The Antarctic Sea Ice Response to the Ozone Hole in Climate Models

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ABSTRACT

It has been suggested that the increase of Southern Hemisphere sea ice extent since the 1970s can be explained by ozone depletion in the Southern Hemisphere stratosphere. In a previous study, the authors have shown that in a coupled atmosphere–ocean–sea ice model the ozone hole does not lead to an increase but to a decrease in sea ice extent. Here, the robustness of this result is established through the analysis of models from phases 3 and 5 of the Coupled Model Intercomparison Project (CMIP3 and CMIP5). Comparison of the mean sea ice trends in CMIP3 models with and without time-varying stratospheric ozone suggests that ozone depletion is associated with decreased sea ice extent, and ozone recovery acts to mitigate the future sea ice decrease associated with increasing greenhouse gases. All available historical simulations with CMIP5 models that were designed to isolate the effect of time-varying ozone concentrations show decreased sea ice extent in response to historical ozone trends. In most models, the historical sea ice extent trends are mainly driven by historical greenhouse gas forcing, with ozone forcing playing a secondary role.

1. Introduction

Antarctic sea ice extent (SIE) has increased by about 1% decade^{-1} since the introduction of reliable (satellite based) measurements in 1979 (e.g., Turner et al. 2013) and reached its highest observed value in September 2013 (Fetterer et al. 2009). The question of why Antarctic sea ice has increased in a warming world represents one of the most fundamental unsolved mysteries in polar climate science. Previous studies have suggested a number of possible explanations. Bintanja et al. (2013) suggest that freshwater input by Antarctic ice sheet melt has driven the observed sea ice trend, but Swart and Fyfe (2013) argue that the contribution of freshwater forcing is too small to explain the observed sea ice increase. Holland and Kwok (2012) showed that most of the 1992–2010 sea ice changes are forced by changing wind patterns, but it is unclear if such wind trends have been driven by natural variability [as suggested by Polvani and Smith (2013) and Swart and Fyfe (2013)] or external forcings.

Some studies have suggested that the SIE increase can be explained by atmospheric circulation changes associated with the Antarctic ozone hole. The positive correlation between intraseasonal variations in the southern annular mode (SAM) and SIE (Hall and Visbeck 2002; Sen Gupta and England 2006) could lead one to infer that the ozone hole, which has induced a positive SAM trend (e.g., Thompson et al. 2011), would indeed lead to increased Antarctic SIE. In an atmosphere-only climate model Turner et al. (2009) found a deepening of the Amundsen–Bellingshausen Sea low in response to ozone depletion, which they linked to regional features of the observed sea ice trends.

By contrast, more recent studies indicate that the ozone hole cannot explain the observed increase in Antarctic SIE. Sigmond and Fyfe (2010, hereafter SF10) directly simulated the Antarctic sea ice response to ozone depletion using a coupled atmosphere–ocean–sea ice model. Contrary to expectations they found that the ozone hole does not lead to an increase but instead to a year-round decrease in SIE. Their conclusions were consistent with other studies that have suggested that the positive trends in the SIE are unrelated to those in the SAM (Liu et al. 2004; Lefebvre et al. 2004; Simpkins et al. 2012). SF10 found that ozone depletion leads to a positive SAM response in austral summer, which mechanically drives warming of the upper ocean and induces sea ice melt. Because of the large thermal inertia of the ocean, this ocean warming persists throughout the year, causing the sea ice decrease to maximize in austral

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spring. Other subsequent studies using various National Center for Atmospheric Research (NCAR) climate model versions have confirmed the SF10 result that the ozone hole leads to decreased SIE (Bitz and Polvani 2012; Smith et al. 2012). However, this result has not been fully accepted by the scientific community because it has only been demonstrated for two models. Here we establish the robustness of this result between different models through the analysis of transient simulations of climate models participating in phases 3 and 5 of the Coupled Model Intercomparison Project (CMIP3 and CMIP5).

2. CMIP3 results

We analyze sea ice trends in CMIP3 simulations of the past using observed radiative forcing [twentieth-century climate simulation (20C3M)] and of the future using a moderate radiative forcing scenario (A1B simulation). Because ozone forcing was not constrained in the CMIP3 experimental setup, some CMIP3 models included time-varying stratospheric ozone (i.e., ozone depletion for the past and ozone recovery for the future) while other models were forced with monthly climatological ozone fields that do not change from year to year. This has provided a unique opportunity to derive the effect of ozone depletion and recovery on climate by comparing climate trends in CMIP3 models with and without time-varying stratospheric ozone. The assumption here is that the trend difference caused by the different ozone forcing between the two groups is larger than the difference caused by the fact that both groups are composed of different models that may have different sensitivities to ozone forcing. This assumption was shown to be valid for various climate variables (Son et al. 2009), which encouraged us to repeat the analysis for Antarctic SIE, which is defined as the total area with at least 15% ice cover. For our analysis, we employ all models of Son et al. (2009) for which sea ice variables were available but exclude the Flexible Global Ocean–Atmosphere–Land System Model gridpoint, version 1.0 (FGOALS-g1.0), which suffered from an unusually large sea ice bias. Details of the CMIP3 models can be found in Table 1. The results of this analysis are shown in Fig. 1 and can be summarized as follows:

- For the past, the group with ozone depletion shows a statistically significant decrease in SIE, while the sea ice response is not statistically different from zero in the constant ozone forcing group. We thus find that ozone depletion is associated with decreased SIE, which is consistent with SF10 and Bitz and Polvani (2012). It has to be noted though that the sea ice trend in the ozone depletion group is not well separated from that in the constant ozone forcing group as the uncertainty bars (which represent the 95% confidence intervals) overlap strongly.
- For the future, the simulated sea ice decrease is smaller in the group with ozone recovery than in the group with constant ozone forcing. In other words, ozone recovery acts to mitigate the future sea ice decrease associated with increased greenhouse gases, which is consistent with Smith et al. (2012). The uncertainty bars of the two groups overlap, but the overlap is smaller than for the past trends.

In summary, while the large uncertainty bars on the CMIP3 model mean values prevent us from drawing firm conclusions regarding the role of stratospheric ozone in Antarctic sea ice trends, the CMIP3 model results are not inconsistent with the conclusions of previous studies.

3. CMIP5 results

a. *Impact of ozone depletion*

In this section, we analyze all CMIP5 models from which the ozone impact can be derived. To isolate the ozone impact, single forcing runs are required, which were available for six CMIP5 models (Table 2). We first consider the response of the atmospheric circulation as quantified by the SAM index. The red bars in Fig. 2 show the historical trend of the December–February (DJF) SAM index in the six CMIP5 models with available ozone attribution runs. Consistent with previous modeling studies (e.g., Son et al. 2009; SF10; McLandress et al. 2011) all models show a statistically significant positive SAM trend (note the inverse scale on the left axis: the error bars represent the 5%–95% confidence interval and are calculated from the time series of the mean of all ensemble members for each model). The mean trend and its confidence internal (shown in Fig. 2 on the right) is calculated from the mean time series averaged over all 27 available CMIP5 ensemble members. As a side result, we find that the poleward jet shift associated with the positive SAM trend is stronger for models with a more equatorward jet position. The correlation between the mean SAM (averaged between 1951 and 2005) and the SAM trend over that period is −0.89. Such a relationship has already been identified in previous studies for the response to increasing greenhouse gases (Kidston and Gerber 2010), but this is the first time that this relationship is reported for the response to ozone depletion. It is consistent with the fluctuation–dissipation theory and suggests that current climate models, which tend to have an equatorward bias in the climatological

TABLE 1. CMIP3 Models used in this study.

Model	Expanded model name	Time-varying O_3	Ensemble members 20C3M/A1B
BCCR-BCM2.0	Bjerknes Centre for Climate Research Bergen Climate Model, version 2.0	No	1/1
CCCma CGCM3.1 (T63)	Canadian Centre for Climate Modelling and Analysis Coupled GCM, version 3.1 (T63 resolution)	No	1/1
CCSM3.0	Community Climate System Model, version 3	Yes	7/6
CNRM-CM3	Centre National de Recherches Météorologiques Coupled Global Climate Model, version 3	No	1/1
CSIRO Mk3.0	Commonwealth Scientific and Industrial Research Organisation Mark, version 3.0	Yes	3/1
ECHAM5	—	Yes	3/3
GFDL CM2.0	Geophysical Fluid Dynamics Laboratory Climate Model, version 2.0	Yes	3/1
GFDL CM2.1	Geophysical Fluid Dynamics Laboratory Climate Model, version 2.1	Yes	5/1
GISS-AOM	Goddard Institute for Space Studies, Atmosphere–Ocean Model	No	2/2
GISS-ER	Goddard Institute for Space Studies Model E-R	Yes/No*	9/5
HadCM3	Hadley Centre Coupled Model, version 3	Yes	2/1
HadGEM1	Hadley Centre Global Environment Model, version 1	Yes	2/1
INM-CM3.0	Institute of Numerical Mathematics Coupled Model, version 3.0	No	1/1
IPSL-CM4	L'Institut Pierre-Simon Laplace Coupled Model, version 4	No	2/1
MIROC3.2(medres)	Model for Interdisciplinary Research on Climate, version 3.2 (medium resolution)	Yes	3/3
MRI CGCM2.3.2	Meteorological Research Institute Coupled Atmosphere–Ocean General Circulation Model, version 2.3.2a	No	5/5

* GISS-ER has time-varying ozone in the historical (20C3M) simulations and constant ozone forcing in the future (A1B) simulations.

jet position, may overestimate the SAM response to ozone variations.

Since all CMIP5 models considered in this study reproduce the observed positive correlation between intraseasonal variations in the SAM and SIE (not shown), the positive SAM response suggests that SIE might increase in response to the ozone forcing. On the other hand, previous studies have shown that the positive SAM response does not lead to increased but instead to decreased SIE. To investigate the robustness of this result, we now turn to the sea ice response in the CMIP5 ozone attribution runs. The key result of this study is depicted by the purple bars in Fig. 2. They show that the annual mean Antarctic SIE trends in the ozone attribution runs are significantly negative for all six models. In other words, all CMIP5 models consistently show that the positive SAM associated with ozone depletion induces decreased Antarctic SIE, confirming the surprising conclusions of previous single model studies. The SIE response calculated from the time series averaged over all 27 CMIP5 ensemble members is $-0.13 \pm 0.02 \times 10^6\,km^2\,decade^{-1}$, which, over the entire 1951–2005 period, is equivalent to $-0.69 \pm 0.12 \times 10^6\,km^2$ (95% confidence interval). This value is quite similar to that found with time-slice simulations in SF10 ($-0.55 \times 10^6\,km^2$) and comparable to the values found in Bitz and Polvani (2012) (from -0.77 to $-0.85 \times 10^6\,km^2$) and Smith et al. (2012) ($-0.47 \times 10^6\,km^2$).

The ozone forcing in the CMIP5 runs combine tropospheric and stratospheric forcing. Although tropospheric ozone forcing is thought to affect the NH circulation (Allen et al. 2012), additional simulations with the CanESM2 indicate that the effect of tropospheric ozone forcing on the simulated SAM and Antarctic SIE trends is small. Over the 1951–2005 period, CanESM2 simulations with only stratospheric ozone forcing exhibited a DJF SAM trend of $0.32 \pm 0.27\,hPa\,decade^{-1}$ and an annual mean Antarctic SIE trend of $-1.26 \pm 0.46 \times 10^6\,km^2$. These trends are statistically indistinguishable from the trends due to the combined stratospheric and tropospheric ozone forcing depicted in Fig. 2 ($0.44 \pm 0.30\,hPa\,decade^{-1}$ and $-0.94 \pm 0.50 \times 10^6\,km^2\,decade^{-1}$, respectively). In other words, the results of these additional simulations indicate that the SAM and SIE trends in the CMIP5 ozone attribution simulations are primarily driven by stratospheric ozone depletion.

Figure 3 shows the seasonality of the SAM and SIE responses. We find that, consistent with previous modeling studies, the SAM trend in most models peaks in DJF. Statistically significant SAM responses are also found for March–May (MAM) in the L'Institut Pierre-Simon Laplace (IPSL) and the two Goddard Institute for Space Studies (GISS) models, in June–August (JJA) for the Commonwealth Scientific and Industrial Research Organisation (CSIRO) model, and for September–November (SON) in the two GISS models. Although

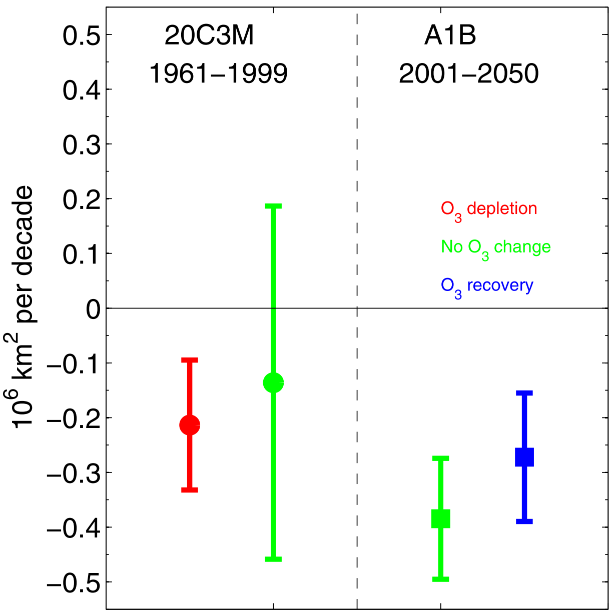

FIG. 1. Past and future Antarctic SIE trends in CMIP3 models. For each model the linear trends are computed for 1961–99 in the 20C3M integrations and 2000–49 in the A1B scenario integrations. The mean trend and its 95% confidence interval is shown by the red circle and bar for the group of models with ozone depletion and by the blue square and bar for the group of models with ozone recovery. The mean trend and confidence interval for models without time-varying stratospheric ozone is shown by the green symbols and bars. SIE is defined as the total area with at least 15% ice cover.

the response of the atmospheric circulation (as quantified by the SAM) generally peaks in DJF, most models show negative SIE trends in all seasons. In fact, the SIE response tends to peak in SON, the season with the largest climatological SIE, which is consistent with the findings of SF10.

b. *Impact of ozone depletion in the context of other forcings*

To place the SAM and SIE responses to ozone depletion in the context of other historical forcings, we analyze historical simulations that combine all anthropogenic and natural forcings (ALL) and historical simulations in which only greenhouse gases (GHG) or anthropogenic aerosols (AntrAer) are varied in time (Table 2). Figure 4 (top) shows that in response to all historical forcings, all CMIP5 models considered here show a positive and statistically significant SAM trend in DJF. The residual SAM trends are statistically indistinguishable from zero, which indicates linear additivity of the SAM responses to the historical forcings. In half of the models (CCSM4 and the two GISS models) ozone depletion is the dominant driver of the historical SAM trend, which is consistent with the general scientific consensus (e.g., Thompson et al. 2011). However, it is interesting to note that in the other half of the models the contribution of the GHG forcing is similar to or even larger than that of ozone depletion. Even though this finding may seem to contradict previous literature, we note that some other studies (Staten et al. 2011; Hardiman et al. 2012; Fyfe et al. 2012) have also reported on a more prominent role of historical GHG forcing in driving the historical SAM trend in DJF. This is an interesting finding that is left for further investigation. Finally, we note that in four of the five models with AntrAer simulations, historical trends in anthropogenic aerosols act to decrease the SAM, which is consistent with Gillett et al. (2013).

Figure 4 (bottom) shows that all CMIP5 models simulate a statistically significant decrease of Antarctic SIE in response to all historical forcings. The SIE response in this subset of CMIP5 models is consistent with that

TABLE 2. Number of ensemble members available for historical CMIP5 simulations that combine all anthropogenic and natural forcings and for single forcing simulations of ozone, greenhouse gas, and anthropogenic aerosols.

Model	Expanded model name	O_3	GHG	AntrAer	ALL
CanESM2	Second Generation Canadian Earth System Model	5	5	5	5
CCSM4	Community Climate System Model, version 4	3	3	0*	6
CSIRO Mk3.6.0	Commonwealth Scientific and Industrial Research Organisation Mark, version 3.6.0	5**	5	5	10
GISS-E2H	Goddard Institute for Space Studies Model E2, coupled with the Hybrid Coordinate Ocean Model (HYCOM)	5	5	5	15
GISS-E2-R	Goddard Institute for Space Studies Model E2, coupled with the Russell ocean model	5	5	5	18
IPSL-CM5A-LR	L'Institut Pierre-Simon Laplace Coupled Model, version 5, coupled with Nucleus for European Modelling of the Ocean (NEMO), low resolution	4**	5	1	6

* For CCSM4, no single forcing simulations for anthropogenic aerosols were available. The residual trend is calculated from the difference between the ALL and the sum of the GHG and O_3 simulations and therefore includes the effects of anthropogenic aerosol forcing.
** The CSIRO Mk3.6.0 and IPSL-CM5A-LR O_3 runs are simulations with ozone concentrations fixed at preindustrial levels with all other forcings varying in time. The effect of the ozone depletion is derived indirectly by comparison with the ALL simulations.

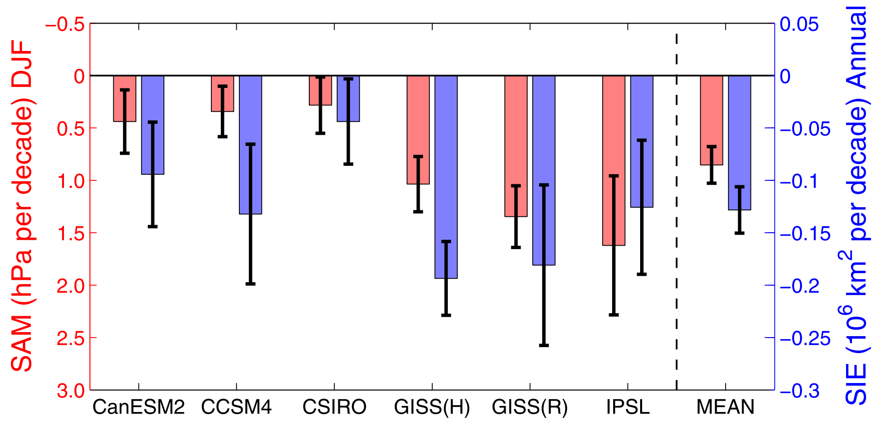

FIG. 2. Ozone induced trends in the SAM (DJF) and Antarctic SIE (annual mean) in CMIP5 models. Red bars show the SAM trend (inverted scale on the left axis), purple bars show the SIE trend (scale on right axis), and the black error bars show the 5%–95% confidence intervals as calculated from the ensemble mean time series. Trends are shown for 1951–2005 and all CMIP5 models with available ozone attribution simulations. The SAM is defined as the zonal mean sea level pressure difference between 40° and 65°S. Here and in subsequent plots, the mean trend and its error bar (labeled MEAN) are calculated from the time series averaged over all ensemble members and models.

found in the entire CMIP5 archive (Turner et al. 2013). The single forcing simulations show that in most models (all except the two GISS models) the dominant driver of the historical sea ice trend is the GHG forcing, with ozone depletion playing a secondary role. This is not surprising as GHG forcing presumably combines dynamical (SAM) and radiative forcing changes, which both facilitate decreased SIE. Finally we note that, in response to historical anthropogenic aerosol changes, four of the five models show increased SIE. This SIE increase is consistent with the SAM decrease found in response to anthropogenic aerosols in those models.

4. Summary and discussion

Many recent studies have attempted to explain the increase of Antarctic sea ice since the 1970s. Some have suggested that atmospheric circulation trends driven by the Antarctic ozone hole can explain the sea ice increase, while the results of recent single model studies are inconsistent with this view. In this study, we have analyzed all available CMIP3 and CMIP5 model simulations suitable to address this question and found new modeling evidence that ozone depletion is not associated with increased but instead with decreased Antarctic sea ice extent (SIE).

We caution that our conclusion is based on climate models that are imperfect, especially regarding the simulation of the Antarctic climate (e.g., Turner et al. 2013). However, we note that the negative SIE response to ozone depletion is robustly found for all six CMIP5 models, which each have a distinct Antarctic sea ice climatology and variability as shown by Fig. 2 of Zunz et al. (2013). Hence, our main result does not seem to depend on the quality of the simulation of Antarctic sea ice.

Based on this analysis, it cannot be ruled out that all coupled climate models lack or misrepresent critical physical processes, resulting in unrealistic simulations

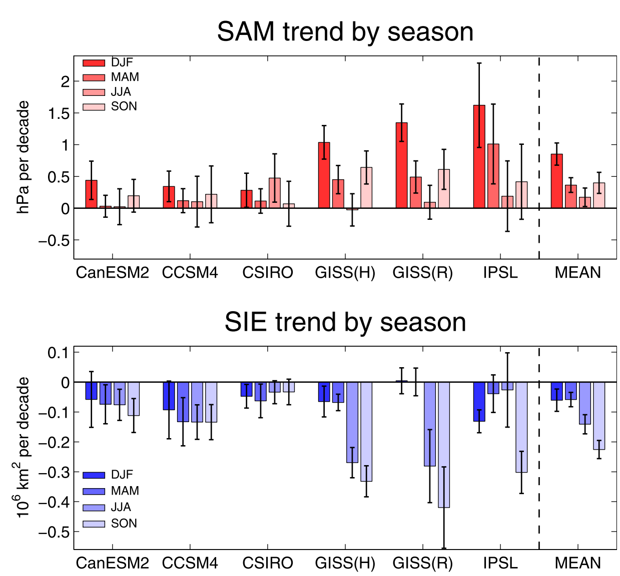

FIG. 3. Ozone induced SAM and Antarctic SIE trends in CMIP5 models as a function of season and their 5%–95% confidence intervals.

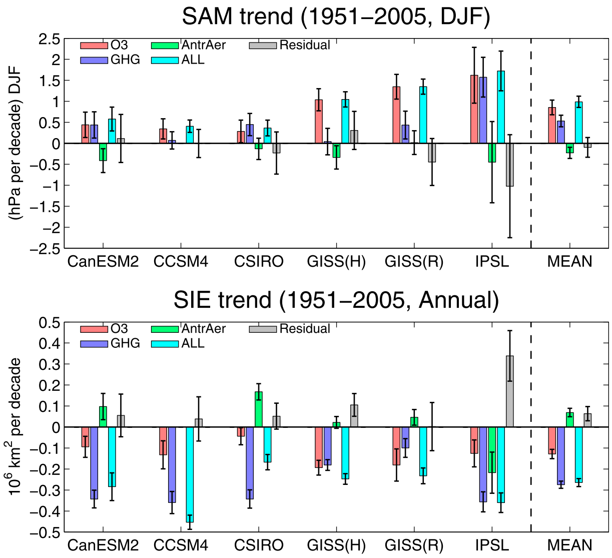

FIG. 4. Historical DJF SAM and annual mean Antarctic SIE trends due to all combined anthropogenic and natural forcings, time-varying ozone, greenhouse gas, and anthropogenic aerosol forcing and the residual trend. The residual trend and its uncertainty is calculated from the time series of the difference between ALL and the sum of the O_3, GHG, and AntrAer simulations.

of the SIE response to stratospheric ozone forcing. However, we do not have reason to believe that is the case. The statistical analysis of Swart and Fyfe (2013) showed that when accounting for internal variability, the average CMIP5 sea ice area trend is statistically consistent with the observed trend, suggesting that the SIE response to external forcings simulated by these models are credible. Other studies have also highlighted the large internal variability, which may play a critical role in explaining the observed increase in Antarctic sea ice cover (Zunz et al. 2013; Polvani and Smith 2013; Mahlstein et al. 2013).

In summary, the CMIP3 and CMIP5 model results presented here provide important confirmation of the surprising conclusions of previous single model studies that processes not linked to stratospheric ozone depletion must be invoked to explain the observed increase in Antarctic sea ice.

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