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Key Points:

- Observations and climate models show a weakening sea surface temperature (SST) seasonal cycle induced by the delayed warming of summer SST over Southern Ocean (SO)
- The summer mixed layer depth and wind stress show increasing trends during the same period over the SO
- The summer wind-induced mixed layer deepening suppresses SO surface warming and thus weakening the SST seasonal cycle

Supporting Information:

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

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Summer Westerly Wind Intensification Weakens Southern Ocean Seasonal Cycle Under Global Warming

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Abstract Since the 1950s, observations and climate models show an amplification of sea surface temperature (SST) seasonal cycle in response to global warming over most of the global oceans except for the Southern Ocean (SO), however the cause remains poorly understood. In this study, we analyzed observations, ocean reanalysis, and a set of historical and abruptly quadrupled CO_2 simulations from the Coupled Model Intercomparison Project Phase 6 archive and found that the weakened SST seasonal cycle over the SO could be mainly attributed to the intensification of summertime westerly winds. Under the historical warming, the intensification of summertime westerly winds over the SO effectively deepens ocean mixed layer and damps surface warming, but this effect is considerably weaker in winter, thus weakening the SST seasonal cycle. This wind-driven mechanism is further supported by our targeted coupled model experiments with the wind intensification effects being removed.

Plain Language Summary The Southern Ocean (SO) sea surface temperature (SST) has experienced a decreased seasonal cycle since the 1950s, in contrast with the overall amplified seasonal cycle in the rest of global oceans. Here we investigated observations and climate model simulations and found that the decrease of SST seasonal cycle was associated with less warming in summer than in winter during the historical period. The suppressed warming in summer is accompanied by a deepened ocean mixed layer due to the intensification of surface westerlies. An enhanced mixed layer depth means the incoming heat flux will be trapped in a deeper mixed layer in summer, causing a cooler summer SST, which then leads to a weaker SST annual cycle. When the wind intensification effect is removed in our model simulations, the decreased SST seasonal cycle in the SO disappears.

1. Introduction

Although the increase of well-mixed greenhouse gases is nearly uniform in space, the sea surface temperature (SST) response shows strong spatial heterogeneity (Xie et al., 2010). In contrast to the background global warming, the Southern Ocean (SO) SST has exhibited a significant delayed warming since 1950 (Armour et al., 2016) or even a multidecadal cooling over the period 1980–2015 (Armour et al., 2016; Cavalieri et al., 2003; Zhang et al., 2019, 2022). The delayed warming or cooling of the SO SST has been attributed to a variety of physical processes (Armour et al., 2016; Chung et al., 2022; Doddridge & Marshall, 2017; Haumann et al., 2016, 2020; Hausmann et al., 2016; Kirkman & Bitz, 2011; Li et al., 2021; Meehl et al., 2016; Zhang et al., 2022).

In addition to the delayed warming feature, the SO is also unique in terms of its seasonal cycle changes. The seasonal cycle serves as the dominant mode of SST variability especially in extratropical oceans (Levitus, 1987; Wu et al., 2008; Yang & Wu, 2022). It is therefore critical to understand how the SST seasonal cycle responds to climate change (Dwyer et al., 2012; Stine et al., 2009; Yang & Wu, 2024). Climate models generally project an amplification of the seasonal cycle in most ocean regions, including the Artic, North Atlantic, North Pacific and South Indian Oceans (Jo et al., 2022; Liu et al., 2020, 2024; Shi et al., 2024). Chen and Wang (2015) argued that global warming would induce a thinner summer mixed layer over the North Pacific, and the resultant, smaller effective heat capacity would produce a stronger SST seasonal cycle. Liu et al. (2020) showed that wind-driven oceanic adjustment could further amplify the enhancement of the SST seasonal cycle in the midlatitude oceans due to the direct CO_2 impact. Jo et al. (2022) confirmed the influence of upper ocean stratification changes on the amplification of the SST seasonal cycle via a quantitative heat budget analysis. In the Arctic, the increase of the

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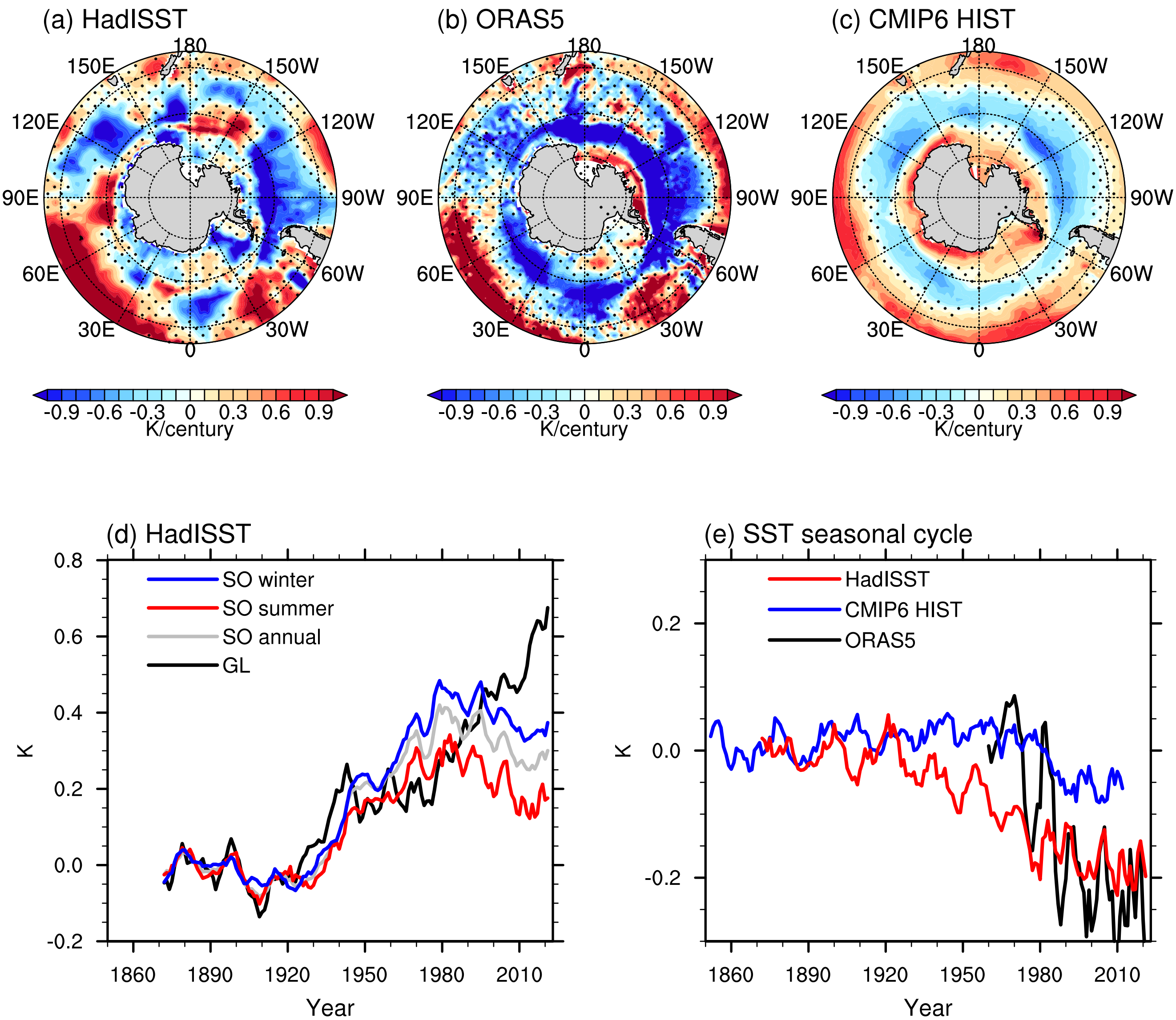

Figure 1. Observed and simulated weakening of Southern Ocean (SO) sea surface temperature (SST) seasonal cycle. (Top) The color shading shows the trend of SST seasonal cycle in (a) Hadley Center sea ice and SST (HadISST) during 1950–2023, (b) Ocean Reanalysis System 5 (ORAS5) during 1958–2023 and (c) Coupled Model Intercomparison Project Phase 6 (CMIP6) historical simulations during 1950–2014. (Bottom) (d) The time series of SST anomalies averaged over global ocean (black), SO (gray), Summer SO (red) and winter SO (blue) in HadISST during 1870–2023. (e) The time series of SST seasonal cycle anomalies in HadISST (red) during 1870–2023, CMIP6 HIST (blue) during 1850–2014 and ORAS5 (black) during 1958–2023. All anomalies are relative to the first 20 years mean of each data set. Stippling in all panels indicates statistically insignificant trends at the 95% confidence level using the Student's *t*-test.

SST seasonal cycle is found to be related to the loss of sea ice (Carton et al., 2015). Liu et al. (2024) find that the global SST seasonal cycle has intensified by 3.9 ± 1.6% in the recent four decades, with hotspot regions such as the northern subpolar gyres experiencing an intensification of up to 10%. Both Liu et al. (2024) and Shi et al. (2024) mainly attributed the intensification of SST seasonal cycle to the increasing of greenhouse gases. In the SO where the seasonal cycle accounts for over 80% of the SST variability, however, we find that most of the historical delayed warming occurs during summer, indicating a weakened seasonal cycle (Figures 1a–1c).

In the SO, where intense winds are forced by both stratospheric ozone depletion (Gillett et al., 2003; Waugh et al., 2013) and anthropogenic greenhouse gas emissions (Fyfe & Saenko, 2006), extreme buoyancy fluxes create some of the thickest ocean mixed layers on Earth (de Boyer Montégut et al., 2004; Sallée et al., 2013). As surface wind intensifies, the enhanced ocean vertical mixing deepens the ocean mixed layer and cools SST by bringing up more subsurface cold water. Therefore, SST tends to decrease as ocean mixed layer depth (MLD) increases, and vice versa. Moreover, previous studies suggest a relationship between the anomalous SO SST and MLD changes (Purich et al., 2021; Wilson et al., 2023). Doddridge et al. (2021) suggests that the summertime westerly winds over the SO enhance vertical mixing, cooling the summertime SST and warming the subsurface waters. The subsurface heat will return to the mixed layer and lead to warm SST anomalies in winter. However, it remains unclear how the wind-induced MLD changes contribute to the extraordinary change in the SST seasonal cycle following an increase in CO_2 emissions.

The primary goal of this work is to understand the cause of the weakened SST seasonal cycle in the SO under global warming with a particular focus on the MLD change processes. Section 2 describes the observations, model simulations, and definitions used in this study. Section 3 investigates the change of SST seasonal cycle in observations. Section 4 investigates the change of the SST seasonal cycle during the historical period and under the quadrupled CO_2 scenario as simulated by the climate models from the phase 6 of the Coupled Model Intercomparison Project (CMIP6; Eyring et al., 2016). To further confirm the mechanisms, we analyze large-ensemble, mechanically decoupled simulations with the Community Earth System Model version 2 (CESM2; Danabasoglu et al., 2020) in Section 4. Conclusions and discussion are presented in Section 5.

2. Data, Model, and Methods

2.1. Observational Data Sets

For SST observations, we use the monthly Hadley Center sea ice and SST data set (HadISST, Rayner et al., 2003) with a time period of 1870–2023 and a horizontal resolution of $1° \times 1°$. We also use the SST, MLD and surface wind stress variables from ocean reanalysis product, Ocean Reanalysis System 5 (ORAS5, Copernicus Climate Change Service, 2021) for a time period of 1958–2023 with a resolution of $0.25° \times 0.25°$.

2.2. CMIP6 Simulations

To better understand the underlying mechanisms of the SO seasonal cycle change, we analyze a set of climate model simulations with a nominal resolution of $1° \times 1°$ (Table S1 in Supporting Information S1). We analyze the historical experiments (HIST; 30 models), the preindustrial control experiments (piControl; 32 models), and the abruptly quadrupled CO_2 experiments (abrupt-4xCO_2; 32 models) from the CMIP6 archive (Eyring et al., 2016). The historical experiments are integrated from 1850 to 2014 and branched from the stable preindustrial climate generated in the piControl, using the same historical forcing data provided by CMIP6. The abrupt-4xCO_2 experiments simulate an idealized global warming scenario in which the atmospheric concentration of CO_2 is instantaneously quadrupled from its initial preindustrial value and then held fixed. Note here, the SO SST shows a fast (over decades) and slow (hundred years or longer) response to a given forcing (Ferreira et al., 2015; Kostov et al., 2017; Long et al., 2014). For the abrupt-4xCO_2 experiments, we choose the average over years 1–30 relative to a 50-year average from the piControl to represent the transient response. In our analysis, we only analyze the first member run (r1i1p1f1) of each model to ensure equal weight in inter-model analysis.

2.3. Single Model Ensembles

We use two CESM2 ensembles forced by realistic, time-varying 1850–2014 external forcing. In the Fully Coupled Model (FCM) ensemble, the ocean and atmosphere exchange time-varying buoyancy and wind stress (momentum) fluxes. In the Mechanically Decoupled Model (MDM), the ocean and atmosphere exchange time-varying buoyancy fluxes, but the ocean is forced by a fixed, 6-hourly wind stress climatology, calculated from preindustrial conditions. In the MDM, only the surface wind stress (i.e., momentum flux) is decoupled from the ocean and restored to the climatological values. Meanwhile, the atmospheric circulation and resulting near-surface wind speed in the atmosphere model remains freely evolving and unconstrained. Therefore, the MDM and FCM differ in surface wind stress forcing on the ocean but may still simulate similar near-surface wind speed. The FCM ensemble was created by branching 50 ensemble members from a FCM piControl run, and the MDM ensemble was created by branching 20 ensemble members from an MDM piControl run. We calculate the ensemble mean of FCM and MDM to remove the internal variability. This model set-up allows us to isolate the impact of wind-driven ocean circulation from the thermodynamic impacts of wind speed changes through turbulent heat fluxes. A detailed description of these simulations can be found in Larson et al. (2018) and McMonigal et al. (2023).

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2.4. Definitions

In the current paper, we define the SO as the ice-free latitude band of 50°S–65°S, which envelops the core of the circumpolar westerly jet. We calculate the climatological seasonal cycle using observational and model data sets and find that the SO exhibits a maximum in February and minimum in September (Figure S1 in Supporting Information S1). So, the amplitude of the SST seasonal cycle is defined as the difference between the summer mean SST and winter mean SST. In the Southern Hemisphere, including the SO, summer and winter are defined as January–March and August–October, respectively (Figure S1 in Supporting Information S1).

3. Robust Weakening of SO SST Seasonal Cycle Since the 1950s

As is well documented by previous studies (Cavalieri et al., 2003; Zhang et al., 2019), the annual-mean SST in the SO has experienced a suppressed warming trend (i.e., a relatively slow warming rate; 0.015°C/decade) since the 1950s, in clear contrast with the overall strong global ocean warming (0.079°C/decade; Figure 1d; Armour et al., 2016). This suppressed SO warming is particularly evident during its local summer (0.001°C/decade) as compared to winter (0.025°C/decade), suggesting a weakened seasonal cycle of SST. The SST seasonal cycle exhibits a prominent negative (i.e., weakened) trend within 50°S–65°S seen across observational and reanalysis data sets (Figures 1a and 1b), consistent with Shi et al. (2024).

The delayed SO warming since the 1950s is suggested to be a robust signal under global warming (Armour et al., 2016; Marshall et al., 2015), even well captured by a coarse-resolution general circulation model in early studies (e.g., Bryan et al., 1988). Our analysis further suggests that the weakening of SO seasonal cycle is also a robust feature seen across observational and reanalysis data sets (Figures 1a and 1b). Notably, the weakening of the SO seasonal cycle is also well captured by CMIP6 historical simulations with a similar spatial structure (Figure 1c; cf. Figure 1a), implying it is externally forced. In terms of timing, observations and CMIP6 simulations consistently show that the SO seasonal cycle began weakening around the 1950s and has persisted since then (Figure 1e). Understanding the cause of suppressed SO warming during the summertime is a key to both the weakening of SO seasonal cycle and the suppressed annual-mean SO warming.

4. Mechanisms of the Weakening of SO SST Seasonal Cycle Under Global Warming

4.1. Hypothesis Motivated From Observational Hints

Why has the SST seasonal cycle weakened over the SO (Figure 2a)? The answer to this question is not obvious, especially while the seasonal cycle has strengthened in most of the global oceans (Jo et al., 2022; Liu et al., 2020, 2024; Shi et al., 2024). To investigate further, ocean MLD changes are investigated using the ocean reanalysis, ORAS5. The summertime ocean MLD has significantly increased since the 1950s within 50°–65°S, collocated with the ocean regions where the SST seasonal cycle weakens (Figures 2a and 2b). The strong deepening of summer MLD is in turn associated with an intensification of summer westerly wind stress (Figures 2c and 2d). Such effects are much weaker during local winter for two reasons (Figure S2 in Supporting Information S1). First, the background MLD is much deeper in winter than in summer (Figure S3 in Supporting Information S1), which makes SST relatively insensitive to MLD changes. Second, the wintertime MLD is in fact found to become shallower since the 1950s possibly dominated by the surface warming effect, as the westerly wind intensification is rather weak in winter (Figure S2 in Supporting Information S1; also see Swart & Fyfe, 2012). In summary, we propose the following hypothesis as informed by observational analysis: An intensification of summer surface westerly winds since the 1950s can potentially lead to a deepening of ocean mixed layer over the SO and therefore suppresses the local warming, giving rising to a weakened seasonal cycle. To test the hypothesis, we analyze a suite of climate simulations in Sections 4.2–4.4.

4.2. Attribution to External Forcing: CMIP6 Historical Experiments

To determine the role of external forcing, we analyze the historical simulations of 32 climate models participating in the CMIP6. In the multi-model mean, a circumpolar band of weakened SST warming is identified in the latitude band of 50°S–65°S for summer, but much stronger for winter (Figure S4 in Supporting Information S1). As a result, the amplitude of the SST seasonal cycle over the SO weakens during 1950–2014, in contrast with the surrounding ocean regions (Figure 3a). These results suggest that the weakened SO SST seasonal cycle observed since the 1950s is at least partly linked to the historical global warming, indicative of external forcing.

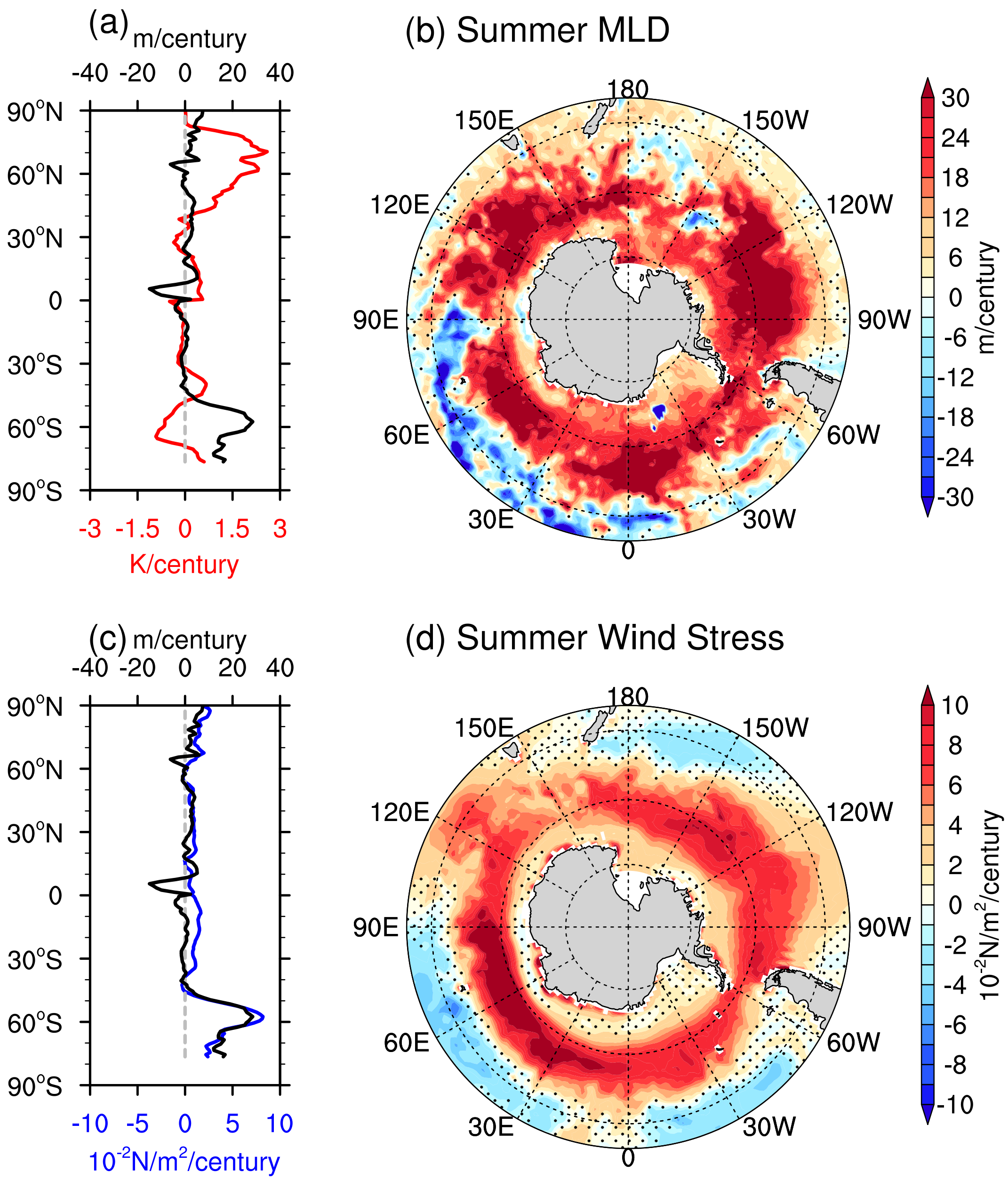

Figure 2. (a, c) The zonal mean of the trend of sea surface temperature seasonal cycle (red), summer mixed layer depth (MLD) (black) and summer wind stress (blue) during 1958–2023 in Ocean Reanalysis System 5 (ORAS5). The zero-line is shown in dashed gray line. (b, d) The trend of summer MLD and summer wind stress during 1958–2023 in ORAS5. Stippling in all panels indicates statistically insignificant trends at the 95% confidence level using the Student's *t*-test.

Furthermore, we find that the weakened SST seasonal cycle only became evident after the 1950s, also consistent with the observations (Figure 1e).

Our further investigations suggest that the weakening of SO SST seasonal cycle collocates with a circumpolar band of deepened summer MLD (Figure 3a), in contrast with the MLD decrease outside 50°S–65°S. Interestingly, three local maxima of MLD increase are found around 120°W, 120°E, and 30°E, respectively, where the strongest weakening of SST seasonal cycle are also found (Figures 3a and 3b). The tripole pattern may be related to the zonal wave 3 pattern in the atmosphere (Raphael, 2004), which was suggested to be a preferred atmospheric response in the Southern Hemisphere high latitudes to zonally asymmetric deep convection in the tropics (Goyal, Jucker, et al., 2021). Moreover, a similar band of summer surface westerly intensification is found within 50°S–

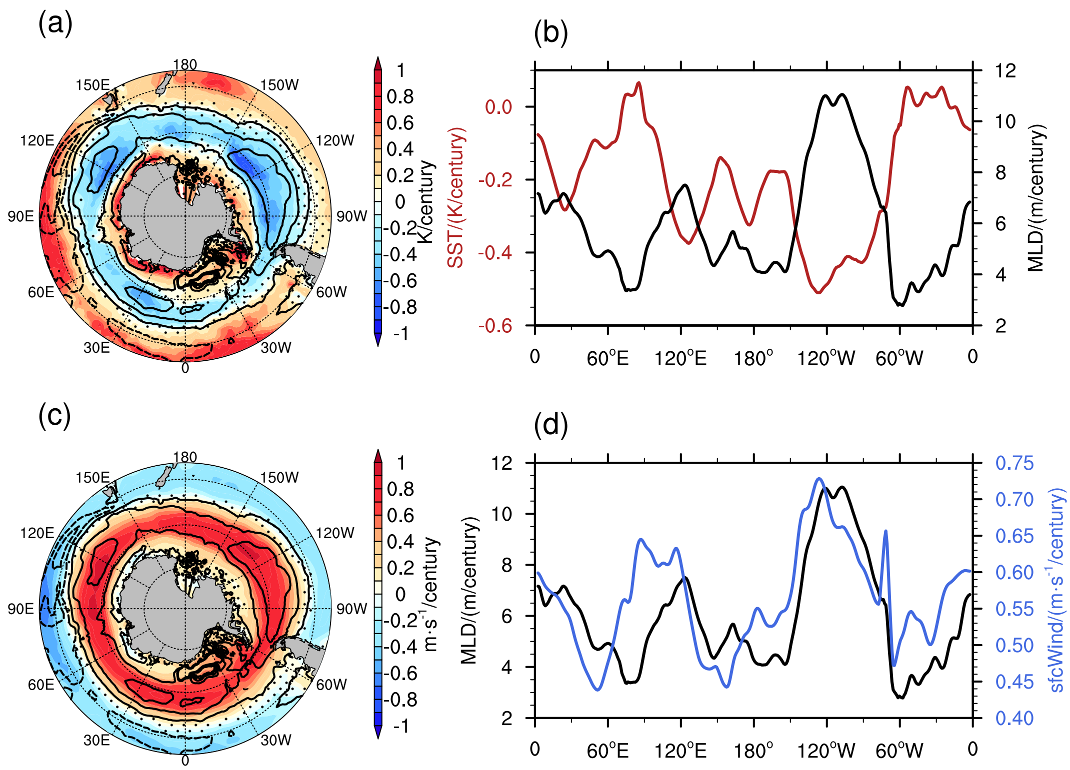

Figure 3. The weakening of Southern Ocean sea surface temperature (SST) seasonal cycle in Coupled Model Intercomparison Project Phase 6 historical models. (a, c) The color shading shows the trend of (a) SST seasonal cycle and (c) summer surface wind speed during 1950–2014. The trend of summer mixed layer depth (MLD) (contours, from −15 to 15, solid lines mean positive and dashed lines mean negative) is also shown for comparison. Units: m/century. (b, d) Latitudinal mean from 50°S to 65°S of the trend of (b) SST seasonal cycle (red) and summer MLD (black) and (d) summer surface wind speed (blue) and summer MLD (black). Stippling in all panels indicates statistically insignificant trends at the 95% confidence level using the Student's *t*-test.

65°S, and the locations of its local maxima also agree well with the aforementioned regions (Figures 3c and 3d). These results are all consistent with the observations, implying a critical role of summer westerly winds intensification in the weakening of SO SST seasonal cycle. Why has the westerly wind strengthened? Is the increase of greenhouse gases or other external forcing (e.g., aerosols or ozone changes) responsible for this feature? To address those questions, we analyzed CMIP6 DAMIP experiments and found that it was mainly caused by the greenhouse gas and ozone forcings (Polvani et al., 2011; Figure S5 in Supporting Information S1).

4.3. Attribution to Greenhouse Gas Increase: CMIP6 Abrupt-4xCO_2 Experiments

Our previous analysis suggests that the weakening of SO SST seasonal cycle is a robust feature found in both observations and historical simulations, which implies that it is perhaps a forced response to external radiative forcing. Given that westerly wind intensification is the primary mechanism for SST seasonal cycle weakening and that an increase in pure greenhouse gas forcing could lead to a westerly wind intensification, we analyze the abrupt-4xCO_2 experiments from 32 CMIP6 models. In the first 30 years after the CO_2 quadrupling, the same features as observations and the historical runs are identified over the SO, including a weakening of SST seasonal cycle, a strong deepening of summer MLD, and an intensification of summer surface westerly winds (Figure 4). These results suggest that the transient response to the increase of greenhouse gas can lead to a weakened SST seasonal cycle over the SO as observed and simulated by CMIP6 models since the 1950s.

4.4. Further Evidence From the CESM2 Mechanically Decoupled Simulations

In order to quantify the contribution of MLD effect to the SST seasonal cycle change, we compare two large-ensemble simulations within CESM2, FCM, and MDM. The details of these two ensembles are introduced in

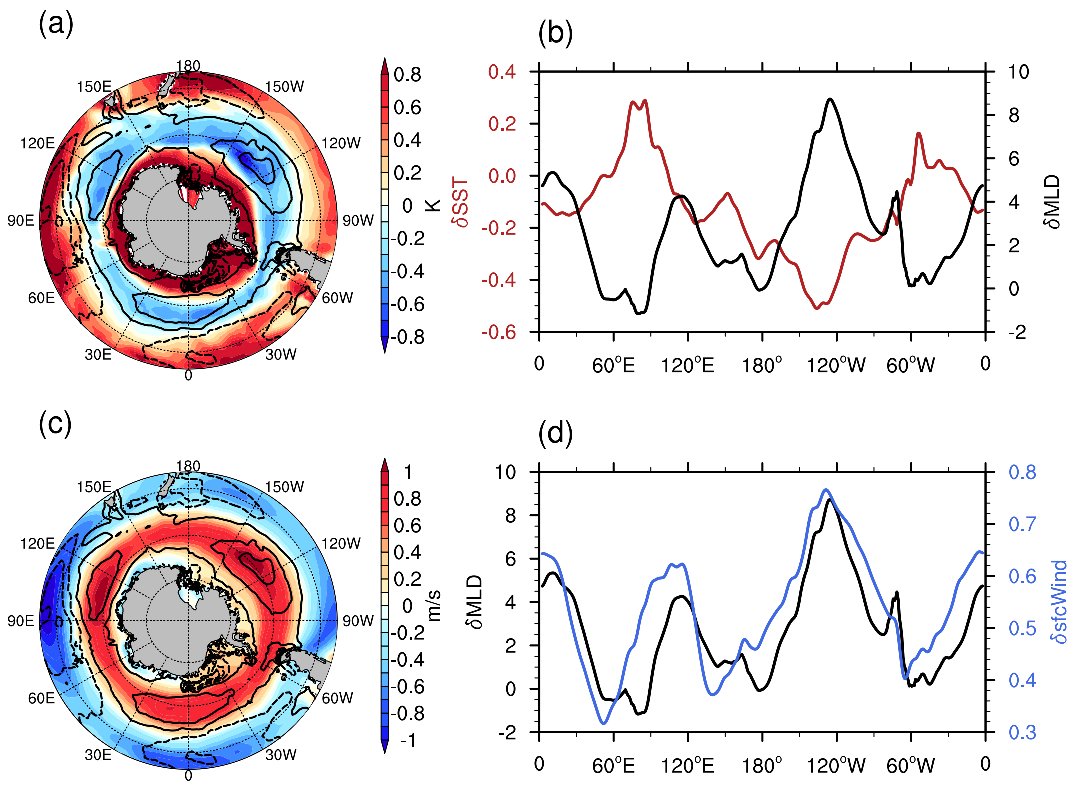

Figure 4. Same as Figure 3, but for the changes of first 30 years relative to control run in Coupled Model Intercomparison Project Phase 6 abrupt 4xCO_2 experiment.

Section 2. In short, FCM represents the standard historical simulations as in the CMIP6 archive, while MDM highlights the historical scenario without the influence of the changes in wind-driven ocean circulations. The difference between the ensemble mean FCM and MDM experiments isolates the impacts of the externally forced changes in surface wind stress on the ocean circulation, including the impacts on MLD. The FCM results are broadly consistent similar with the CMIP6 historical runs as expected (Figure 5a). However, when the wind stress changes are not communicated to the ocean as in the MDM, the circumpolar band structures in both the SST seasonal cycle and summer MLD changes disappear (Figure 5b). The similar circumpolar bands of weakened SST seasonal cycle, increased summer MLD, and intensified summer surface westerly winds in FCM-MDM provide direct evidence for the physical mechanisms identified in observations and CMIP6 simulations. That is, the enhanced summer winds can indeed decrease the seasonal cycle in the SO by deepening the summer MLD.

5. Conclusions and Discussion

By analyzing available observations and ocean reanalysis, we find that the SO SST seasonal cycle has been weakening since the 1950s. Through CMIP6 model analysis, this observed feature is found to be well captured by the historical simulations, pointing to an externally forced origin, and also by the transient response in the abrupt-4xCO_2 experiments. These modeling results suggest that the weakening of SO SST seasonal cycle is a robust signature of ozone and greenhouse gas-induced westerly wind intensification. Our analysis further reveals that the weakening of SO SST seasonal cycle is due mainly to the intensification of summer surface westerlies over the SO, which acts to deepen the MLD and suppress the surface warming. This mechanism is consistently identified in ocean reanalysis, CMIP6 historical and abrupt-4xCO_2 simulations, and further confirmed by CESM2 mechanically decoupled simulations, wherein externally forced wind stress changes on the ocean circulation under the historical warming are suppressed.

Our study has direct implications for understanding the SO response to global warming. Previous studies highlight the important role of climatological upwelling in delaying the SO warming (Armour et al., 2016; Bryan et al., 1988). Our study instead emphasizes the role of surface westerly intensification, a robust fingerprint of

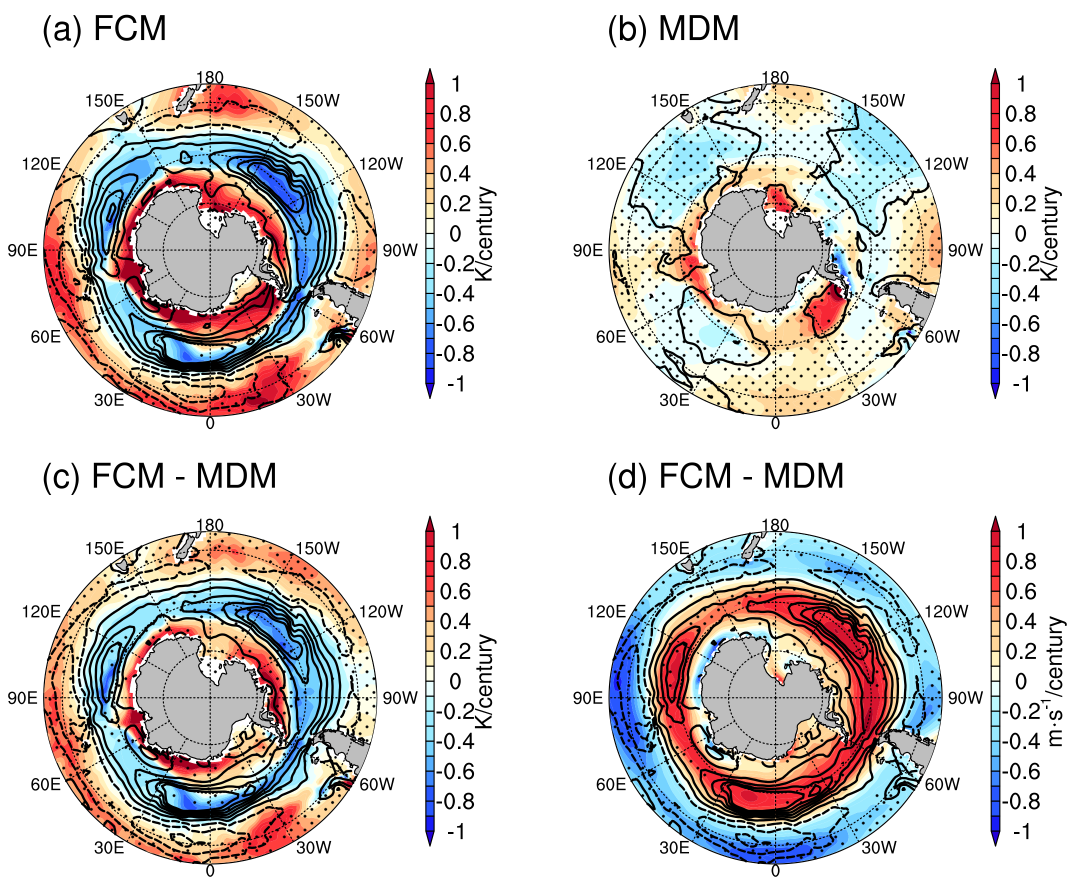

Figure 5. The trend of sea surface temperature seasonal cycle (shading) and summer mixed layer depth (MLD) (overlayed contours) during 1950–2014 in (a) Fully Coupled Model (FCM), (b) Mechanically Decoupled Model (MDM) and (c) FCM-MDM. (d) The trend of summer surface wind speed (shading) and summer MLD (overlayed contours) in FCM-MDM for the period 1950–2014. All contours overlayed span from −15 to 15. Units: m/century. Stippling in all panels indicates statistically insignificant trends at the 95% confidence level using the Student's *t*-test.

global warming, in the suppressed SO warming via deepening the ocean mixed layer. The mechanism proposed in our study is found to be more effective in local summer both because the wind intensification reaches the strongest in summer (Swart & Fyfe, 2012) and that the background MLD is smaller in summer. Our mechanism is not exclusive to the climatological upwelling mechanism but rather provides a complementary factor that further contributes to the suppressed SO warming especially in summer.

Previous studies found that both the direct CO_2 effect and the total wind effect contribute to the overall enhancement of the SST seasonal cycle (Liu et al., 2020, 2024). The contribution from wind stress–driven oceanic adjustment is much more important than the thermodynamic wind speed feedback, especially to the seasonal cycle enhancement in the SH midlatitudes. However, Liu et al. (2020, 2024) focus on the region between 50°S and 50°N latitudes and do not fully include the SO. Our study complements this. Liu et al. (2024) and Shi et al. (2024) suggest that the greenhouse gases are the primary driver of the intensified global SST seasonal cycle. However, in the regional oceans, especially the SO where ozone changes also play a role, ozone is the main factor contributing the decrease of SST seasonal cycle (Cai, 2006; Polvani et al., 2011; Figure S6 in Supporting Information S1).

Despite these emerging results, the limitations of past and present observational systems in SO reduce our confidence of these multidecadal climate changes. We attribute the decrease of the SST seasonal cycle over SO to the external forcing in Sections 4.2 and 4.3. However, it is likely that natural variability may also play an important role in the strengthening of wind stress during 1950–2014 (Goyal, Sen Gupta, et al., 2021; Zhang et al., 2019). Another caveat is that although CMIP6 and single model ensembles could capture the feature of the weakening of SST seasonal cycle in the SO, models seem to underestimate the magnitude of weakening compared to the observation. The reduction in amplitude in climate simulations is weaker than in observations. Additionally, the observations show a weakening beginning around 1920, much earlier than in the model simulations. There are three possibilities to explain the mismatch between the observations and model ensembles. First, the observational data before the satellite era is less reliable and has large data uncertainties. Second, the models may not accurately represent the SO processes and may contain biases. Third, the model-observation discrepancy may also be caused by the presence of internal climate variability (Zhang et al., 2019).

Conflict of Interest

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

Data Availability Statement

For observational data sets, the HadISST version 1.1 data are available through Rayner et al. (2003); ORAS5 data are available through the Copernicus Climate Change Service's Climate Data Store (Copernicus Climate Change Service, 2021). The CMIP6 historical, piControl and abrupt-4xCO_2 data are available through Eyring et al. (2016) via the link: https://esgf-node.llnl.gov/search/cmip6. CESM2 Fully-Coupled (FC) large ensemble members at available through Rodgers et al. (2021) via the link: https://www.cesm.ucar.edu/projects/community-projects/LENS2/. The data analyzed from CESM2 MDM are available from Zhang et al. (2024). Code to make the figures is available in Zhang (2024).

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