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Key Points:

- Stratospheric ozone depletion changes surface winds, causing a surface cooling over the Southern Ocean during 1982–2005
- This ozone forcing results in the advection of cold water, attributed to increased Ekman transports and modified meridional sea surface temperature gradients
- The effect of cold-water advection outweighs the surface heat fluxes and vertical advection, producing a sustained surface cooling

Supporting Information:

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

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Stratospheric Ozone Depletion Causes Southern Ocean Surface Cooling

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Abstract Stratospheric ozone depletion strongly influences Southern Ocean climate change. Using coupled climate model simulations, we quantify the transient effect of stratospheric ozone depletion on sea surface temperature (SST) over the Southern Ocean from 1982 to 2005. We find that stratospheric ozone depletion intensifies surface zonal winds south of 46°S, which increases northward Ekman transports and promotes cold water advection, resulting in SST cooling there. In addition, meridional SST gradients are enhanced across the Southern Ocean, which, in turn, prompt colder water advection driven by climatological surface winds to exacerbate the SST cooling between 46°S and 60°S. Because of the increase in stratospheric ozone depletion from 1982 to the early 2000s, the sustained Ekman transport induced horizontal cold-water advection—though partially compensated by changes in surface heat flux and vertical advection below the mixed layer—plays a central role in maintaining Southern Ocean SST cooling and regional Antarctic sea ice expansion.

Plain Language Summary Since the start of the satellite era, the Southern Ocean has been one of the few regions to experience surface cooling, showing a unique trend of global surface change. We demonstrate that stratospheric ozone depletion has caused significant surface cooling over the Southern Ocean during 1982–2005. In particular, both enhanced Ekman transport and altered meridional sea surface temperature gradients promote cold-water advection over the Southern Ocean, which persists over 1982–2005 and outweighs the effects of surface heat fluxes and vertical advection, serving as the primary mechanism of ozone-driven surface cooling. The results advance our understanding of the climate impact of stratospheric ozone depletion and ongoing Southern Ocean climate change.

1. Introduction

Since the start of the satellite era, the Southern Ocean has exhibited a surface cooling trend against the remarkable global warming (Fan et al., 2014; Liu, 2025a; Zhang & Deser, 2024). The observed Southern Ocean cooling was accompanied by an Antarctic sea ice expansion prior to 2016 (Parkinson & Cavalieri, 2012; Simpkins et al., 2013), and was suggested to link to surface temperature and atmospheric circulation changes in the tropics (Dong et al., 2022; Kang, Ceppi, et al., 2023; Kim et al., 2022). A variety of mechanisms were proposed to explain the recent Southern Ocean surface cooling, encompassing the internal variability in the Southern Ocean (Cabr   et al., 2017; Hartmann, 2022; Zhang et al., 2019), teleconnection with low latitudes (Li et al., 2014; Matear et al., 2015; Polvani & Smith, 2013; Purich, England, et al., 2016) and freshwater input due to Antarctic ice-sheet melt (Pauling et al., 2016; Purich & England, 2023; Rye et al., 2020). Particularly, Southern Hemisphere westerly winds, which shifted poleward and intensified over the last several decades, play a vital role in generating the Southern Ocean surface cooling via wind-driven Ekman transport (Doddridge & Marshall, 2017; Kostov et al., 2017; Lee et al., 2017; Purich, Cai, et al., 2016; Roach et al., 2023).

Stratospheric ozone depletion during this period was identified as one important driver of the poleward intensified westerly winds (Arblaster & Meehl, 2006). By cooling the low stratosphere and upper troposphere, stratospheric ozone depletion brought about a poleward intensification of westerly winds akin to the positive phase of the Southern Annual Mode (Gillett & Thompson, 2003; Polvani et al., 2011; Sigmond et al., 2011) and thus potentially influenced Southern Ocean sea surface temperature (SST). However, the effect of stratospheric ozone depletion on Southern Ocean SST change was suggested to be time-scale dependent, with a fast cooling in the first few years followed by a slow warming on decadal timescale (Ferreira et al., 2015). The fast surface cooling is

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attributed primarily to an enhanced wind-driven equatorward Ekman transport of cold water, while the slow warming is associated with upwelling of warm water from below the oceanic mixed layer. In addition to warm water, upwelling also brings salty water to the surface, enlarging surface buoyancy and reducing the stratification, prompting salinity-convective feedback (Morioka et al., 2024). Meanwhile, increases in wind-driven upwelling could be offset by changes in eddy-induced flow (Doddridge et al., 2019). Albeit with uncertainty in the timescale to transition from surface cooling to warming, the two-timescale pattern of SST change was evident in multiple climate models in response to abrupt changes in stratospheric ozone concentrations (Marshall et al., 2014; Seviour et al., 2016, 2019), ozone-driven shortwave absorption reduction (Ferreira et al., 2015) or the Southern Annual Mode index (Kostov et al., 2017, 2018).

Efforts from climate model experiments with prescribed changes in column ozone concentration ensued (e.g., Seviour et al., 2019; Sigmond & Fyfe, 2010, 2014). These prescribed ozone concentrations include stratospheric ozone depletion and tropospheric ozone increases (Liu et al., 2022), both of which concurrently modulate Southern Ocean SSTs. As a result, the stratospheric-ozone-driven SST change can seldom be inferred directly from such experiments. Furthermore, constant ozone changes were abruptly imposed on the models (e.g., Ferreira et al., 2015; Seviour et al., 2016; Sigmond et al., 2010), in contrast with the realistic time-evolving ozone change and hence may not be suitable for determining the exact ozone effect on Southern Ocean SSTs in the real world. In short, it remains unclear how the time-evolving stratospheric ozone depletion has driven Southern Ocean SST change during the past several decades.

To tackle the above scientific question, we combine observations and climate model simulations from the Coupled Model Intercomparison Project fifth and sixth phases (CMIP5/6). Although the ozone forcing protocol changed from CMIP5 (total ozone) to CMIP6 (stratospheric ozone-only), some CMIP5 models have stratospheric ozone-only simulations while some CMIP6 models have total ozone simulations. We thus use stratospheric ozone-only simulations with both the CMIP5 and CMIP6 models. Unlike previous model experiments, these stratospheric ozone-only simulations focus solely on changes in historical stratospheric ozone concentrations while keeping other forcing agents constant at preindustrial levels, allowing for an investigation of the climate impact of stratospheric ozone depletion.

2. Data and Methods

2.1. Observations

We use monthly 1-degree Centennial in situ Observation-Based Estimates of the Variability of SST (COBE-SST) version 1 and 2, 2-degree NOAA Extended Reconstructed Sea Surface Temperature (ERSST) versions 4 and 5, and daily 0.25-degree NOAA Optimum Interpolation Sea Surface Temperature (OISST) version 2.1 (Hirahara et al., 2014; Huang et al., 2015, 2017, 2021; Ishii et al., 2005). We look at annual mean SST trends from 1982 to 2005 when data are available from all the observations and model simulations. We find Southern Ocean SST cooling trends in all five SST observational products, despite some differences in the details (Figure S1 in Supporting Information S1), and we average them to reduce observation uncertainty (Figure 1a). We also use the National Snow and Ice Data Center's monthly Antarctic sea ice concentration product (Meier et al., 2024), in the polar stereographic projection at a grid spacing of about 0.25°. We analyze the trend of annual mean sea ice concentration around Antarctica between 1982 and 2005.

2.2. Model Simulations

We leverage preindustrial, historical, and single-forcing simulations from five CMIP5/6 models (CanESM2, CanESM5, GISS-E2-1-G, IPSL-CM6A-LR, and MIROC6, see Table S1 in Supporting Information S1). The historical simulation is forced by all historical forcing agents that evolve during the historical period, whereas the stratospheric ozone-only simulation is forced solely by historical stratospheric ozone concentrations that are prescribed as the historical evolution, while other forcing agents are held constant at their preindustrial levels (Gillett et al., 2016). Thus, the difference between the stratospheric ozone-only simulation and preindustrial control thus demonstrates the climate impact of stratospheric ozone depletion. In addition to the stratospheric ozone-only simulation, we employ anthropogenic aerosol-only, greenhouse gas-only, natural forcing-only and total ozone-only simulations in which models are forced solely by historical anthropogenic aerosols, well-mixed greenhouse gases, natural factors such as solar variations and volcanic eruptions and the whole column ozone. The CanESM2 single-forcing simulations (except greenhouse gas-only) are part of the Canadian Earth System

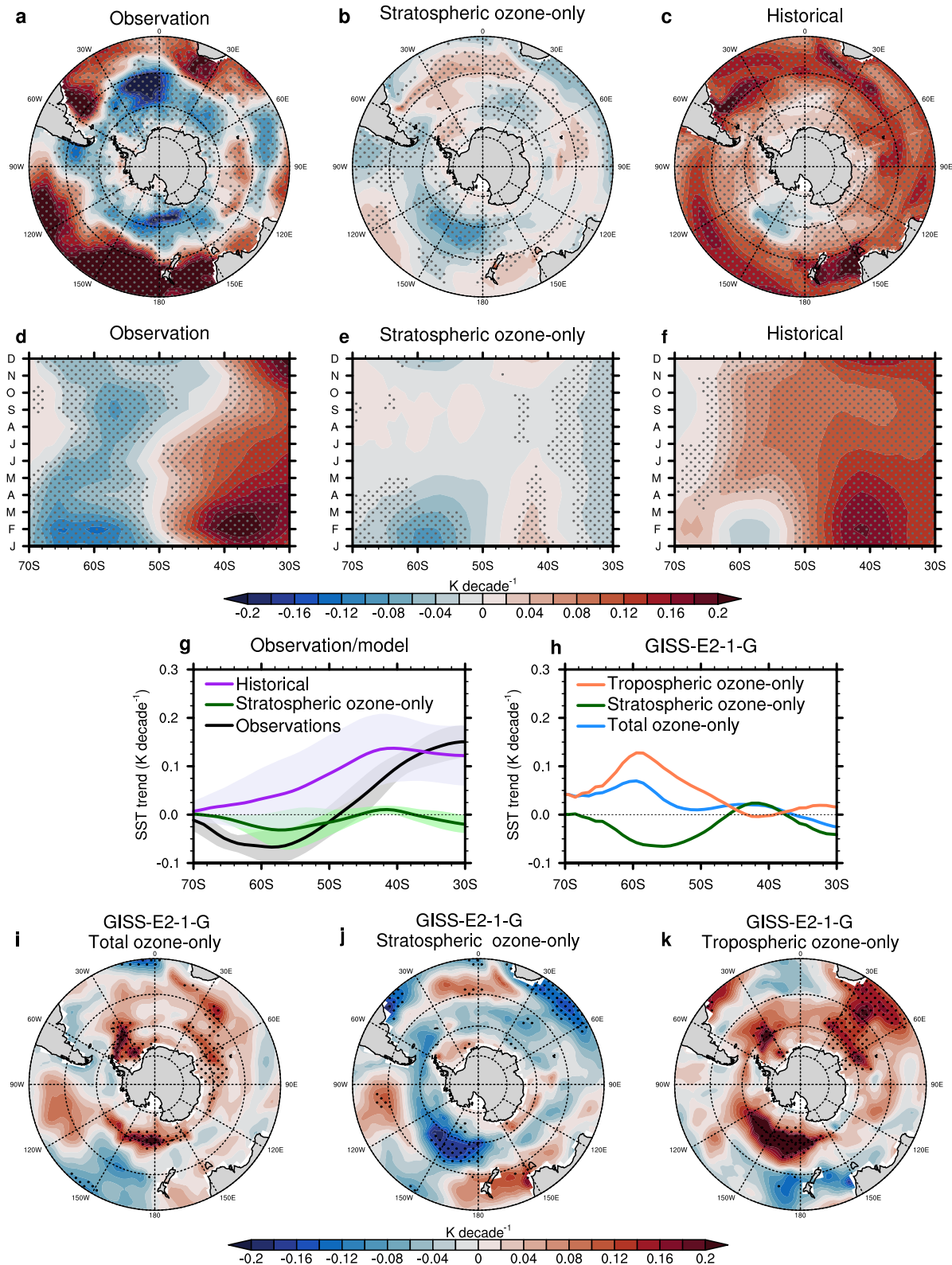


Figure 1.

Model Large Ensembles (Kirchmeier-Young et al., 2017), while others are part of the CMIP6 Detection and Attribution Model Intercomparison Project (DAMIP, Gillett et al., 2016). To minimize the influence of internal variability and model difference, we first average the members for each model (Table S1 in Supporting Information S1), and then average over models.

2.3. Ekman Transport Induced SST Tendency

We calculate the annual and zonal mean Ekman-transport-induced SST tendency ($\frac{dSST'_E}{dt}$) as:

$$\frac{dSST'_E}{dt} = \frac{dSST'_w}{dt} + \frac{dSST'_M}{dt} + \text{Res} \quad (1)$$

where $\frac{dSST'_w}{dt}$ represents the component due to changes in surface wind stress acting on the mean meridional surface temperature gradient during 1982–2005, $\frac{dSST'_M}{dt}$ represents the component due to changes in surface meridional temperature gradient carried by the mean wind-driven Ekman transport during 1982–2005, and Res denotes the residual term due to non-linear effects, which we find to be an order of magnitude smaller than other terms.

In particular, $\frac{dSST'_w}{dt}$ and $\frac{dSST'_M}{dt}$ are expressed as:

$$\frac{dSST'_w}{dt} = \left\langle \frac{\tau'_x}{\rho f Z_{\text{Ekman}}} \frac{\partial SST_0}{\partial y} \right\rangle \quad (2)$$

$$\frac{dSST'_M}{dt} = \left\langle \frac{\tau_{x0}}{\rho f Z_{\text{Ekman}}} \frac{\partial SST'}{\partial y} \right\rangle \quad (3)$$

ρ is sea water density, f is Coriolis parameter, Z_{Ekman} is Ekman layer thickness, τ'_x denotes changes in zonal surface wind stress relative to the preindustrial level (τ_{x0}), $\frac{\partial SST'}{\partial y}$ denotes changes in meridional surface temperature gradient relative to the preindustrial level ($\frac{\partial SST_0}{\partial y}$). Angle brackets $\langle \cdot \rangle$ denotes zonal average.

We also assess the effect of upwelling below the mixed layer on SST change at time t' as:

$$\frac{dSST'}{dt} \Big|_{t=t'} = -t' \gamma^{-1} \sigma \left(\frac{\partial}{\partial y} \left(\frac{\tau'_x}{f} \right) \frac{\Delta_Z \theta}{Z_{\text{sub}}} \right) \quad (4)$$

as in Ferreira et al. (2015) and Seviour et al. (2016). In Equation 4, γ denotes the mixed layer entrainment timescale, σ is the compensation efficiency of eddy-induced circulation on Ekman upwelling, $\frac{\Delta_Z \theta}{Z_{\text{sub}}}$ refers to the climatological maximum temperature inversion $\Delta_Z \theta$ within a thickness Z_{sub} in preindustrial times.

3. Results

3.1. Southern Ocean SST Trend Over 1982–2005

We first investigate the Southern Ocean SST change in observations from 1982 to 2005, corresponding to the end of CMIP5 historical simulation and a period marked by evident stratospheric ozone depletion. The observed Southern Ocean SST reveals distinct regional characteristics in its annual mean trend over 1982–2005, with

Figure 1. Annual mean sea surface temperature (SST) trends over the Southern Ocean (shading in K decade^{-1}) for (a) observational average, multi-model means in the (b) stratospheric ozone-only and (c) historical simulations over 1982–2005. Monthly and zonal mean SST trends (shading in K decade^{-1}) for (d) observation average, multi-model means in the (e) stratospheric ozone-only and (f) historical simulations. (g) Zonal mean for (a–c) with observation (black), historical (purple) and stratospheric ozone-only (green), as well as their one standard deviations (gray, light purple and green shadings). A 5-degree running mean is applied. (h) Same as (g) but only for GISS-E2-1-G total (blue) and stratospheric (green) ozone-only simulations and total minus stratospheric ozone (red) to represent tropospheric ozone-only effect. (i–k) Same as (a–c) but for total, stratospheric and tropospheric ozone-only effects in GISS-E2-1-G. Stipples refer to the regions where at least four of five observations/models agree with the sign of the observation average/multi-model mean in (a–f), and changes are statistically significant at the 95% confidence level on Student's t -test in (i–k).

strong cooling mainly in the Ross Sea, Weddell Sea and outer sea ice zone in the Amundsen Sea and Bellingshausen Sea up to $-0.18 \text{ K decade}^{-1}$ while warming along the Bellingshausen Sea coast (Figure 1a). The zonally averaged SST trend shows a dipole-like pattern of cooling south of around 47°S and warming to the north (Figure 1g). The multi-model mean of the historical simulation, on the other hand, exhibits a general SST warming over the Southern Ocean except a marginal cooling in the Ross Sea during the same period (Figures 1c and 1g). The discrepancy between observed and simulated Southern Ocean SST trends was attributed to the increase of Antarctic meltwater (e.g., Purich & England, 2023), mismatched internal climate variability between model and observation in the Southern (e.g., Chung et al., 2022; Zhang et al., 2019), Pacific (Meehl et al., 2016) and Atlantic (Li et al., 2014) Oceans, potentially linked to the remote discrepancy in the tropical southeast Pacific (Kim et al., 2022) through atmospheric teleconnections (Dong et al., 2022) and cloud feedback (Kang, Yu, et al., 2023).

Unlike the historical simulation, the multi-model mean of the stratospheric ozone-only simulation illustrates a widespread SST cooling around the Antarctic, peaking at $-0.12 \text{ K decade}^{-1}$ in the Ross Sea, albeit slightly weaker than that in observations (Figure 1b). When zonally averaged, the SST trend displays a conspicuous cooling over the Southern Ocean, peaking at around 58°S at a rate of $-0.03 \text{ K decade}^{-1}$ (Figure 1g). Corresponding to the stratospheric ozone hole formation which occurs in the austral spring, monthly SST trends suggest pronounced cooling mainly in the austral summer (December-January-February) up to $-0.10 \text{ K decade}^{-1}$ in the stratospheric ozone-only simulation (Figure 1e). Based on the simulation and analysis, stratospheric ozone depletion clearly contributes to the observed cooling of Southern Ocean SST. The stratospheric ozone-driven SST cooling also contrasts with previous findings in which Southern Ocean SST warms in response to concurrent stratospheric ozone depletion and tropospheric ozone increase (Bitz & Polvani, 2012; Sigmond & Fyfe, 2010, 2014), implying that the cooling effect by stratospheric ozone depletion might be masked by tropospheric ozone-driven warming.

3.2. Mechanism of Stratospheric Ozone Depletion on Driving SST Trend

We then probe the mechanism of the above SST change driven by stratospheric ozone depletion. Relative to the preindustrial simulation, stratospheric ozone depletion leads to a pronounced atmospheric cooling to the south of 40°S during 1982–2005, mainly in the lower stratosphere up to -1.70 K (Figure 2a). The stratospheric cooling at middle-high latitudes consequently produces an enhanced meridional temperature gradient between the polar regions and the low latitudes. This shifts the Southern Hemisphere polar vortex westerly winds poleward and strengthens them by 0.96 m s^{-1} (Figure 2c). The response of atmospheric winds to stratospheric ozone depletion extends down to the ocean surface, manifesting as surface wind stress intensification at the southern flank of the Antarctic Circumpolar Current but relaxation at the northern flank (Figure 2e). Such dipole-like change in wind stress is also present at its zonal mean pattern, in the form of negative anomalies to the north of around 46°S but positive anomalies to the south, with a maximum appearing at around 56°S (Figure 2b).

Surface wind anomalies further modify Ekman transport. In preindustrial simulations, westerly winds drive northward Ekman transport in the Southern Hemisphere middle latitudes, bringing cold water to lower latitudes and thereby reducing the meridional surface temperature gradient. During 1982–2005, stratospheric ozone depletion intensifies wind-driven Ekman transport at the southern flank of the Antarctic Circumpolar Current, thus strengthening the northward cold-water transport and subsequently leading to SST cooling there (Figure 3b). By contrast, on the north flank of the Antarctic Circumpolar Current, the northward wind-driven Ekman transport diminishes or appears as southward anomaly, which reduces equatorward advection thus contributing to SST warming. As a result, the zonal mean change in the Ekman-transport-induced SST tendency ($\frac{dSST'_E}{dt}$) follows a dipole-like pattern of surface wind change, with warming over 46°S – 67°S and cooling to the north of 46°S (Figure 3d).

Surface wind and mean meridional SST gradient changes can affect $\frac{dSST'_E}{dt}$. To isolate their contributions, we decompose $\frac{dSST'_E}{dt}$ into components due to changes in wind-driven Ekman flow acting on the mean meridional SST gradient ($\frac{dSST'_M}{dt}$), due to changes in meridional SST gradient carried by the mean wind-driven Ekman flow ($\frac{dSST'_M}{dt}$), and due to a negligible residual term (Res) representing non-linearity. In response to stratospheric ozone depletion, the altered Ekman transports by poleward-intensified westerly winds act on the mean meridional SST

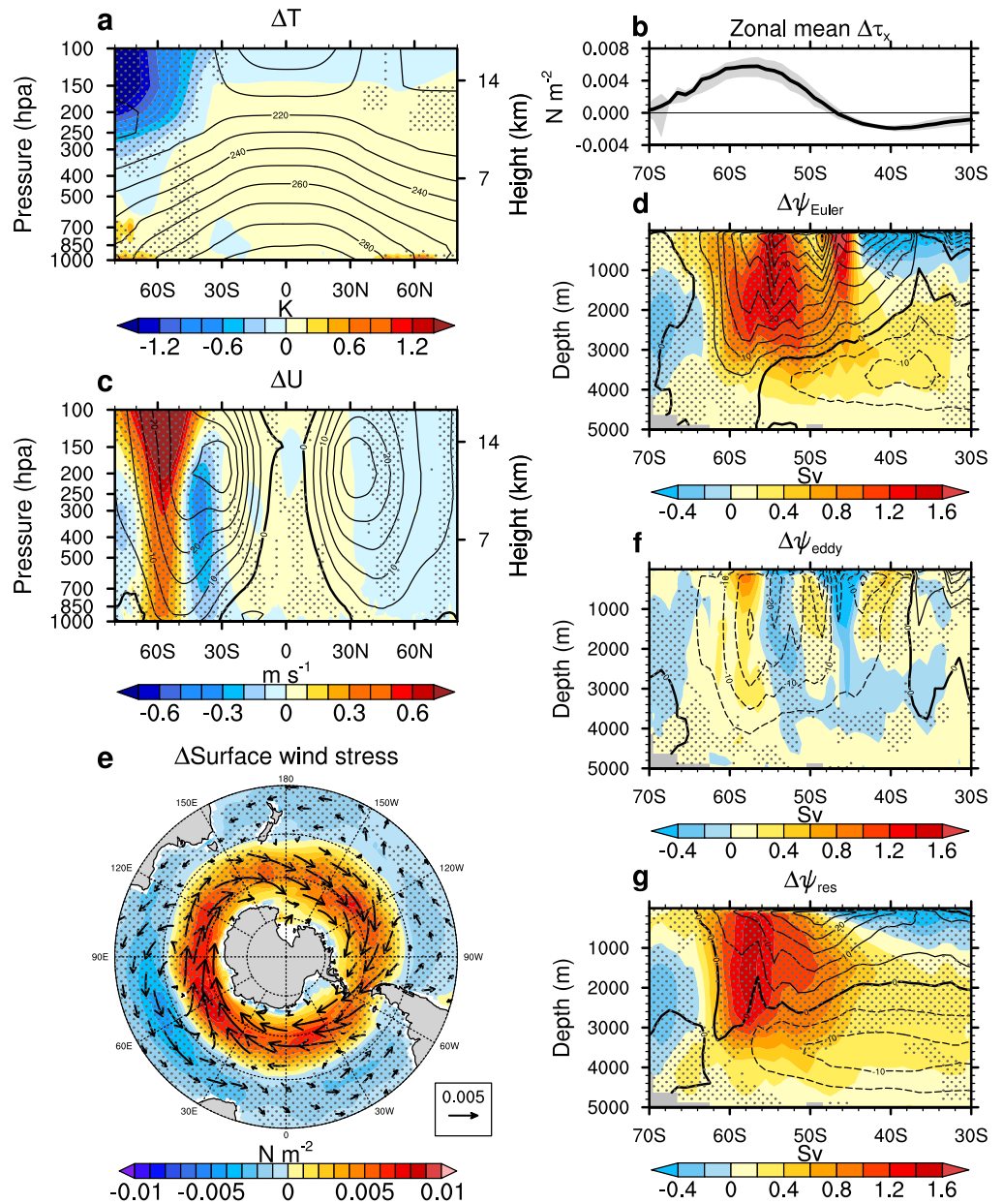


Figure 2. Changes for the multi-model mean of the stratospheric ozone-only simulation over 1982–2005 relative to preindustrial times in annual and zonal mean (a) atmospheric temperature (shading in K) and (c) zonal winds (shading in m s^{-1} , preindustrial climatology for contours with intervals of 10 K for temperature and 5 m s^{-1} for winds), (e) annual mean surface wind stress (vector in N m^{-2}) and zonal wind stress (shading in N m^{-2}), (b) annual and zonal mean zonal wind stress (multi-model mean, black; one standard deviation among models, gray shading) over the Southern Ocean, and annual mean Southern Ocean (d) Eulerian-mean, (f) eddy-induced, and (g) residual meridional overturning circulations (MOCs, shading in Sv, preindustrial climatology for contours with a contour interval of 5 Sv, solid positive, dashed negative and zero thickened), during 1982–2005 relative to preindustrial times. The multi-model mean in (d, f, and g) is defined as the mean of CanESM5, GISS-E2-1-G and IPSL-CM6A-LR due to data availability. Stipples refer to the regions where at least four of five (in a, c, and e) or two of three (in d, f, and g) models agree with the sign of the multi-model mean.

gradient, leading to negative $\frac{d\text{SST}'_w}{dt}$ anomalies between 46°S and 70°S , peaking at around 58°S with a trend of up to $-2.21 \text{ K decade}^{-1}$ (Figures 3e and 3h) and positive $\frac{d\text{SST}'_w}{dt}$ anomalies to the north of 46°S , respectively. On the other hand, the dipole-like SST response favors a stronger meridional SST gradient. Carried by the mean wind-driven Ekman flow, this enhanced temperature gradient gives rise to negative $\frac{d\text{SST}'_M}{dt}$ anomalies to the south of 43°S

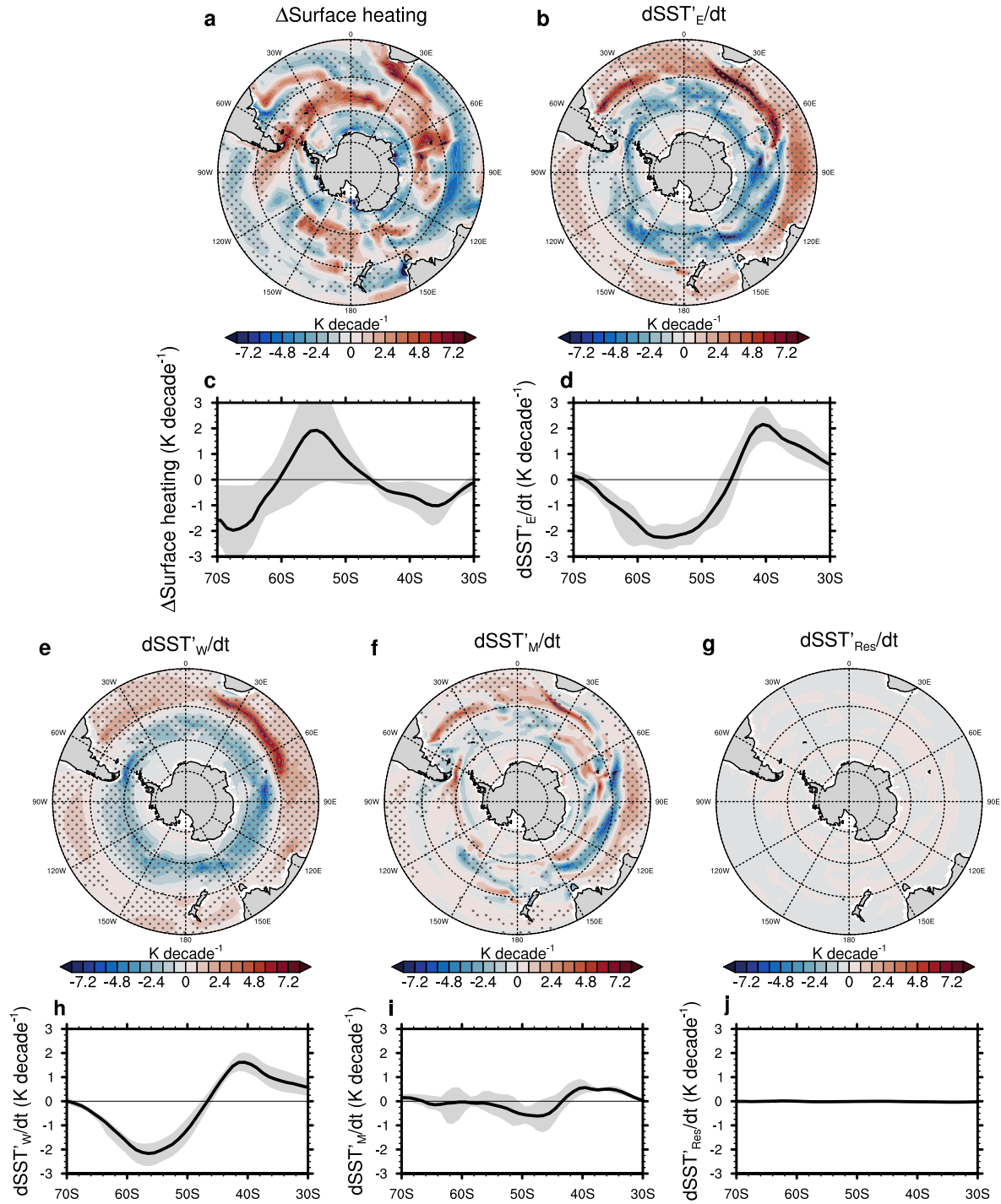


Figure 3. Annual mean (a) surface heat flux induced sea surface temperature (SST) change, that is, $\Delta\text{SHF}/(\rho C_p Z_{\text{Ekman}})$ where ΔSHF denotes the change in the net downward surface heat flux, C_p is sea water heat capacity, ρ is sea water density and Z_{Ekman} is Ekman layer thickness, and (b) Ekman transport induced SST trend ($\frac{d\text{SST}'_E}{dt}$) in response to stratospheric ozone depletion (shading in K decade^{-1}) for the multi-model mean of the stratospheric ozone-only simulation over 1982–2005 relative to preindustrial times. Stipples refer to the regions where at least four of the five models agree with the sign of the multi-model mean. (c, d) Zonal mean of (a, b) with a 5-degree running mean applied (multi-model mean, black; one standard deviation among models, gray shading). In panels (e, g) Same as (a, b) but for the components of Ekman transport due to changes in (e) wind ($\frac{d\text{SST}'_W}{dt}$) and (f) meridional surface temperature gradient ($\frac{d\text{SST}'_M}{dt}$) as well as the (g) residual term (Res). (h–j) Same as (c, d) but for the (h) $\frac{d\text{SST}'_W}{dt}$, (i) $\frac{d\text{SST}'_M}{dt}$ and (j) Res, respectively.

peaking at about 50°S at a rate of $-0.69 \text{ K decade}^{-1}$ and positive $\frac{dSST'_M}{dt}$ anomalies to the north up to $0.61 \text{ K decade}^{-1}$ (Figures 3f and 3i). Between 1982 and 2005, $\frac{dSST'_w}{dt}$ accounts for approximately three quarters of $\frac{dSST'_E}{dt}$ change, and $\frac{dSST'_M}{dt}$ for one quarter of the change (Figures 3h and 3i vs. Figure 3d). This highlights the important role of mean meridional SST gradient alteration in the Ekman-driven SST cooling over the Southern Ocean and reveals a key mechanism that was previously overlooked.

Besides oceanic advection, surface heat flux change can have an impact on Southern Ocean SST. Compared to preindustrial simulations, stratospheric ozone depletion leads to anomalous ocean heat uptake between 48°S and 60°S and anomalous heat loss north of 48°S during 1982–2005 (Figures 3a and 3c). This warms the higher latitudes while cooling the lower latitudes, offsetting the influence of oceanic advection processes on Southern Ocean SST ($\frac{dSST'_E}{dt}$). It should be noted that the majority of the dipole-like changes in the net surface heat flux come from those in turbulent heat fluxes (Figure S2 in Supporting Information S1; Bitz & Polvani, 2012; Li et al., 2021), with negative SST-turbulent heat flux feedback playing a role (Zhang & Cooke, 2021). Both Ekman transport and surface heat fluxes exhibit a rapid response to stratospheric ozone depletion on a seasonal timescale, resulting in a fast-cooling response of SST that can last for 3–25 years (Ferreira et al., 2015; Kostov et al., 2017; Seviour et al., 2016, 2019).

We also examine the slow SST response to stratospheric ozone depletion, which was thought to be primarily caused by changes in Southern Ocean upwelling. We find that the ozone-induced Ekman transport increase south of 46°S promotes northward cold-water advection, thereby intensifying the upwelling beneath the Ekman layer. Although this wind-driven Eulerian-mean upwelling is partially compensated by eddy-induced flows (Zhu & Liu, 2025), stratospheric ozone depletion can exacerbate residual upwelling (Figures 2d, 2f, and 2g). Over the Southern Ocean, there is a vertical temperature inversion mostly to the south of 55°S (Figure S3a in Supporting Information S1), prescribed as warmer water in the subsurface and colder water near the surface due to seasonal sea ice melting/freezing and export. As a result, the residual upwelling there brings warm water to the surface (Morioka et al., 2024), consequently leading to SST warming on a multi-year or longer timescale. This serves as a slow response following the fast-cooling response produced by Ekman transports and surface heat fluxes (Holland et al., 2017).

By assessing an Ekman layer thickness Z_{Ekman} of 30 m, sea water density ρ of 1024 kg m^{-3} , mixed layer entrainment timescale γ of 1.5 years and eddy-compensation in upwelling change σ of 30% in response to stratospheric ozone depletion (Figures 2d, 2f, and 2g; Ferreira et al., 2015; Kostov et al., 2017; Li et al., 2021; Li et al., 2016; Solomon et al., 2015), we discover that the intensified residual upwelling due to stratospheric ozone depletion contributes to SST warming mainly to the south of 55°S, with a peak of about $0.17 \text{ K decade}^{-1}$ at 65°S (Figure S3b in Supporting Information S1). By contrast, between 40°S and 55°S, where the vertical temperature inversion is weaker, upwelling induces cooling of less than $-0.10 \text{ K decade}^{-1}$. Both changes create a dipole-like SST change in the Southern Ocean. When we compare the SST change due to horizontal advection via Ekman transport with that due to vertical advection by upwelling, we find that the former is much larger than the latter. Although the timescale of the fast cooling and slow warming may still remain controversial among models that might slightly affect the magnitude of the compensation (Ferreira et al., 2015; Seviour et al., 2016, 2019), our results suggest that the sustained Ekman transport induced horizontal cold-water advection plays a crucial role in generating the Southern Ocean SST cooling over 1982–2005 when a more precise stratospheric ozone forcing is applied.

To further elucidate the transient response of Southern Ocean SST to the sustained stratospheric ozone concentration change, we show the evolution of zonal mean SST anomalies from 1982 to 2005 in the stratospheric ozone-only simulation relative to preindustrial times (Figure 4). Along with stratospheric ozone depletion, the surface Southern Ocean cools to the south of 50°S throughout the whole period. Such persistent SST cooling is primarily maintained by the constant Ekman transport induced cooling via horizontal advection ($\frac{dSST'_E}{dt}$; Figure 4a). Ozone-induced intensification of zonal winds brings on a cooler $\frac{dSST'_w}{dt}$ from $-1.05 \text{ K decade}^{-1}$ in 1982 to approximately $-3.74 \text{ K decade}^{-1}$ in 2005 (Figure 4b). Changes in the mean meridional SST gradient, meanwhile, amplify wind-driven SST changes, with $\frac{dSST'_M}{dt}$ rising from $-0.44 \text{ K decade}^{-1}$ in 1982 to $-2.20 \text{ K decade}^{-1}$ in 2005 (Figure 4c).

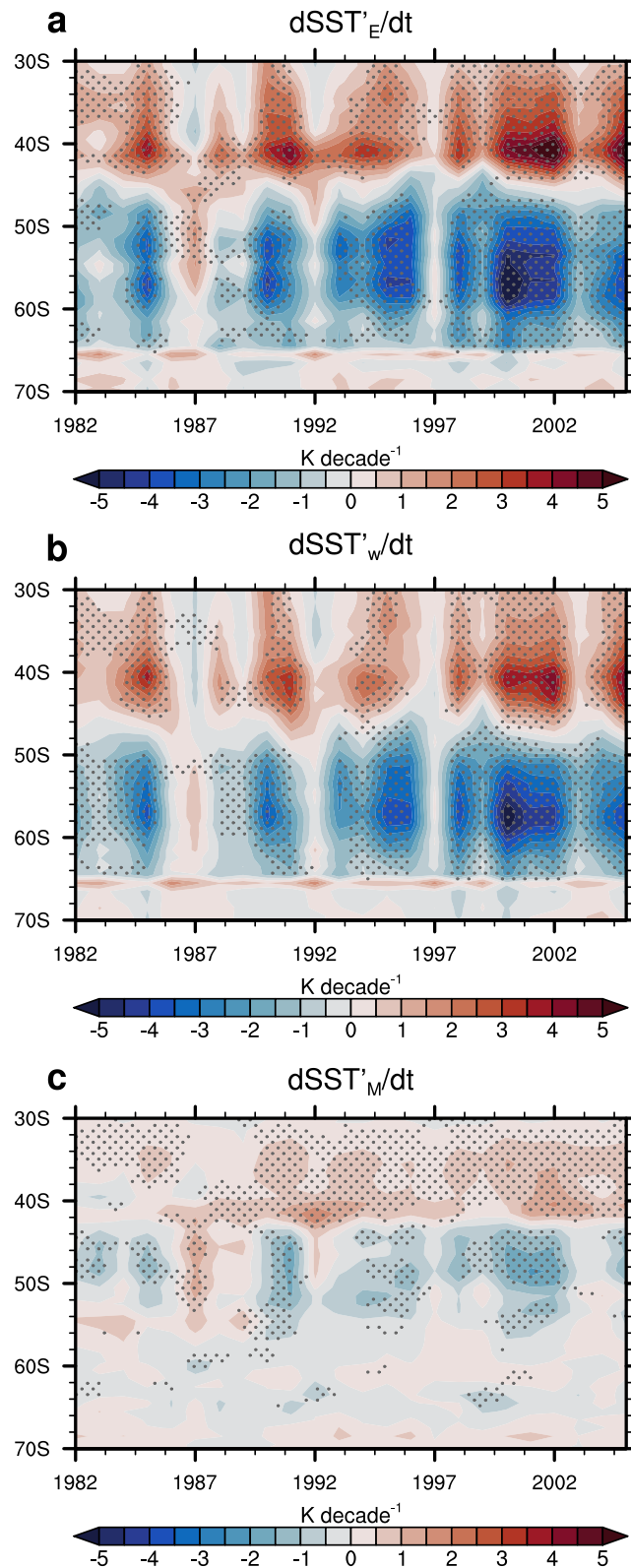


Figure 4. Annual and zonal mean (a) Ekman transport induced sea surface temperature (SST) change over the Southern Ocean, and the contributions from (b) surface wind change and (c) meridional SST gradient change (shading in K decade⁻¹) for the multi-model mean of the stratospheric ozone-only simulation relative to preindustrial times. Stipples refer to the regions where at least four of five models agree with the sign of the multi-model mean.

4. Discussion and Conclusion

In summary, we have looked into the impacts of stratospheric ozone depletion on Southern Ocean SST changes using stratospheric ozone-only simulations with CMIP5/6 models. We show that stratospheric ozone depletion intensifies and shifts poleward the Southern Hemisphere westerly winds, increasing northward Ekman transports and cold-water advection, and promoting Southern Ocean SST cooling south of 46°S. Meanwhile, meridional SST gradients alter over the Southern Ocean, causing colder water advection carried by mean surface winds to amplify SST cooling to the south of 43°S, serving as a key mechanism in Ekman transport-induced SST cooling. The horizontal cold-water advection via Ekman transport is partially compensated by modified surface heat fluxes and vertical advection of the water below the mixed layer. As a result, the Southern Ocean witnesses a surface cooling under stratospheric ozone depletion between 1982 and 2005.

Ozone-induced SST cooling is not limited to the Southern Ocean but occurs in many other regions of the world's oceans (Figure S4b in Supporting Information S1), which could be understood from the perspective of ozone's radiative forcing. In the comparison between stratospheric ozone-only and preindustrial simulations, negative anomalies of top-of-atmosphere radiative flux are pronounced over Antarctica (Figure S4a in Supporting Information S1) so that the global average of top-of-atmosphere radiative flux anomalies due to stratospheric ozone depletion amounts to -0.02 W m^{-2} , consistent with previous findings (Checa-Garcia et al., 2018; Myhre et al., 2013). This negative radiative forcing induces a global SST cooling trend of $-0.02 \text{ K decade}^{-1}$ between 1982 and 2005.

Along with Southern Ocean SST cooling, stratospheric ozone depletion affects Antarctic sea ice. From 1982 to 2005, the multi-model mean of stratospheric ozone-only simulation shows a significant sea ice increase in the Ross Sea and a weak and isolated increase in the outer sea ice zone of the Somov Sea, as consistent with observations in both regions (Figures S5a and S5b in Supporting Information S1), while sea ice decreases in many other areas. The sea ice increases and decreases generally associate with the SST cooling and warming in these places. The multi-model mean of historical simulation, on the other hand, depicts a general decrease in sea ice concentration around Antarctica (Figure S5c in Supporting Information S1). Our findings align with previous results (Ferreira et al., 2015) and indicate that stratospheric ozone depletion promotes Antarctic sea ice expansion in several regions during recent decades. It is also worth noting that ozone-induced sea ice increases have a smaller amplitude and cover smaller areas than observed, implying that stratospheric ozone depletion can contribute to but may not be the primary driver of the observed Antarctic sea ice expansion (Polvani et al., 2021).

Leveraging the GISS-E2-1-G total ozone-only and stratospheric ozone-only experiments (Table S1 in Supporting Information S1; Kelley et al., 2020), we can bridge the gap between our findings and those previous studies. The total ozone change contributes to the warming of Southern Ocean SST south of 36°S over 1982–2005 (Figure 1h) as consistent with previous results (Seviour et al., 2019; Sigmond & Fyfe, 2010, 2014). This is because the warming effect of tropospheric ozone increase surpasses the cooling effect from stratospheric ozone depletion (Figures 1h–1k). The tropospheric-ozone-induced surface warming is primarily driven by ocean heat uptake across most regions of the Southern Ocean (Figure S6 in Supporting Information S1), albeit the warming from surface heat flux is partially compensated by the cooling due to ocean dynamics.

Aside from stratospheric ozone depletion, anthropogenic aerosols and natural forcings such as solar variability and volcanic eruptions can also produce Southern Ocean SST cooling between 1982 and 2005 (Figure S7 in Supporting Information S1). Nevertheless, all of these forced SST cooling trends are overwhelmed by the strong SST warming trend caused by rising greenhouse gases, leading to an overall SST warming over the Southern Ocean in the historical simulation (Figure S7 in Supporting Information S1). This finding suggests that the simulated Antarctic sea ice change (Schneider & Deser, 2018) in climate models may be unduly sensitive to external forcing such as greenhouse gases (Schneider & Deser, 2018), which potentially influences the simulated high-latitude Southern Ocean SST change (Liu, 2025a, 2025b). It also suggests that internal climate variability (Liu, 2025a, 2025b), anomalous meltwater from ice sheets and ice shelves as a historical forcing (Schmidt et al., 2023), or oceanic eddy-resolved climate modeling (Yeager et al., 2023) need to be invoked for a better understanding of the Southern Ocean SST trend discrepancy between observations and models.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

CMIP6 model data are available at <https://esgf-node.ipsl.upmc.fr/projects/cmip6-ipsl/>. Figures are generated via the NCAR Command Language (2018).

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