Large increase in incident shortwave radiation due to the ozone hole offset by high climatological albedo over Antarctica

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ABSTRACT

Despite increasing scientific scrutiny in recent years, the direct impact of the ozone hole on surface temperatures over Antarctica remains uncertain. Here, we explore this question by using the Community Earth System Model - Whole Atmosphere Community Climate Model (CESM-WACCM), contrasting two ensembles of runs with and without stratospheric ozone depletion. We find that, during austral spring, the ozone hole leads to a surprisingly large increase in surface downwelling shortwave (SW) radiation over Antarctica of 3.8 \( \text{W/m}^2 \) in clear-sky and 1.8 \( \text{W/m}^2 \) in all-sky. However, despite this large increase in incident SW radiation, no ozone-induced surface warming is seen in the model. We show that the lack of a surface temperature response is due to reflection of most of the increased downward SW, resulting in an insignificant change to the net SW radiative heating. To first order, this reflection is simply due to the high climatological surface albedo of the Antarctic snow (97% in visible SW), resulting in a net zero ozone-induced surface SW forcing. In addition, we show that stratospheric ozone depletion has a negligible effect on longwave (LW) radiation and other components of the surface energy budget. These results suggest a minimal role for ozone depletion in forcing Antarctic surface temperature trends on a continental scale.
1. Introduction

Among the climatic effects of stratospheric ozone depletion in the Southern Hemisphere (SH; see Previdi and Polvani (2014) for a comprehensive review), the most evident include the large cooling (8 K) of the Antarctic lower stratosphere during spring (Randel et al., 2009), and delayed breakup of the stratospheric polar vortex (Waugh et al., 1999). Observations in the SH also show a positive trend in the Southern Annular Mode (SAM) in summertime (Marshall, 2003), which is associated with a poleward shift of the mid-latitude jet (Archer and Caldeira, 2008), and poleward expansion of the Hadley cell (Min and Son, 2013). There is robust modeling evidence pointing to a dominant role for ozone depletion in driving these trends (Gillett and Thompson, 2003; Polvani et al., 2011; Min and Son, 2013). However, while the effects of the ozone hole on atmospheric circulation in the middle to low latitudes of the SH are well established, its influences on Antarctic surface climate remain poorly understood.

Observed Antarctic surface temperature trends over recent decades show a distinct warming of the Antarctic Peninsula and of West Antarctica (Turner et al., 2005; Monaghan et al., 2008; Steig et al., 2009). In contrast, slight cooling trends have been reported over East Antarctica (Schneider et al., 2012). It has been suggested that stratospheric ozone depletion could have contributed to the spatial structure of these trends through changes in the SAM (Thompson and Solomon, 2002; Gillett and Thompson, 2003; Schneider et al., 2012). However, the largest SAM trends in recent decades are found in the summer, whereas the largest Antarctic temperature trends occur in different seasons (Smith and Polvani, 2016). An alternative, and as yet unexplored, pathway whereby the ozone hole could affect Antarctic surface temperatures is through direct forcing of the surface energy budget.
Idealized modeling studies have shown that a decrease in stratospheric ozone concentration has a large impact on radiative forcing (RF) at the tropopause, with opposite effects on SW and long-wave (LW) fluxes (Ramanathan and Dickinson, 1979; Ramaswamy et al., 1992; Conley et al., 2012; Myhre et al., 2013). The annual mean, global mean RF associated with stratospheric ozone depletion is quite small, and on the order of -0.05 W/m$^2$ [cf. Conley et al. (2012), Table 2]. However, the RF can locally be much larger, such as over Antarctica during austral spring [cf. Myhre et al. (2013), Figure 8.23]. The ozone hole effects on surface climate could not be investigated in these studies due to either simplicity of the models employed (Ramanathan and Dickinson, 1979; Ramaswamy et al., 1992), or the fixed tropospheric temperatures used in standard RF calculations (Conley et al., 2012; Myhre et al., 2013).

Here, using ensembles of simulations from a coupled atmosphere-ocean climate model with interactive ozone photochemistry (CESM-WACCM), we quantify in detail the impact of ozone depletion on the Antarctic surface energy budget. We show that the ozone hole leads to a sizable late 20th century increase in incident (downward) SW radiation on the Antarctic surface. However, despite this large SW perturbation, the modeled Antarctic surface temperature does not increase significantly. This lack of a surface temperature response is shown to be due to the high climatological snow albedo over Antarctica, which reflects the increased incident SW flux, thus leading to negligible net surface RF.

2. Methods

We employ the Community Earth System Model (CESM) with the atmospheric component being the stratosphere-resolving Whole Atmosphere Community Climate Model, version 4 (WACCM4) (Marsh et al., 2013). WACCM4 has a horizontal resolution of 1.9° latitude by 2.5° longitude, with 66 vertical levels, extending up to 140 km, and realistically simulates the chem-
ical effects of ozone-depleting substances (ODSs) on stratospheric ozone (Marsh et al., 2013).

Additionally, WACCM is coupled to the Parallel Ocean Program (POP) (Gent et al., 2011), and to the Community Land Model version 4 (CLM4) (Lawrence et al., 2011), which incorporates parameterizations for several snow and ice processes, such as grain-size dependent snow aging.

To quantify the impact of 20th century ozone depletion on Antarctic surface climate, we contrast two CESM-WACCM ensembles, each comprising six integrations for the period 1960 to 2005 (see also Marsh et al. (2013); Smith et al. (2013)). For the reference ensemble (labeled “HIST”), all natural and anthropogenic forcings are specified as in CMIP5 (Coupled Model Intercomparison Project phase 5) historical integrations, with individual ensemble members initialized from these CMIP5 integrations. The second ensemble (labeled “fixODS”) is identical to HIST except for the prescribed surface concentrations of ODSs, which are kept constant at year 1955 levels. Therefore, HIST includes the ODS-induced stratospheric ozone depletion during the 20th century, while fixODS does not. Focus will be given on the late austral spring (October-November-December, hereafter OND), which is the season when stratospheric ozone depletion maximizes, and when the strongest surface RF is therefore expected.

3. Results

The evolution of springtime (OND) total ozone, averaged over the Antarctic continent, is shown in Fig. 1a. In the HIST ensemble, half of the ozone column is depleted by the year 1990, as compared to the fixODS ensemble in which there are no discernible ozone trends. The climatological ozone column in WACCM4 is a little low, but the total ozone loss simulated in the historical ensemble (140 DU) is in good agreement with MIPAS satellite data (Peck et al., 2015).

Accompanying this large stratospheric ozone depletion, one sees a large increase in clear-sky downwelling SW radiation at the Antarctic surface in the HIST ensemble (Fig 2a). After clouds
are taken into account (“all-sky”), this increase in SW radiation is reduced, especially over West Antarctica (Fig 2b). The partial compensation by clouds is best seen by comparing the SW flux changes in visible and UV (\(\lambda < 750\) nm) (Fig. 2c) with changes in the near-infrared (750 nm < \(\lambda < 1500\) nm) (Fig. 2d). The increase in the broadband integrated SW flux displayed in Fig.2a lies entirely in the visible and UV range (Fig. 2c). However, an increase in cloud cover over West Antarctica in HIST reduces the incident near-infrared SW flux at the surface (Fig. 2d), owing to enhanced cloud absorption (?). Nevertheless, the reduction in near-infrared is smaller than the increase in at shorter wavelengths. As a result, the overall SW flux change integrated over all wavelengths (Fig 2b) is significant over most of the continent, and is on average +1.8 W/m\(^2\).

Additional offline calculations using the Parallel Offline Radiative Transfer (PORT) model (Conley et al., 2012) reveal that the increase in clear-sky downwelling SW radiation in HIST is directly linked to the decrease in stratospheric ozone concentrations (not shown).

One might question whether the simulated ozone-induced changes in SW radiation are realistic, given the relatively coarse spectral resolution of the solar radiation scheme in WACCM4. To investigate this, we have performed single-column clear-sky calculations with the line-by-line LibRadTran model (Mayer et al., 2005), using total column ozone values corresponding to the 1990-2005 Antarctic average for the fixODS and HIST ensembles simulated by WACCM4, i.e. 300 DU and 160 DU, and a zenith angle of 80\(^\circ\) (representative of Antarctic conditions in spring). The resulting downwelling clear-sky broadband integrated SW spectral irradiance is shown in Fig. 3. In response to the imposed ozone depletion, we find an enhanced SW flux of 3.61 W/m\(^2\) (i.e., the area between the black and the red curves), in good agreement with the WACCM4 model output (3.4 W/m\(^2\), see Fig. 2c). Interestingly, the LibRadtran calculations reveal that the contribution from the UV range (250-350 nm) is relatively small (0.37 W/m\(^2\)), and that the bulk of the incident SW increase (3.01 W/m\(^2\)) is produced at visible wavelengths (500-650 nm), where a
peak in ozone absorptivity is located (see the dashed green line in Fig. 3), known as the Chappuis band (Anderson and Mauersberger, 1992). While the Chappuis band is three orders of magnitude weaker than the Hartley-Huggins UV bands near 250-300 nm, it is located in the spectral region of maximum solar emission (Goody and Yung, 1989): hence, it is of importance for the SW flux perturbation due to the ozone hole. From this, we conclude that the sizable OND increase in incident SW flux induced by the ozone hole seen in Fig. 2 is a realistic feature. In spite of a large SW perturbation, both WACCM ensembles show a similar warming trend in Antarctic mean surface temperature in spring (Fig. 1b), as well as in other seasons (not shown). The lack of an enhanced surface warming in the presence of the ozone hole implies the existence of a mechanism that opposes the increased downward SW flux. To determine this mechanism, we carefully examine the surface energy balance.

For both the HIST and fixODS ensembles, we calculate the spring (OND) changes between the pre (1960-1975) and post (1990-2005) ozone hole periods, for each of the terms in the surface energy budget. Over this period, changes in energy storage are negligible, due to the presence of dry snow with low heat conductivity, such that surface temperature adjusts rapidly to changes in the surface energy budget (van den Broeke et al., 2004). Contrasting the red (fixODS) and black (HIST) symbols in Fig. 4, one sees that the ozone-hole has no influence on turbulent energy exchange, or in downwelling and upwelling LW radiation. Unlike the LW, a clear separation between the two ensembles is apparent in the SW surface clear-sky downward flux, with an increase in this flux of about 3 W/m$^2$ in the HIST and a decrease of 1 W/m$^2$ in the fixODS ensembles, respectively. Note that this increase in clear-sky SW radiation in the HIST ensemble is of the same

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$^1$Note that the lack of a surface LW change with ozone depletion is in contrast to what occurs at the tropopause, where the net LW forcing from ozone depletion is negative (see e.g. Ramanathan and Dickinson (1979); Ramaswamy et al. (1992); Conley et al. (2012)): this suggests that the Antarctic polar troposphere is opaque to LW changes originating in the stratosphere.
magnitude as the simulated increase over the 1960-2005 period in downward surface LW radiation
associated with greenhouse-gases (GHGs) (3-5 W/m², see Fig. 4).

Note, furthermore, that the opposite-signed long-term changes in surface downwelling SW radi-
ation in the two ensembles are due to the opposing effects: the GHGs induced moistening (which
decreases the SW↓ flux) and the ozone hole itself (which increases the SW↓ flux). The clear-sky
difference in the downwelling SW flux between the two ensembles is partly reduced in all-sky
conditions, due to an increase in total cloud cover in the HIST ensemble (see Fig. 2b). Most
importantly, the increase in downward SW radiation in HIST, under both clear and all-sky con-
ditions, is approximately balanced by an increase in the upward SW flux (SW↑), leaving a very
small change in the net absorbed surface SW radiation (SWn).

To elucidate the origin of the increase in upward SW flux (and thus of the lack of surface temper-
are changes), we analyse the evolution of the surface albedo computed by the land component
of CESM-WACCM (CLM4) over Antarctica, which is shown in Fig. 5 for visible and UV bands.
The mean climatological albedo in WACCM is 0.97, and is broadly consistent with the albedo
of Antarctic snow as derived from modeling (Wiscombe and Warren, 1980) and observational
campaigns (Grenfell et al., 1994). Since the ozone-induced SW flux changes are produced al-
most entirely in the highly reflective visible range (Fig. 3), near all (97%) of the increase in the
broadband integrated upward SW (SW↑ in Fig. 4) is due to the increase in the downward SW
flux, which is simply reflected: this is the familiar ”albedo” effect of the Antarctic surface. Thus,
of the 3.4 W/m² increase in UV/visible downwelling radiation (Fig. 2c), the albedo effect alone
cancels 3.3 W/m². Interestingly, we also find a very small positive trend in the UV/visible (Fig. 5)
albedo in the HIST ensemble. This trend is a mere 0.1% (0.971 to 0.972) but is statistically signif-
icant (p<0.01). As shown in the supplementary section, this increase in albedo is associated with
positive trends in Antarctic snowfall.
Observational records of radiative fluxes would be highly valuable to validate the model results presented in this work. However, high-quality station data of SW and LW radiation over Antarctica only extend back to the early 1990s (Frederick and Hodge, 2011), and thus do not encompass the period of rapid springtime polar ozone loss in the 1970s and 1980s (e.g., see Fig. 1a). It is worth noting, though, that the continental broadband average albedo in WACCM (0.82) is close to the values obtained from remote sensing (Laine, 2008). In addition, direct measurements support the notion that Antarctic snow albedo is very high in the spectral bands where ozone has the largest effect (Grenfell et al., 1994; Flanner and Zender, 2006). Hence, ozone depletion has little potential for radiatively influencing the Antarctic surface energy budget.

4. Conclusions

We have investigated the impact of springtime stratospheric ozone depletion on the Antarctic surface temperature. The main results are as follows:

- The ozone hole leads to a considerable increase (3.8 W/m²) in downward surface SW radiation over the Antarctic continent (in OND). Offline calculations with a line-by-line radiative transfer model suggest that the ozone-induced increase in downwelling surface SW radiation in WACCM is realistic, and is due to reduced stratospheric absorption in the Hartley-Huggins (250-350 nm) and Chappuis (550-600 nm) ozone bands, with the latter playing a dominant role.

- Despite the large ozone hole induced increase in the downward SW flux, there is little change in the net SW absorption at the Antarctic surface. This is primarily due to the high albedo of Antarctic snow in the spectral bands where ozone has a large effect. The high albedo inhibits any direct radiative effect of the ozone hole at the Antarctic surface.
Changes in the surface downwelling LW radiation associated with ozone depletion could potentially have a much greater effect on Antarctic surface temperature, given the high absorptivity of Antarctic snow at these wavelengths (Tedesco, 2014). However, these LW changes are small compared to the ozone-induced SW perturbations (Fig. 4): this explains the minimal role for ozone depletion in forcing surface temperature trends on a continental scale (Fig. 1b). Finally, we note that even though our results are based on a single model, they are likely to be robust across models with realistic Antarctic albedo. On the other hand, the snowfall-induced albedo trends that are simulated in WACCM (Fig. 5a) may depend on the snow aging scheme, and are therefore likely to be model dependent. Further work is needed to elucidate this aspect.

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