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

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

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Key Points:

- Many CMIP5 models are able to capture the observed seasonal correlation between summertime SAM and Antarctic sea ice extent
- The SAM, however, only explains 15% of the year-to-year SIE variability in the fall, in both models and observations
- SAM trends, and ozone depletion, are not the primary drivers of the observed Antarctic 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).

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

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

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

A new modeling approach was proposed by Ferreira et al. (2015). They advocated studying the response to ozone depletion using an idealized “step-like” ozone forcing, rather than to a transient and realistic historical ozone forcing, in order to obtain the so-called Climate Response Function (CRF, as detailed in Marshall et al., 2014). That method emphasized that, over the Southern Ocean, the SST response occurs in two distinct phases: a “fast” cooling phase, dominated by Ekman transport of cold waters away from the Antarctic continent, and a “slow” warming phase, caused by the upwelling of warmer water from below. This approach was pursued in a number of subsequent studies (Kostov et al., 2017; Seviour et al., 2016; Holland et al., 2017), who examined a large number of climate models and found that SSTs over the Southern Ocean do indeed respond with an early cooling and later warming phase. However, a corresponding sea ice growth phase was *never* found: all CMIP-class[1] models have shown a continuous melting of sea ice following impulsive ozone forcing (see Fig. 9 of Seviour et al., 2019), confirming earlier modeling studies with more realistic ozone forcing (e.g., Bitz & Polvani, 2012; A. Solomon et al., 2015).

Although the *modeling* evidence showing that ozone depletion melts Antarctic sea ice is now overwhelming, the possibility that ozone – forcing SAM trends – could nonetheless be responsible for the observed expansion of Antarctic sea ice has remained tantalizing, because the seasonal cooling phase of the SST response to the SAM rests on a well-tested physical mechanism which was shown to be operative in observations. Specifically, confirming earlier studies (Liu et al., 2004; Simpkins et al., 2012), Doddridge and Marshall (2017, hereafter DM17) recently analyzed the observed interannual relationship between SAM and SIE over the period 1979-2017, and demonstrated how positive summertime SAM anomalies are followed by colder sea surface temperatures (SST) leading to anomalous SIE in the fall, with the largest effect occurring in April. Since the largest SAM trends over that period are observed in the summer, DM17 conclude that "*The results presented in this paper suggest that anthropogenic ozone depletion, by forcing the atmosphere toward a positive SAM state in DJF, may have contributed to a seasonal cooling of SST near Antarctica and an increase in Antarctic sea ice extent during the austral autumn.*"

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

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

After a brief exposition of the models and the methods used herein, we show that the answer to the first question is "yes", and to the second question is "no". We conclude with a discussion on the implications of these findings for the role of ozone depletion 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

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

3 Results

We start by validating the key observational finding of DM17, shown by the black line in Figure 1a: positive summer SAM anomalies result in increased Antarctic SIE in the following fall, with the maximum occurring in April, when an additional 0.18 million km^2 of sea ice is observed after one unit increase the summer SAM index. Next, in Figure 1b, we demonstrate that the CESM-LE model is capable of simulating this relationship: nearly all CESM-LE runs show increased fall SIE following positive summer SAM anomalies (the ensemble mean is shown in panel a).

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

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

Nonetheless, we are now ready to turn our attention to the second question: does the physical mechanism connecting the DJF SAM to the fall sea ice extent operate on multidecadal time scales, and help us explain the long-term trends? To answer that question, let us start by considering the amount of monthly SIE variance that is explained by the preceding DJF SAM. This is shown in Figure 2, for the observations, the CMIP5 models, and the CESM-LE, respectively. Notice first the good agreement across the three panels: all agree the strongest linkage in MAM, and are quantitatively close (between 0.10 and 0.15). This confirms that many models are capturing the physics of the SAM-SIE relationship correctly. The CESM-LE (panel) Figure 2c, provides an excellent example.

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

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

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

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

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

Again, focusing on the modeled trends in those panels, we see that the SAM-regressed trends in MAM are much smaller than the actual SIE trends in that season, indicating that the summer SAM trends have very little predictive power over the modeled SIE in the subsequent fall over decadal timescales. Also, note that the models runs that capture the internannual SAM/SIE relationship (green and purple) do not show a superior relationship between the long-term SAM-regressed and actual SIE trends than the models that do not capture the internannual SAM/SIE relationship (orange), again demonstrating that the SAM is not the major driver of the modeled SIE trends. Nonetheless, contrasting panels b and c, one can see that models runs which capture the internannual SAM/SIE relationship show slightly positive trends over the ozone-depletion period (panel b), and that these disappear in the ozone-recovery period (panel c: compare the means, shown in the larger dots).

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

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

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

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

4 Summary and Discussion

Building on the observational study of DM17, we have here explored whether the Ekman mechanism whereby positive SAM anomalies in summer (DJF) cause positive SIE anomalies in the fall (MAM) is actually captured by state-of-the-art coupled climate models; the rational is that the potential lack of such a mechanism in models may be responsible for the poor agreement between modeled and observed SIE over the last four decades. Our analysis has revealed that many (though not most) models are able to simulate the observed interannual SAM/SIE relationship. However, it has also shown that their ability to capture that relationship has basically no influence of a model's ability to capture the observed trends, as most models show sea ice melting over the last four decades, irrespective of whether or not the SAM/SIE relationship is accurately modeled.

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

Further evidence in support of this conclusion is offered by the strong longitudinal asymmetry of the recent Antarctic sea ice trends. It is widely appreciated that the polar-cap-averaged SIE trends discussed above are relatively small compared to the regional trends, owing to large cancellations between different sectors, notably the Ross, Amundsen-Bellingshausen, and Weddell seas (Turner et al., 2015; Parkinson, 2019). Because the SAM is, by definition *annular*, one would naively expect its impact to be similar at most[2] longitudes. Thus, the simple fact that trends of opposite sign are observed at different longitudes is a strong indication that the SAM is unlikely to be the main driver of those trends. We stress that this argument is based solely on observational evidence, and does not suffer from any potential or actual model deficiencies.

Our findings have implications for the role of ozone depletion on Antarctic sea ice. Contradictory claims are found in the literature, with some studies suggesting that ozone depletion may be responsible for positive trends in SIE (e.g., Turner et al., 2009; Ferreira et al., 2015), and others arguing that ozone depletion leads to negative SIE trends (e.g., Sigmond & Fyfe, 2014; Landrum et al., 2017). The results presented here lead us to conclude that stratospheric ozone depletion has not been the primary driver of SIE trends although, acting via the SAM, it may have contributed a fraction of the SIE trends before the year 2000. That fraction, however, may not be very large, if one keeps in mind that the observed SAM trends are not due to ozone depletion alone, but also to increasing 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 continent. See for instance, Fig. 7c of (Sen Gupta & England, 2006), illustrating the sea ice concentrations regressed onto the SAM, averaged from January to March.

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

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

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

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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.

Gillett, N. P., & Thompson, D. W. (2003). Simulation of recent southern hemisphere climate change. *Science*, *302*(5643), 273–275.

Goosse, H., Lefebvre, W., de Montety, A., Crespin, E., & Orsi, A. H. (2009). Consistent past half-century trends in the atmosphere, the sea ice and the ocean at high southern latitudes. *Climate Dynamics*, *33*(7-8), 999–1016.

Hall, A., & Visbeck, M. (2002). Synchronous variability in the Southern Hemisphere atmosphere, sea ice, and ocean resulting from the annular mode. *Journal of Climate*, *15*(21), 3043–3057.

Handcock, M. S., & Raphael, M. N. (2020). Modeling the annual cycle of daily antarctic sea ice extent. *The Cryosphere*, *14*(7), 2159–2172.

Holland, M. M., Landrum, L., Kostov, Y., & Marshall, J. (2017). Sensitivity of Antarctic sea ice to the Southern Annular Mode in coupled climate models. *Climate Dynamics*, *49*(5-6), 1813–1831.

Jones, J., Gille, S., Goosse, H., Abram, N., Canziani, P., Charman, D., … Vance, T. (2016). Assessing recent trends in high-latitude Southern Hemisphere surface climate. *Nature Climate Change*, *6*(10), 917–926.

Kay, J. E., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., … Vertenstein, M. (2015). The Community Earth System Model (CESM) Large Ensemble Project: A community resource for studying climate change in the presence of internal climate variability. *Bulletin of the American Meteorological Society*, *96*(8), 1333-1349.

Kohyama, T., & Hartmann, D. L. (2016). Antarctic sea ice response to weather and climate modes of variability. *Journal of Climate*, *29*(2), 721–741.

Kostov, Y., Marshall, J., Hausmann, U., Armour, K. C., Ferreira, D., & Holland, M. M. (2017). Fast and slow responses of Southern Ocean sea surface temperature to SAM in coupled climate models. *Climate Dynamics*, *48*(5-6), 1595–1609.

Landrum, L. L., Holland, M. M., Raphael, M. N., & Polvani, L. M. (2017). Stratospheric ozone depletion: An unlikely driver of the regional trends in Antarctic Sea Ice in Austral fall in the late twentieth century. *Geophysical Research Letters*, *44*(21), 11–062.

Lefebvre, W., Goosse, H., Timmermann, R., & Fichefet, T. (2004). Influence of the Southern Annular Mode on the sea ice–ocean system. *Journal of Geophysical Research: Oceans*, *109*(C9).

Liu, J., Curry, J. A., & Martinson, D. G. (2004). Interpretation of recent Antarctic sea ice variability. *Geophysical Research Letters*, *31*(2).

Marshall, J., Armour, K. C., Scott, J. R., Kostov, Y., Hausmann, U., Ferreira, D.,

. . . Bitz, C. M. (2014). The ocean's role in polar climate change: asymmetric Arctic and Antarctic responses to greenhouse gas and ozone forcing. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *372*(2019), 20130040.

Meehl, G. A., Arblaster, J. M., Bitz, C. M., Chung, C. T., & Teng, H. (2016). Antarctic sea-ice expansion between 2000 and 2014 driven by tropical pacific decadal climate variability. *Nature Geoscience*, *9*(8), 590–595.

Parkinson, C. L. (2019). A 40-y record reveals gradual antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the arctic. *Proceedings of the National Academy of Sciences*, *116*(29), 14414–14423.

Pauling, A. G., Bitz, C. M., Smith, I. J., & Langhorne, P. J. (2016). The response of the southern ocean and antarctic sea ice to freshwater from ice shelves in an earth system model. *Journal of Climate*, *29*(5), 1655–1672.

Polvani, L. M., Previdi, M., England, M. R., Chiodo, G., & Smith, K. L. (2020). Substantial twentieth-century Arctic warming caused by ozone-depleting substances. *Nature Climate Change*, *10*(2), 130–133.

Polvani, L. M., & Smith, K. L. (2013). Can natural variability explain observed Antarctic sea ice trends? New modeling evidence from CMIP5. *Geophysical Research Letters*, *40*(12), 3195–3199.

Polvani, L. M., Waugh, D. W., Correa, G. J., & Son, S.-W. (2011). Stratospheric ozone depletion: The main driver of twentieth-century atmospheric circulation changes in the Southern Hemisphere. *Journal of Climate*, *24*(3), 795–812.

Previdi, M., & Polvani, L. M. (2014). Climate system response to stratospheric ozone depletion and recovery. *Quarterly Journal of the Royal Meteorological Society*, *140*(685), 2401–2419.

Purich, A., England, M. H., Cai, W., Chikamoto, Y., Timmermann, A., Fyfe, J. C., . . . Arblaster, J. M. (2016). Tropical pacific sst drivers of recent antarctic sea ice trends. *Journal of Climate*, *29*(24), 8931–8948.

Roach, L. A., Dörr, J., Holmes, C. R., Massonnet, F., Blockley, E. W., Notz, D., . . . others (2020). Antarctic sea ice area in CMIP6. *Geophysical Research Letters*, *47*(9), e2019GL086729.

Rye, C. D., Marshall, J., Kelley, M., Russell, G., Nazarenko, L. S., Kostov, Y., . . . Hansen, J. (2020). Antarctic glacial melt as a driver of recent southern ocean climate trends. *Geophysical Research Letters*, *47*(11), e2019GL086892.

Schneider, D. P., Deser, C., & Fan, T. (2015). Comparing the impacts of tropical sst variability and polar stratospheric ozone loss on the southern ocean westerly winds. *Journal of Climate*, *28*(23), 9350–9372.

Schneider, D. P., Okumura, Y., & Deser, C. (2012). Observed antarctic interannual climate variability and tropical linkages. *Journal of Climate*, *25*(12), 4048–4066.

Sen Gupta, A., & England, M. H. (2006). Coupled ocean–atmosphere–ice response to variations in the southern annular mode. *Journal of Climate*, *19*(18), 4457–4486.

Seviour, W., Codron, F., Doddridge, E. W., Ferreira, D., Gnanadesikan, A., Kelley, M., ... Waugh, D. (2019). The southern ocean sea surface temperature response to ozone depletion: a multimodel comparison. *Journal of Climate*, *32*(16), 5107–5121.

Seviour, W., Gnanadesikan, A., & Waugh, D. (2016). The transient response of the Southern Ocean to stratospheric ozone depletion. *Journal of Climate*, *29*(20), 7383–7396.

Sigmond, M., & Fyfe, J. (2010). Has the ozone hole contributed to increased Antarctic sea ice extent? *Geophysical Research Letters*, *37*(18).

Sigmond, M., & Fyfe, J. C. (2014). The Antarctic sea ice response to the ozone hole in climate models. *Journal of Climate*, *27*(3), 1336–1342.

SIMIP. (2020). Arctic Sea Ice in CMIP6. *Geophysical Research Letters*, *47*(10), e2019GL086749.

Simpkins, G. R., Ciasto, L. M., Thompson, D. W., & England, M. H. (2012). Seasonal relationships between large-scale climate variability and Antarctic sea ice concentration. *Journal of Climate*, *25*(16), 5451–5469.

Singh, H., Polvani, L. M., & Rasch, P. J. (2019). Antarctic Sea Ice Expansion, Driven by Internal Variability, in the Presence of Increasing Atmospheric CO2. *Geophysical Research Letters*, *46*(24), 14762–14771.

Smith, K. L., Polvani, L. M., & Marsh, D. R. (2012). Mitigation of 21st century Antarctic sea ice loss by stratospheric ozone recovery. *Geophysical Research Letters*, *39*(20).

Solomon, A., Polvani, L. M., Smith, K., & Abernathey, R. (2015). The impact of ozone depleting substances on the circulation, temperature, and salinity of the Southern Ocean: An attribution study with CESM1 (WACCM). *Geophysical Research Letters*, *42*(13), 5547–5555.

Solomon, S., Ivy, D. J., Kinnison, D., Mills, M. J., Neely, R. R., & Schmidt, A. (2016). Emergence of healing in the Antarctic ozone layer. *Science*, *353*(6296), 269–274.

Stroeve, J. C., Kattsov, V., Barrett, A., Serreze, M., Pavlova, T., Holland, M., & Meier, W. N. (2012). Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophysical Research Letters*, *39*(16).

Stroeve, J. C., Serreze, M. C., Holland, M. M., Kay, J. E., Malanik, J., & Barrett, A. P. (2012). The Arctics rapidly shrinking sea ice cover: a research synthesis. *Climatic change*, *110*(3-4), 1005–1027.

Stuecker, M. F., Bitz, C. M., & Armour, K. C. (2017). Conditions leading to the unprecedented low Antarctic sea ice extent during the 2016 austral spring season. *Geophysical Research Letters*, *44*(17), 9008–9019.

Sun, S., & Eisenman, I. (2021). Observed Antarctic sea ice expansion reproduced in a climate model after correcting biases in sea ice drift velocity. *Nature Communications*, *12*(1), 1–6.

Swart, N., & Fyfe, J. C. (2012). Observed and simulated changes in the southern hemisphere surface westerly wind-stress. *Geophysical Research Letters*, *39*(16).

Thomas, J. L., Waugh, D. W., & Gnanadesikan, A. (2015). Southern Hemisphere extratropical circulation: Recent trends and natural variability. *Geophysical Research Letters*, *42*(13), 5508–5515.

Thompson, D. W., & Solomon, S. (2002). Interpretation of recent southern hemisphere climate change. *Science*, *296*(5569), 895–899.

Turner, J., Bracegirdle, T. J., Phillips, T., Marshall, G. J., & Hosking, J. S. (2013). An initial assessment of Antarctic sea ice extent in the CMIP5 models. *Journal of Climate*, *26*(5), 1473–1484.

Turner, J., Comiso, J. C., Marshall, G. J., Lachlan-Cope, T. A., Bracegirdle, T., Maksym, T., … Orr, A. (2009). Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent. *Geophysical research letters*, *36*(8).

Turner, J., Hosking, J. S., Bracegirdle, T. J., Marshall, G. J., & Phillips, T. (2015). Recent changes in Antarctic sea ice. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *373*(2045), 20140163.

Turner, J., Phillips, T., Marshall, G. J., Hosking, J. S., Pope, J. O., Bracegirdle, T. J., & Deb, P. (2017). Unprecedented springtime retreat of Antarctic sea ice in 2016. *Geophysical Research Letters*, *44*(13), 6868–6875.

Zunz, V., Goosse, H., & Massonnet, F. (2013). How does internal variability influence the ability of cmip5 models to reproduce the recent trend in southern ocean sea ice extent. *Cryosphere*, *7*(2), 451–468.

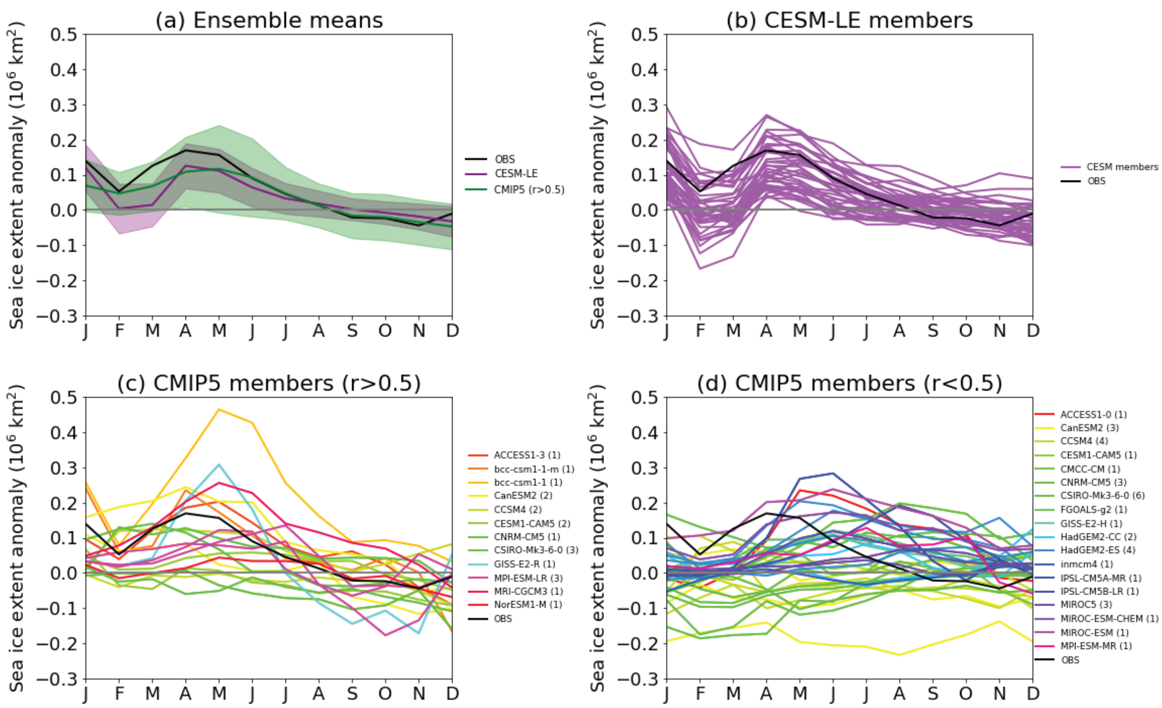

Figure 1. Monthly anomalies in Antarctic sea ice extent (SIE), in millions of km^2, following one unit of DJF SAM anomaly, from the detrended regression analysis. (a) The observations (black), the multi-model CMIP5 ensemble mean (green, from the runs in panel c), and the CESM-LE ensemble mean (purple); the shading indicates the 1-σ 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.

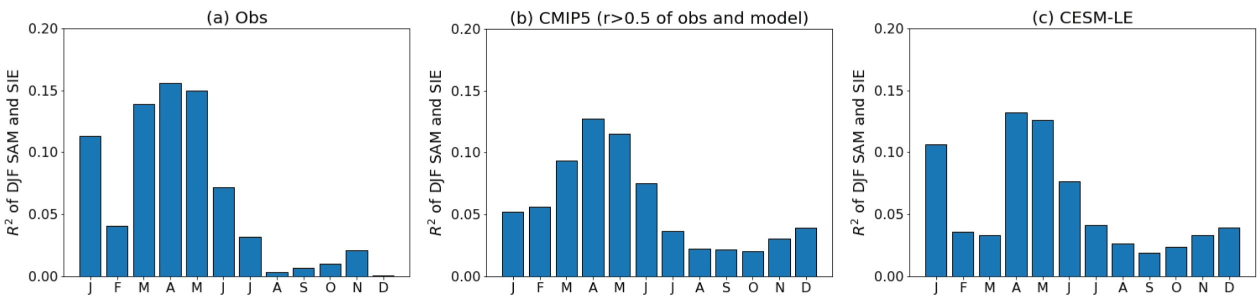

Figure 2. Monthly variance (R^2) in SIE explained by the SAM in the previous DJF months for (a) the observations, (b) the CMIP5 model runs shown in Fig. 1c, and (c) the CESM-LE runs.

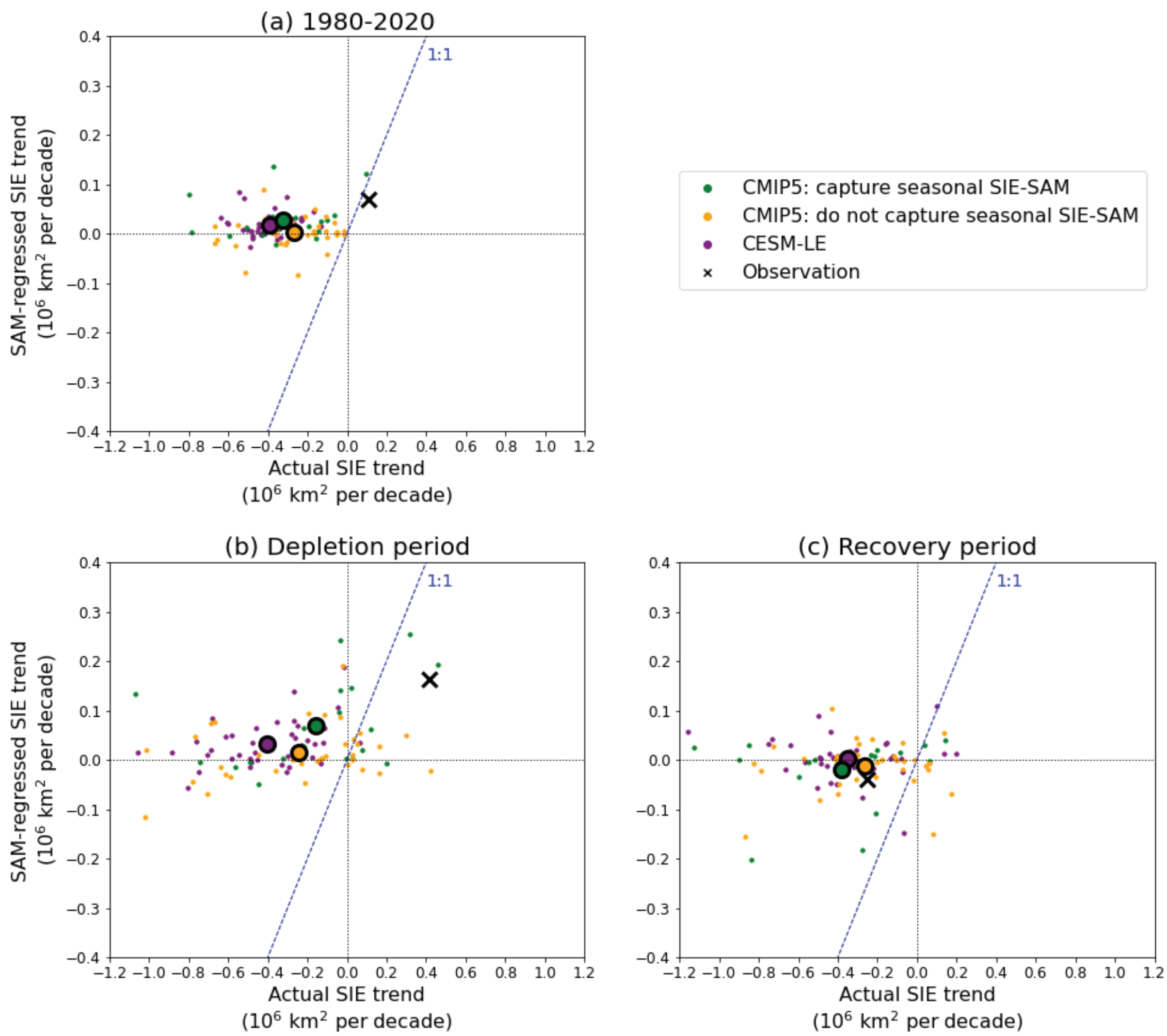

Figure 3. SAM-regressed vs actual SIE in MAM trends for (a) the entire 1980-2020 period, (b) the ozone depletion period 1980-2000, and (c) the ozone recovery period 2000-2020, in millions of km^2 per decade. The large encircled dots show the model average, by color, as indicated in the legend. The one-to-one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

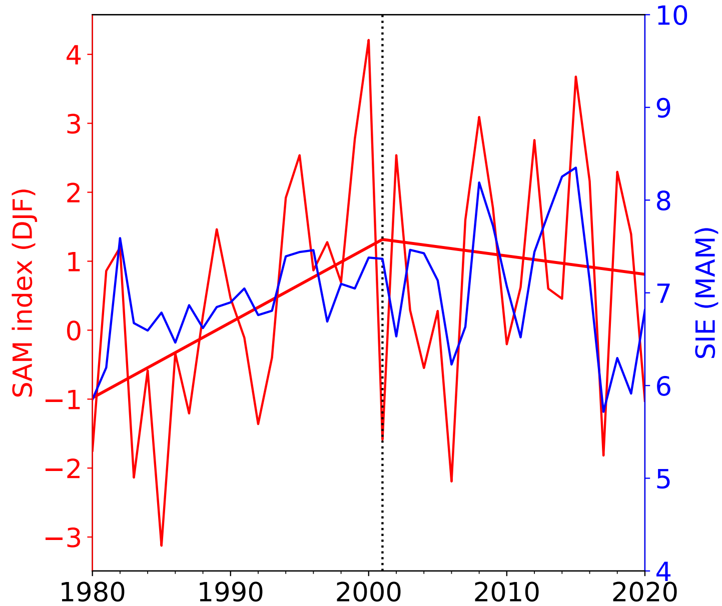

Figure 4. Time series of the observed SAM (in DJF, red) and SIE (in MAM, blue) from 1980 to 2020. The SAM values are shifted by one year from the convention adopted in DM17; e.g. the SAM value for the three month average December 1980, January 1981 and February 1981 is shown at the 1981 value on the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