GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L18502, doi:10.1029/2010GL044301, 2010

Has the ozone hole contributed to increased Antarctic sea ice extent?

M. Sigmond[1] and J. C. Fyfe[2]

Received 11 June 2010; revised 23 July 2010; accepted 5 August 2010; published 29 September 2010.

[1] Since the 1970s sea ice extent has decreased dramatically in the Northern Hemisphere and increased slightly in the Southern Hemisphere, a difference that is potentially explained by ozone depletion in the Southern Hemisphere stratosphere. In this study we consider the impact of stratospheric ozone depletion on Antarctic sea ice extent using a climate model forced with observed stratospheric ozone depletion from 1979 to 2005. Contrary to expectations, our model simulates a year-round decrease in Antarctic sea ice due to stratospheric ozone depletion. The largest percentage sea ice decrease in our model occurs in the austral summer near the coast of Antarctica, due to a mechanism involving offshore Ekman sea ice transport. The largest absolute decrease is simulated in the austral winter away from the coast of Antarctica, in response to an ocean warming that is consistent with a poleward shift of the large-scale pattern of sea surface temperature. Our model results strongly suggest that processes not linked to stratospheric ozone depletion must be invoked to explain the observed increase in Antarctic sea ice extent. **Citation:** Sigmond, M., and J. C. Fyfe (2010), Has the ozone hole contributed to increased Antarctic sea ice extent?, *Geophys. Res. Lett.*, *37*, L18502, doi:10.1029/2010GL044301.

1. Introduction

[2] While the Northern Hemisphere sea ice extent has decreased dramatically during the past few decades, opposite trends have been observed in the Southern Hemisphere: *Comiso and Nishio* [2008] showed that between 1978 and 2006, Antarctic sea ice extent (SIE) has undergone a small, but statistically significant, positive trend of 0.9 ± 0.2% per decade. Over the same period, large changes have been observed in the atmospheric circulation in austral summer, which are often described as a shift towards the positive phase of the Southern Annular Mode (SAM). Model simulations consistently show that this shift can be largely attributed to stratospheric ozone depletion [e.g., *Gillett and Thompson*, 2003]. The trends are characterized by a poleward shift of the large-scale circulation patterns, including the westerly jet, the storm tracks and the Hadley-cell boundary [*Son et al.*, 2009], and have played an important role in shaping the observed surface temperature trends. However, it is presently unclear what role, if any, these ozone hole induced circulation trends have played in recent Antarctic SIE trends.

[3] The goal of this study is to isolate the impact of stratospheric ozone depletion on Antarctic SIE. Relatively few studies have considered this question, and a consistent picture is still lacking. *Goosse et al.* [2009] used a climate model with data assimilation to argue that the increasing Antarctic SIE was due to changing atmospheric circulation. *Turner et al.* [2009] showed some physical consistency between the autumn trend patterns in Antarctic sea ice concentration (SIC) and 500 hPa geopotential height, with the latter showing some agreement with the pattern obtained from an atmosphere-only climate model forced with stratospheric ozone depletion. *Lefebvre et al.* [2004] and *Goosse et al.* [2009] used the correlations between intraseasonal SAM and Antarctic SIE variations to infer the influence of SAM trends on Antarctic SIE trends. By considering model simulations that are set up to directly assess the impact of ozone induced circulation trends on Antarctic sea ice, we will show that such inferences can not be justified.

2. Models and Methodology

[4] We employ a coupled climate model with well resolved stratosphere, troposphere and interactive ocean and sea ice components. The model and experimental set-up is the same as of *Sigmond et al.* [2010, hereafter SFS10], to which we refer the reader for details. The atmospheric component is the Canadian Middle Atmosphere Model [*Scinocca et al.*, 2008], the upward extension of the CCCma atmospheric general circulation model (version 3), with 71 levels from the surface to around 100 km at T63 horizontal resolution. The ocean component is based on a modified version of the National Center for Atmospheric Research community ocean model (NCOM1.3), with 40 vertical levels and a horizontal resolution of approximately 1.41° (longitude) by 0.94° (latitude). Sea ice thermodynamics is governed by an energy balance model, whereas sea ice dynamics uses a cavitating-fluid rheology.

[5] The response to stratospheric ozone depletion is derived by comparing a control simulation to “ozone hole” simulations which include a prescribed climatological monthly-varying ozone perturbation that represents the observed change in stratospheric ozone from 1979 to 2005. We study the 100-year coupled control and ozone hole simulations of SFS10. For the present study we ran two additional 100-year ozone hole simulations, which were initiated from slightly perturbed initial conditions. In the rest of this letter the response to ozone depletion refers to the

---

[1] Department of Physics, University of Toronto, Toronto, Ontario, Canada.

[2] Canadian Centre for Climate Modelling and Analysis, Environment Canada, Victoria, British Columbia, Canada.

0094-8276/10/2010GL044301

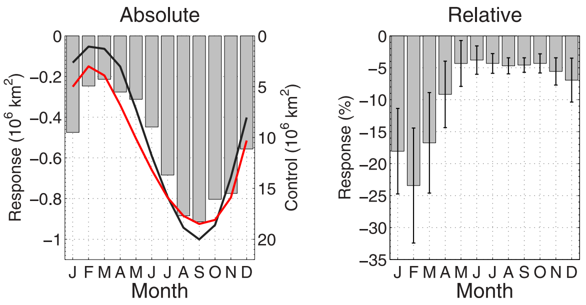

Figure 1. The (left) absolute (in 10^6 km^2) and (right) relative (in %) Antarctic SIE response to stratospheric ozone depletion as a function of calendar month. Figure 1 (left) also shows Antarctic SIE (inverted scale on the right axis) in the control simulation (solid black line) and in observations (solid red line [*Cavalieri and Parkinson*, 2008]). The error bars in Figure 1 (right) represent the 95% confidence interval according to a standard *t*-test).

difference between the climatology of the control run and the average of the three ozone hole runs.

3. Results

3.1. Climatology and SAM-Related Variability of Antarctic Sea Ice

[6] We first assess the model's ability to simulate the monthly climatology and SAM-related variability of Antarctic SIE. Figure 1 (left) shows the Antarctic SIE (defined as the total area with at least 15% ice cover) in the control simulation (black solid line) and in observations (red solid line; inverted scale on the right axis). The simulated SIE agrees well with the observations, except that the amplitude of the seasonal cycle is slightly overestimated.

[7] We define the SAM as the monthly zonal mean sea-level-pressure difference between 65°S and 40°S. Consistent with observations [e.g., *Sen Gupta and England*, 2006], a positive SAM anomaly in austral summer/fall is associated with a fairly zonally symmetric pattern of positive SIC anomalies, and an increase in total Antarctic SIE (Figure S1 of the auxiliary material).[1] This leads one to infer, erroneously as we will see, that a positive SAM response to stratospheric ozone depletion induces increased Antarctic SIE. In austral winter/spring a positive SAM anomaly is associated with a zonally asymmetric pattern of SIC anomalies, resulting in no significant overall increase or decrease in total Antarctic SIE (Figure S1), which is also consistent with observations.

3.2. Antarctic Sea Ice Response to Stratospheric Ozone Depletion

[8] We now turn to the response to ozone depletion. As shown by *Sigmond et al.* [2010, Figure 4], this model displays a strong seasonal cycle in the SAM response to stratospheric ozone depletion. Ozone depletion peaks in austral spring, but has the largest impact on the SAM response in austral summer, with values exceeding +4 hPa in December and January and near-zero values in the other seasons.

[9] The main result of this study is summarized in Figure 1, which shows the absolute (Figure 1, left) and relative (Figure 1, right) response of Antarctic SIE to the stratospheric ozone depletion. Contrary to expectations based on intra-seasonal variability, we find a statistically significant decrease of Antarctic SIE in response to stratospheric ozone depletion. The relative response peaks in January–March, lagging the maximum SAM response by one month. The sea ice response is not limited to austral summer, but occurs in all calendar months. In fact, the absolute sea ice response peaks in August–October, at the time of maximum climatological SIE (solid line). The percent change in annual mean SIE is ~−5.4%. As this represents the total SIE change at equilibrium (i.e., over the 26 years between 1979 and 2005), this is equivalent to ~−2.1% per decade. Given the observed rate of ~+0.9% per decade, this result suggests that mechanisms not involving the ozone hole are responsible for the observed SIE trends. The timeseries of the annual mean SIE reveal that in all three ozone hole simulations the equilibrium response is set within five years after the start of the simulations (not shown). This relatively short response time establishes the relevance of our equilibrium solutions to the real-world transient response to ozone depletion.

[10] The latitudinal structure and seasonal cycle of the sea ice response is further explored in Figure 2, which shows the zonal mean response of SIC (shading) and screen level air temperature (contours) as a function of calendar month. As in Figure 1, we find the largest absolute zonal mean sea ice response in August–October. The sea ice response tends to peak close to the climatological sea ice edge (denoted by the green line), i.e., as the sea ice grows between March and September, both the climatological sea ice edge and maximum sea ice response shift equatorward. The decrease in SIC is accompanied by large zonal mean near surface warming of up to 0.9°C in September. We now focus on December–February (DJF), the season with the largest atmospheric circulation response, and August–October (ASO), the season with the largest (absolute) sea ice response. Figure 3 shows the change in sea ice fraction (shading), screen level air temperature (contours) and the surface wind stress (vectors) in DJF (Figure 3, left) and ASO (Figure 3, right). The sea ice response is fairly zonally symmetric in both seasons, with sea ice decreasing in all sectors of the Southern Ocean. It is accompanied by a near surface warming that is particularly large in ASO (up to 2.0°C). Note that the peak of the sea ice response occurs close to the sea ice edge in ASO, but closer to the continent in DJF. The surface wind stress anomalies are restricted to DJF, where they reflect poleward intensified surface winds in response to stratospheric ozone depletion (i.e., a SAM-like response). The DJF cooling over the Antarctic continent is consistent with previous studies [e.g., *Gillett and Thompson*, 2003].

[11] Figure 4 shows the bimonthly zonal-mean response of ocean temperature (shading) and overturning streamfunction (contours). The cyan contour denotes the 0°C isotherm in the control simulation, which at the surface is a proxy for the position of the sea ice edge. Many features in the ocean temperature response in the austral summer can be understood by considering changes in the overturning streamfunction. The poleward shifted and intensified west-

---

[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GL044301.

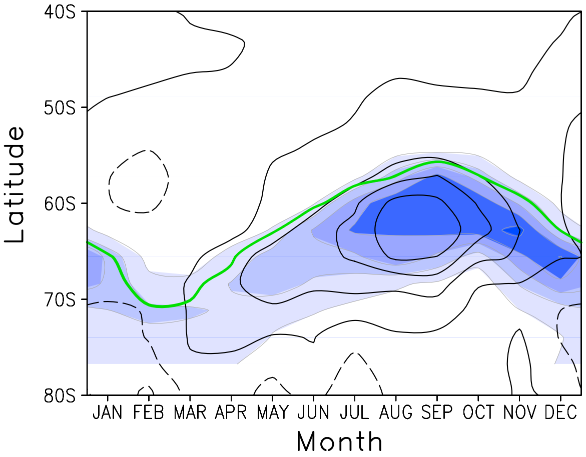

Figure 2. Zonal-mean response of the sea ice fraction (shading interval is 1% (…,−1.5, −0.5%)) and screen level air temperature (contour interval is 0.2°C (…, −0.3, −0.1, 0.1,…)). The green line represents the sea ice edge in the control simulation (defined as the 5% contour line of the zonal-mean sea ice fraction). Here and in subsequent plots solid (dashed) contours and red (blue) shades denote positive (negative) values.

erly wind stress in austral summer induces deep anomalous meridional circulation cells, with anomalous Ekman pumping (suction) centered around 45°S (65°S). The temperature response in the shallow summer mixed layer is consistent with changes in upper branch of the anomalous meridional circulation cells with equatorward (poleward) flow advecting cold (warm) water near 57°S (40°S). The warming response directly beneath the surface cooling around 57°S is consistent with a deepened mixed layer, reflecting the combined influences of intensified surface winds and cooler surface temperatures.

[12] Surprisingly, we also find significant ocean temperature changes outside austral summer. The ocean temperature response beneath the mixed layer and equatorward of ~60°S is dominated by a year-round ocean warming. Outside austral summer this warming extends to the mixed layer. This warming pattern is consistent with a poleward shift of the ocean isotherms, which is linked to the poleward shifted westerly wind stress in austral summer, as described in the next subsection.

3.3. Physical Mechanisms

[13] The direct radiative effect of stratospheric ozone depletion acts to weakly cool the lower troposphere [*Grise et al.*, 2009] thus facilitating increased rather than decreased SIE. Therefore, the primary mechanisms for the modeled SIE decrease presumably involve dynamical rather than radiative forcing. The mechanisms for summer and winter sea ice melt are physically and geographically distinct, and are thus discussed separately.

3.3.1. Austral Summer Melt

[14] The SIE decrease in summer near the Antarctic coast is consistent with an established mechanism involving enhanced offshore Ekman sea ice transport arising from the stronger westerlies [e.g., *Fyfe et al.*, 2007]. This leads to enhanced regrowth of new sea ice replacing that transported away from the Antarctic coast, with the ice on average becoming thinner (as verified in the model, not shown). The thinner ice is consistent with decreased SIC near the continent and decreased Antarctic SIE overall. The associated brine rejection and heat loss result in enhanced convection, cooling the deep ocean and warming the surface ocean, as seen around 75°S in Figure 4 (top left). The resulting surface warming acts to melt even more ice, representing a positive feedback.

3.3.2. Austral Winter Melt

[15] The SIE decrease in winter away from the Antarctic coast and near the climatological sea ice edge results from an ocean warming due to a poleward shift of the ocean isotherms (of about 0.4° latitude between about 40°S and 60°S), which acts to limit the equatorward development of sea ice during its season of maximal growth. This poleward shift of ocean isotherms is driven in summer by the poleward shift of the westerly jet, but the large thermal inertia of the ocean prevents the isotherms from returning to their original positions in winter. As it takes several years after turning the ozone forcing on for the winter isotherms to equilibrate to their new poleward shifted positions, it would

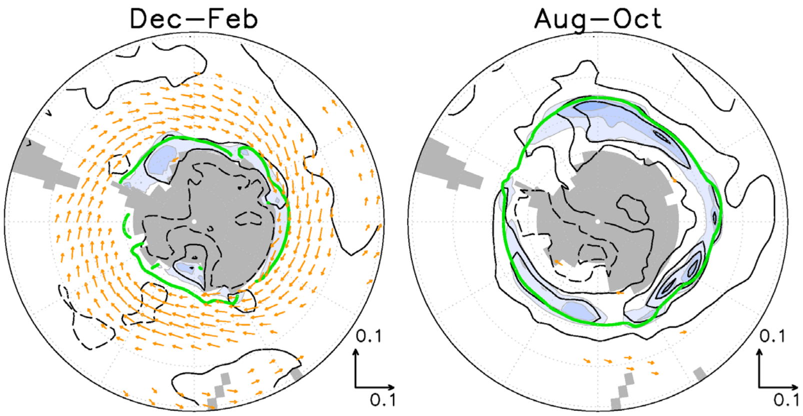

Figure 3. (left) December–February and (right) August–October response of the sea ice fraction (shading interval is 5% (−22.5, −17.5, …, −2.5)), screen level air temperature (contour interval is 0.4°C (…, −0.6, −0.2,0.2,…)) and surface wind stress vector (Scale at bottom, in Pa, only vectors with a magnitude exceeding 0.015 Pa are plotted). The green line represents the sea ice edge in the control simulation (defined as the 15% contour line of sea ice fraction).

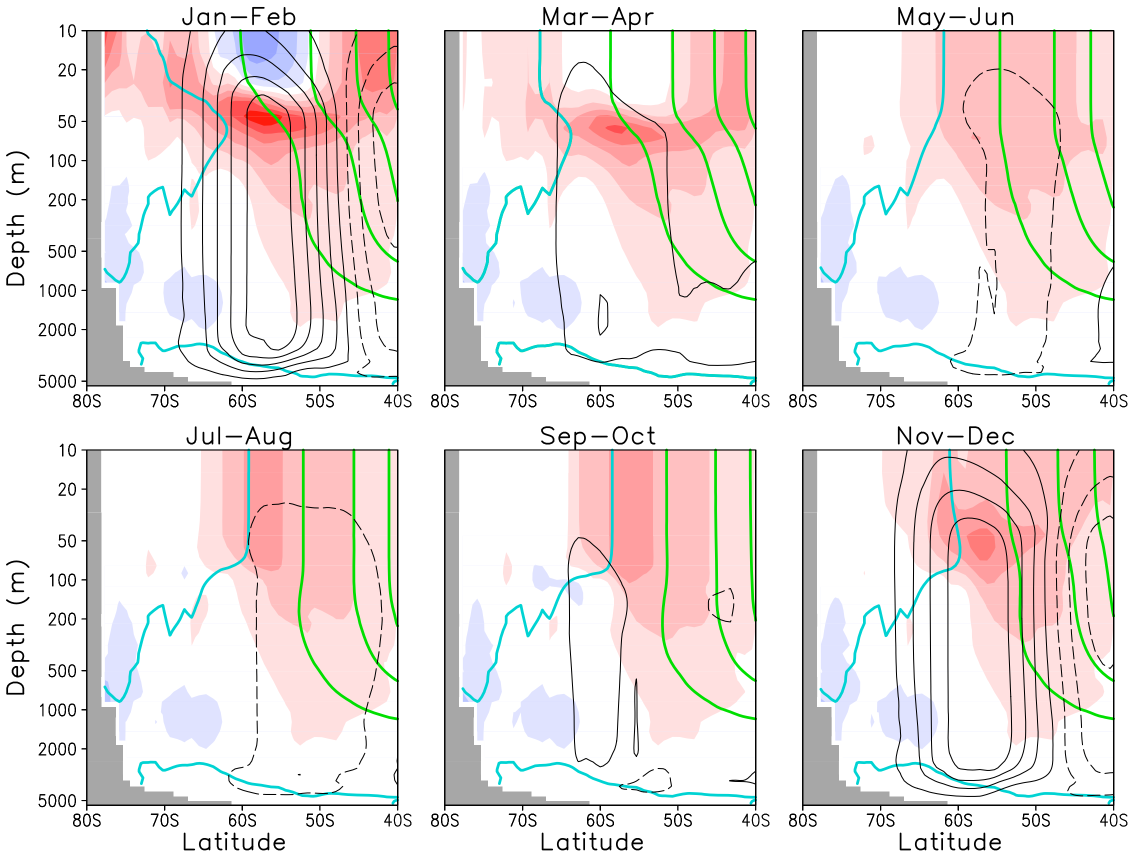

Figure 4. Bimonthly response of ocean overturning streamfunction (black contours, interval is 1 Sv (…, −1.5, −0.5, 0.5, …) and ocean temperature (shading interval is 0.06°C (…, −0.09, −0.03, 0.03,…)), and the ocean temperature in the control simulation (cyan contour at 0°C and green contours at 4, 8, …°C).

take several years for the isotherms to equilibrate back to their original positions after turning off the ozone forcing. However, since the ozone forcing is repeated every summer the isotherms never return to their original positions.

4. Summary and Discussion

[16] In this study we have investigated the impact of stratospheric ozone depletion on Antarctic sea ice extent (SIE). To this end we have employed the Canadian Middle Atmosphere Model coupled to an interactive ocean and sea ice model, which was shown to produce a realistic SIE climatology and credible sea ice variability associated with variations in atmospheric circulation. The response to ozone depletion was derived by comparing the climatologies of simulations with and without a monthly varying stratospheric ozone perturbation based on observations over the period from 1979 to 2005. We found a year-round decrease in Antarctic SIE in response to ozone depletion, with a maximum relative decrease in January–March, consistent with a mechanism involving offshore sea ice transport. We also found a large absolute SIE decrease in August–October, in response to an ocean warming that is consistent with a poleward shift of the large-scale pattern of sea surface temperature.

[17] Consistent with previous studies we found a positive correlation between variations in the Southern Annular Mode (SAM) and total SIE in austral summer. At the same time, we found that a SAM-like circulation response to ozone depletion is accompanied by a decrease in SIE. This implies, for reasons unknown at this time, that relationships between intra-seasonal variations of atmospheric circulation and SIE can not be used to derive the SIE response to stratospheric ozone depletion. It also implies that the pattern of SAM-related sea ice variability arises from mechanisms other than, or in addition to, the offshore Ekman sea ice transport mechanism involved in ozone depletion.

[18] It is presently unclear why the observed Southern Hemisphere SIE trends are so different from those in the Northern Hemisphere. Previous studies have suggested that the cause might be related to atmospheric circulation changes induced by the stratospheric ozone hole. The results in this study are not consistent with this view and highlight the need for continued investigations of Antarctic SIE trends.

[19] **Acknowledgments.** MS is a member of the CSPARC network, and gratefully acknowledges the support of the Canadian Foundation for Climate and Atmospheric Sciences. We thank Greg Flato, Bill Merryfield, Nathan Gillett, Marc D'Orgeville and two anonymous reviewers for their insightful comments.

References

Cavalieri, D. J., and C. L. Parkinson (2008), Antarctic sea ice variability and trends, 1979–2006, *J. Geophys. Res.*, *113*, C07004, doi:10.1029/2007JC004564.

Comiso, J. C., and F. Nishio (2008), Trends in the sea ice cover using enhanced and compatible AMSR-E, SSM/I, and SMMR data, *J. Geophys. Res.*, *113*, C02S07, doi:10.1029/2007JC004257.

Fyfe, J. C., O. A. Saenko, K. Zickfeld, M. Eby, and A. J. Weaver (2007), The role of poleward-intensifying winds on southern ocean warming, *J. Clim.*, *20*, 5391–5400.

Gillett, N. P., and D. W. J. Thompson (2003), Simulation of recent Southern Hemisphere climate change, *Science*, *302*(5643), 273–275.

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

Grise, K. M., D. W. J. Thompson, and P. M. Forster (2009), On the role of radiative processes in stratosphere-troposphere coupling, *J. Clim.*, *22*, 4154–4161.

Lefebvre, W., H. Goosse, R. Timmermann, and T. Fichefet (2004), Influence of the Southern Annular Mode on the sea ice–ocean system, *J. Geophys. Res.*, *109*, C09005, doi:10.1029/2004JC002403.

Scinocca, J. F., N. A. McFarlane, M. Lazare, J. Li, and D. Plummer (2008), Technical note: The CCCma third generation AGCM and its extension into the middle atmosphere, *Atmos. Chem. Phys.*, *8*(23), 7055–7074.

Sen Gupta, A., and M. H. England (2006), Coupled ocean-atmosphere-ice response to variations in the Southern Annular Mode, *J. Clim.*, *19*(18), 4457–4486.

Sigmond, M., J. C. Fyfe, and J. F. Scinocca (2010), Does the ocean impact the atmospheric response to stratospheric ozone depletion?, *Geophys. Res. Lett.*, *37*, L12706, doi:10.1029/2010GL043773.

Son, S.-W., N. F. Tandon, L. M. Polvani, and D. W. Waugh (2009), Ozone hole and Southern Hemisphere climate change, *Geophys. Res. Lett.*, *36*, L15705, doi:10.1029/2009GL038671.

Turner, J., J. C. Comiso, G. J. Marshall, T. A. Lachlan-Cope, T. Bracegirdle, T. Maksym, M. P. Meredith, Z. Wang, and A. Orr (2009), Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent, *Geophys. Res. Lett.*, *36*, L08502, doi:10.1029/2009GL037524.

J. C. Fyfe, Canadian Centre for Climate Modelling and Analysis, Environment Canada, University of Victoria, PO Box 3065 STN CSC, Victoria, BC V8W 3V6, Canada.

M. Sigmond, Department of Physics, University of Toronto, 60 St. George St., Toronto, ON M5S 1A7, Canada. (sigmond@atmosp.physics.utoronto.ca)