Drivers of past and future Southern Ocean change: Stratospheric ozone versus greenhouse gas impacts

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[1] We study the separate impacts of changing atmospheric greenhouse gas (GHG) and stratospheric ozone concentrations on past (1960–2010) and future (2010–2100) Southern Ocean conditions. To this end we employ a coupled atmosphere-ocean model with interactive stratospheric chemistry. In our model we separately prescribe i) GHGs that monotonically increase to 2100 and ii) ozone depleting substances (ODSs) that rapidly increase to a maximum in 1995 and then slowly return to 1960 values around 2100, following moderate emission scenarios. Past GHG and ODS changes in our model drive, in about equal measure in the annual mean, poleward intensified surface winds which act to strengthen the sub polar meridional ocean circulation cell and Antarctic Circumpolar Current (ACC). Future GHG-induced oceanic changes continue nearly monotonically to 2100, while the ODS-induced ACC transport peaks, and then reverses, a couple of decades after the ODS maximum in 1995. The ODS impact on ACC transport exceeds the corresponding GHG impact up to the second quarter of the 21st century, a result that highlights the importance of often-neglected stratospheric ozone trends for the simulation of the ocean circulation. Citation: Sigmond, M., M. C. Reader, J. C. Fyfe, and N. P. Gillett (2011), Drivers of past and future Southern Ocean change: Stratospheric ozone versus greenhouse gas impacts, Geophys. Res. Lett., 38, L12601, doi:10.1029/2011GL047120.

1. Introduction

[2] The summertime atmospheric circulation in the Southern Hemisphere extratropics has undergone large changes over the past few decades [Thompson and Solomon, 2002], which are associated with a positive trend in the Southern Annular Mode (SAM) index. Previous studies have shown that the main drivers of SAM changes are increasing greenhouse gases (GHGs) and stratospheric ozone trends, with the latter being responsible for most of the observed summertime trends in the recent past [e.g., Son et al., 2008; Polvani et al., 2011]. For the future, model simulations predict small or even reversed summertime trends, as the effect of the anticipated recovery of the ozone hole will be to counteract that of increasing GHGs [Perlwitz et al., 2008; Son et al., 2008].

[3] A positive SAM trend implies a poleward shift of the surface wind stress and its curl, which will affect the ocean circulation. Previous studies have quantified the effects of GHG induced wind changes on the meridional overturning circulation [Saenko et al., 2005] (which is closely linked to the global carbon cycle [Le Quéré et al., 2007]), the meridional distribution of ocean warming [Fyfe et al., 2007] and the Antarctic Circumpolar Current [Fyfe and Saenko, 2005]. However, most of these modeling studies only consider the effects of increasing GHGs, while often neglecting stratospheric ozone trends [World Meteorological Organization (WMO), 2010, chap. 4].

[4] In this study, we employ a coupled atmosphere-ocean model with interactive stratospheric chemistry to study the effects of GHG and stratospheric ozone trends on the Southern Ocean. Using a suite of experiments covering the 1960–2100 period we will, for the first time, report on the separate GHG and ozone impacts on the ocean. The use of interactive stratospheric chemistry is itself novel as previous studies on the ocean response have imposed zonal-mean ozone trends, which Waugh et al. [2009] suggest leads to an underestimation of surface wind stress trends. Finally, we note that our results are for a global climate model that (like almost all other current global coupled climate models) does not explicitly resolve mesoscale ocean eddies. This most likely leads to an overestimation of the ocean sensitivity to surface wind stress change, as previous studies indicate that the current parameterization of such mesoscale eddies does not fully capture their compensating effect to the Ekman transport response to a wind shift, and the eddy saturation of the ACC [e.g., Böning et al., 2008; Hallberg and Gnanadesikan, 2006].

2. Model and Simulations

[5] The model and simulations employed in this study are identical to those presented by McLandress et al. [2011] (who describe the tropospheric circulation response), to which we refer the reader for details. CMAM [Scinocca et al., 2008] is the vertical extension of the Canadian Centre for Climate Modelling and Analysis third generation coupled general circulation model (CGCM3). The atmospheric component has 71 vertical levels stretching from the surface to ~100 km and is run at T31 (about 5.6° × 5.6°) horizontal resolution. It includes a standard set of chemical species and reactions relevant for stratospheric chemistry, including chlorine, bromine and heterogeneous chemistry on polar stratospheric clouds. The ocean component is based on a modified version of the National Center for Atmospheric Research Community ocean model (NCOM 1.3) [Arora et al., 2009]. It has a horizontal resolution of 1.86° with 29 vertical levels whose thickness vary from >300m in the deep ocean to 50m near the
surface. Isopycnal mixing of tracers is represented by Gent and McWilliams’ [1990] parameterization.

Three sets of transient simulations are examined, each with three ensemble members simulating the 1960–2100 period. The first set of experiments (commonly referred to as the “REF-B2 simulation”) is forced with time evolving concentrations of both GHGs (following the moderate A1B scenario) and Ozone Depleting Substances (ODSs) (following WMO’s [2010] A1 scenario), in accordance with specifications of Phase 2 of the Chemistry Climate Model Validation (CCMVal-2) project [SPARC CCMVal, 2010]. These REF-B2 simulations have been analyzed extensively within the CCMVal-2 project. It was found that CMAM is one of the better performing models and that the simulated Antarctic ozone hole agrees reasonably well with observations [SPARC CCMVal, 2010, chap. 6]. CMAM was the only model of the 18 Chemistry Climate Models participating in CCMVal-2 that included an interactive ocean. The interactive ocean allows for atmosphere-ocean feedbacks producing self-consistent SSTs leading to more credible atmospheric predictions than in the uncoupled models (although Sigmond et al. [2010] found that such feedbacks do not significantly affect the extratropical circulation response). It also allows, for the first time, the impact of time-varying GHGs and ODSs on the ocean to be examined in a fully coupled chemistry climate model.

The second and third set of experiments enable the separation of the effects of time-varying GHGs and ODSs, and are referred to as the GHG and ODS simulations. The GHG simulation is forced with time varying GHGs (including the time-varying radiative effects of ODSs), while the ODSs (as seen by the chemistry code) are kept constant at 1960 levels. Conversely, the ODS simulation is forced with time varying ODSs (in the chemistry code), while keeping the GHGs (and the radiative effects of ODSs) constant at 1960 levels. For all sets of simulations we present the average of the three ensemble members. To account for model drift in the ocean, which is a common feature for transient simulations with coupled atmosphere-ocean models [e.g., Sen Gupta et al., 2009], the response to the ODS forcing is defined as the difference between the REF-B2 and GHG simulations, while the response to the GHG forcing is defined as the difference between the REF-B2 and the ODS simulations. We note that as we use 1960 as a reference, the response to GHG forcing is due to GHG increases since 1960 only, and not due to GHG increases since the preindustrial era. Finally, we note that sulphate aerosol forcing is included in all experiments but by differencing its impacts are effectively canceled (assuming that the responses to ODS and GHG forcings add linearly).

Figure 1. Forcing agents and atmospheric response: (a) the global and annual mean CO₂ concentration relative to 1960 in the REF-B2 and GHG simulations, and the polar cap (60°–90°S) averaged 50 hPa SH spring (Sept-Nov) total inorganic chlorine Clᵢ difference between the REF-B2 and GHG simulations. The 11-year running mean SAM response to the (b) GHG and (c) ODS forcings as function of calender year and month (hPa). Black dots indicate a statistically significant response at the 95% confidence level (details in text). (d) The annual mean SAM responses.

3. Results

Figure 1a shows the time evolution of the main GHG and ODS forcing agents. The global and annual mean CO₂

Figure 2. Ocean response: the 11-year running mean annual mean response to the GHG and ODS forcings of the zonal mean (a) meridional Ekman transport at 50°S, (b) vertical Ekman transport difference between 40°S and 60°S, (c) 25m ocean temperature difference between 40°S and 60°S, and (d) the zonal transport through the Drake passage.
concentration relative to 1960 as prescribed in the REF-B2 and GHG simulations increases monotonically with time. The ODS forcing is expressed as the anomaly in the REF-B2 simulation (with time varying ODS emissions) relative to the GHG simulation (with constant 1960 ODS emissions) of total inorganic chlorine (Cl\textsubscript{y}), for SH spring averaged over 60°–90°S at 50 hPa. We consider the lower stratospheric Cl\textsubscript{y} rather than the surface ODS emissions, as this is more closely related to the stratospheric ozone response. The ODS forcing exhibits a rapid increase from 1960 to ∼1995, followed by a slower decrease after 1995.

[9] We first examine the atmospheric circulation response as quantified by the SAM. Figures 1b and 1c show, as a function of calendar month and year, the 11-year running mean time series of the SAM response (defined here as the zonal mean sea-level-pressure difference between 65°S and 40°S) to the GHG and ODS forcings. Black dots indicate a statistically significant response at the 95% confidence level according to a standard two-sample Student’s t-test, applied to three ensemble members and the 11 years included in the running mean, and assuming independent residuals (for most calendar months the autocorrelation of the residuals is less than 0.1). Consistent with previous studies we find a positive SAM response to the GHG forcing, which has a weak seasonal cycle and maximizes in April–June.

[10] The SAM response to the ODS forcing, on the other hand, has a strong seasonal cycle and is mainly restricted to austral summer. In concert with the ODS forcing, the summertime response peaks in the 1990s, and is statistically significant between 1980 and 2020. During that period, it largely exceeds the response to GHGs, confirming the conclusions of previous studies that the observed summertime SAM change since the 1960s is mainly due to ozone depletion. Although the SAM response to the ODSs is restricted to one season, its annual mean response (Figure 1d) is comparable to that due to GHGs until the early 2020s. As the ODS forcing does not change sign, the large negative SAM event in the 2050s in the ODS response is probably due to large natural interdecadal variability, and may be an artifact of the limited sample size.

[11] We next present time series of the 11-year running annual mean responses of various aspects of the Southern Ocean. Figures 2a and 2b show the time series of the responses of meridional and vertical components of the wind-driven ocean circulation, which show a close correspondence to the time series of the annual mean SAM response in Figure 1d. This can be explained as follows. A positive SAM anomaly is associated with a poleward intensified zonal wind stress \( \tau \) around 50°S, which results in a positive (northward) meridional Ekman transport \( V_e = -\frac{\tau}{\rho_0 f} \), where \( \rho_0 \) is the reference density for sea water and \( f \) is the Coriolis parameter. This explains the high correlation between time series of the SAM responses and that of \( V_e \) at 50°S plotted in Figure 2a. Corresponding changes in the wind stress curl are associated with anomalous (positive) upward Ekman pumping centered around 60°S and (negative) downward Ekman pumping around 40°S. This results in a high (negative) correlation between the SAM and the zonal mean vertical Ekman transport difference between 40°S and 60°S (\( \Delta W_{v,40-60} \)) plotted in Figure 2b (note the inverse vertical scale).

[12] Both the meridional and vertical Ekman transport are expected to affect the thermal structure of the ocean: upward Ekman pumping centered around 60°S brings cold water to the surface, northward Ekman transport leads to local ocean cooling, and downward Ekman pumping around 40°S leads to ocean warming. The net effect is an increased meridional temperature difference between 40°S and 60°S in the uppermost
ocean layer ($\Delta T_{40-60^\circ S,25m}$), as evidenced by the positive correlation between its time series (plotted in Figure 2c) and the SAM time series ($r = 0.88$).

An increased meridional temperature gradient acts to increase the meridional slope of lines of constant density, thus intensifying the baroclinic part of the ACC. Indeed, the time series of the ACC responses (expressed as the ocean transport through the Drake passage and plotted in Figure 2d) roughly follow those of $\Delta T_{40-60^\circ S,25m}$ (and thus of the SAM). A striking difference, however, is the much smaller variability in the ACC response. Also, the ACC response to the ODS forcing peaks around 2015 lagging the ODS SAM response by 20 years (as confirmed by lag correlation analysis), which reflects an apparent inertia of the ACC to changes in the atmospheric circulation. A key result of this paper is that the ODS-induced ACC response exceeds that due to increasing GHGs up to ~2035, and that it persists up to ~2050.

The spatial pattern of the Southern Ocean response is further explored in Figure 3, which shows latitude-depth cross sections of the overturning streamfunction and zonal mean temperature response averaged over two periods, representing the present (1990–2010) and the future (2079–2099). For the present, when the annual mean SAM responses to GHGs and ODSs are of comparable magnitude, the overturning circulation response is of comparable magnitude as well. In response to ODSs (Figure 3c), this circulation cell is associated with ocean cooling around 60°S and warming around 40°S. In response to the GHG forcing (Figure 3a), the direct radiative effects cause an overall warming of the Southern Ocean, which rapidly decreases with depth. The meridional circulation shapes the latitudinal structure of this warming, which shows a minimum around 55°S and maximum around 35°S. For the present, the GHG induced temperature response is larger than that due to ODSs, although the ODS induced cooling around 60°S is of comparable magnitude to the GHG induced warming at that latitude. Consistent with the SAM response, the amplitude of the GHG induced circulation and temperature response in the future (Figure 3b) is about three times larger than for the present (note that the shading interval in Figure 3b is three times larger than in the other panels). The structure of the future circulation and temperature response is very similar to that of the present, except that the warming penetrates deeper into the ocean. Also consistent with the SAM response, the future ocean circulation and temperature responses to ODSs (Figure 3d) are very small.

4. Summary

While stratospheric ozone trends are acknowledged to have played and are anticipated to play a significant role in past and future atmospheric circulation trends, their effects are often not included in studies of the ocean. Employing a coupled atmosphere-ocean model with interactive stratospheric chemistry, we have assessed the importance of these often-neglected ozone forcings for the ocean circulation, by comparing their effects to those induced by increasing GHGs. We find that the impacts of decreasing ozone on the ocean circulation are very similar to those due to increasing GHGs. Like the GHG trends, the decreasing ozone is associated with a poleward shift of the surface wind stress, inducing an anomalous meridional overturning ocean cell. This provides a mechanism connecting the stratosphere and the deep ocean, and will have global impacts through its effects on the global carbon cycle, as shown by Lenton et al. [2009]. The anomalous meridional overturning cell is also associated with changes in the meridional temperature structure of the ocean and the Antarctic Circumpolar Current (ACC). In our model, the ODS induced ACC response lags the forcing by about 20 years, and exceeds that due to increasing GHGs until the second quarter of the 21st century. Although the exact amplitude of the impacts are likely model dependent, especially in regard to the response of unresolved ocean eddies, our study shows that the ODS forcings are crucial for understanding the past and future ocean circulation, and should be included in future ocean modeling studies.

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