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Key Points:

- We nudge winds to observations and add estimates of observed freshwater from ice sheet and ice shelf melt in a coupled climate model
- Southern Ocean sea surface temperature trends and variability better match observations, with both winds and meltwater being important
- The constrained model simulates strong Antarctic sea ice expansion and only partially captures recent sea ice lows

Supporting Information:

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

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Winds and Meltwater Together Lead to Southern Ocean Surface Cooling and Sea Ice Expansion

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Abstract Southern Ocean surface cooling and Antarctic sea ice expansion from 1979 through 2015 have been linked both to changing atmospheric circulation and melting of Antarctica's grounded ice and ice shelves. However, climate models have largely been unable to reproduce this behavior. Here we examine the contribution of observed wind variability and Antarctic meltwater to Southern Ocean sea surface temperature (SST) and Antarctic sea ice. The free-running, CMIP6-class GISS-E2.1-G climate model can simulate regional cooling and neutral sea ice trends due to internal variability, but they are unlikely. Constraining the model to observed winds and meltwater fluxes from 1990 through 2021 gives SST variability and trends consistent with observations. Meltwater and winds contribute a similar amount to the SST trend, and winds contribute more to the sea ice trend than meltwater. However, while the constrained model captures much of the observed sea ice variability, it only partially captures the post-2015 sea ice reduction.

Plain Language Summary While most of the globe has warmed in recent decades, the Southern Ocean around Antarctica cooled at the surface and its sea ice expanded from the beginning of satellite observations in 1979 through 2015. This unexpected behavior has been linked to changes in winds and to the addition of cold, fresh water from the melting of Antarctic's ice sheet and ice shelves. However, the importance of these two potential drivers has been unclear, partly because global climate models have often struggled to reproduce the observed changes. Here, we modify a climate model, constraining it to simulate observed winds and adding in realistic amounts of meltwater. With these changes, the model can simulate changes in SST and sea ice that are similar to observations. Winds and meltwater both play an important role. However, they cannot fully explain the large Antarctic sea ice reductions that were observed after 2015, suggesting that other factors may be at play.

1. Introduction

The Southern Ocean is of critical importance for global climate. Connecting three major ocean basins, it plays a key role in global ocean circulation via sea ice formation (Abernathy et al., 2016) and is responsible for a large majority of global ocean heat and carbon uptake (Frölicher et al., 2015). It drives melt of the Antarctic ice sheet (AIS), impacting global and regional sea level rise (Rignot et al., 2019)—a major threat to societies around the world. Changes in the Southern Ocean may also impact the climate of other regions via atmospheric teleconnections (Kim et al., 2022). Besides these physical climate impacts, the subpolar Southern Ocean provides nutrients that shape global biological productivity (Sarmiento et al., 2004).

While most of the globe has warmed in recent decades as greenhouse gas concentrations have increased, the Southern Ocean has cooled on average at the surface, with cooling strongest in the Pacific. Concurrently, the areal coverage of Antarctic sea ice shows a negligible overall trend, consisting of a weak expansion from 1979 through 2015 and strong lows thereafter. The Southern Ocean surface cooling and associated freshening enhance upper ocean stratification, leading to greater subsurface and abyssal warming (Purkey & Johnson, 2013; N. C. Swart et al., 2018).

The latest generation of coupled climate models in the Climate Model Intercomparison Project Phase 6 (CMIP6; Eyring et al., 2016) generally does not capture the observed Southern Ocean cooling nor Antarctic sea ice expansion over the recent historical period (Beadling et al., 2020; Roach et al., 2020; Wills et al., 2022), leading to large uncertainty in projections of future Antarctic and Southern Ocean change (Fox-Kemper et al., 2021).

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Southern Ocean SSTs and Antarctic sea ice are tightly coupled (Blanchard-Wrigglesworth et al., 2021; X. Zhang et al., 2021). In CMIP6 models, the Southern Ocean is typically biased warm and fresh relative to observations, with some models being exceptionally warm (Beadling et al., 2020). Models are broadly unable to capture the observed SST trends over the Southern Ocean, even when considering the internal variability in large ensembles (Wills et al., 2022). Many models simulate strong declines in Antarctic sea ice, unlike the observations, and none capture the observed spatial distribution of sea ice trends (Roach et al., 2020). It has been unclear to what extent the mismatch is due to biases in the forced response versus an underestimation of natural variability (Chung et al., 2022; Roach et al., 2020). Understanding the physical processes driving Southern Ocean SST and sea ice change and how they are represented in climate models is critical to be able to separate the observed behavior into externally forced changes and internal variability, and to improve future projections.

The SST cooling from 1979 to present and sea ice expansion from 1979 through 2015 have been linked to two main factors that we focus on here: changes in atmospheric circulation (e.g., Blanchard-Wrigglesworth et al., 2021; Chung et al., 2022; Kostov et al., 2017), and increases in freshwater fluxes (e.g., Dong et al., 2022; Pauling et al., 2016; Rye et al., 2020). Other work has hypothesized that changes in eddy-driven poleward heat transport, which are not captured at the typical resolution of today's climate models, may play an important role (Rackow et al., 2022).

Winds exert a strong control on the Southern Ocean meridional overturning circulation, Antarctic Circumpolar Current, water mass structure, and gyre strength and position. Winds are also a key driver of sea ice evolution, through changes in both ice advection and thermodynamics (P. R. Holland & Kwok, 2012). In recent decades, the Southern Annular Mode (SAM) has strengthened and shifted polewards, largely forced by stratospheric ozone depletion, but with some contribution from greenhouse gases and internal variability (Fogt & Marshall, 2020; J. L. Thomas et al., 2015). Much previous research focused on the hypothesized “two-timescale” response to increased westerly winds: a fast ocean cooling response as Ekman drift advects cold water northward, followed by a slow warming response (and sea ice reduction) sustained by Ekman upwelling of warmer subsurface water (Ferreira et al., 2015). However, the importance of this mechanism has since been called into question (M. M. Holland et al., 2017; Seviour et al., 2019). Atmospheric circulation changes over the Southern Ocean have also been influenced by tropical teleconnections. In particular, the sea ice expansion from 1979 through 2015 has been linked to the negative phase of the Interdecadal Pacific Oscillation (Chung et al., 2022; Meehl et al., 2016). Note that in coupled climate models, the winds alone cannot fully account for the observed sea ice trend (Blanchard-Wrigglesworth et al., 2021; Sun & Eisenman, 2021).

Concurrently, freshwater input to the Southern Ocean has increased due to melt of Antarctica's grounded ice, ice shelves and icebergs (Slater et al., 2021), as well as increases in precipitation minus evaporation (Fyfe et al., 2012; Purich et al., 2018). The role of AIS melt is particularly uncertain as interactive ice sheets are only now being included in state-of-the-art climate models, and were not included in any CMIP6 model. Applying freshwater representing AIS melt as forcing to ocean and/or climate models generally results in Southern Ocean cooling and sea ice expansion, although many studies apply large, idealized amounts and the magnitude of response varies (e.g., Bronselaer et al., 2018; Dong et al., 2022; Pauling et al., 2016; Purich & England, 2023; Purich et al., 2018; Rye et al., 2020; Sadai et al., 2020) - see Table 1 in N. Swart et al. (2023) for a comprehensive list. The net global impact remains highly uncertain (e.g., Li, England, et al., 2023; Li, Marshall, et al., 2023; Sadai et al., 2020).

Most studies investigating Southern Ocean SST and sea ice trends have thus far only considered one factor in isolation, so the relative roles of atmospheric circulation and Antarctic meltwater are unclear. Here, we offer a unique perspective on these two potential drivers of the observed Southern Ocean surface changes, by considering both factors within a common modeling framework. We find that constraining a climate model to observed winds and meltwater fluxes from 1990 through 2021 gives SST variability and trends consistent with observations.

2. Methods

2.1. NASA GISS E2.1 Climate Model

We use the NASA Goddard Institute for Space Studies (GISS) version E2.1 climate model (GISS-E2.1-G), which was part of the official submission to CMIP6 (Eyring et al., 2016). The atmospheric component has 2° by 2.5° latitude and longitude resolution respectively, 40 vertical layers and a model top at 0.1 hPa. The ocean component, GISS Ocean v1, is mass-conserving with a free surface, natural surface boundary conditions for heat and

freshwater fluxes, horizontal resolution of 1° by 1.25° in latitude and longitude respectively, and 40 vertical layers. The sea ice component has two mass layers with two thermal layers in each mass layer, and uses viscous-plastic rheology (J. Zhang & Rothrock, 2000) and a “brine-pocket” parameterization (Bitz & Lipscomb, 1999; Schmidt et al., 2004). Land ice is represented by a simple two-layer model topped by snow cover (Alexander et al., 2019; Schmidt et al., 2014). If surface heating melts the upper-layer land ice, meltwater is directed into the ocean near southern Greenland and low-lying Antarctica to conserve ice sheet mass and energy (see Text S1 in Supporting Information S1). Comprehensive reviews of the model physics, historical and future climate change simulations are provided in Kelley et al. (2020), Miller et al. (2021), and Nazarenko et al. (2022).

Here, we consider a 20-member control ensemble (denoted CTRL) and experiments that impose wind nudging (WIND), anomalous meltwater forcing (MW), or both (WIND&MW), with varying numbers of ensemble members (Table S1 in Supporting Information S1). Historical simulations are extended through 2021 either using SSP2-4.5 or using observed greenhouse gases and solar forcing, while keeping composition and land use/land change at 2014 levels (Table S1 in Supporting Information S1); results are robust to these choices.

2.2. Wind Nudging

Wind-nudging simulations impose the observed large-scale circulation in the atmosphere, and therefore constrain uncertainty due to atmospheric dynamics (Blanchard-Wrigglesworth et al., 2021; Roach & Blanchard-Wrigglesworth, 2022; Roach et al., 2022). This is done by including an additional term in the model's governing equations,

$$\frac{dx}{dt} = F(x) + F_{\text{nudge}},$$

where $x(t)$ is the model state vector at model timestep t and $F(x)$ the internal tendency of the system without nudging. The nudging term F_{nudge} is proportional to the difference between the target analysis at a future analysis timestep, $O(t'_{\text{next}})$, and the model state at the current timestep, $x(t)$,

$$F_{\text{nudge}} = \frac{\alpha}{\tau} (O(t'_{\text{next}}) - x(t)),$$

where α is the nudging coefficient, and the relaxation timescale of the nudging is $\tau = t'_{\text{next}} - t$.

Here, we apply wind nudging globally and at all vertical layers in the atmosphere. We use reanalysis winds from MERRA-2 (Gelaro et al., 2017), which begins in 1980. A weak nudging coefficient, $\alpha = 0.001$, is sufficient to constrain the modeled atmospheric circulation, such that the simulated SAM is strongly correlated with MERRA-2 ($R^2 = 0.96$ for detrended monthly timeseries smoothed with a 3-month moving average). Approximately 6 years of spin-up are required for the surface ocean to adjust to the onset of wind-nudging (Figure S1 in Supporting Information S1). For consistency with other experiments (below), we show results after the spin-up period, from 1990 through 2021.

2.3. Meltwater Forcing

Climatological ice sheet discharge is included in GISS-E2.1-G based on an assumption of hemispheric ice sheet mass and energy balance. We add freshwater forcing that is *anomalous* with respect to ice sheet mass balance, based on the observed post-1990 “ice imbalance” from melting ice shelves and ice sheets in Antarctica and Greenland. The amounts used are based on satellite altimetry, satellite gravimetry and input–output data sets (Mankoff et al., 2021; Slater et al., 2021) and are listed in Table S2 and Figure S2 in Supporting Information S1. Anomalous meltwater is added to the ocean with a fixed, uniform spatial distribution and from the surface to 200 m (Text S1 and Figure S3 in Supporting Information S1). Note that in reality meltwater input is heterogeneous in space; this is discussed further below. Observational estimates for Antarctica are only available from 1994 to 2016; from 2017 through 2021 and from 1990 through 1994 the amounts are extrapolated from the first and last three years of the record. The influence of meltwater on global climate and sea level in free-running GISS-E2.1-G experiments is discussed by Schmidt et al. (2023).

2.4. Metrics & Observations

We take the Southern Ocean as $50\text{--}65^\circ\text{S}$ (results are similar for other definitions). Sea ice area (SIA) is computed as the summed product of ice concentration and grid cell area, using Bootstrap, NASA Team and Climate Data

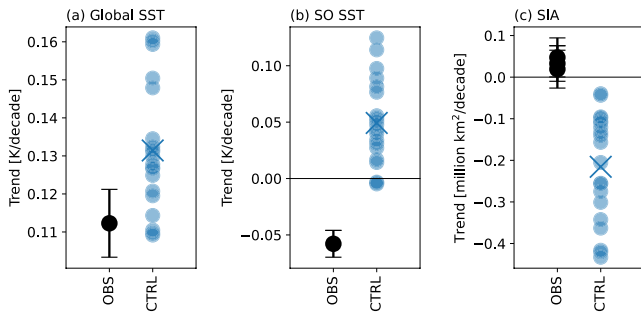


Figure 1. Trends from 1979 through 2021 in global mean sea surface temperature (SST), Southern-Ocean average SST and Antarctic sea ice area in NSIDC observations (Climate Data Record, Bootstrap and NASA Team, all black) and the GISS-E2.1-G control ensemble (20 members, blue). Blue crosses mark the ensemble mean. Error bars show the standard error of the linear trend in observations.

Record (CDR) ice concentration observations from the NSIDC CDR version 4 (Meier et al., 2021). Atmospheric variables are from MERRA-2 (Gelaro et al., 2017), and the SAM is defined from sea level pressure following Marshall (2003). We use SSTs from the NOAA Extended Reconstructed SST V5 data set (Huang et al., 2017a), ARGO (Argo, 2023) temperature and salinity from Roemmich and Gilson (2009), and ARGO mixed layer depths computed by E. A. Wilson et al. (2023).

2.5. Statistical Tests

To determine the consistency of modeled and observed trends, we use a statistical test that includes both observational uncertainty and ensemble spread, following Santer et al. (2008). The test statistic, d , for a trend T in a given variable is given by

$$d = |\overline{T_m} - T_o| / \sqrt{s < T_m >^2 + s T_o^2}, \quad (1)$$

where T_m are the model trends and the overline represents the ensemble mean, T_o is the observed trend for a given observational product, $s < T_m >$ is the standard deviation of the model trends, T_m , and $s T_o$ is the standard error of the observed trend, T_o . We assume that d has a two-tailed Student's t distribution and the number of degrees of freedom is the number of ensemble members, n_e , minus one, $n_e - 1$.

3. Results

3.1. Simulated SST Change in the Southern Ocean

Global-mean SST trends from 1979 through 2021 in the GISS-E2.1-G 20-member ensemble encompass the observations (Figure 1a). However, the observed statistically significant cooling in the Southern Ocean (50–65°S) is not captured in any GISS-E2.1-G ensemble member from 1979 through 2021 (Figure 1b). Accounting for ensemble spread and variance in the observed trend (Subsection 2.5), the observations are not consistent with the ensemble ($p < 5\%$) over this time period. Despite the mismatch in the circumpolar Southern Ocean SST trend, some ensemble members have SST trend patterns that partially resemble observations from 1979 through 2021: for example, r4i1p1f2 has a pronounced cooling in the Pacific sector of the Southern Ocean (Figure S4 in Supporting Information S1, also see Figure 2b for the trend from 1990 through 2021). For shorter periods, for example, from 1990 through 2021 as considered below, the ensemble SST trend is consistent with observations ($p < 5\%$, Figure 3b).

Simulated Southern Ocean SSTs and Antarctic SIA are negatively correlated across the ensemble, with $R^2 = 0.58$. Accounting for ensemble spread and variance in the observed trend, SIA trends in the model and in observations are consistent at the 5% confidence level over from 1979 through 2021 (Figure 1c) and from 1990 through 2021 (Figure 3d). CMIP6 evaluations have highlighted model-observation discrepancies in both Southern Ocean SSTs and Antarctic sea ice (e.g., Roach et al., 2020; Wills et al., 2022). In a model that simulates historical global mean SST change in line with observations, neutral Antarctic sea ice trends and Southern Ocean SST patterns comparable to observations can arise in some ensemble members due to internal variability, but are unlikely. We now investigate how this is influenced by winds and by anomalous meltwater fluxes.

3.2. Role of Winds

In wind-nudging simulations with GISS-E2.1-G (WIND), initial condition uncertainty arising from atmospheric dynamics is largely constrained, such that two ensemble members starting from high and low 1980 Antarctic sea ice conditions are in close agreement after the spin-up period (Figure S1 in Supporting Information S1, compare solid and dashed red lines). The Southern Ocean SSTs in all WIND ensemble members closely follow the variability in NOAA-ERSSTv5 (compare red and black lines in Figure 3a). From 1990 through 2021, the SST trends are slightly lower than the GISS-E2.1-G control ensemble mean, but do not reach the Southern Ocean average cooling in observations (Figure 3b). Compared to the control ensemble mean, the WIND experiments

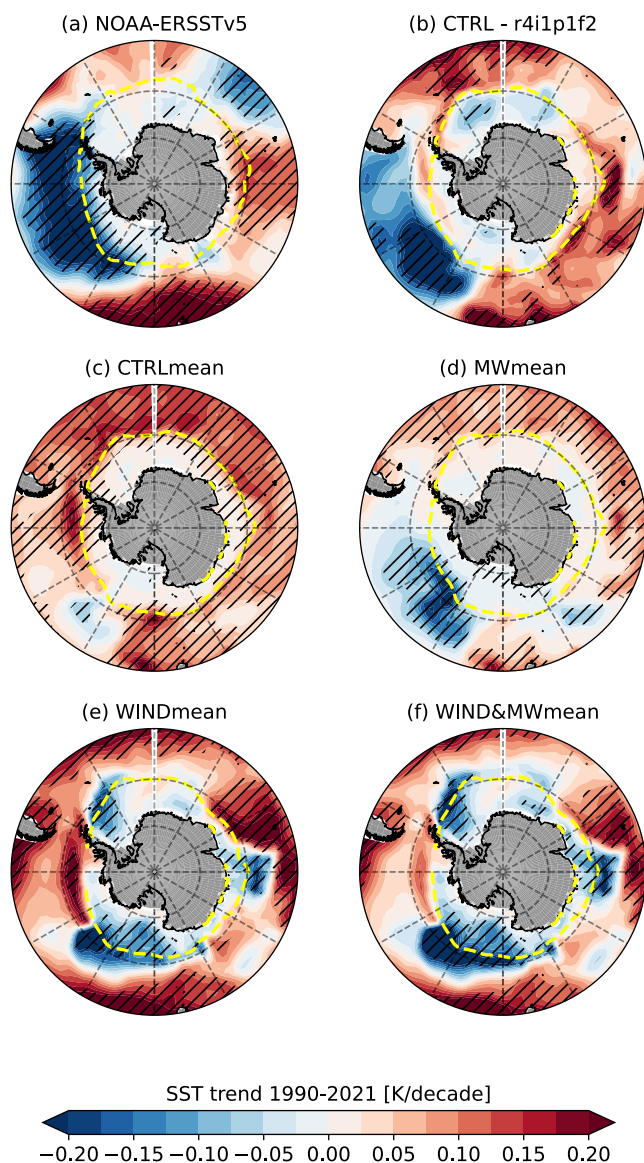


Figure 2. Sea surface temperature trends from 1990 through 2021. Hatching marks trends that are significant at the 95% level and gray represents the model land mask. The yellow dashed line marks the 15% sea ice concentration contour for the 1990–2021 annual mean.

show regions of strong Southern Ocean cooling, particularly in the Pacific (Figure 2e). The WINDmean SST trend is most negative around 130°W, in agreement with observations, but misses the observed cooling between 50 and 140°W (Figures 2a and 2e).

The control GISS-E2.1-G annual-mean SIA is biased low, largely due to biases in the summer (Figure S5 in Supporting Information S1), and wind-nudging acts to further reduce SIA in this model. However, sea ice variability in the WIND simulations largely follows that in observations until 2015 (Figure 3c). After 2015, only around half of the observed reduction in sea ice is captured, as we discuss below. From 1990 through 2021, the WIND simulations show Antarctic sea ice expansion, while the observations show no significant trend in sea ice (Figure 3d).

Previous work shows that nudging winds in a different climate model (the Community Earth System Model 1, CESM1) to the ERA-Interim reanalysis from 1979 through 2018 can explain a portion of the model-observation mismatch in Antarctic sea ice, but cannot account for the full SIA trend (Blanchard-Wrigglesworth et al., 2021). We find that wind-nudging has similar impacts in both CESM1 and GISS-E2.1-G (a reduction of 0.03 K/decade in Southern Ocean SST from the ensemble mean for both models, Figure S6 in Supporting Information S1). However, the GISS-E2.1-G Southern Ocean SST, sea ice and wind speed trends in the control ensemble are closer to observations than those in CESM1, and the wind-nudged GISS-E2.1-G SST trends move closer to zero and the SIA trends become more positive than the wind-nudged CESM1 simulations (Figure S6 in Supporting Information S1). For both models, the wind speed trends in the wind-nudged simulations are higher than the ensemble mean (Figure S6c in Supporting Information S1), pointing to the influence of strengthening westerlies.

Roach et al. (2022) conduct simulations where CESM1 winds are nudged to ERA-Interim anomalies (i.e., the nudging target is constructed as the sum of model climatology and reanalysis anomalies). Analyzing Southern Ocean SSTs and sea ice in these experiments shows that nudging toward reanalysis wind anomalies has a more muted impact on Antarctic sea ice and Southern Ocean SSTs than nudging to the full wind field (Figures S6a and S6b in Supporting Information S1). This suggests that the impact of observed winds on Antarctic sea ice and Southern Ocean SSTs in these models is due to a combination of changes in wind anomalies and mean state, which directly influence surface fluxes and the advection of heat and moisture, as well as sea ice motion.

3.3. Role of Anomalous Meltwater and Winds

We next consider the impact of AIS meltwater. We apply interannually varying anomalous meltwater based on observational estimates from 1990 through 2021 to GISS-E2.1-G. These runs (MW) simulate ensemble-mean negative SST trends (green markers in Figure 3) and give an ensemble-mean SST trend pattern that more closely resembles observations than the standard ensemble (Figures 2c and 2d; Schmidt et al., 2023).

We use this anomalous meltwater forcing in simulations with wind-nudging (WIND&MW), branched from WIND simulations in 1990. In WIND&MW, the Southern Ocean SST trend decreases to match the observed value (Figure 3b). The SST variability also closely resembles NOAA ERSSTv5 (Figure 3a). The SST trend pattern is similar to that from nudging winds alone, but with more pronounced cooling (Figure 2f). Like WIND, WIND&MW also captures Antarctic SIA variability from 1990 through 2015 (Figure 3c). However, adding the

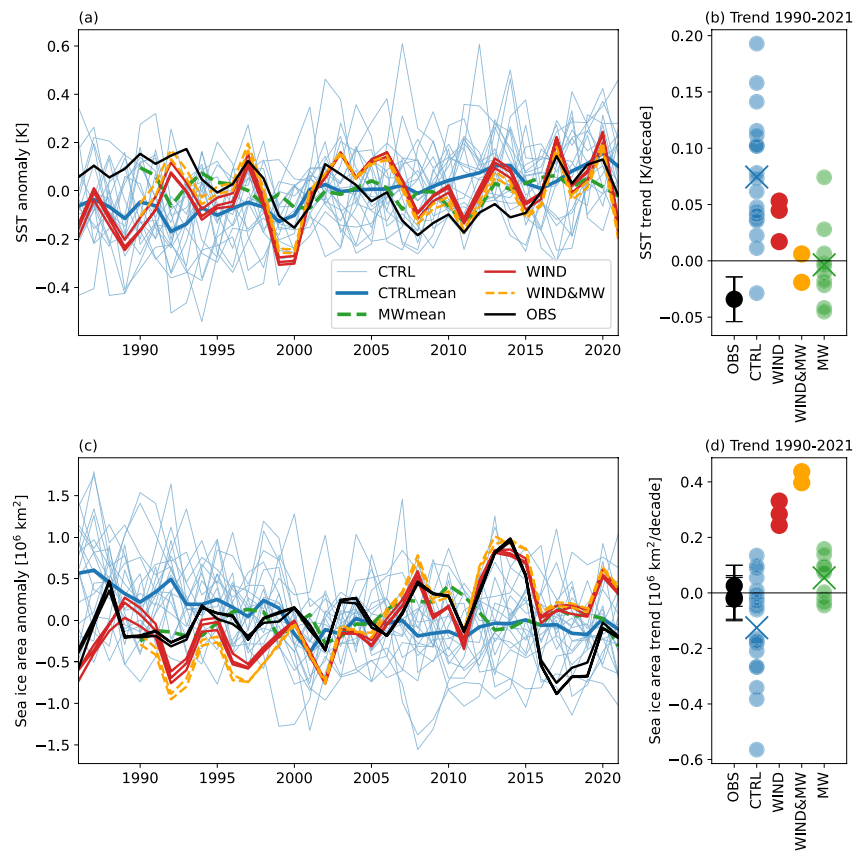


Figure 3. (a) Southern Ocean average sea surface temperature anomalies computed relative to the period from 1990 through 2021, and (b) linear trends corresponding to each line shown in panel (a). The error bars in panel (b) show the standard error of the linear trend in the NOAA ERSSTv5 observations, and crosses mark ensemble means. (c–d) as (a–b) but for Antarctic sea ice area, with observations from NSIDC CDRv4.

meltwater further overestimates the sea ice expansion and similarly misses the decline seen in observations after 2015 (Figures 3c and 3d).

The constrained experimental design allows us to quantify the timescales and magnitude of response in SST and sea ice to anomalous meltwater forcing in this model. The anomalous meltwater forcing is highly (negatively) correlated with the difference in Southern Ocean SST between WIND&MWmean and WINDmean, with a maximum correlation of 0.90 at a 4-year lag (Figure S7 in Supporting Information S1). The anomalous meltwater is highly positively correlated with the difference in Antarctic SIA between the two experiments, with a maximum correlation of 0.92 at a 2-year lag (Figure S7 in Supporting Information S1). At these lags, a linear fit gives a response of 0.14 K Southern Ocean cooling and 0.6 million km² of Antarctic sea ice expansion per 1,000 Gt of anomalous meltwater forcing.

4. Discussion

Our experimental design offers insight into the relative roles of winds and anomalous meltwater in driving Southern Ocean SST and sea ice change. In the nudged-wind simulations with NASA GISS-E2.1-G (WIND), we correct biases in the modeled winds and impose the observed realization of atmospheric variability. In the meltwater and nudged-wind simulations (WIND&MW), we also include observation-based estimates of AIS melt to represent ice sheet and ice shelf mass loss. Subtracting CTRLmean from WINDmean, the observed winds cause a Southern Ocean cooling of 0.04 ± 0.02 K/decade and a sea ice expansion of 0.41 ± 0.06 million km²/decade from 1990 through 2021. Note that subtracting MWmean from WIND&MWmean gives a smaller Southern Ocean cooling trend as a result of changes in winds, although the difference in sea ice trend remains similar; this non-linearity suggests that the impact of wind-nudging is partially to correct model biases. Subtracting WINDmean from

WIND&MWmean, the anomalous meltwater causes a Southern Ocean cooling trend of 0.04 ± 0.003 K/decade and a sea ice expansion of 0.13 ± 0.02 million km²/decade over the same time period. The anomalous meltwater therefore has a similar influence to the observed winds on the SST trends, while winds have a larger influence than meltwater on the SIA trends. Clearly, both winds and meltwater play an important role in this model.

Note that this decomposition is based on correcting model biases or missing processes, so the breakdown might be different if the winds were better represented in the standard model ensemble, or if ice sheet and ice shelf change were represented dynamically. It is also important to stress that these results are obtained with a single model and at a spatial resolution that cannot resolve many important processes in the region. Prior studies that have applied anomalous meltwater as forcing have obtained differing magnitudes of impact in different models (Table 1 in N. Swart et al., 2023). The response to meltwater may differ depending on the vertical distribution of meltwater input (M. Thomas et al., 2023), climatological stratification and/or model spatial resolution, with higher resolution permitting improved representation of ocean circulation and the Antarctic slope current (Beadling et al., 2022). Given the lack of available products regarding the spatial distribution of anomalous meltwater entering the ocean around Antarctica, we have assumed a uniform spatial distribution (Figure S3 in Supporting Information S1). Observations suggest around 70% might enter in West Antarctica alone, compared with 15% in East Antarctica and 15% in the Antarctic peninsula (Rignot et al., 2019). Preliminary tests using this modified spatial distribution suggest that it has limited impact on sea ice and SST trends, however this should be more rigorously tested in future work. Another source of uncertainty comes from the choice of reanalysis product used for wind-nudging. In this region, there are differences among observational products as well as relatively large biases near the coast and at high wind speeds, although wind speed variability is generally well-represented across products (Caton Harrison et al., 2022).

The literature has not yet converged on a mechanism that is responsible for the Antarctic sea ice lows after 2015 (Purich & Doddridge, 2023). They have been linked with anomalously low SAM and strong shoaling of the mixed layer at the start of the summer, allowing rapid warming and sea ice melt (E. A. Wilson et al., 2023). In both the WIND and WIND&MW simulations, Southern Ocean SSTs and the SAM agree closely with observations (Figures 4a and 4b). The mixed layer shoals concurrently with the rapid warming and low SAM, in phase with observations (Figure 4c). However, only around half of the observed SIA decrease after 2015 is captured in our simulations (Figure 4d). This might suggest that there are biases in the representation of sea ice–mixed layer interactions, sea ice–atmosphere interactions and/or small-scale ocean processes, such that the model is not sufficiently sensitive to atmospheric forcing. We find that reducing the meltwater forcing to zero from 2015 onwards has no impact on simulated Antarctic sea ice variability, suggesting that decreased meltwater input is not a dominant factor in the sea ice lows (Figure S8 in Supporting Information S1). The extent to which overestimated sea ice expansion and underestimated sea ice reduction are linked remains unclear.

5. Conclusions

Due to the complex nature of the coupled interactions across the Antarctic climate system, and significant biases in coupled climate models in this region, there is large uncertainty in projections of future Antarctic climate and cryosphere change. The observed Southern Ocean SST cooling and Antarctic sea ice expansion followed by large sea ice lows have been unexpected, partly as they are largely not captured by climate models. We first show that the NASA GISS-E2.1-G climate model can capture some aspects of the observed SST trend pattern as well as neutral sea ice trends from 1979 through 2021, but the model Southern Ocean average SST trend from 1979 through 2021 is not consistent with observations.

Constraining winds in the model to reanalysis, the model largely captures the observed Southern Ocean SST trends and temporal variability, as well as Antarctic sea ice variability through 2015. Additionally applying anomalous meltwater estimated to result from AIS melt improves agreement with the observed Southern Ocean SST trend, supporting the inclusion of dynamic ice sheets in earth system models. Combining the winds and the meltwater, the Southern Ocean average SST trends match those in observations. The cooling is concentrated in the Pacific, but with some regional differences from observations. We find that similar patterns can arise simply due to internal variability in the control model ensemble without including winds or meltwater, but become more likely when meltwater is included. The observed sea ice evolution is harder to capture: NASA GISS-E2.1-G with winds and meltwater overestimates sea ice expansion before 2015 and underestimates sea ice

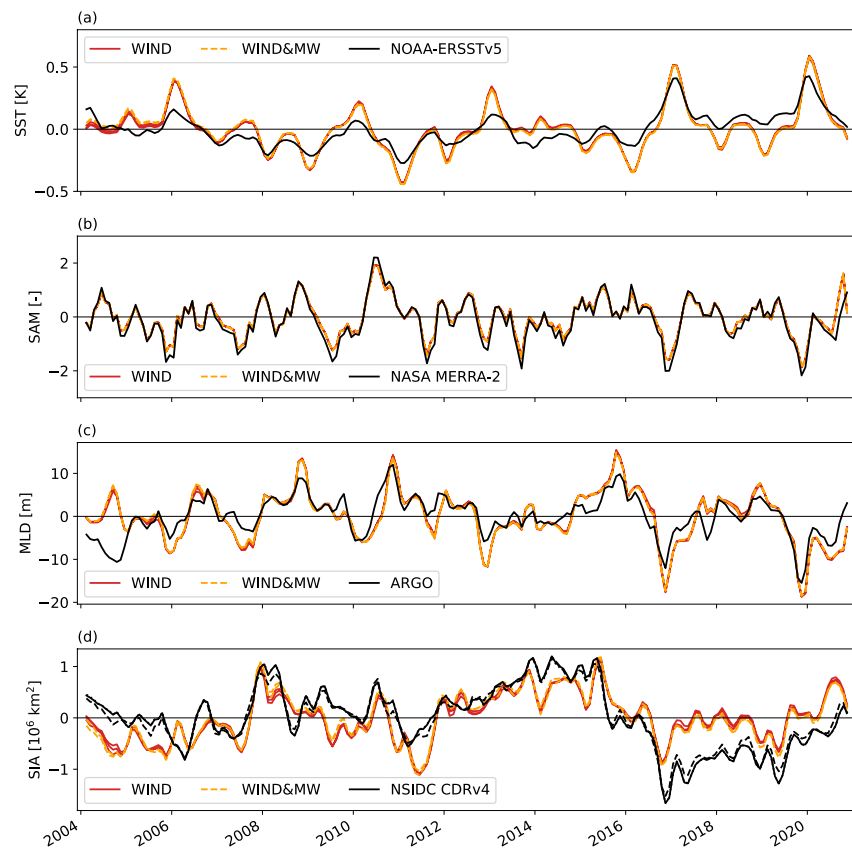


Figure 4. Time series of anomalies in Southern Ocean sea surface temperature, the Southern Annular Mode, Southern Ocean mixed layer depth, and Antarctic sea ice area over 2004–2020 from monthly data smoothed with a 3-month rolling average in observations and the WIND and WIND&MW simulations.

reduction after 2015. Note that our experiments are with a single, relatively coarse-resolution climate model, use a single reanalysis product for wind-nudging and assume a spatial uniform distribution for anomalous meltwater forcing.

We find that the combined effect of observed winds and anomalous AIS meltwater together can explain much of the observed trends and variability in Southern Ocean SSTs in this model. This emphasizes the tightly coupled nature of interactions across the atmosphere, ocean, sea ice, ice sheet and ice shelves in the Antarctic climate system. That the model misses the depth of the Antarctic sea ice lows in 2016 and 2020 suggests that there are other missing processes, incorrect forcings or biases still to diagnose, and more work is required to unravel the processes driving the ongoing highly anomalous Antarctic sea ice change.

Data Availability Statement

We use atmospheric parameters from the NASA Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2, Gelaro et al., 2017; GMAO, 2015). Sea ice observations from 1979 through present are from the NSIDC Climate Data Record version 4 sea ice concentration (Meier et al., 2021). We use SSTs from the NOAA Extended Reconstructed SST V5 dataset (Huang et al., 2017a, 2017b). Argo temperature and salinity are from Roemmich and Gilson (2009); Argo (2023), and we use the Argo mixed layer depths computed by E. A. Wilson et al. (2023); E. Wilson and Bonan (2022). Processed model output and analysis code is available via Zenodo (Roach, 2023) and full GISS model output (Table S1 in Supporting Information S1) is available from the NCCS portal at https://portal.nccs.nasa.gov/datashare/giss_cmip6/CMIP/NASA-GISS/GISS-E2-1-G/ and via the Earth System Grid Federation (NASA-GISS, 2023).

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