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Impacts of Stratospheric Ozone Recovery on Southern Ocean Temperature and Heat Budget

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Key Points:

- The decrease of ozone depleting substances in the 21st century causes a decrease of the Southern Ocean heat
- The ozone-induced Southern Ocean heat decrease is driven by weakened poleward ocean heat transport (OHT)
- The weakened poleward OHT is driven by the equatorward shift of the surface winds and meridional overturning circulation

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract The impacts of stratospheric ozone recovery on Southern Ocean surface and interior temperature, heat content, heat uptake, and heat transport are investigated by contrasting two ensemble chemistry-climate model simulations in 2005–2099: one with fixed ozone depleting substances (ODSs) and another with decreasing ODSs. In our simulations ozone recovery significantly affects Southern Ocean temperature, with large latitudinal and vertical variations. Ozone recovery causes a dipole change of the full-depth ocean heat content (OHC) with an increase south of 60°S and a decrease between 45°S and 60°S. Integrated over latitudes south of 40°S, OHC decreases in response to ozone recovery. This ocean heat loss is shown to be driven by weakened poleward ocean heat transport (OHT) across 40°S, which is partly canceled by enhanced heat uptake. The weakening of poleward OHT into the Southern Ocean is caused by the ozone-induced equatorward shift of the meridional overturning circulation.

Plain Language Summary With the phaseout of ozone depleting substances as controlled under the Montreal Protocol and its amendments, the stratospheric ozone layer is projected to recover to the pre-ozone hole levels in this century. Stratospheric ozone recovery can influence temperature and circulation in the atmosphere and ocean. Here we study how stratospheric ozone recovery affects Southern Ocean temperature and heat content using a coupled atmosphere-ocean-chemistry model. The strong surface westerlies over the Southern Ocean play a crucial role in ocean circulation and climate. We find that ozone recovery influences Southern Ocean through its impact on the surface westerlies. Our model results show that ozone recovery causes a weakening and equatorward shift of the strong westerlies over the Southern Ocean. As a result, the ocean circulation in the Southern Ocean weakens, leading to a weaker poleward heat transport from the lower latitude into the Southern Ocean. A weaker heat transport results in Southern Ocean cooling and a decrease of the Southern OHC.

1. Introduction

The Southern Hemisphere (SH) midlatitude surface westerlies play a crucial role in Southern Ocean climate through its impact on the meridional overturning circulation (MOC) (Marshall & Speer, 2012). Variations of the location and strength of the SH midlatitude westerlies have profound influences on Southern Ocean temperature, ventilation, heat and carbon uptake, heat transport, and Antarctic sea ice (e.g., Armour et al., 2016; Delworth & Zeng, 2008; Liu et al., 2018; Oke & England, 2004; Russell et al., 2006; Saenko et al., 2002).

The variability of the SH midlatitude westerly winds represents the leading mode of SH extratropical variability, that is, the Southern Annular Mode (SAM). In the past 4–5 decades stratospheric ozone depletion promotes the positive polarity of the SAM and causes poleward intensification of the SH westerlies in austral summer (e.g., Polvani et al., 2011; Previdi & Polvani, 2014). Through its impact on surface winds, stratospheric ozone depletion is an important driver of recent Southern Ocean change. Studies find that stratospheric ozone depletion causes Southern Ocean warming (Bitz & Polvani, 2012; Sigmond & Fyfe, 2010; Solomon et al., 2015) and significantly contributes to the increase of Southern ocean heat uptake (OHU) and heat content (S. Li et al., 2021; Liu et al., 2022; Solomon et al., 2015).

The stratospheric ozone layer is projected to recover in the next several decades with the decline of ozone depleting substances (ODSs). Stratospheric ozone recovery is expected to partly cancel SH climate change from rising greenhouse gases (GHGs) (Banerjee et al., 2020; Barnes et al., 2014; Son et al., 2008). A small number of studies have investigated the influence of ozone recovery on Southern Ocean. These studies find that ozone recovery causes Southern Ocean cooling (Ivanciu et al., 2022; Smith et al., 2012) and an equatorward shift of the ocean circulation (Smith et al., 2012; Wang et al., 2014). However, no study has examined how ozone recovery affects Southern Ocean heat budget.

The purpose of this study is to investigate the impacts of stratospheric ozone recovery on Southern Ocean surface and interior temperature, heat content, heat uptake, and meridional OHT. Using coupled atmosphere-ocean-chemistry simulations, we find that stratospheric ozone recovery reduces Southern ocean heat content (OHC), which is driven by weakened poleward OHT into the Southern Ocean.

2. Model and Experiments

We used the coupled atmosphere-ocean Goddard Earth Observing System Chemistry-Climate Model (GEOSCCM) in this study. The details of the model were described in F. Li et al. (2016). The atmospheric model is GEOS-5 Ganymed-4_0 and the ocean model is the Modular Ocean model version 5 (Griffies, 2012). The model includes a comprehensive stratospheric chemistry scheme that is coupled with radiation and dynamics (Oman & Douglass, 2014). The atmospheric model has 72 levels to the top at 0.01 hPa. The ocean model has 50 layers with 10 m resolution in the top 200 m. The simulations were conducted with horizonal resolution of 2.5° longitude × 2° latitude for the atmosphere model and 1° × 1° for the ocean model.

We conducted a pair of four-member ensemble transient simulations for 2005–2099. The **Control** ensemble is forced with the Representative Concentration Pathway 6.0 GHG scenario and the WMO-2014 baseline (A1) ODS scenario. The **HighODS** ensemble has the same setup as the Control except that the ODSs are fixed at year 2005 levels. Thus, the HighODS is a GHG-only experiment. The climate impact of ODS decrease is defined as the ensemble-mean differences between Control and HighODS (Control minus HighODS). Note that the differences between Control and HighODS are caused by ODS-induced stratospheric ozone recovery and direct radiative effects of ODS decrease, but here we just refer these differences as due to stratospheric ozone recovery. It should also be noted that our simulations do not capture tropospheric ozone changes. Thus, this study does not investigate the impacts of 21st century tropospheric ozone changes on Southern Ocean, an important topic that needs to be addressed using climate models with tropospheric chemistry mechanisms.

3. Results

There are great interests to understand stratospheric ozone's impact on Southern Ocean sea surface temperature (SST) (Bitz & Polvani, 2012; Sigmond & Fyfe, 2010; Smith et al., 2012). Sigmond and Fyfe (2010) were the first to show that the response of the SST around Antarctica to ozone depletion is cooling, not warming as one would expect from the negative interannual relationship between enhanced surface winds and SST (Fan et al., 2014; Sen Gupta & England, 2006). Ferreira et al. (2015) proposed a two-timescale mechanism to reconcile this inconsistency. The enhanced surface westerlies over the circumpolar ocean increase northward Ekman drift and strengthen the MOC. At seasonal to interannual timescale, SST around Antarctica cools due to enhanced northward Ekman drift of cold sea water. But at decadal and multi-decadal timescale, SST response reverses from cooling to warming as increased upward heat flux from the subsurface inversion layer overwhelms Ekman cooling.

The two-timescale theory is based on idealized step ozone hole forcing (Ferreira et al., 2015; Kostov et al., 2017; Seviour et al., 2019). The transient Southern Ocean SST response to stratospheric ozone recovery has not been discussed before in the context of the two-timescale mechanism. One might expect that it is a reverse of the response to ozone depletion, that is, an initial warming and then transitions to cooling. Figure 1a shows the evolution of ozone recovery-induced annual and zonal mean Southern Ocean SST changes from 2005 to 2099 in GEOSCCM simulations. There are large interannual variations before 2040. After 2040 a dipole pattern emerges, with warming in 60°S–75°S and cooling in 40°S–60°S. This dipole pattern is consistent with the weakening and equatorward shift of surface wind stress over the Southern Ocean (Figure 1b), which causes anomalous poleward (equatorward) Ekman transport south (north) of 55°S, that is, the fast response in the two-timescale mechanism. In the last 10 years of the 21st century the subpolar warming becomes weaker and the midlatitude cooling extends southward, suggesting that the subsurface process starts to dominate the SST response. The subpolar warming does not transition to cooling at the end of the 21st century, indicating that GEOSCCM has a long transition period from warming to cooling under ozone recovery forcing.

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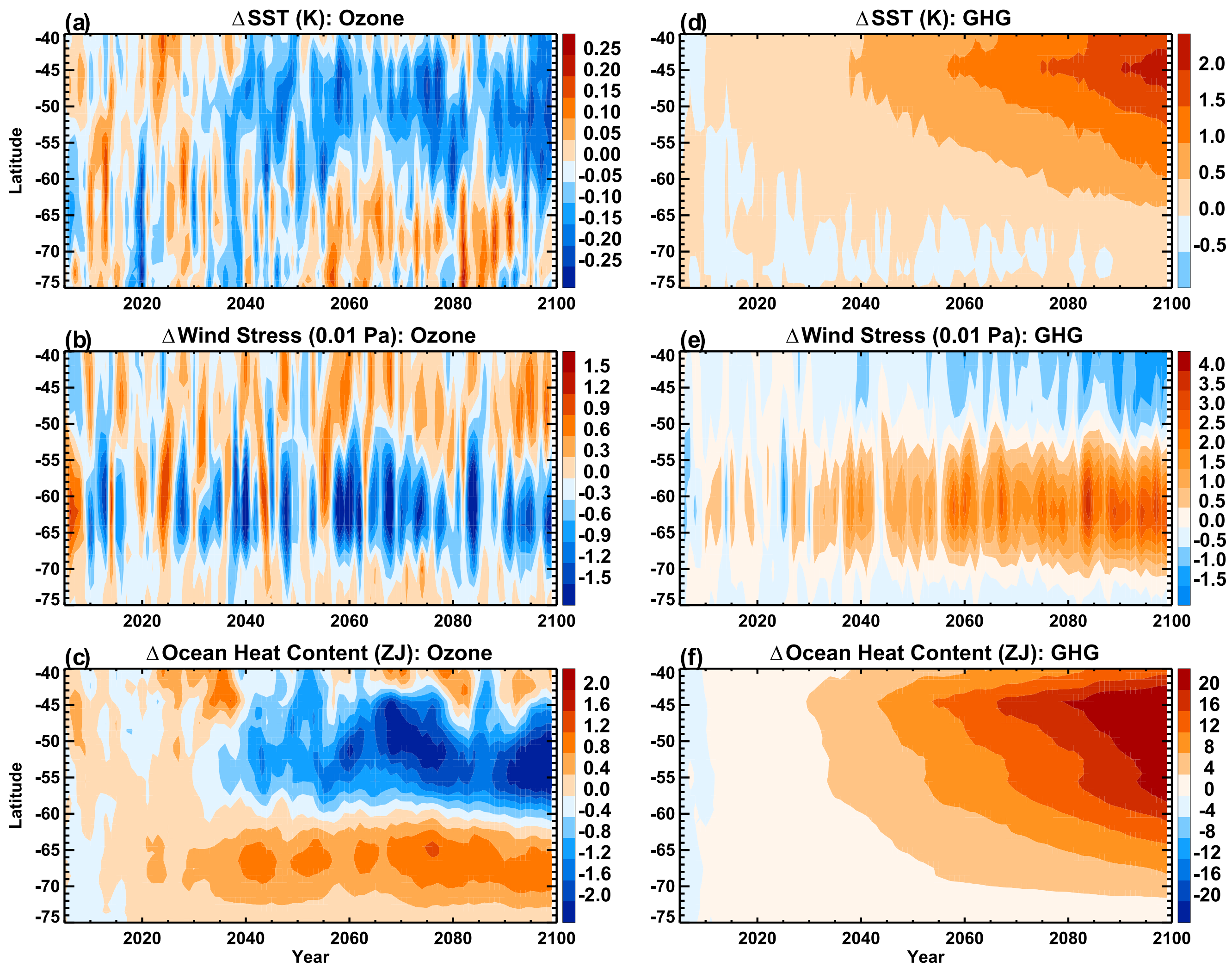

Figure 1. (a) Evolution of the annual and zonal mean sea surface temperature (SST) response to stratospheric ozone recovery, calculated as the difference between Control and HighODS experiments. Panel (b) same as panel (a), but for the zonal wind stress. Panel (c) same as panel (a), but for the ocean heat content (OHC). (d) Evolution of the annual and zonal mean SST response to increasing greenhouse gases, calculated as the anomalies relative to the 2005–2014 mean in the HighODS experiment. Panel (e) same as panel (d), but for the zonal wind stress. Panel (f) same as panel (d), but for the OHC.

While it is important to understand ozone recovery's impact on Southern Ocean SST, it is also imperative to investigate ozone recovery's effects on ocean temperature for the full depth, that is, OHC. This is because changes in OHC are closely related to changes in OHU and meridional OHT, which have significant implications on global climate change (He et al., 2019; S. Li et al., 2021; Liu et al., 2018). Figure 1c shows the evolution of annual-mean zonal-integrated OHC response to ozone recovery. The OHC response also has a dipole pattern with positive anomalies at 60°S–75°S and negative anomalies at 45°S–60°S. This dipole response is found in all four ensemble members (Figure S1 in Supporting Information S1). Integrating OHC changes south of 40°S, we find that ozone recovery leads to a 11.8 ZJ (1 ZJ = 10^{21} J) decrease of the Southern Ocean OHC in 2070–2099.

Our result that stratospheric ozone recovery causes a decrease of Southern Ocean OHC is qualitatively consistent with previous studies who found that ozone depletion causes an increase of Southern Ocean OHC (S. Li et al., 2021; Liu et al., 2022; Solomon et al., 2015). However, quantitative comparison is not straightforward because previous studies used different definitions for Southern Ocean OHC. Solomon et al. (2015) defined Southern Ocean OHC as the full-depth OHC poleward of 40°S, which is the same definition used in the above paragraph. They showed that ozone depletion causes an increasing trend of 6 ZJ/decade in 1955–2005. S. Li et al. (2021) reported an ozone-induced OHC trend of 2.78 ZJ/decade in 1958–2005 in the upper 2,000 m between 35°S and 70°S. Liu et al. (2022) found that stratospheric ozone depletion causes an OHC increase in the upper

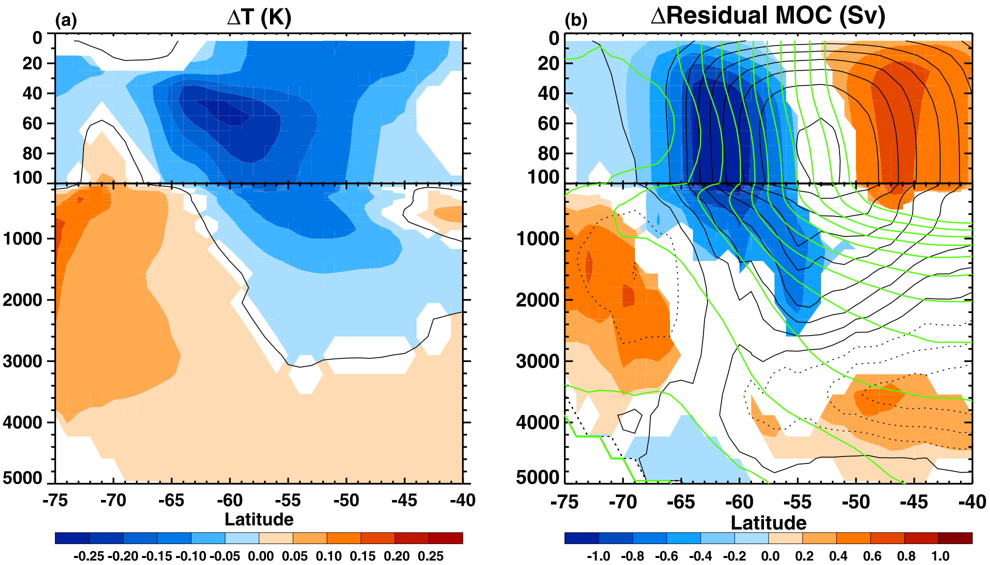

Figure 2. (a) Color shading is the annual and zonal mean Southern Ocean temperature response to stratospheric ozone recovery averaged in 2070–2099. Only statistically significant response is plotted (5% significant level based on two sample *t*-test). The black contour indicates zero temperature change. (b) Color shading is the annual-mean residual meridional overturning circulation (MOC) response to ozone recovery averaged in 2070–2099. Black contours are the residual MOC climatology and green contours are ocean temperature climatology averaged in 2070–2099 of the HighODS simulation.

2,000 m between 30°S and 60°S with a 1.84 ZJ/decade trend in 1955–2000. Using the definitions of Solomon et al. (2015), S. Li et al. (2021), and Liu et al. (2022), we find that stratospheric ozone recovery causes OHC decrease of −2.4, −3.6, −3.9 ZJ/decade respectively, which are within the large spread of the reported Southern Ocean heat change due to ozone depletion.

These Southern Ocean changes induced by stratospheric ozone recovery are very different from those induced by GHG increase. Rising GHGs in the 21st century cause an increase in the Southern Ocean SST (Figure 1d) and OHC (Figure 1f), both of which peak at ∼45°S and with a peak magnitude about 10 times larger than that induced by ozone recovery. GHG forcing causes a strengthening and poleward shift of the zonal surface wind stress (Figure 1e). Comparing Figures 1b and 1e indicates that ozone recovery compensates about 1/3 of GHG-induced surface wind stress strengthening in 55°S–70°S.

To understand the OHC response to ozone recovery, we examine the vertical and latitudinal structures of ocean temperature changes during 2070–2099 (Figure 2a). Similar results are found if we choose other averaging period after year 2040. There is a weak and statistically insignificant surface warming poleward of ∼65°S. Below this high-latitude shallow surface warming, ocean temperature decreases, but the subsurface cooling does not extend into the interior ocean. The subpolar ocean warms below ∼100 m, overwhelming the subsurface cooling and leading to OHC increase. The high latitude deep ocean warming extends northward to 40°S. Between 45°S and 60°S, a cold tongue develops that extends from high latitude subsurface to 3,000 m depth at 45°S. This cooling is partly canceled by warming below, but the net result is a decrease of the full-depth OHC in 45°S–60°S.

The response of the Southern Ocean temperature to ozone recovery is strongly impacted by changes in the MOC. Ozone recovery causes the weakening and equatorward shift of the surface westerlies over the Southern Ocean, which leads to similar changes of the wind-driven Eulerian-mean MOC, or the Deacon Cell. Changes in the Eulerian-mean MOC are compensated partly by changes in the parameterized eddy MOC (Figure S2 in Supporting Information S1). As a result, the residual MOC shifts equatorward (Figure 2b). Consequently, poleward of ∼60°S the circumpolar upwelling weakens and reduces the upward heat flux transport from the inversion layer, leading to subsurface cooling. Note that the upper ocean inversion layer only exists in the seasonal sea ice zone poleward of ∼60°S, which can be seen from the climatological temperature profile (green contours in Figure 2b). Between ∼45°S and 60°S anomalous upwelling associated with the equatorward shift of the residual MOC results in cooling from subsurface to 3,000 m depth. These results are qualitatively consistent with previous studies on responses of Southern Ocean temperature and MOC to ozone

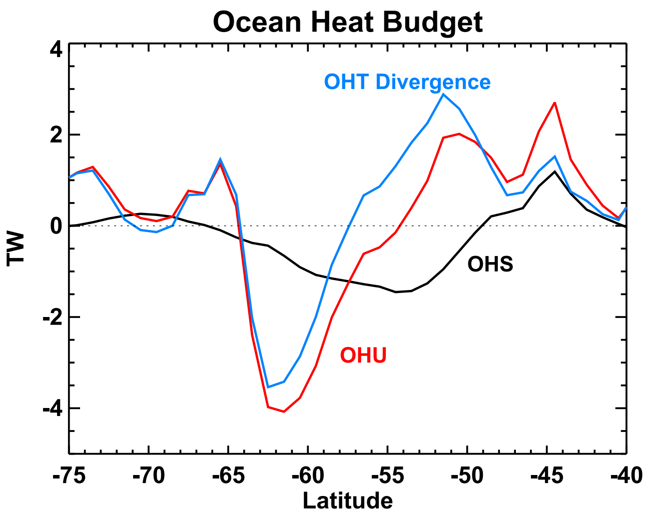

Figure 3. Response of ocean heat storage, ocean heat uptake, and ocean heat transport divergence to stratospheric ozone recovery averaged in 2070–2099.

recovery/depletion (Ivanciu et al., 2022; Sigmond & Fyfe, 2010; Smith et al., 2012; Solomon et al., 2015) or surface wind changes (Delworth & Zeng, 2008).

The Antarctic abyssal overturing circulation (located south of the Deacon Cell), which represents the formation of the Antarctic bottom water, weakens in response to ozone recovery. Rahmstorf and England (1997) and Delworth and Zeng (2008) found that weakened surface winds reduce the strength of the abyssal overturning circulation. The mechanism was explained by Saenko et al. (2002) and Fyfe et al. (2007) in the scenario of strengthened surface westerlies. They found that strengthened winds increases the formation of new ice around Antarctica by enhancing offshore ice transport. The brine release associated with new ice formation and growth reduces upper ocean stratification and enhances convection and Antarctic bottom water formation. We find that, in response to stratospheric ozone recovery, the subpolar upper ocean salinity and density increases (not shown). Our result is consistent with the mechanism proposed by Saenko et al. (2002) and Fyfe et al. (2007), that is, weakened surface winds suppress new ice formation, increases upper ocean stratification, and reduces convection. A weaker formation of the Antarctic bottom water results in warming of the deep ocean poleward of ~60°S and the deep ocean warming spreads to midlatitudes.

The vertical redistribution of heat plays an important role in determining the vertical structure of Southern Ocean temperature response to ozone recovery. However, changes in the full-depth OHC are determined only by OHU and meridional OHT. At a given latitudinal band, changes in the zonally and full-depth integrated OHC, or ocean heat storage (OHS), is the sum of the OHU and meridional OHT convergence (e.g., Liu et al., 2018), that is,

$$\frac{\partial}{\partial t}(\mathrm{OHC}) = \mathrm{OHS} = \mathrm{OHU} - \frac{\partial}{\partial y}(\mathrm{OHT}) \tag{1}$$

OHU is the net surface heat fluxes into the ocean, including shortwave and longwave radiative fluxes, latent and sensible heat fluxes, and advective heat fluxes associated with passage of precipitation and evaporation across the ocean surface (Griffies, 2012). OHS is calculated as time derivative of OHC, and OHT convergence is calculated as the difference between OHU and OHS. From Equation 1, we can attribute changes in ocean heat to those from OHU and OHT.

Figure 3 shows the latitudinal distribution of ozone-induced changes in OHS, OHU, and OHT divergence averaged in 2070–2099. In response to stratospheric ozone recovery, Southern Ocean loses heat to atmosphere (OHU < 0) between 54°S and 64°S and gains heat poleward and equatorward of this region. These OHU changes are largely compensated by OHT, with convergence between 57°S and 64°S and divergence poleward and equatorward of this region. The magnitude and latitudinal structure of OHS changes are determined by the combined effects of these two processes. The peak OHU loss occurs at ~ 62°S, but increased meridional heat transport into this region shifts the peak OHS decrease to ~55°S. Our results are qualitatively consistent with S. Li et al. (2021), who showed that stratospheric ozone depletion during 1958–2005 has nearly the opposite effects on Southern Ocean heat budget (their Figure 5b).

If we consider the whole Southern Ocean domain, that is, integrate Equation 1 from South Pole to 40°S, we get

$$\int_{90\mathrm{S}}^{40\mathrm{S}} \mathrm{OHS}dy = \int_{90\mathrm{S}}^{40\mathrm{S}} \mathrm{OHU}dy - \mathrm{OHT}|_{40\mathrm{S}}. \tag{2}$$

OHT across 40°S is calculated as the difference between the area integral of OHS and OHU. From Equation 2, we find that ozone recovery causes a decrease of Southern Ocean OHS of −9.3 TW (1 TW = 10^{12}W), an increase of OHU of 5.6 TW, and a decrease of poleward OHT across 40°S of −14.9 TW during 2070–2099. In comparison, rising GHGs causes a Southern Ocean OHS increase of 145 TW, an OHU increase of 163 TW, and a decrease of poleward OHT across 40°S of −18 TW, which is calculated as the 2070–2099 mean relative to the 2005–2014 mean in the HighODS experiment.

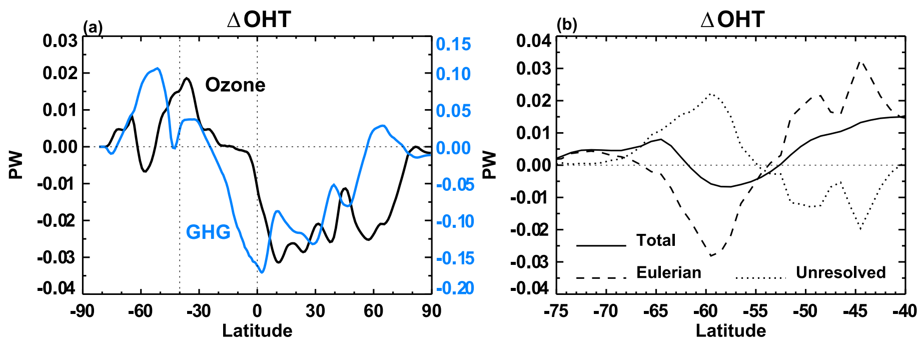

Figure 4. (a) Response of the northward ocean heat transport (OHT) to stratospheric ozone recovery (black line, left axis) and to rising greenhouse gases (blue line, right axis) averaged in 2070–2099. (b) Responses of the total (solid), Eulerian-mean (dash), and unresolved (dotted) northward OHT to ozone recovery averaged in 2070–2099.

In our simulations the poleward OHT into the Southern Ocean weakens in response to ozone recovery. The meridional OHT is a fundamental climate process (Ganachaud & Wunsch, 2000). Modeling studies project a decrease of poleward OHT in both hemispheres in the 21st century with increasing GHGs (He et al., 2019). The Northern Hemisphere (NH) OHT decrease is driven by the weakening of the Atlantic MOC (e.g., Cheng et al., 2013). In the SH, rising GHGs enhance the Southern Ocean OHU that peaks at around 60°S. The surface flow of the Southern Ocean MOC transports this anomalous heat gain equatorward and weakens the poleward OHT (Armour et al., 2016; He et al., 2019).

Ozone recovery plays a crucial role in future SH OHT change. Figure 4a compares northward OHT changes due to increasing GHGs and ozone recovery. GHG-induced OHT changes are calculated as the OHT differences between 2070–2099 and 2005–2014 in the HighODS simulation. Note that the vertical scale for ozone-induced OHT changes is 1/5 of that of GHG-induced changes. Increasing GHGs causes a decrease of poleward OHT south of ~20°S and north of the Equator, consistent with previous studies. Stratospheric ozone recovery weakens SH poleward OHT except at ~52°S–62°S. The poleward OHT across 40°S is reduced by 0.015 PW (1 PW = 10^{15} W) by ozone recovery during 2070–2099, which is similar to the 0.018 PW reduction from increasing GHGs. Ozone recovery also reduces poleward OHT in the NH, amplifying GHG-induced decrease from 10°N to 60°N by about 20%–25%.

We can further decompose OHT changes into changes from Eulerian-mean and unresolved components. The Eulerian-mean OHT is calculated as $C_p \int_{\text{bottom}}^{\text{surface}} \rho v T\, dz$, where C_p is the specific heat of sea water, ρ is density, v is resolved meridional flow, and T is ocean temperature. The unresolved OHT includes OHT by eddies and diffusion (Liu et al., 2018) and is calculated as the residual of total OHT and Eulerian-mean OHT. Figure 4b shows that ozone recovery causes anomalous northward Eulerian-mean OHT equatorward of ~55°S and anomalous southward Eulerian-mean OHT at ~55°S–70°S. This Eulerian-mean OHT dipole is largely balanced by opposite unresolved OHT changes. The net result is to weaken the climatological southward OHT at ~40°S–52°S and 62°S–75°S but enhance the southward OHT at 52°S–62°S.

The mechanism that could explain the weakening of poleward OHT into the Southern Ocean is the equatorward shift of the MOC. The surface flow of the Southern Ocean MOC transports high latitude cold sea water northward. As the MOC shifts equatorward in response to ozone recovery, its northward surface flow becomes stronger north of 52°S (Figure 2b), leading to reduced poleward OHT. Similar mechanisms were proposed by Hall and Visbeck (2002) and Oke and England (2004) to explain why a poleward shift of surface winds increases poleward OHT into the Southern Ocean.

4. Discussion and Conclusions

This study investigates the impacts of stratospheric ozone recovery in the 21st century on Southern Ocean temperature, heat content, heat uptake, and meridional heat transport. Two transient ensemble simulations, each with four ensemble members, were performed for 2005–2099 using the coupled atmosphere-ocean GEOSCCM. The two ensembles differ in ODS forcing: the Control was forced with projected declining ODSs and the HighODS was run with fixed 2005-level ODSs. The differences between Control and HighODS quantify the climate impacts of stratospheric ozone recovery and ODS decrease.

The Southern Ocean SST has a dipole response to stratospheric ozone recovery after ∼2040, with high latitude warming and midlatitude cooling. These SST changes are driven by anomalous Ekman drift and the equatorward shift of the MOC. The warming of SST around Antarctica weakens at the end of the 21st century, consistent with the two-timescales mechanism (Ferreira et al., 2015) that at long timescale the subsurface process becomes more important than the Ekman surface process. However, subpolar SST response does not reverse to cooling, suggesting that GEOSCCM has a long transition period from warming to cooling under ozone recovery forcing.

The full-depth Southern Ocean OHC also has a dipole response to ozone recovery with an increase south of 60°S and a decrease between 45°S and 60°S. Heat budget analysis shows that OHU and OHT responses largely balance each other. For Southern Ocean poleward of 40°S, ozone recovery causes a reduction of OHS (−9.3 TW) and OHC (−11.8 ZJ) during 2070–2099. This heat loss is driven by weakened poleward OHT (−14.9 TW) across 40°S, which is partly canceled by enhanced OHU (5.6 TW). Importantly, the weakening of OHT into the Southern Ocean due to ozone recovery is comparable to that due to increasing GHGs.

Previous studies do not agree on how historical ozone forcing affects SH OHT. S. Li et al. (2021) showed that past ozone changes strengthen the poleward OHT into the Southern Ocean, but Solomon et al. (2015) found that stratospheric ozone depletion does not affect OHT across 40°S. Here we find that the equatorward shift of the MOC causes anomalous northward transport across 40°S, reducing the poleward OHT. Thus, ozone's impact on Southern Ocean OHT is closely related to MOC changes. Different OHT responses to ozone forcing in previous studies could be related to different MOC responses. Note that in our simulations OHT response to ozone recovery has large latitudinal variations (Figure 4a). Therefore, OHT response also depends on how Southern Ocean is defined. For example, Figure 4a shows that ozone recovery has little effect on OHT across 55°S and that ozone-induced poleward OHT weakening across 30°S is only 1/5 of that due to rising GHGs.

The magnitude of Southern Ocean temperature and OHC response to ozone recovery is affected by model-dependent factors such as the implementation of the eddy MOC parameterization and the mean state. The version of GEOSCCM used in this study has a cold bias in Southern Ocean SST and a poleward bias in SH midlatitude jet in the present-day climate (F. Li et al., 2016). These biases suggest that GEOSCCM might overestimate SST cooling by the anomalous equatorward Ekman transport north of 55°S and that the simulated dipole changes of SST and OHC might be too close to the pole. The newer version of GEOSCCM has significantly reduced these biases (F. Li & Newman, 2020). Improvements in the SH jet latitude have also been found in CMIP 6 relative to CMIP 5 models (Bracegirdle et al., 2020). It remains to be examined how these improvements would quantitatively affect ozone recovery's impact on Southern Ocean.

This study does not consider tropospheric ozone changes, which is a potent GHG and could have significant impact on future ozone forcing. Liu et al. (2022) found that in the second half of 20th century tropospheric ozone increases cause stronger Southern Ocean warming than does stratospheric ozone depletion. Future tropospheric ozone changes are affected by many factors such as ozone-precursor emissions, stratospheric ozone recovery, stratosphere to troposphere transport, and changes in tropospheric temperature and humidity. Models participated in the Atmospheric Chemistry and Climate Model Intercomparison Project simulate a decrease of tropospheric ozone in the 21st century under the low and medium radiative forcing scenarios, but an increase under the high radiative forcing scenario (Young et al., 2013). Further research is needed to understand how 21st century tropospheric ozone changes affect Southern Ocean heat budget.

Data Availability Statement

The GEOSCCM simulations are stored in the data storage facility of NASA Center for Climate Simulation. Selected data, including those used in the generation of the figures of this paper are available at https://portal.nccs.nasa.gov/datashare/io3/pub/SouthernOcean.

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