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Key Points:
- A chemistry-climate model quantifies the impacts of ozone hole on Southern Ocean
- Majority of changes in ocean MOC from 1955 to 2005 are caused by ozone depletion
- One third of the changes in temperature and salinity are due to ozone depletion

Supporting Information:
- Supporting Information S1

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The impact of ozone depleting substances on the circulation, temperature, and salinity of the Southern Ocean: An attribution study with CESM1(WACCM)

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Abstract Observations show robust changes in the circulation, temperature, and salinity of the Southern Ocean in recent decades. To what extent these changes are related to the formation of the ozone hole in the late twentieth century is an open question. Using a comprehensive chemistry-climate Earth system model, we contrast model runs with varying and with fixed surface concentrations of ozone depleting substances (ODS) from 1955 to 2005. In our model, ODS cause the majority of the summertime changes in surface wind stress which, in turn, induce a clear poleward shift of the ocean's meridional overturning circulation. In addition, more than 30% of the model changes in the temperature and salinity of the Southern Ocean are caused by ODS. These findings offer unambiguous evidence that increased concentrations of ODS in the late twentieth century are likely to have been been an important driver of changes in the Southern Ocean.

1. Introduction

Anthropogenic emissions of ozone depleting substances (ODS), in the late twentieth century, are an important driver of climate change whose full suite of impacts is only now starting to be appreciated. The immediate consequence of increased atmospheric concentrations of ODS is the formation of an ozone hole over Antarctica, during austral spring each year [*Solomon et al.*, 1986]. The photochemical destruction of ozone causes a strong cooling of the polar lower stratosphere, which induces a poleward shift of the westerly winds reaching all the way to the surface [*Thompson and Solomon*, 2002; *Lee and Feldstein*, 2013]. This wind shift has been widely discussed in terms of the Southern Annular Mode, whose observed summertime trends in recent decades have been linked to a host of surface changes in the Southern Hemisphere (see *Previdi and Polvani*, [2014] for a recent review). Whether the formation of the ozone hole is felt below the sea surface, and how deep it penetrates into the Southern Ocean, remains an open question.

This question is motivated by recent observations, which show that the Southern Ocean has warmed and freshened in the second half of the twentieth century [*Böning et al.*, 2008; *Gille*, 2008]. Also, observations of sea surface height suggest that the Antarctic Circumpolar Current has shifted southward by 60 km, indicating a change in the latitudinal structure of the meridional overturning circulation (MOC) in the Southern Ocean [*Sokolov and Rintoul*, 2009]. These findings are supported by observations of changes in the mean age of water in the Southern Ocean, associated with changes in the ventilation and subduction of water masses [*Waugh*, 2014]. Can any of these observed changes be attributed to the formation of the ozone hole?

A few recent studies have sought to answer that question. *Sigmond and Fyfe* [2010] and *Bitz and Polvani* [2012] have analyzed pairs of "time-slice" model runs (i.e., multidecadal runs in which forcings do not vary from year to year): constrasting runs with high and low concentrations of polar stratospheric ozone, they have shown that ozone depletion causes a very robust warming of the Southern Ocean, down to 1000 m below the surface. However, analyzing a set of "transient" model runs in which ODS were the only time-varying forcing between 1960 and 2010, *Sigmond et al.* [2011] reported that ODS cause a slight cooling of the Southern Ocean in their model. And more recently, using highly idealized ozone forcing, i.e., forming an ozone hole instantaneously in a model, *Ferreira et al.* [2015] have suggested that two distinct mechanisms may be at play: a fast one that cools the ocean and a slower one that warms the ocean. The goal of our paper is therefore to bring clarity to this somewhat confused situation.

We do so by using the most comprehensive model configuration presently available to us: a stratosphere-resolving atmospheric model, with interactive ozone chemistry, coupled to fully prognostic land, ocean, and sea ice components. Over the period 1955–2005, we analyze the most realistic simulations of recent climate change available, the so-called "historical" runs performed for the Coupled Model Intercomparison Project, Phase 5 (CMIP5). Contrasting historical runs with and without trends in ODS (i.e., with and without the formation of an ozone hole), we find that ozone depletion causes the majority of the poleward MOC shift, and nearly a third of the ocean warming in our model. We also find that ozone depletion has a robust impact on the salinity of the Southern Ocean and causes more than 30% of the freshening in the model, south of 40°S, between 1955 and 2005.

2. Methods

We here employ a state-of-the-art chemistry-climate model, the Community Earth System Model (CESM1) with the Whole Atmosphere Chemistry Climate Model (WACCM) configuration. In addition to interactive chemistry for stratospheric ozone, CESM1(WACCM) includes the fully coupled Parallel Ocean Program (POP) ocean component [*Danabasoglu et al.*, 2012]. As shown in *Bitz and Polvani* [2012] and *Bryan et al.* [2014], with an eddy parameterization, the coarse-resolution (nominally 1°) POP version used here is able to capture the response to anthropogenic forcings of the corresponding eddy-resolving model version (nominally 0.1°).

Chemistry-climate models coupled to interactive ocean (and sea ice) components are a relatively recent tool, owing to the prohibitive computational cost of the interactive chemistry. To date, only two studies [*Sigmond et al.*, 2011; *Smith et al.*, 2012] have used such models to understand ODS-induced changes in the Southern Ocean. Hence, in terms of modeling tools, the present study is very much at the frontier of model complexity.

Two ensembles of 50-year runs with CESM1(WACCM), each comprising six members, are analyzed here. The first ensemble consists of standard "historical" CMIP5 integrations from 1955 to 2005, with all forcing prescribed, including the trends of anthropogenic greenhouse gases and ozone depleting substances. These runs were carefully analyzed in *Marsh et al.* [2013], where full details about the model configuration and the forcings can be found. We will refer to this ensemble as the HISTORICAL runs.

The second ensemble is identical to the first in all aspects but one: the surface concentration of ODS is time independent and held fixed at the year 1955. We will refer to this ensemble as the FIXED OZONE runs, although ozone itself is computed interactively in our model, and it is ODS that are the specified external forcing. In this second ensemble stratospheric ozone has no trends, since the concentrations of ODS are fixed.

Finally, in all figures below the reader will find a third set of curves or plots: these are labeled OZONE HOLE, although they do not correspond to a third ensemble. They are obtained by taking the difference between HISTORICAL and FIXED OZONE ensembles. Subject to the same caveats as above (ODS versus ozone concentrations), the choice of label follows from the fact the attribution is completely unambiguous: only ODS are changed between the two ensembles, and they act primarily by creating an ozone hole.

3. Results

Since the atmosphere affects the ocean through surface fluxes of momentum, heat, and fresh water, we start by considering what changes in these fluxes the ocean experiences in our model. Each panel in Figure 1 shows three curves: the HISTORICAL changes (black) are decomposed into the component due to the formation of the ozone hole (red) and that due to all other forcings (blue). All changes are computed as the difference between the first and last decade of each run. Figures 1a, 1c, and 1e are for the summer season (December–February, DJF) and Figures 1b, 1d, and 1f for the winter season (June–August, JJA). For simplicity and clarity, we define statistical significance to exist when five of six members agree on the sign of the difference between the last and first decade in each ensemble.

Consider first the changes in zonal wind stress: clearly the two seasons have very distinct signatures. In DJF (Figure 1a), we find a significant dipole, which is entirely caused by the formation of the ozone hole. Increased wind stress near 60°S and decreased wind stress to the north of the climatological jet, which resides at 51°S in this model, reflect the poleward shift of the near surface westerly winds; this is a well documented consequence of stratospheric ozone depletion [see, e.g., *Previdi and Polvani*, 2014]. In JJA (Figure 1b), however, the other forcing terms—likely the increasing levels of carbon dioxide—cause significant increases in surface wind stress, an effect which seems to be partially offset by the formation of the ozone hole.

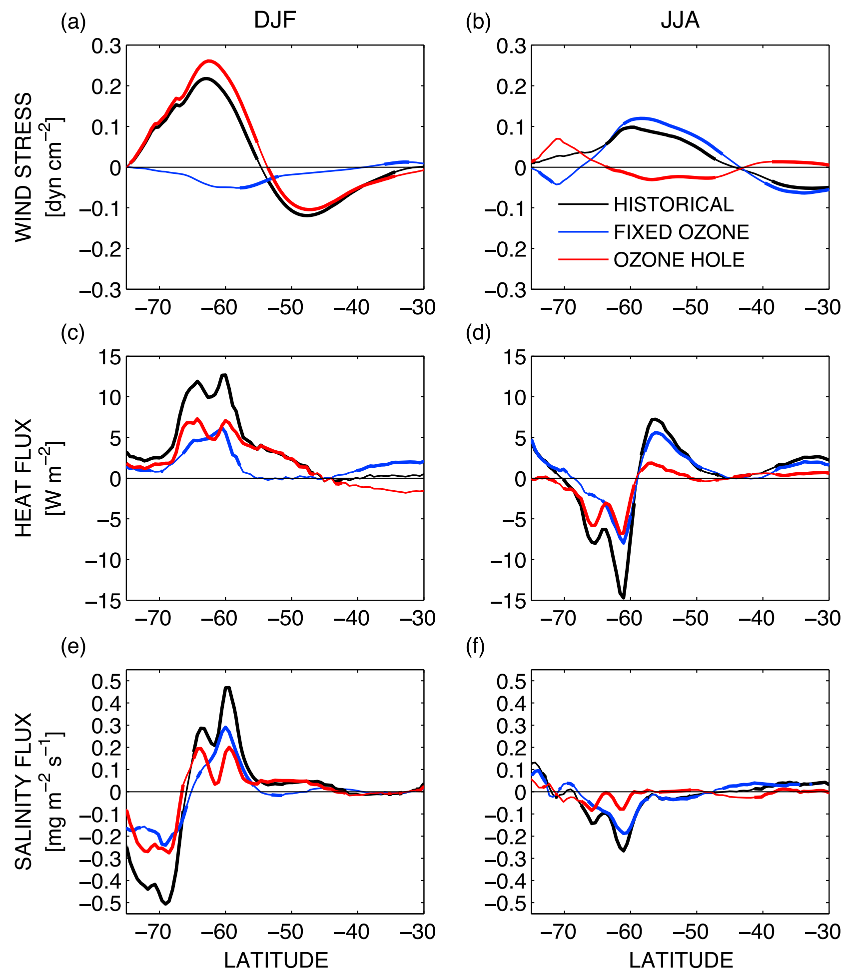

Figure 1. Seasonal, zonally averaged changes in sea surface fluxes. (a, b) zonal wind stress in dyn cm^{-2}. (c, d) Surface heat flux in W m^{-2}; positive values indicate increased heat flux into the ocean. (e, f) Surface salinity flux in mg m^{-2} s^{-1}; positive values indicate increased salinity flux into the ocean. (Figures 1a, 1c, and 1e) Summer and (Figures 1b, 1d, and 1f) winter. Black: HISTORICAL change, blue: FIXED OZONE changes, and red: black minus blue. Curves show the ensemble mean, bolded where five of six members agree on the sign of the difference between the last and first decade of each run.

Consider next the changes in surface heat flux, shown in Figures 1c and 1d. We show here the total heat flux, including both radiative and turbulent fluxes, calculated such that a positive value indicates increased flux into the ocean. The changes appear to be evenly divided between the ODS and the other forcing terms. In DJF (Figure 1c), ODS induce changes that are larger than those due to other forcings at nearly all latitudes south of 45°S. In JJA, the increased heat flux into the ocean north of 60°S is primarily due to other forcing terms. Yet, south of 60°S the reduced heat flux is largely due to the ozone hole, despite its very limited influence on the atmospheric circulation during the winter months [see, e.g., *Polvani et al.*, 2011].

Thirdly, consider the surface salinity flux changes. We show here the total salinity flux, such that a positive flux increases the salinity of the surface ocean (see supporting information for additional details). In DJF the change has a dipole pattern (Figure 1e), with increased salinity flux between 65°S and 50°S and reduced flux to the south. These changes are divided quite evenly between the ozone hole and other forcing terms. Again, this decomposition may seem surprising since the stratospheric ozone hole has no direct influence on the salinity flux; however, the poleward shift of the atmospheric circulation influences precipitation, evaporation, melting and export of sea ice. In JJA, the changes in salinity flux are generally smaller, and not associated with ODS.

As one might expect, changes in wind stress have a direct effect on the meridional overturning circulation (MOC) of the Southern Ocean. We show here the sum of the Eulerian stream function and the eddy-driven

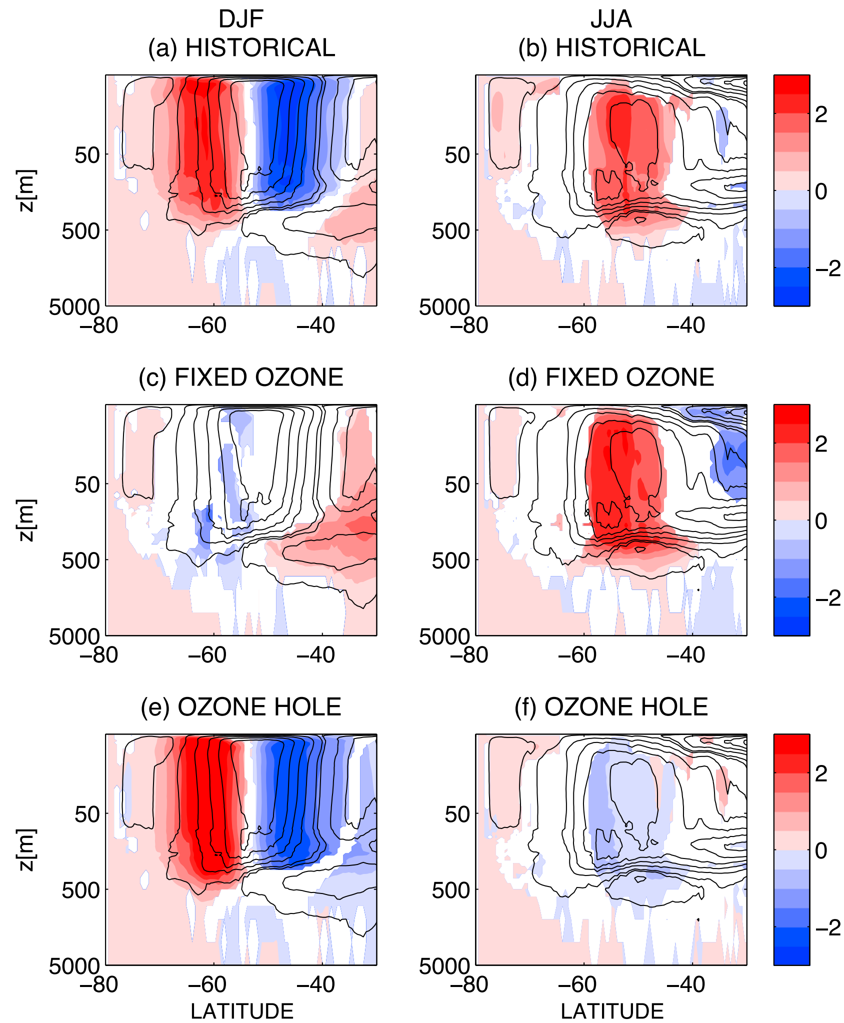

Figure 2. Ensemble mean changes in the meridional overturning circulation (MOC), with c.i. of 0.5 Sv; red is clockwise, blue is counterclockwise. Changes are computed as the difference between the first and last decade of each run. Black contours: climatological MOC (c.i. 5 Sv). (a, c, and e) Summer and (b, d, and f) winter. (Figures 2a and 2b) The HISTORICAL runs. (Figures 2c and 2d) The FIXED OZONE runs. (Figures 2e and 2f) Figures 2a and 2b minus Figures 2c and 2d. Ensemble mean changes are colored only when five of six ensemble members agree on the sign of the change (white indicates nonsignificant changes).

streamfunction, as in *Danabasoglu et al.* [2012, Figure 10a]. In each season, the climatological MOC is dominated by a clockwise cell (positive), indicated by the black contours in Figure 2: this cell, whose strength exceeds 20 Sv in our model, is centered at 51°S and upwells water near 60°S and downwells at 40°S. In the HISTORICAL runs, one can see significant changes to the MOC in both DJF and JJA (colors in Figures 2a and 2b). These changes exhibit a very distinct seasonal character, similar to the changes in wind stress (Figures 1a and 1b). In DJF, we find a dipole pattern reflecting a poleward shift of the MOC, and it is almost entirely due to ODS (Figure 2e). In JJA, however, the change is an intensification of the overturning cell due to other forcing terms, which is slightly offset by the presence of an ozone hole (Figures 2d and 2f). These changes in the MOC are in agreement with the findings of *Sigmond and Fyfe* [2010], *Sigmond et al.* [2011] and *Bitz and Polvani* [2012], who used different models and also different methodologies. Hence, this result appears to be robust, at least in the context of present generation atmosphere-ocean models.

In contrast to the MOC, the temperature changes in our model show little seasonal variation, due to the thermal inertia of the ocean, which integrates the effects of surface flux anomalies throughout the year. In the annual mean, the HISTORICAL runs (with all forcings specified) reveal a broad pattern of warming, mostly confined above 100m depth (Figure 3a). Unsurprisingly, much of this warming is caused by forcing terms other

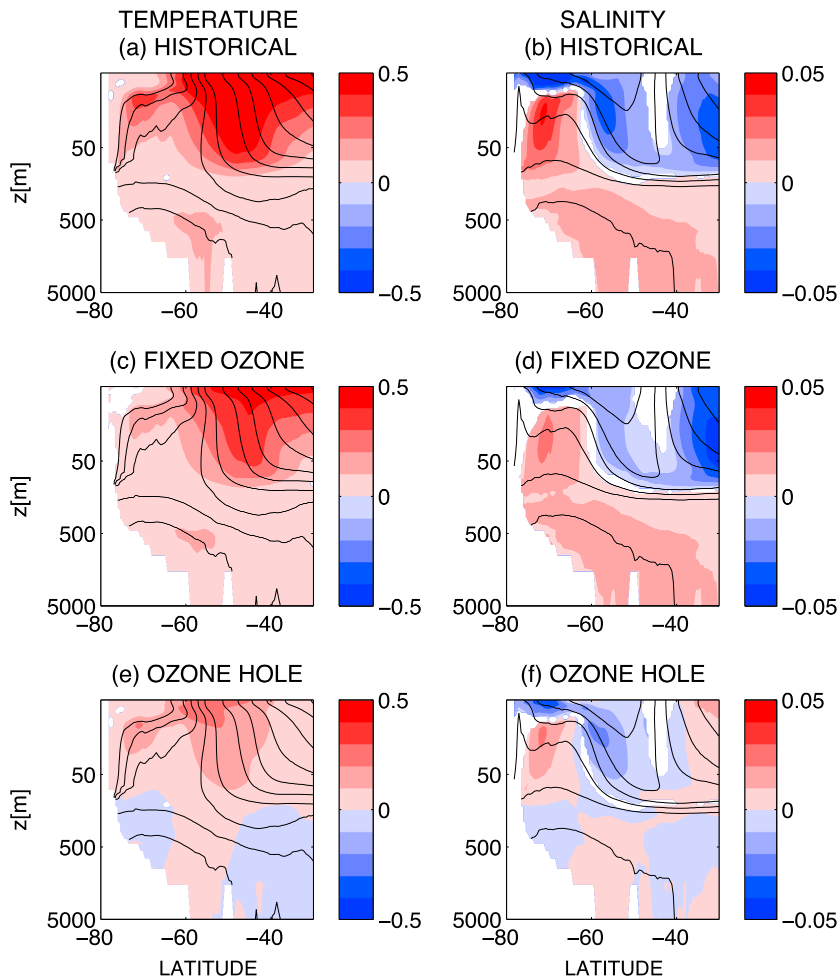

Figure 3. As in Figure 2, but for annual mean, zonal mean ocean temperature (left) and salinity (right). Contour interval is 0.1°C for temperature changes, and 3°C for the climatology. Contour interval is 0.01 g kg^{-1} for the salinity changes, 0.25 g kg^{-1} for the climatology.

than ODS: it is likely dominated by increasing greenhouse gases (Figure 3c), as aerosols play only a secondary role over the Southern Ocean.

More interesting, we suggest, is the result seen in the bottom left panel: a small but significant fraction of the warming South of 40°S can actually be attributed to increasing ODS (Figure 3e). Warming of the Southern Ocean accompanying the formation of the ozone hole has been reported in the time-slice experiments of *Sigmond and Fyfe* [2010] and *Bitz and Polvani* [2012]. Recall that the latter study employed two different ocean models, an eddy permitting one (with a nominal 0.1°resolution) and a standard one (with a nominal 1°resolution), and found ocean warming with ozone depletion at both resolutions—with good quantitative agreement. This result was further confirmed, indirectly, by the modeling study of *Smith et al.* [2012], who showed cooling of the ocean caused by the closing of the ozone hole, which is expected to occur in the coming half century as ODS dramatically decrease as a consequence of the Montreal Protocol.

Lastly, we consider the impacts of ODS on annual mean salinity in the Southern Ocean. Over the period 1955-2005, the HISTORICAL runs reveal a broad pattern of freshening above the halocline at all latitudes (Figure 3b). However, below the layer of surface freshening and, in particular, south of 60°S the model indicates a robust increase in salinity (exceeding .05 g kg^{-1}), the deep ocean becoming slightly saltier. A similar pattern of salinity changes is seen in the FIXED OZONE runs (Figure 3d). However, note that south of 50°S, the change in salinity again shows a sizable contribution coming from increased ODS (Figure 3f).

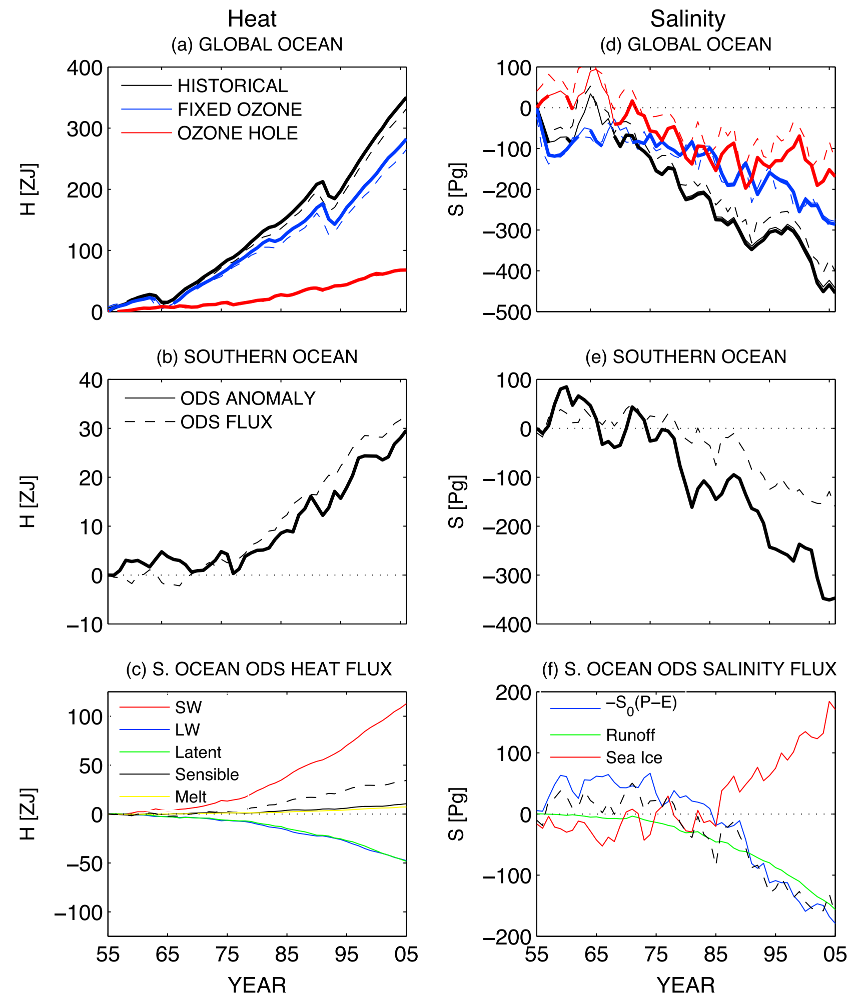

Figure 4. Top row: time series of annual mean ocean heat (left) and salinity (right) volume integrated anomalies (solid), with their respective integrated surface fluxes (dashed); HISTORICAL ensemble (black), FIXED OZONE ensemble (blue), and their difference showing the effects of ODS (red); curves show the ensemble mean, bolded where 5 of 6 members agree on the sign of the change. Middle row: as in the top row, but for effects of ODS on the Southern Ocean, defined to be the region south of 40°S. Bottom row: the total surface flux due to ODS into the Southern Ocean (dashed black curve, reproduced from the middle panels), and the individual components, as indicated in the legends; heat on the left, and salinity on the right.

We now place these results in the context of the global budgets of ocean heat and salinity. We start by defining the ocean heat anomaly $H(t)$, over a volume V, as

$$H(t) \equiv \rho c_p \int_V [T(t) - T(t_0)]dV = \int_{t_0}^{t} \int_A f_s dAdt + F_{\partial V} \quad (1)$$

where T is the ocean temperature, t is time, and ρ and c_p are the density and heat capacity of seawater (both taken to be constant here). The heat anomaly is defined with respect to a reference time t_0, which we here take to be the year 1955 (the starting point of our model integrations). This equation simply states that H is the sum of the surface heat flux f_s (integrated over the area A bounding V at the ocean surface) and the lateral transport $F_{\partial V}$ across the side boundaries. Obviously, $F_{\partial V} = 0$ if V is taken to be the global ocean.

Figure 4a shows $H(t)$ for the global ocean, for both the HISTORICAL (solid black) and the FIXED OZONE (solid blue) integrations. In the HISTORICAL integrations, the global ocean has accumulated $350 \pm 9 \times 10^{21}$ J of anomalous heat between 1955 and 2005. The difference between the two integrations, plotted in red, reveals that the effects of ODS account for 19% of that increased heat uptake.

Now focus on this difference in H over the Southern Ocean (defined as the ocean volume south of 40°S), shown in Figure 4b. The surface heat flux (dashed) is quite close to the volume integrated anomaly H (solid), indicating that ODS have little net effect on the transport of heat across 40°S. Rather, the ODS induced warming of the Southern Ocean comes from increased shortwave heating (see Figure 4c). This enhanced shortwave heating results from a decrease in midlatitude cloud cover associated with the poleward shift of the westerlies, as discussed in *Grise et al.* [2013].

A similar analysis is carried out for salinity: over any volume V an ocean salinity anomaly S is defined analogously to H (see the supporting information for details). As seen in Figure 4d, the global salinity budget reveals that the ocean has freshened significantly in our model, due to an increase in the global surface fresh water flux. Furthermore, the effects of ODS (red) account for 37% of the global change in ocean salinity.

The Southern Ocean shows a large change in the surface fluxes of salinity due to ODS Figure 4e (dashed). However, we can also see that more than half of the Southern Ocean freshening caused by ODS is due to a change in transport, as seen in the difference between the solid and dashed curves. Since the ozone hole has affected both the salinity flux and the ocean circulation, understanding this altered ocean salinity transport requires additional analysis which, however, is beyond the scope of this brief letter.

For completeness, however, we plot the individual components of the ODS induced salinity fluxes into the Southern Ocean in Figure 4f: the net freshening (black dashed curve) is due to increased precipitation and runoff (blue and green). It may be surprising that the net effect of sea ice loss is an increase in salinity (red curve). To understand this, note the anti-correlation between sea ice salinity flux and the net effect of precipitation (P) minus evaporation (E), given by $-S_0$(P-E) (red an blue curves). This is in part due to the fact that sea ice loss exposes previously covered ocean to precipitation.

We conclude by quantifying the effects of increasing ODS on the Southern Ocean. In other words, we seek to answer the simple question: what fraction of changes from 1955 to 2005 are caused by ODS? Aiming to construct the answer in the form of a single number, from 0 to 100%, we proceed as follows. Let X be any of the three variables we have been considering: the MOC, the temperature T, or the salinity S. Then let δX_{HIST} denote the ensemble mean, zonal mean, seasonal changes, from 1955 to 2005, in the HISTORICAL runs. We then compute the spatial RMS integral of δX_{HIST}, which we denote as ΔX_{HIST}, defined as follows:

$$\Delta X_{HIST} = \left[\int_A (\delta X_{HIST})^2 dA \right]^{(1/2)}, \tag{2}$$

where A is the region from 40°S to the Antarctic continent, and from the surface to 1000m. Applying the same procedure to the second ensemble of model runs, those with fixed ODS, we similarly compute ΔX_{FIXODS}.

The fractional effect of the ozone hole on the 1955-2005 changes is then easily quantified by the simple expression

$$1 - \frac{\Delta X_{FIXODS}}{\Delta X_{HIST}}. \tag{3}$$

For the three variables we have been considering, Table S1 in the supporting information summarizes all the percentage impact of ODS. In our model, more than 80% of MOC changes in DJF are due to the ozone hole, as a consequence of the poleward shift of the seasonal westerly winds and the associated effect on the sea surface wind stress. During JJA, the ozone hole appears to slightly offset the increase in wind stress caused by the other forcing terms, resulting in a 9% smaller change of the MOC in the HISTORICAL integrations than the FIXED OZONE integrations.

As we have already mentioned, the changes in temperature and salinity show little seasonal variation, despite the highly seasonal nature of the forcing. The ozone hole, in our model, contributes over 30% of the HISTORICAL temperature and salinity changes, in the Southern Ocean, during the second half of the twentieth century.

4. Summary and Discussion

Using CESM1(WACCM), a stratosphere-resolving atmospheric model, with interactive ozone chemistry, coupled to fully prognostic land, ocean, and sea-ice components, we have shown that increasing concentrations of ODS in the second half of the twentieth century affect the Southern Ocean in a number of important ways. We find that the formation of the ozone hole results in a considerable warming of the Southern Ocean, down to depths of about 1 km. We have, for the first time, quantified this ODS effect, and find it amounts to about 30% of the total warming from 1955 to 2005 in our model.

The ozone-induced changes confirm three earlier studies, which have used different models and experimental set-ups *Sigmond and Fyfe* [2010]; *Bitz and Polvani* [2012]; *Smith et al.* [2012]: in all cases, increasing ODS and ozone depletion cause warming of the Southern Ocean. Only the study of *Sigmond et al.* [2011], using an ensemble of 3 transient runs, appears to be at odds with this: they have reported a slight ocean cooling in their model with increasing ODS. The reason for this discrepancy is unclear, but we suggest that a 3-member ensemble might be too small; as one can see in Figure 3c of *Sigmond et al.* [2011], their ODS cooling is relatively small and, more importantly, the statistical significance of that result is not reported.

We also wish to put our findings in the context of the recent paper of *Ferreira et al.* [2015]. Using an earlier version of the CESM model (CCSM3.5), a low-top atmospheric model without coupled chemistry, they have examined an ensemble of "abrupt ozone-hole" runs (i.e. the ozone hole is prescribed to appear instantaneously in their model). They report that sea-surface temperatures cool at first in their model, for a few years, but thereafter the ocean warms, as we find here. They deduce that two different mechanisms are at play − a fast one which cools the ocean at first, and a slow one which warms it on longer time scales − and suggest that the fast cooling mechanism might be responsible for the observed trends of expanding of sea ice around Antarctica in recent years.

In our model runs, we note a small cooling of the ocean surface with ozone depletion (see the weak blue shading, from 1975 to 1995, near 60°S in Figure S1e of the supporting information). However, several points should be noted. First, this cooling is highly seasonal (see Figure S1f), and does not operate in the month of maximum sea ice, nor does it survive annual averaging. Second, this cooling is sufficiently weak that it never actually manages to cause any increase in annual mean Antarctic sea ice extent in our model (see Figure S2). Third, any cooling that might be associated with the fast mechanism is totally overwhelmed by the warming associated with increased greenhouse gases (Figures S1c and S1d), whose growing concentrations are not in dispute. Thus, keeping in mind that the forcings in our model runs are much closer to reality that those employed in *Ferreira et al.* [2015], our results indicate that ozone depletion (via the associated fast mechanism) is unlikely to have been the main cause behind the recent, surprising, observations of increased sea ice extent around Antarctica [*Parkinson and Cavalieri*, 2012].

In fact, a growing body of modeling and observational evidence [*Polvani and Smith*, 2013; *Meier et al.*, 2013; *Simpkins et al.*, 2013; *Fan et al.*, 2014; *Gagné et al.*, 2015] is pointing to large internal variability of the Antarctic climate system. Of course one does not expect a model such as ours, in which the ocean and sea ice components are not initialized from observations, to faithfully reproduce the observed trends if they result from internal variability. This does not, however, invalidate the key finding of our study, which is concerned with the forced response: increased ODS and formation of the ozone hole have been important drivers of change in the circulation, temperature and salinity of the Southern Ocean.

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