polvani, L. M., & Smith, K. L. (2013). Can natural variability explain observed
 463 Antarctic sea ice trends? New modeling evidence from CMIP5. *Geophysical*
 464 *Research Letters*, 40(12), 3195–3199.
- 465 Polvani, L. M., Waugh, D. W., Correa, G. J., & Son, S.-W. (2011). Stratospheric
 466 ozone depletion: The main driver of twentieth-century atmospheric circulation
 467 changes in the Southern Hemisphere. *Journal of Climate*, 24(3), 795–812.
- 468 Previdi, M., & Polvani, L. M. (2014). Climate system response to stratospheric
 469 ozone depletion and recovery. *Quarterly Journal of the Royal Meteorological*
 470 *Society*, 140(685), 2401–2419.
- 471 Purich, A., England, M. H., Cai, W., Chikamoto, Y., Timmermann, A., Fyfe, J. C.,
 472 ... Arblaster, J. M. (2016). Tropical pacific sst drivers of recent antarctic sea
 473 ice trends. *Journal of Climate*, 29(24), 8931–8948.
- 474 Roach, L. A., Dörr, J., Holmes, C. R., Massonnet, F., Blockley, E. W., Notz, D., ...
 475 others (2020). Antarctic sea ice area in CMIP6. *Geophysical Research Letters*,
 476 47(9), e2019GL086729.
- 477 Rye, C. D., Marshall, J., Kelley, M., Russell, G., Nazarenko, L. S., Kostov, Y., ...
 478 Hansen, J. (2020). Antarctic glacial melt as a driver of recent southern ocean
 479 climate trends. *Geophysical Research Letters*, 47(11), e2019GL086892.
- 480 Schneider, D. P., Deser, C., & Fan, T. (2015). Comparing the impacts of tropical sst
 481 variability and polar stratospheric ozone loss on the southern ocean westerly
 482 winds. *Journal of Climate*, 28(23), 9350–9372.

- 483 Schneider, D. P., Okumura, Y., & Deser, C. (2012). Observed antarctic interan-
484 nual climate variability and tropical linkages. *Journal of Climate*, *25*(12),
485 4048–4066.
- 486 Sen Gupta, A., & England, M. H. (2006). Coupled ocean–atmosphere–ice response
487 to variations in the southern annular mode. *Journal of Climate*, *19*(18), 4457–
488 4486.
- 489 Seviour, W., Codron, F., Doddridge, E. W., Ferreira, D., Gnanadesikan, A., Kel-
490 ley, M., ... Waugh, D. (2019). The southern ocean sea surface temperature
491 response to ozone depletion: a multimodel comparison. *Journal of Climate*,
492 *32*(16), 5107–5121.
- 493 Seviour, W., Gnanadesikan, A., & Waugh, D. (2016). The transient response of the
494 Southern Ocean to stratospheric ozone depletion. *Journal of Climate*, *29*(20),
495 7383–7396.
- 496 Sigmond, M., & Fyfe, J. (2010). Has the ozone hole contributed to increased Antarc-
497 tic sea ice extent? *Geophysical Research Letters*, *37*(18).
- 498 Sigmond, M., & Fyfe, J. C. (2014). The Antarctic sea ice response to the ozone hole
499 in climate models. *Journal of Climate*, *27*(3), 1336–1342.
- 500 SIMIP. (2020). Arctic Sea Ice in CMIP6. *Geophysical Research Letters*, *47*(10),
501 e2019GL086749.
- 502 Simpkins, G. R., Ciasto, L. M., Thompson, D. W., & England, M. H. (2012). Sea-
503 sonal relationships between large-scale climate variability and Antarctic sea ice
504 concentration. *Journal of Climate*, *25*(16), 5451–5469.
- 505 Singh, H., Polvani, L. M., & Rasch, P. J. (2019). Antarctic Sea Ice Expansion,
506 Driven by Internal Variability, in the Presence of Increasing Atmospheric CO₂.
507 *Geophysical Research Letters*, *46*(24), 14762–14771.
- 508 Smith, K. L., Polvani, L. M., & Marsh, D. R. (2012). Mitigation of 21st century
509 Antarctic sea ice loss by stratospheric ozone recovery. *Geophysical Research*
510 *Letters*, *39*(20).
- 511 Solomon, A., Polvani, L. M., Smith, K., & Abernathey, R. (2015). The impact of
512 ozone depleting substances on the circulation, temperature, and salinity of the
513 Southern Ocean: An attribution study with CESM1 (WACCM). *Geophysical*
514 *Research Letters*, *42*(13), 5547–5555.
- 515 Solomon, S., Ivy, D. J., Kinnison, D., Mills, M. J., Neely, R. R., & Schmidt, A.
516 (2016). Emergence of healing in the Antarctic ozone layer. *Science*, *353*(6296),
517 269–274.
- 518 Stroeve, J. C., Kattsov, V., Barrett, A., Serreze, M., Pavlova, T., Holland, M., &
519 Meier, W. N. (2012). Trends in Arctic sea ice extent from CMIP5, CMIP3 and

- 520 observations. *Geophysical Research Letters*, *39*(16).
- 521 Stroeve, J. C., Serreze, M. C., Holland, M. M., Kay, J. E., Malanik, J., & Barrett,
522 A. P. (2012). The Arctics rapidly shrinking sea ice cover: a research synthesis.
523 *Climatic change*, *110*(3-4), 1005–1027.
- 524 Stuecker, M. F., Bitz, C. M., & Armour, K. C. (2017). Conditions leading to the un-
525 precedented low Antarctic sea ice extent during the 2016 austral spring season.
526 *Geophysical Research Letters*, *44*(17), 9008–9019.
- 527 Sun, S., & Eisenman, I. (2021). Observed Antarctic sea ice expansion reproduced in
528 a climate model after correcting biases in sea ice drift velocity. *Nature Commu-
529 nications*, *12*(1), 1–6.
- 530 Swart, N., & Fyfe, J. C. (2012). Observed and simulated changes in the south-
531 ern hemisphere surface westerly wind-stress. *Geophysical Research Letters*,
532 *39*(16).
- 533 Thomas, J. L., Waugh, D. W., & Gnanadesikan, A. (2015). Southern Hemisphere
534 extratropical circulation: Recent trends and natural variability. *Geophysical
535 Research Letters*, *42*(13), 5508–5515.
- 536 Thompson, D. W., & Solomon, S. (2002). Interpretation of recent southern hemi-
537 sphere climate change. *Science*, *296*(5569), 895–899.
- 538 Turner, J., Bracegirdle, T. J., Phillips, T., Marshall, G. J., & Hosking, J. S. (2013).
539 An initial assessment of Antarctic sea ice extent in the CMIP5 models. *Journal
540 of Climate*, *26*(5), 1473–1484.
- 541 Turner, J., Comiso, J. C., Marshall, G. J., Lachlan-Cope, T. A., Bracegirdle, T.,
542 Maksym, T., . . . Orr, A. (2009). Non-annular atmospheric circulation change
543 induced by stratospheric ozone depletion and its role in the recent increase of
544 Antarctic sea ice extent. *Geophysical research letters*, *36*(8).
- 545 Turner, J., Hosking, J. S., Bracegirdle, T. J., Marshall, G. J., & Phillips, T. (2015).
546 Recent changes in Antarctic sea ice. *Philosophical Transactions of the Royal
547 Society A: Mathematical, Physical and Engineering Sciences*, *373*(2045),
548 20140163.
- 549 Turner, J., Phillips, T., Marshall, G. J., Hosking, J. S., Pope, J. O., Bracegirdle,
550 T. J., & Deb, P. (2017). Unprecedented springtime retreat of Antarctic sea ice
551 in 2016. *Geophysical Research Letters*, *44*(13), 6868–6875.
- 552 Zunz, V., Goosse, H., & Massonnet, F. (2013). How does internal variability in-
553 fluence the ability of cmip5 models to reproduce the recent trend in southern
554 ocean sea ice extent. *Cryosphere*, *7*(2), 451–468.

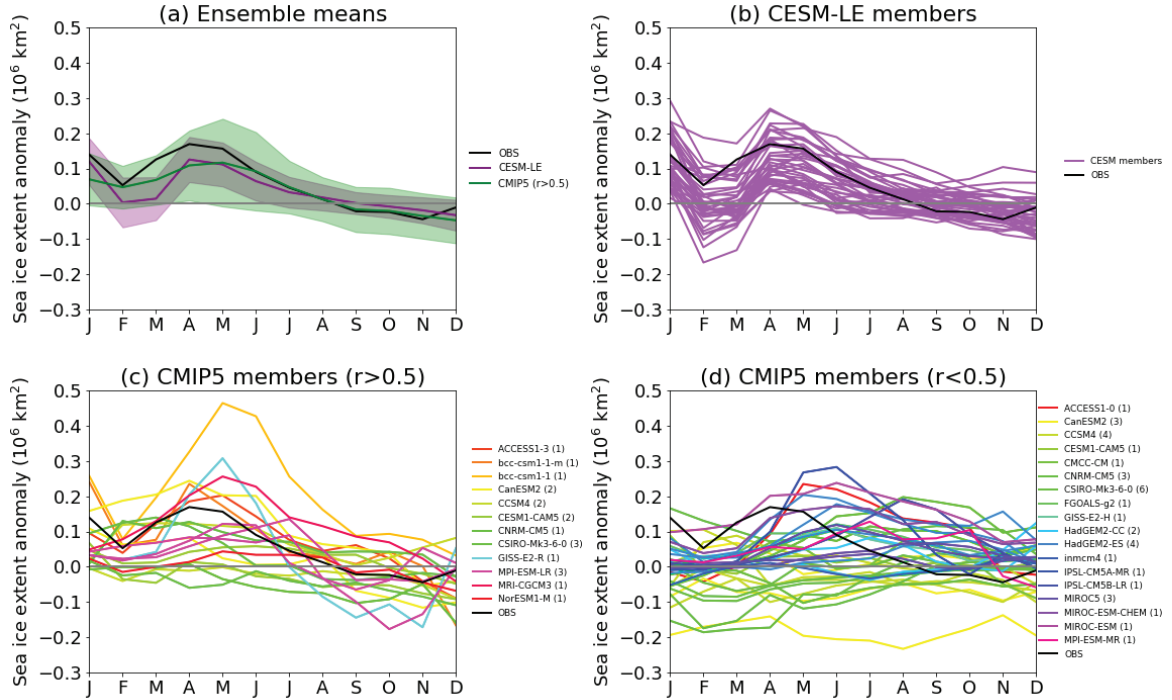


Figure 1. Monthly anomalies in Antarctic sea ice extent (SIE), in millions of km^2 , following one unit of DJF SAM anomaly, from the detrended regression analysis. (a) The observations (black), the multi-model CMIP5 ensemble mean (green, from the runs in panel c), and the CISM-LE ensemble mean (purple); the shading indicates the $1-\sigma$ spread across the respective ensembles. (b) The 40 members of the CISM-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.

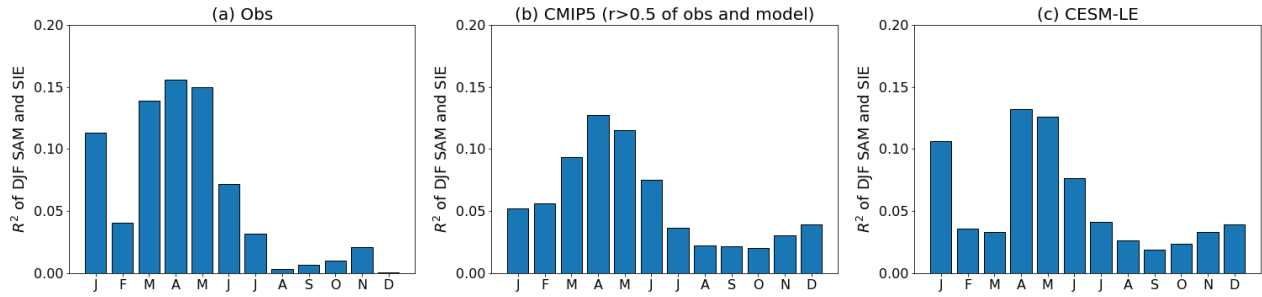


Figure 2. Monthly variance (R^2) in SIE explained by the SAM in the previous DJF months for (a) the observations, (b) the CMIP5 model runs shown in Fig. 1c, and (c) the CESM-LE runs.

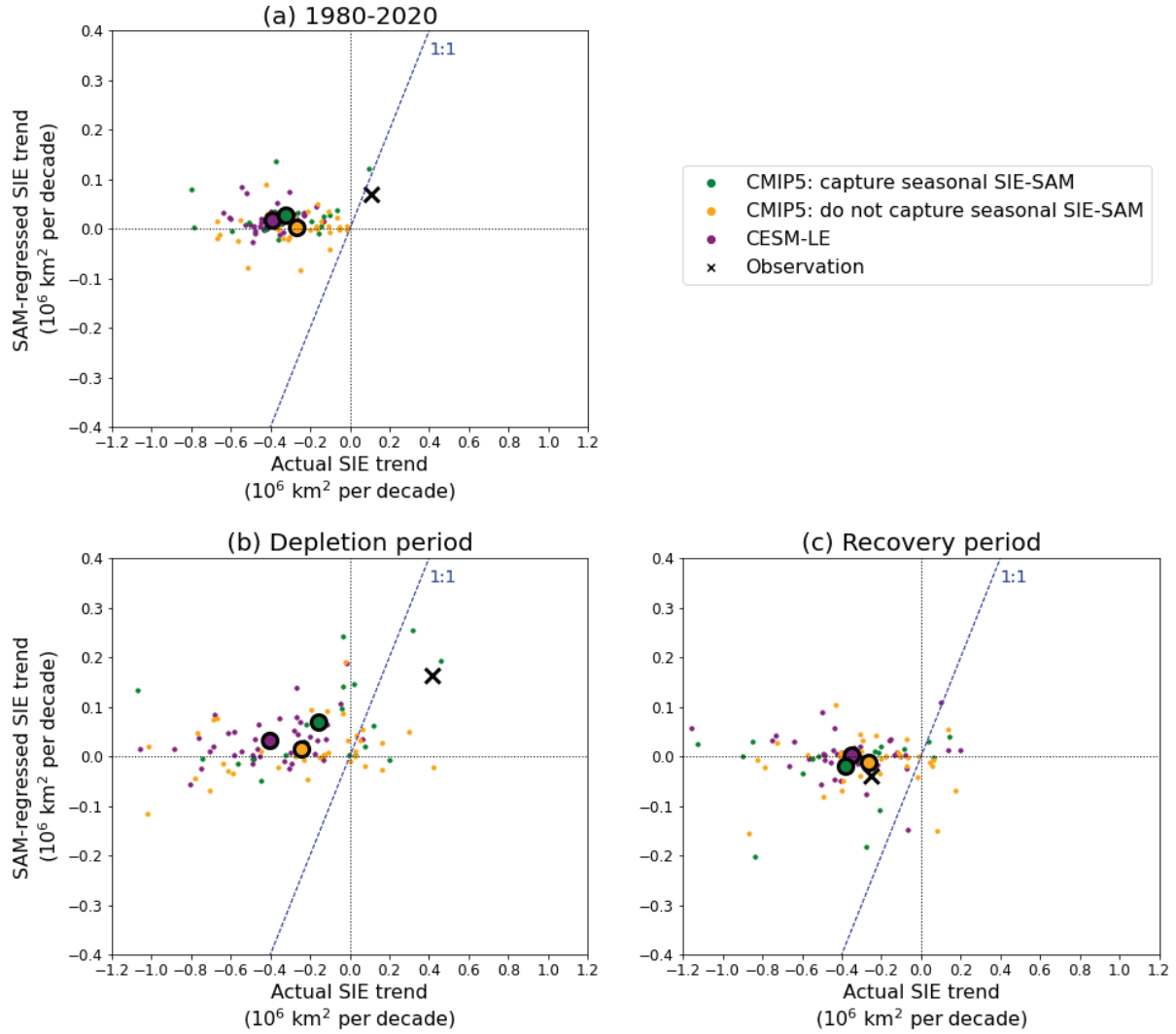


Figure 3. SAM-regressed vs actual SIE in MAM trends for (a) the entire 1980-2020 period, (b) the ozone depletion period 1980-2000, and (c) the ozone recovery period 2000-2020, in millions of km² per decade. The large encircled dots show the model average, by color, as indicated in the legend. The one-to-one line is in blue (dashed). The back crosses show the observations. The SAM-regressed SIE trends are computed using the SAM trends in DJF.

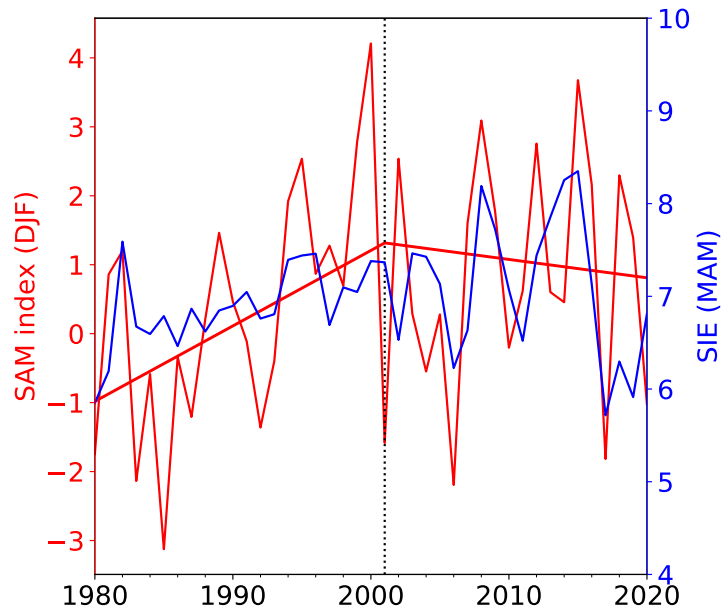


Figure 4. Time series of the observed SAM (in DJF, red) and SIE (in MAM, blue) from 1980 to 2020. The SAM values are shifted by one year from the convention adopted in DM17; e.g. the SAM value for the three month average December 1980, January 1981 and February 1981 is shown at the 1981 value on the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