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Antarctic climate response to stratospheric ozone depletion in a fine resolution ocean climate model

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[1] We investigate the impact of stratospheric ozone depletion on Antarctic climate, paying particular attention to the question of whether eddy parameterizations in the ocean fundamentally alter the results. This is accomplished by contrasting two versions of the Community Climate System Model (version 3.5), one at 0.1° ocean and sea ice resolution and the other at 1° with parameterized ocean eddies. At both resolutions, pairs of integrations are performed: one with high (1960) and one with low (2000) ozone levels. We find that the effect of ozone depletion is to warm the surface and the ocean to a depth of 1000 m and to significantly reduce the sea ice extent. While the ocean warming is somewhat weaker when the eddies are resolved, the total loss of sea ice area is roughly the same in the fine and coarse resolution cases. **Citation:** Bitz, C. M., and L. M. Polvani (2012), Antarctic climate response to stratospheric ozone depletion in a fine resolution ocean climate model, *Geophys. Res. Lett.*, *39*, L20705, doi:10.1029/2012GL053393.

1. Introduction

[2] Stratospheric ozone depletion has had profound effects on the Southern Hemisphere (SH) climate, as recently reviewed by *Thompson et al.* [2011], and it is believed to have been the dominant driver of SH atmospheric circulation changes in the second half of the 20th Century [*Polvani et al.*, 2011]. Among these changes perhaps the most dramatic is a poleward shift of the summertime midlatitude jet, extending from the lower stratosphere all the way to the surface. Some have argued that this poleward shift of the surface westerlies may have been the cause of the observed expansion of sea ice extent over the satellite era [e.g., *Turner et al.*, 2009].

[3] In contrast, a recent study with a coupled model has reported that ozone depletion actually causes a decrease in modeled sea ice [*Sigmond and Fyfe*, 2010] (henceforth referred to as SF10) unlike what is seen in the observations. That study, however, suffers from the common limitation of present generation global climate models: a relatively coarse ocean resolution, such that the ocean eddies are unresolved and thus need to be parameterized. This raises the question of whether an ozone depletion experiment with an eddy-resolving ocean model would yield a different result from SF10. The goal of our paper is to address this question.

[4] As summarized in *Marshall and Speer* [2012], in the current debate about resolved versus parameterized eddies in the Southern Ocean, little has been said about sea ice, despite the fact that at its maximum extent, sea ice spans the region from the Antarctic continent to the Polar Front. In this paper, comparing pairs of model integrations in which a single forcing (ozone) is changed from 1960 to 2000 values, we document the effect of ozone depletion on Antarctic sea ice and the entire Southern Ocean. Running our model at both 0.1° and 1° resolution in the ocean and sea ice (the latter with a state-of the-art ocean eddy parameterization), we demonstrate that ozone depletion warms the ocean and decreases sea-ice irrespective of how ocean eddies are represented. Confirming the findings of SF10, we thus provide new evidence of the profound impact of stratospheric ozone depletion on Antarctic climate.

2. Methods

[5] We use the Community Climate System Model version 3.5 (CCSM3.5) at two resolutions, with set-ups that are identical to those in *Gent et al.* [2010] and *Kirtman et al.* [2012]. In all cases, the atmosphere component has the finite-volume dynamical core and horizontal resolution of $0.47° \times 0.63°$ and 26 vertical levels. The horizontal grid of the land is the same as the atmosphere. The ocean and sea ice resolution is either nominally 0.1° or 1°. The ocean eddy parameterization is a Gent and McWilliams (GM) form, with GM coefficient varying in space and time [*Danabasoglu and Marshall*, 2007]. The simulated climate at both resolutions is described in *Kirtman et al.* [2012]. Henceforth, we refer to our cases as either 1° or 0.1°, although it should be understood that these values only refer to the ocean and sea ice.

[6] We initialize our integrations at year 110 of control integrations (at each resolution) from *Kirtman et al.* [2012], with greenhouse gases and aerosols fixed at 1990s level. The ozone concentration in the control integrations were those used in CCSM3 [*Kiehl et al.*, 1999], and were intended to be representative of the 1990s level. However, compared to more recent estimates of ozone concentrations from the Atmospheric Chemistry and Climate and Stratospheric Processes and their Role in Climate (AC&C/SPARC) data set [*Cionni et al.*, 2011], the CCSM3 CMIP3 estimates for 1990s resemble the level of ozone depletion in the Antarctic stratosphere of approximately 1980, or about half the level of depletion since preindustrial times.

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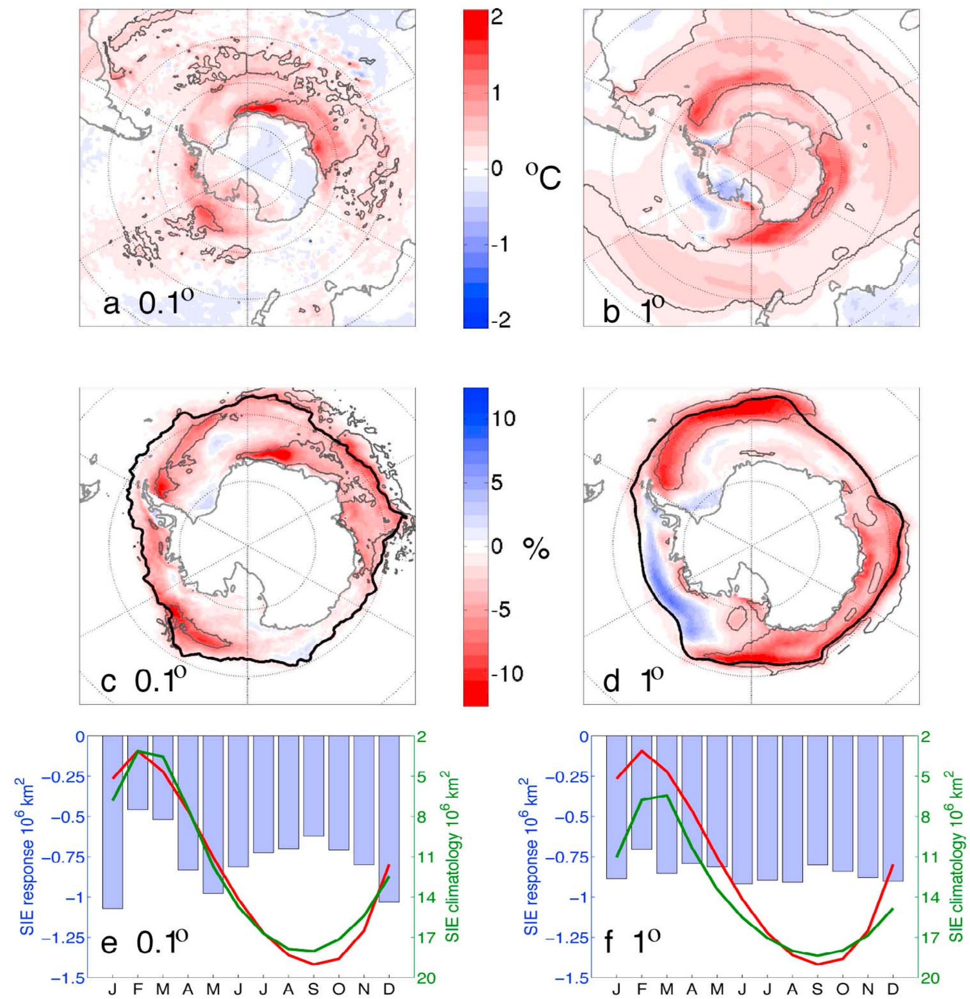

Figure 1. Annual mean response to ozone depletion of (a and b) surface skin temperature, (c and d) sea ice concentration, and (e and f) total Southern Hemisphere sea ice extent by month. Thick black contour in middle panels marks the winter (Jun.–Aug.) sea ice 15% concentration; thin black contours in top and middle panels indicate regions where the response is significant at the 5% confidence level. Curves in bottom panels show the sea ice extent climatology in the model (green lines) and from passive microwave 1987–2006 (red lines) NASA bootstrap algorithm [*Meier et al.*, 2011].

[7] To investigate the full impact of modern stratospheric ozone depletion from 1960 to 2000, we conducted pairs of ozone integrations branched from the 1990s control integrations, with one integration raising stratospheric ozone concentrations and the other lowering them over 20 years. The ozone concentration was then held fixed for an additional 30 years at the 1960s level in the runs that had ozone ramped up and at the 2000s level in the runs that had ozone ramped down. (See Figure S1 of the auxiliary material for an illustration.)[1] The ozone was modified by adding anomalies constructed using the AC&C/SPARC data set to the ozone field that was used in the control runs. In what follows, the "response" to ozone depletion is reported as the difference between the low ozone and high ozone runs (low-high), averaged over the last 30 years of integration. This represents, approximately, the quasi-equilibrated impact of ozone depletion in the 20th century.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL053393.

3. Results

[8] The key result of our paper is shown in Figure 1: the Southern Ocean surface warms over large areas as a consequence of ozone depletion (top row) and Antarctic sea ice concentration (SIC) decreases markedly (middle row). Furthermore, sea ice extent (SIE) is found to decrease in all seasons (bottom row), although ozone depletion in the stratosphere is a highly seasonal phenomenon. Finally, note that these responses occur whether ocean eddies in the model are resolved (left column) or parameterized (right column).

[9] Hence, our integrations largely confirm the findings of SF10. In our model the magnitude of sea ice loss relative to the amplitude of ozone depletion is roughly 1/3 smaller than in SF10, and it is more uniform throughout the year. Such a discrepancy is not surprising, since both the magnitude and

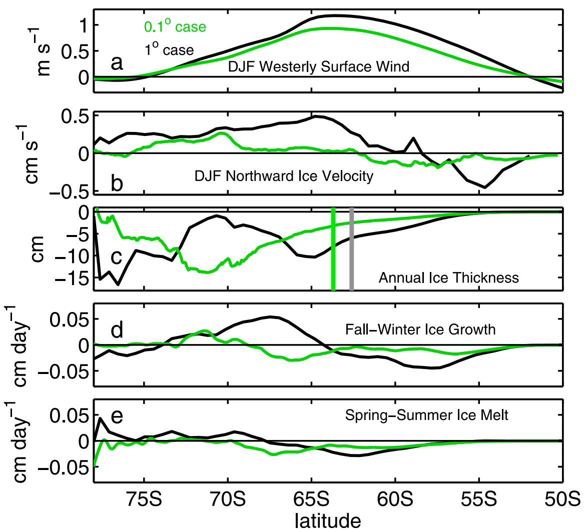

Figure 2. Response to ozone depletion in the zonal mean Dec.–Feb. (a) surface zonal wind stress, (b) northward ice velocity, (c) annual sea ice thickness, (d) spring–summer (Sep.–Feb.) sea ice melt rate, and (e) fall–winter (Mar.–Aug.) sea ice growth rate. Black lines indicate the 1° case, and green lines the 0.1° case. Vertical lines in Figure 2c show the position of the annual mean 15% SIC. Note that in Figures 2b–2e the areas are only averaged over the ocean surface.

seasonality of sea ice loss are likely to vary among models, because the mean states can differ considerably, and the forced response of sea ice is known to depend on the mean state [e.g., *Bitz and Roe*, 2004]. Note, however, that the seasonality of the SIE in our integrations compares well with those in passive microwave satellite observation (compare the green and red lines Figures 1e and 1f and see Figure S2 in the auxiliary material).

[10] Contrasting our low and high resolution models, we see that most sea ice loss occurs near the ice edge in the 1° case, as found by SF10, while loss in the 0.1° case tends to be more broadly distributed (the small areas of increased SIC are not significant). In spite of these differences, and although the area of significant surface warming is larger in the 1° case, we obtain the surprising results that the total annual loss of Antarctic SIE is nearly independent of resolution, at 0.77×10^6 km^2 in the 0.1° case and 0.85×10^6 km^2 in the 1° case. This corresponds to approximately 6% of the annual mean SIE.

[11] We now turn to the mechanism that allows ozone depletion to impact the Southern Ocean. The loss of sea ice is initiated by an intensification of the surface westerly wind, which peaks in Dec.–Feb., though the ozone depletion peaks in Oct. (See *Polvani et al.* [2011] for a more complete discussion of the seasonality of the atmospheric circulation response to ozone depletion.). The zonal-mean intensification in Dec.–Feb. is about 1 m s^{-1}, on average, from 60–65°S: this gives rise to an increase in the zonal direction of the Dec.–Feb. surface wind stress (Figure 2a). The enhancement of the zonal components of both the wind and surface wind stress in the 0.1° case is smaller than in the 1° case. The reason for this difference with resolution is unknown at this time and is the subject of further study.

[12] The surface wind stress intensification drives an intensified northward ice velocity in Dec.–Feb (Figure 2b). The ice velocity response is much larger in the 1° case compared to the 0.1° case. However, in both cases increased transport away from the continent contributes to the reduction in ice thickness and SIC near the continent in summer. Ice convergence increases in summer south of about 65°S (not shown), yet at these latitudes SIC (see Figures 1c and 1d) and ice thickness (see Figure 2c) decrease with ozone depletion. Hence thermodynamic processes must be responsible for ice loss over most of the Southern Ocean.

[13] Further analysis of the sea ice mass balance response to ozone depletion by season indicates that both reduced growth and increased melt contribute to the sea ice loss (see Figures 2d and 2e). Basal melt responds most substantially in the spring and summer, with more melt nearer the continent and less melt at the ice edge, as less ice is available to melt (Figure 2d). There is more basal melt in winter too (not shown), especially near the continent and near the ice edge in the 0.1° case but only near the ice edge in the 1° case. The basal melt rate response has a strong influence on the pattern of SIC response in Figure 1. Melt at the upper surface is negligible in the Antarctic in this model in all cases.

[14] Sea ice growth rates are generally lower in response to ozone depletion, except in fall and winter south of ~70°S in the 1° case (see Figure 2e) and in some parts of the Weddell Gyre in the 0.1° case (not shown). The reduced growth rates in fall and winter are an indication that the inertia of the ocean is involved in retaining the effects of the summer westerly wind enhancement year round, as found in SF10.

[15] We see no evidence for increased growth and brine rejection in summer, in contrast to SF10 who argued that this would be a positive feedback on sea ice loss. Instead we find increased growth and brine rejection in fall and winter in our 1° case, but not in the 0.1° case. This difference between our study and SF10 could be another reason why our sea ice loss is somewhat smaller than theirs.

[16] As the surface wind response to ozone depletion is largely confined to the summer, it is the surface heat fluxes from the ocean and atmosphere that are responsible for the sea ice loss to occur throughout the year. The enhanced surface westerly winds cause the ocean surface to warm in summer (Figures 3a and 3b), which in turn increases the ocean heat flux to the sea ice. The ocean warming persists year round (Figures 3c and 3d), though it extends further south in summer, when the surface wind stress response is greatest and shortwave feedbacks amplify the warming. The differences in the spatial pattern of ocean warming with model resolution are consistent with the resolution dependence of the sea ice response, with sea ice loss more distributed in the 0.1° case and more focused at the sea ice edge in the 1° case. Indeed, within the sea-ice covered region, the maximum ocean warming in summer is at the surface in the 0.1° case, but below the mixed layer and further north in the 1° case. This pattern is consistent with heightened ocean mixing in summer as indicated by the deeper ocean mixed layer (see Figure 4a), this deepening is more pronounced in the 0.1° case south of 65°. Mixing south of the Polar Front (approximate maximum extent of the sea ice) entrains warmer water from below the mixed layer, and thus increased mixing causes surface warming. These changes suggest that the intensified surface wind stress enhances convection in summer, but increased sea ice melt rates away from the continent prevent the convection from increasing somewhat, especially in the 1° case.

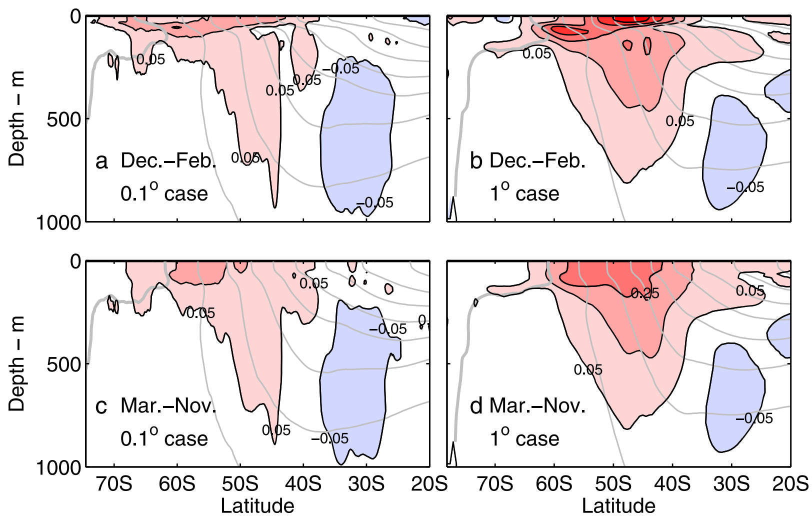

Figure 3. Zonal mean ocean temperature response to ozone depletion for (a and b) Dec.–Feb. and (c and d) the rest of the year, in the 0.1° case (Figures 3a and 3c) and the 1° case (Figures 3b and 3d). Grey lines indicate isotherms from the low ozone run for 0 (heavy lines) and for 3, 6, 9, etc (light lines) °C.

[17] Southern Ocean warming is also a response to the intensified northward Ekman drift in the surface layer, which enhances divergence south of the Polar Front. In agreement with SF10, we find a strengthening of the Southern Ocean overturning circulation (Figure 4b) with upwelling of warmer water at about 65°S. The increased upwelling gives rise to an increased vertical advection of heat of about 1 $\mathrm{Wm^{-2}}$ in the zonal and annual mean at 50 m depth from about 58–62°S at both resolutions. Enhanced downwelling at about 40–50°S advects heat downward and contributes to warming the ocean to about 1000 m depth. The response in the vertical heat advection is roughly the same year round, so we only discuss the annual mean.

[18] The vertical heat flux total in Figure 4c is separated into mean component and eddy components: $\overline{\theta w} = \overline{\theta}\overline{w} + \overline{\theta' w'}$, where w is the vertical velocity component, θ is the potential temperature, the bar denotes a time mean, and the prime denotes the departure from the time mean. Most of the vertical advection response in the 1° case is accomplished by the mean circulation change. However, in the 0.1° case, eddy-convective and mean components contribute nearly equal proportions where the vertical heat flux increases most, at about 53–63°S.

[19] Several recent studies have shown that a greatly intensified zonal surface wind stress in the Southern Ocean gives rise to an enhanced southward heat flux south of about 60°S [*Farneti et al.*, 2010; *Gent and Danabasoglu*, 2011], which would bring heat into the sea-ice covered ocean. This occurs in response to ozone depletion in both our cases (Figure 4d), though with larger magnitude in the 1° case. Eddies are responsible for the enhanced southward heat flux in the 1° case. It is only north of about 60°S, beyond the sea ice covered ocean in most seasons, where the response in eddy heat flux has the opposite sign to the heat flux response from the mean circulation at either resolution. Hence the regions of strong eddy compensation are too far north to be of much consequence to the sea ice.

[20] Sea ice is known to be more sensitive to heat flux anomalies from the ocean than the atmosphere [*Bitz et al.*, 2005], and changes of order 1 $\mathrm{Wm^{-2}}$ can cause substantial changes to the sea ice concentration and thickness, and hence the heat conducted from ocean to atmosphere, must change to compensate. In our integrations at either

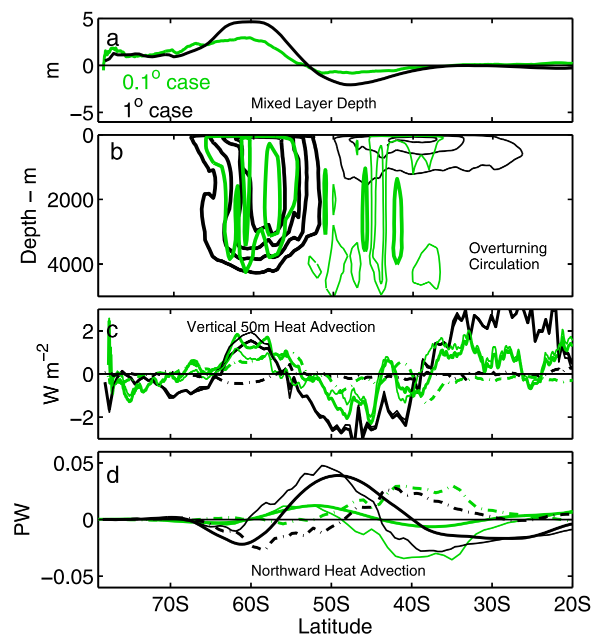

Figure 4. Response to ozone depletion in the (a) Dec.–Feb. ocean mixed layer depth, (b) annual-mean upward ocean heat flux at 50 m depth, (c) ocean meridional overturning streamfunction Eulerian mean component, and (d) northward ocean heat flux. In Figures 4b and 4d the total heat flux (heavy lines) is decomposed into mean (light lines) and eddy (dot-dashed line) components. In Figure 4b the overturning stream function heavy contours are 0.25, 0.75, 1.25, and 1.75 Sv and light contours are −0.25, −0.75, and −1.25 Sv. In all panels, black lines indicate the 1° case and green lines the 0.1° case.

resolution, the surface absorbed shortwave flux increases by more than 6 Wm^{-2} in the zonal mean at about 65°S in summer (see Figure S3 of the auxiliary material) due in equal proportions to a reduction in low cloud and SIC, this is a consequence of direct surface warming due to depleting ozone. Hence the increased surface absorbed shortwave flux is part of a positive feedback. However, the thinner and less compact ice cover conducts more heat from the ocean to atmosphere, increasing upward sensible and latent heat fluxes in winter, and this brings the annual surface heat budget back into balance.

4. Summary and Discussion

[21] The Antarctic climate response to ozone depletion in our model integrations consists of a broad surface warming, substantial sea ice loss, and warming of the Southern Ocean in the upper 1000 m. This climate response is found to have the same sign in the 0.1° and 1° resolution cases, with the ocean warming at high resolution being somewhat more muted. The total loss of sea ice area is about the same in the 0.1° and 1° cases, but the sea ice concentration decrease is more broadly distributed in the former case.

[22] Confirming previous work, we find that the ocean warming is driven by the enhanced westerly surface winds strengthening the Southern Ocean overturning circulation, with greater upwelling of warm water from beneath the mixed layer and increased convection under the sea ice. Downwelling of warm surface water beyond the sea ice zone contributes to ocean warming there down to about 1000 m. An increase in the southward ocean heat transport by eddies contributes to the ocean warming in the 1° case, but not in the 0.1° case. However, the additional warming in the 1° case is mostly beyond the sea ice edge: this makes the sea ice response to ozone depletion less sensitive to model resolution than might have been expected.

[23] Although our findings indicate that the magnitude of the response to ozone depletion depends, to some extent, on model resolution, we are fundamentally in agreement with the key conclusions of SF10, as our results suggest ozone depletion is unlikely to have been the cause of the observed increase in Antarctic SIE over the past 30 years. Hence modeling studies are consistent with observational-based studies that have concluded the recent sea-ice expansion is unrelated to the trend in the Southern Annular Mode (SAM) [*Lefebvre et al.*, 2004; *Liu et al.*, 2004; *Simpkins et al.*, 2012], as the SAM's trend has been associated with ozone depletion [see, e.g., *Thompson et al.*, 2011]. The recent sea-ice expansion is more likely due to natural variability, combined with suppressed greenhouse warming from strong ocean heat uptake in the Southern Ocean see, e.g., *Kirkman and Bitz*, 2011]. Our results also support the findings of *Smith et al.* [2012], who show that recovery of stratospheric ozone should mitigate sea ice loss from greenhouse warming in the coming half century.

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