Recent multi-decadal Southern Ocean surface cooling unlikely caused by Southern Annular Mode trends

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Abstract

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Key Points:

- Austral summer SAM variability affects Southern Ocean SST only on seasonal to interannual timescales
- The short-term SAM-SST relationship makes little contribution to the observed multi-decadal Southern Ocean SST trends
- GCMs capture the observed seasonal SAM-SST relationship and yet fail to simulate the observed long-term SO cooling

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Abstract

Over recent decades, the Southern Ocean (SO) has experienced multi-decadal surface cooling despite global warming. Earlier studies have proposed that recent SO cooling has been caused by the strengthening of surface westerlies associated with a positive trend of the Southern Annular Mode (SAM) forced by ozone depletion. Here we revisit this hypothesis by examining the relationships between the SAM, zonal winds and SO sea-surface temperature (SST). Using a low-frequency component analysis, we show that while positive SAM anomalies can induce SST cooling as previously found, this seasonal-to-interannual modulation makes only a small contribution to the observed long-term SO cooling. Global climate models well capture the observed interannual SAM-SST relationship, and yet generally fail to simulate the observed multi-decadal SO cooling. The forced SAM trend in recent decades is thus unlikely the main cause of the observed SO cooling, pointing to a limited role of the Antarctic ozone hole.

Plain Language Summary

Under increased greenhouse gases, the Southern Ocean sea-surface temperatures have cooled over the recent several decades. The cause of Southern Ocean cooling remains a puzzling feature of recent climate change. Earlier studies have proposed that this multi-decadal cooling in the Southern Ocean has arisen in part from the strengthening of surface winds associated with a positive trend in a mode of climate variability know as the Southern Annular Mode (SAM). Here we employ a new statistical method to examine this proposed relationship in both observations and climate models. We found that SAM variability only changes Southern Ocean surface temperature on short-term timescales and makes little contribution to observed long-term trends. Our results thus suggest the SAM trend, via the strengthening of circumpolar westerlies, is unlikely the main cause of the observed long-term Southern Ocean cooling.

1 Introduction

Unlike the Arctic, the Southern Ocean has experienced substantial cooling in recent decades, following an earlier warming period from the 1950s to 1980s (Fig. 1a). This multi-decadal surface cooling over the Southern Ocean has been accompanied by anomalous surface freshening, sub-surface warming, and an expansion of sea ice around Antarctica (Fan et al., 2014; De Lavergne et al., 2014; Armour et al., 2016; Parkinson, 2019; Roach et al., 2020), all of which remain puzzling features of the observed climate change in the Southern Hemisphere. Apart from its local impacts, Southern Ocean surface cooling has been found to have remote effects on the pattern of tropical surface warming (Hwang et al., 2017; Dong, Armour, et al., 2022; Kim et al., 2022), tropical atmospheric circulation (Kang et al., 2020, 2023), and estimates of the global warming rate and climate sensitivity (Dong, Pauling, et al., 2022).

Despite its broad impacts on both the local and global climate, the observed Southern Ocean SST trend remains poorly simulated by global climate models (GCMs) (Fig. 1c). GCM initial-condition large ensembles (Deser et al., 2020) generally produce too strong SO surface warming over recent decades (Wills et al., 2022), along with too weak surface freshening and positive trends in Antarctic sea-ice extent (Roach et al., 2020). These model deficiencies over the historical period thus call into question the reliability of model projections of future Antarctic climate change.

Several hypotheses have been put forward to explain the observed multi-decadal SO cooling, including SO natural variability driven by ocean convection (Polvani & Smith, 2013; Latif et al., 2013; Cabré et al., 2017; Zhang et al., 2019), freshwater input from Antarctic ice-sheet melt (Rye et al., 2020; Pauling et al., 2016; Bintanja et al., 2013; Purich et al., 2018; Purich & England, 2023) or from increased equatorward sea-ice melt (Haumann et al., 2020). These hypotheses, however, are mostly built on modeling evidence, and are thus potentially subject to model biases. An alternative hypothesis is that the observed SO cooling trends may be driven by trends in surface westerlies via the Southern Annular Mode (SAM) through northward Ekman transport (Hall & Visbeck, 2002; Lefebvre et al., 2004; Gupta & England, 2006; Ferreira et al., 2015). It has been robustly observed that the surface westerlies have strengthened and shifted poleward, associated with the positive trend in the austral-summer (DJF) SAM over the second half of the 20th century (Thompson & Solomon, 2002; G. J. Marshall, 2003) (also Fig. 1b). This trend in SAM has been in large part attributed to stratospheric ozone depletion (Polvani et al., 2011; Previdi & Polvani, 2014; Banerjee et al., 2020). The observed SAM trend is generally well captured in GCM simulations (Fig. 1d) (Waugh et al., 2020).

To link SST variability to SAM variability, Doddridge and Marshall (2017) carried out an observational study and reported a robust interannual relationship between the SAM and SO SST. Their results show that positive SAM anomalies in the austral summer lead to anomalous cold SST persisting to the following autumn, suggesting a possible contribution of ozone depletion to SO cooling. On the modeling side, the SAM-SST connection on multi-decadal time scales was supported by idealized model simulations with abrupt SAM or ozone forcing (e.g., Ferreira et al., 2015; Kostov et al., 2018; Seviour et al., 2016). Early "step-like" forcing experiments showed a two-time-scale feature of the SO SST response to wind/SAM anomalies – a fast time-scale SST cooling response driven by the northward Ekman transport of surface waters and a slow time-scale SST warming response driven by the upwelling of warmer waters from below. Although a comprehensive study of such idealized experiments showed a very weak relationship between SAM and SST cooling on decadal time scales (Seviour et al., 2019), the appeal of a simple physical mechanism, the observed interannual modulation of SO SST by the SAM – and thus the Antarctic ozone hole – remains popular as a potential explanation of the multi-decadal cooling trends in the SO (Hartmann, 2022).

On the other hand, the causal relationship between SO SST trends and SAM/wind trends is at odds with several studies which have suggested that stratospheric ozone depletion causes surface *warming*, not cooling, on multi-decadal time scale. Unlike the idealized abrupt-forcing simulations that show a "fast" SO cooling response, GCM simulations with realistic transient or time-averaged ozone forcing robustly simulate a SO warming response along with Antarctic sea-ice melting (Sigmond & Fyfe, 2014; Bitz & Polvani, 2012; Smith et al., 2012; Landrum et al., 2017). Additionally, a recent study by Polvani et al. (2021) re-examined the relationship between the SAM and Antarctic sea-ice extent (SIE) in observations and GCMs. They found that the interannual SAM modulation of Antarctic SIE only explains a small fraction of the year-to-year SIE variability, and thus does not account for multi-decadal SIE trends. These studies collectively suggest that SAM variability, associated with the ozone hole, is unlikely to be the main driver of the observed long-term trends in SO SST and Antarctic SIE, contradicting the conclusion of the idealized modeling studies.

Motivated by these discrepancies in previous findings, we aim to address two questions in this study: (i) Can GCMs simulate the observed interannual relationship between the SAM and SO SST? (ii) To what extent does the interannual SAM modulation of SO SST contribute to the multi-decadal cooling trends in observations?

2 Interannual SAM modulation of Southern Ocean SST

In this section, we first repeat the analysis in Doddridge and Marshall (2017) (hereafter "DM2017") and Polvani et al. (2021) to re-examine the interannual SAM-SST relationship in both observations and GCMs. By comparing the results between observations and models, we assess whether model biases in long-term SO SST trends stem in part from model biases in the short-term SAM-SST modulation.

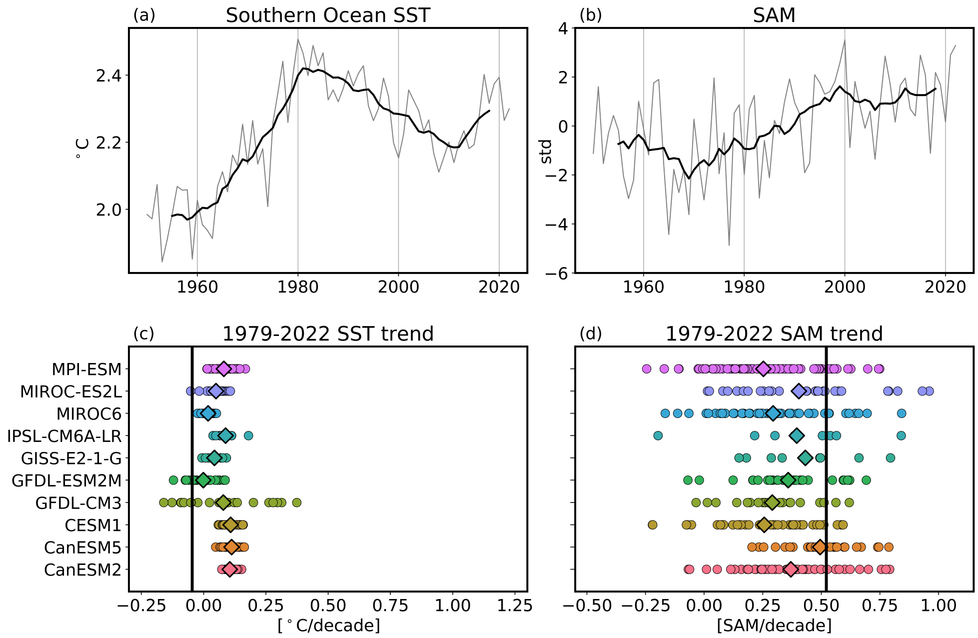

Figure 1. Observed and modeled Southern Ocean SST and SAM. (a – b) the observed annual-mean Southern Ocean SST and the DJF SAM index over 1950–2022. Black thicker lines denote 10-year running means. (c-d) the Southern Ocean SST trends and the SAM trend over 1979–2022 in observations (black line) and model large-ensembles. Circles denote each individual ensemble member; diamonds denote ensemble mean.

2.1 Data

For observations, we use SST from the NOAA Extended Reconstruction Sea Surface Temperature version 5 (ERSSTv5) dataset (Huang et al., 2017) and sea-level pressure (SLP) from the ERA5 Reanalysis dataset (Hersbach et al., 2020), both over the period of 1950–2022. For models, we use SST and SLP from 10 CMIP5 and CMIP6 models, including 5 models participated in multi-model large-ensemble project (Deser et al., 2020) and 5 CMIP6 models that have large ensembles (>10 members) of historical and SSP simulations. The main difference between the CMIP5 and CMIP6 ensembles is that the historical simulations extend to 2005 for CMIP5 but to 2014 for CMIP6. Thus, for the period up until 2022, we use RCP8.5 scenario for CMIP5 models and SSP245 or SSP370 scenario for CMIP6 models (see Table S1). Because forcing scenarios share similar trajectories early on in the 21st century, we expect this to cause little variation across model ensembles (Lehner et al., 2020).

We compute the SO SST index as the spatial average of the SST over 50°S – 70°S following DM2017. The DJF seasonal-mean SAM index is computed as the difference between zonal-mean SLP at 45°S and 60°S, normalized by the 1971-2000 average, following G. J. Marshall (2003). We focus on DJF SAM because the recent SAM trend is only significant in DJF (Swart & Fyfe, 2012; Waugh et al., 2020) and has been robustly attributed to stratospheric ozone depletion (Polvani et al., 2011; Banerjee et al., 2020). For both observations and GCM outputs, we remove the linear trend in DJF SAM and monthly SO SST timeseries over the entire period 1950–2022, before we perform the regression analysis.

2.2 Results

We begin with SO SST regressions against DJF SAM in observations, to examine whether DJF SAM anomalies are followed by anomalous SO SST. That is, we regress the timeseries of the DJF SAM index onto SO SST in every calendar month, ranging from the same year's December to next year's November. Fig. 2 clearly shows that positive DJF SAM anomalies lead to SO SST cooling, which peaks in the same season (DJF) and gradually weakens in the following two seasons before eventually vanishing at the end of the year. This independently confirms the findings of DM2017, who showed that the SAM impact on SO SST (derived from a shorter time period of 1981–2017 in that study) is highly seasonal and does not persist over a year. Furthermore, our analysis reveals that the annually-averaged SST anomaly following a unit of positive SAM is only -0.05 K (Fig. 2a) and the portion of SST variance explained (r^2) is merely 0.2 (Fig. 2b). Therefore, while positive SAM can indeed lead to SO SST cooling, we emphasize that this modulation occurs only on a seasonal timescale and can barely sustain at interannual or longer timescales. A similar result was reported by Polvani et al. (2021) for the DJF SAM modulation of Antarctic SIE.

Next, we repeat this regression analysis with model large ensembles. Perhaps surprisingly, models well reproduce the observed relationship between the DJF SAM and monthly SO SST (Fig. 2a, b grey lines), despite failing to simulate multi-decadal SO cooling (Fig. 1c). In fact, the multi-model mean regression even overestimates the maximum DJF SO SST cooling response and accounts for a higher SO SST variance (higher r^2)(also see Fig. S1 and S2 for individual models).

To further investigate how the SAM modulation of SO SST impacts model-simulated long-term SST trends, we separate all model ensemble members (365 in total) into two groups: one consisting of all the members that simulate a negative trend of SO SST over 1979–2022 (35 members, blue lines in Fig. 2) and the other consisting of the rest of members (330 members, orange lines in Fig. 2). Although the ensemble members that can simulate the long-term SO cooling all produce a stronger SST cooling response to SAM, the members that fail to simulate the long-term cooling are also able to capture or even

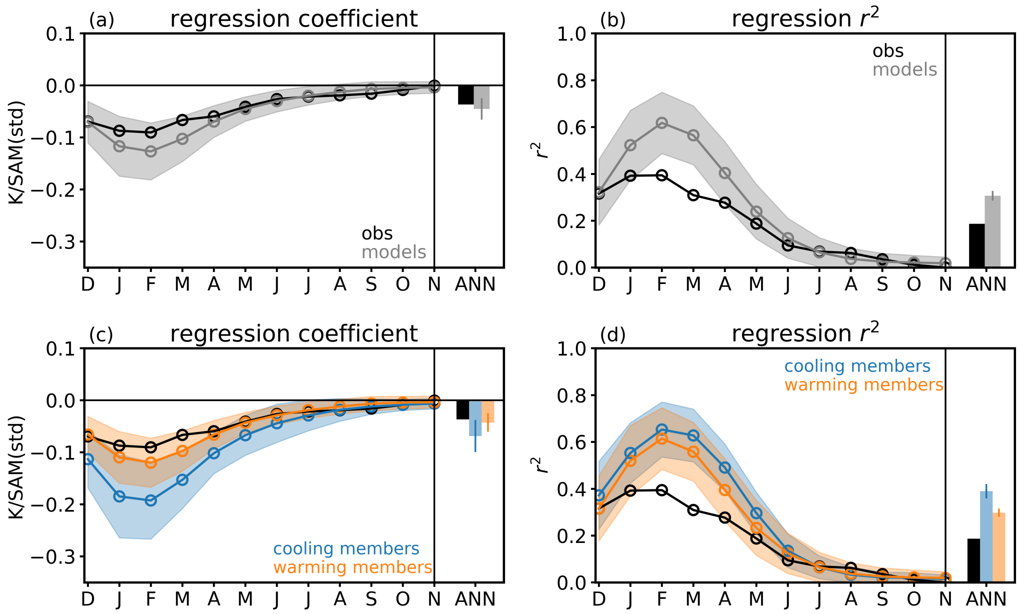

Figure 2. Regressions of monthly Southern Ocean SST (starting from DJF) onto same year's DJF SAM. (a-c) regression coefficient; (b-d) r^2 values of the regressions. Observations are shown in black, multi-model multi-ensemble means in grey, the ensemble members that simulate a negative SO SST trend over 1979–2022 ("cooling members") in blue, and the members that simulate a positive SO SST trend ("warming members") in in orange. All shadings denote one standard deviation across ensemble members.

overestimate the observed SST response to SAM. These results suggest that correctly simulating the seasonal-to-interannual SAM modulation of SO SST does not guarantee the model's performance on multi-decadal SO SST trends, implying that short-term and long-term SST variability may be caused by different processes in models.

3 Low-frequency variability in the Southern Ocean

In the previous section, we have shown that in both observations and models the SO SST cooling response to positive SAM anomalies only occurs in the same and following seasons. This raises a key question: Given the observed long-term SAM trend, to what extent does the short-term SAM-SST relationship contribute to the observed long-term SO cooling?

In the case of Antarctic SIE, Polvani et al. (2021) addressed this question by comparing the actual SIE trend in observation with the estimate based on the SAM-SIE regression. They found that the long-term SAM-regressed SIE trend is much smaller than the actual SIE trend, suggesting that the SAM is not the major driver of the observed long-term SIE trend. We performed the same analysis for the SO SST and found a similar result: the SAM-regressed annual-mean SO SST trend (1979–2022) is only 40% of the actual SO SST trend. However, such an analysis using the zonal-mean SAM index may overlook the spatial heterogeneity in the variability of winds and SST, and the reconstructed SST trend may also be sensitive to the time period selected (an issue reported by Polvani et al. 2021). Therefore, in this section, we revisit this question by employing a novel statistical method called low-frequency component analysis (LFCA; Wills et al., 2018), to identify modes of low-frequency variability in observed zonal winds and the SST changes associated with them.

3.1 LFCA method

LFCA (Wills et al., 2018) is a relatively new statistical technique – similar to the conventional principal component analysis – to compute a linear combination of empirical orthogonal functions (EOFs). LFCA maximizes the ratio of low-pass filtered variance to total variance, such that it isolates leading modes of low-frequency variability and extracts physically-based modes in spatial-temporal signals in climate fields. It has been applied to examine a wide range of climate quantities, including variability in global SST anomalies (Wills et al., 2022), Atlantic ocean heat transport (Oldenburg et al., 2021), and Arctic and Antarctic sea-ice concentration (Dörr et al., 2023; Bonan et al., 2023).

There are several advantages of using LFCA to investigate the relationship between long-term SAM and SST. First, it helps separate low-frequency (decadal to multi-decadal) and high-frequency (interannual) variability in SAM, allowing us to isolate the long-term contribution of SAM to SST trends. Second, instead of directly using the simpler zonal-mean SAM timeseries, we apply LFCA to the observed zonal winds at 850 hPa at each latitude and longitude and find the timeseries associated with the leading mode of wind variability. This gives us a more complete understanding of the relationship between winds and SST as it accounts for spatial variability of winds and SST. This is important because several recent studies have pointed out the non-zonal feature of the observed SAM-associated wind changes (Waugh et al., 2020) and its zonally asymmetric impacts on SO and remote SSTs (Dong, Armour, et al., 2022).

Our analysis uses the observed zonal winds at 850 hPa (U850) from the ERA5 Reanalysis dataset (Hersbach et al., 2020). As with the SAM index analyzed in section 2, we consider DJF U850 over 1950–2022. We apply LFCA to the observed U850 only over 40°S – 80°S, to avoid variability associated with tropical winds. Our LFCA uses a 15-year cutoff low-pass filter to isolate low-frequency variability, and we retain the 5 leading EOFs, which account for 77% of the total U850 variability (we find that increasing the number of EOFs does not lead to substantially more variance explained). The LFCA results remain the same regardless we choose a low-pass filter of 10 year, 15 year or 20 year (compare Fig. S3 to Fig. 3).

3.2 LFCA results

First, let us consider the leading anomaly patterns (i.e., low-frequency patterns, LFPs) and their associated timeseries (i.e., low-frequency components, LFCs) obtained by applying LFCA to the observed DJF U850 over the Southern Ocean. The first 5 LFPs and LFCs are shown in Fig. 3, in the left and right columns, respectively.

The leading mode (LFP1) features a SAM-like annular pattern of wind strengthening that has increased monotonically from 1970s to 2000s (see LFC1). This is well in line with the SAM trend caused by ozone depletion (Banerjee et al., 2020). This mode accounts for 58.3% of the low-frequency variance and has the highest signal-to-noise ratio of 0.4. The next four modes exhibit mostly non-zonal patterns (LFP2-5), where wind anomalies are confined to specific ocean sectors. The LFCs associated with LFP2 and LFP3 have some decadal-to-multi-decadal variability, while the LFCs associated with LFP4 and LFP5 are dominated by interannual variability, consistent with their low signal-to-noise ratio.

Next, we examine the U850 trend pattern (1979–2022) associated with each mode by projecting each LFC onto the corresponding LFP of U850 at each grid point over the SO. Fig. S4 confirms that the total reconstruction based on the five LFPs (Fig. S4b) well reproduces the observed U850 trend pattern (Fig. S4a), which is characterized by a strengthening of the westerlies at high latitudes in the Southern Ocean. Furthermore, the total reconstructed trend pattern remains the same using either the leading five or three LFPs, suggesting that LFP 1-3 are the major contributor to the total U850 trends over recent decades.

3.3 Long-term relationship between SO SST and winds

Having established that the leading modes obtained by LFCA well reproduce the observed U850 trend pattern, we next investigate the long-term relationship between U850 and SO SST by examining how each LFP and LFC influences SST across timescales.

First, we regress the observed DJF SST over the entire period (1950–2022) at each grid box onto the LFC timeseries associated with the three leading wind LFPs, respectively (Fig. 4 a-c). We focus on DJF SST as our earlier results suggest it is the season when the SAM, through surface winds, has the strongest impact on SST. Consistent with the SAM-SST regression result (Fig. 2), the wind LFC-SST regression also shows broad SST cooling anomalies around Antarctica associated with positive LFC anomalies. However, it is interesting that the patterns of SST cooling response do not quite match the wind anomaly patterns (compare Fig. 3 and Fig. 4): All three wind LFPs feature positive wind anomalies throughout the Southern Ocean (LFP1 even has stronger wind anomalies in the Atlantic basin than in the Pacific basin), yet their SST cooling responses are most significant in the Pacific basin. This mismatch in spatial patterns may give us a first hint that the proposed mechanism linking surface winds to SO SST through Ekman heat transport may not sufficiently explain the spatial patterns of wind-SST relationship.

Second, we estimate the long-term SST trends over the period 1979–2022 based on the above linear regression. Specifically, we multiply the regression between each LFC and SST at each grid box with the corresponding LFC, and then take the linear trend of the reconstructed SST timeseries at each grid box (Fig. 4). Although the LFC-based SST trends also occur in the Pacific basin – consistent with observations – one immediately sees that the magnitudes of wind-driven SST trends are much weaker than that observed (cf. Fig. 4 middle row vs. Fig. 4g). Taking a spatial average over the Pacific sector of the Southern Ocean where the observed SST cooling is strongest (150°E – 60°W, 50°S – 70°S), we obtain an SST trend of -0.98 $°C/$decade from the observation, and SST trends of -0.25, -0.14 and -0.02 $°C/$decade from LFC1-3 regressions respectively, which altogether account for less than half of the actual SST trend (Fig. 4i). To further illustrate the inability of winds to account for the time-evolution of SO SST, we plot the timeseries of DJF SO SST anomalies (relative to their climatology) for the observation and for the estimates using LFC1-3 regressions (Fig. 4h). Although each of the LFCs contributes to some SST variability, none of them can produce a multi-decadal SO SST variability as strong as the observed timeseries. Even the sum of all three LFC-regression-based SO SST timeseries fails to explain the much larger multi-decadal trends in the observed SO SST.

Furthermore, our SST trend estimates so far have been focused on DJF, in the same season with wind anomalies, so as to capture the strongest wind impacts on SST. We also repeated the analysis for annual-mean (instead of DJF only) SST (Fig. S5). The annual-mean SST anomalies following a unit of DJF wind LFC changes are even weaker, leading to almost negligible wind-driven annual-mean SST trends over recent decades, i.e., -0.16 $°C/$decade over 1979–2022 from all three leading-mode regressions, compared to -0.9 $°C/$decade of the actual SST trend (Fig. S5j).

Thus, by projecting SO SST onto the leading modes of observed wind variability, we find that although positive DJF wind anomalies can cause some SST cooling in the same season, this modulation does not survive more than a few months, and the resulting wind-driven SST cooling is *too weak* to explain the large multi-decadal trend in the

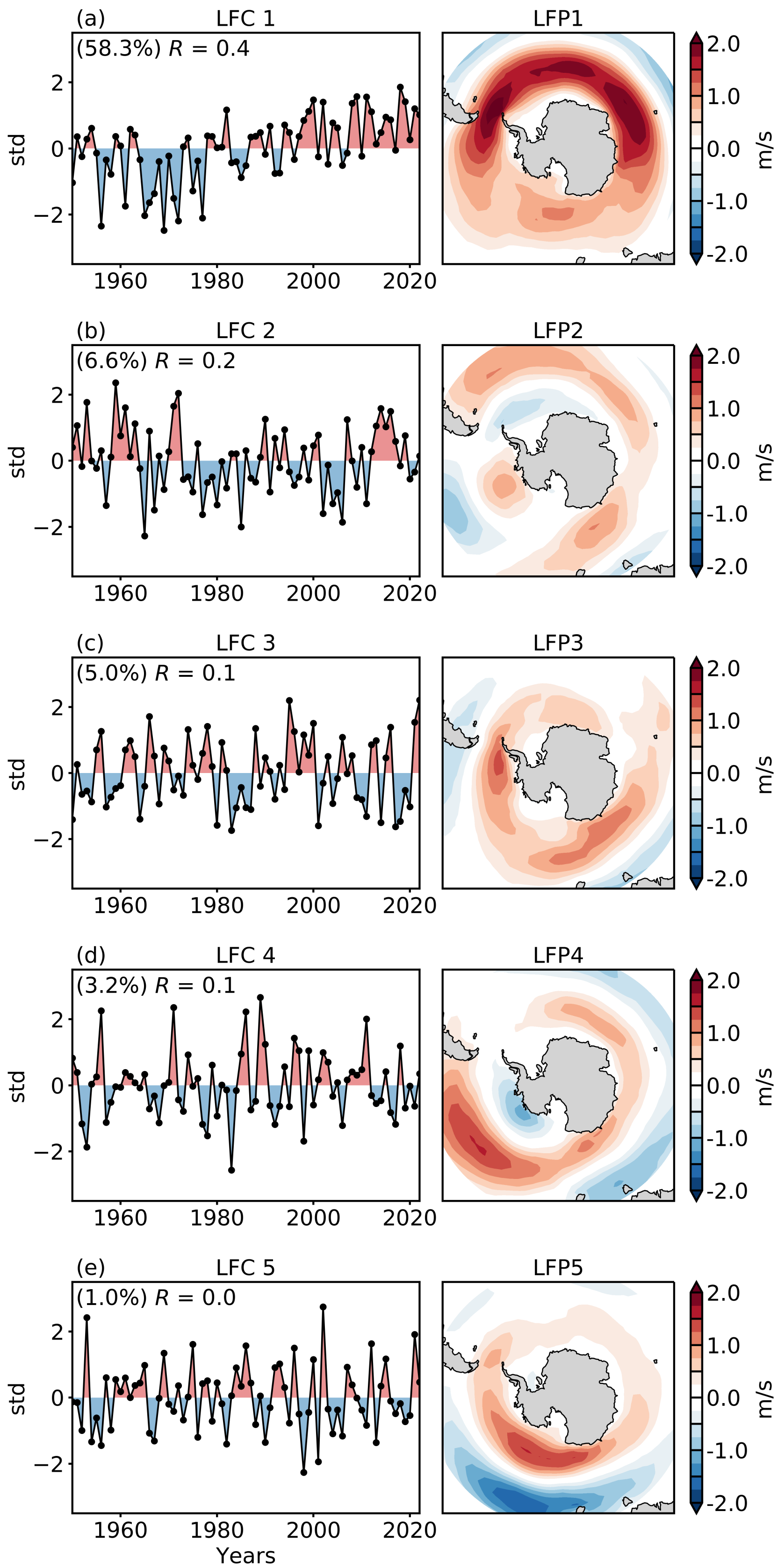

Figure 3. Low-frequency patterns (LFP; right column; unit: m/s) and their associated components (LFC; left column; unit: standard deviation) for the observed DJF U850 wind anomalies. Values in parentheses in the LFC panels denote the low-frequency variance explained by each mode. R values denote the ratio of low-frequency variance explained to the total variance, representing the signal-to-noise ratio.

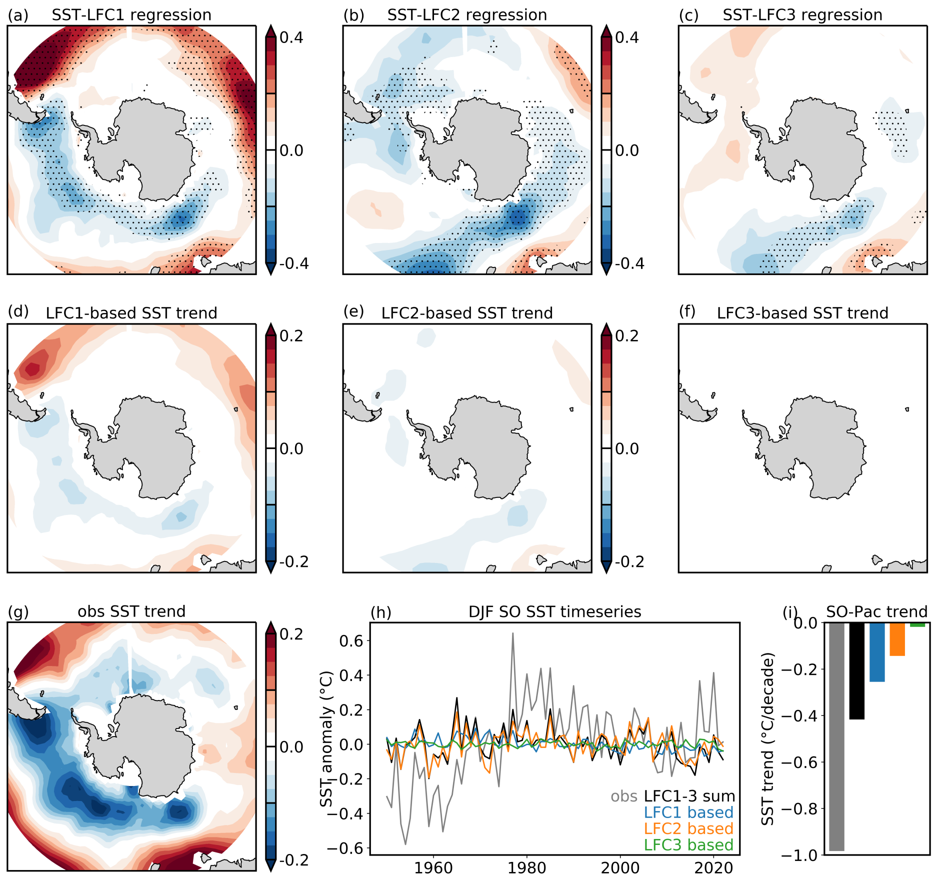

Figure 4. (a-c) DJF SST regression map onto LFC1-3 respectively (unit: $^{\circ}C$/std). Stippling indicates where linear regression is statistically significant at 95% level. (d-g) DJF SST trend patterns over 1979–2022 ($^{\circ}C$/decade) estimated from regressions with LFC 1-3 respectively and ERSSTv5. (i) Timeseries of SO SST anomalies relative to their climatology and (j) SST trends averaged over the Pacific sector over 1979–2022, from the observation (grey), the regressions with LFC1-3 respectively (colored), and all three leading LFCs (black).

observed Southern Ocean SST (Fig. 4). Hence, the recent wind strengthening over the Southern Ocean is unlikely the key driver of the long-term Southern Ocean cooling.

4 Summary and Discussion

In this study, we have re-examined a previously proposed idea that positive SAM anomalies in DJF, associated with a strengthening of the circumpolar westerlies, may in part explain the observed Southern Ocean cooling (J. Marshall et al., 2014; Ferreira et al., 2015; Doddridge & Marshall, 2017; Kostov et al., 2018; Hartmann, 2022). Using GCM large-ensembles, we have found that models are able to capture the observed seasonal-to-interannual modulation of SO SST by the SAM, regardless of whether they are able to simulate the long-term SO cooling. Focusing on observations, we have shown that although positive SAM anomalies and positive zonal wind anomalies in DJF can lead to some SST cooling anomalies in the same season, this mechanism only operates for a few months and does not persist from year to year. These results suggest that the SAM modulation of SO SST, via the strengthening of SO westerlies, is too weak to explain the observed multi-decadal Southern Ocean cooling.

One novel aspect of our study is that we used a low-frequency component analysis to isolate trends in SO zonal winds, rather than focusing on trends in the SAM. While the SAM index has been widely used as a metric to quantify zonal wind changes in the Southern Hemisphere, it only represents zonal-mean features and includes a wide range of variabilities from interannual to decadal timescales. Applying LFCA to the observed wind anomalies has allowed us to (1) obtain the timeseries (LFCs) of the leading modes of wind variability while retaining the spatial pattern of the wind anomalies, and (2) disentangle low-frequency from high-frequency variability.

It could be argued that the weak connection between long-term SAM and SST trends can be immediately deduced from the SAM and SST timeseries alone. A simple visual inspection of their smoothed timeseries (thick curves in Fig. 1a and b, respectively) suffices to note that the kinks in those curves do not match. The SST cooling starts after 1980 and persists past 2010, whereas the positive SAM trend starts well before 1970 and stops after 2000, as a consequence of the Montreal Protocol (Banerjee et al., 2020). Building on this, our new analysis, accounting for spatial-temporal variability, adds additional evidence corroborating the inability of the SAM and surface westerlies to explain the recent multi-decadal SO cooling.

Understanding the causes of the observed Southern Ocean cooling and biases in climate models remains a major challenge. By showing that the SAM-driven SST cooling is too weak to explain the long-term SO SST trends, our results point to a possibly limited role of stratospheric ozone depletion. This finding is also consistent with recent modeling evidence that nudging tropospheric wind anomalies around Antarctica towards observations in a GCM (CESM1) does not produce significant SO SST cooling over recent four decades (Blanchard-Wrigglesworth et al., 2021; Dong, Armour, et al., 2022). Thus, the impact of the Antarctic ozone hole on long-term SO SST via the SAM appears to be less robust than previously proposed. Even so, there is evidence that the ozone hole has caused remote climate impacts on lower latitudes, notably on subtropical precipitation (Kang et al., 2011; Gonzalez et al., 2014; Wu & Polvani, 2017). The Antarctic ozone hole, therefore, may have impacted SST in remote regions (e.g., the tropical Pacific), and those impacts could then have been communicated back to the Southern Ocean SST via atmospheric teleconnections (Ding et al., 2011; Meehl et al., 2016; Chung et al., 2022; Dong, Armour, et al., 2022). Such complex two-way teleconnections, however, remain largely unexplored.

Beyond potential remote impacts from the tropics, other local contributors to the recent SO cooling remain plausible, including freshwater input from Antarctic ice-sheet melt or more equatorward sea-ice melt (Purich et al., 2018; Bintanja et al., 2013; Rye et al., 2020; Dong, Pauling, et al., 2022; Haumann et al., 2020), and Southern Ocean natural variability (Latif et al., 2013; Cabré et al., 2017; Zhang et al., 2019). Whether the recent SO cooling was driven by historical forcings or simply reflects natural variability has important implications for SST trends in the near future. Accurately constraining future projections of Antarctic climate change thus requires a better understanding of the causes of the recent multi-decadal Southern Ocean SST trends.

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Data Availability Statement

ERSSTv5 SST data is available at https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html. ERA5 reanalysis SLP and U850 data is available from the Copernicus Climate Service at https://cds.climate.copernicus.eu/. CMIP5 and CMIP6 model multi-model large ensembles are available via the NCAR Climate Data Gateway and via the ESGF archive at: https://esgf-node.llnl.gov/search/cmip6/.

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Recent multi-decadal Southern Ocean surface cooling unlikely caused by Southern Annular Mode trends

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Key Points:

- Austral summer SAM variability affects Southern Ocean SST only on seasonal to interannual timescales
- The short-term SAM-SST relationship makes little contribution to the observed multi-decadal Southern Ocean SST trends
- GCMs capture the observed seasonal SAM-SST relationship and yet fail to simulate the observed long-term SO cooling

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Abstract

Over recent decades, the Southern Ocean (SO) has experienced multi-decadal surface cooling despite global warming. Earlier studies have proposed that recent SO cooling has been caused by the strengthening of surface westerlies associated with a positive trend of the Southern Annular Mode (SAM) forced by ozone depletion. Here we revisit this hypothesis by examining the relationships between the SAM, zonal winds and SO sea-surface temperature (SST). Using a low-frequency component analysis, we show that while positive SAM anomalies can induce SST cooling as previously found, this seasonal-to-interannual modulation makes only a small contribution to the observed long-term SO cooling. Global climate models well capture the observed interannual SAM-SST relationship, and yet generally fail to simulate the observed multi-decadal SO cooling. The forced SAM trend in recent decades is thus unlikely the main cause of the observed SO cooling, pointing to a limited role of the Antarctic ozone hole.

Plain Language Summary

Under increased greenhouse gases, the Southern Ocean sea-surface temperatures have cooled over the recent several decades. The cause of Southern Ocean cooling remains a puzzling feature of recent climate change. Earlier studies have proposed that this multi-decadal cooling in the Southern Ocean has arisen in part from the strengthening of surface winds associated with a positive trend in a mode of climate variability know as the Southern Annular Mode (SAM). Here we employ a new statistical method to examine this proposed relationship in both observations and climate models. We found that SAM variability only changes Southern Ocean surface temperature on short-term timescales and makes little contribution to observed long-term trends. Our results thus suggest the SAM trend, via the strengthening of circumpolar westerlies, is unlikely the main cause of the observed long-term Southern Ocean cooling.

1 Introduction

Unlike the Arctic, the Southern Ocean has experienced substantial cooling in recent decades, following an earlier warming period from the 1950s to 1980s (Fig. 1a). This multi-decadal surface cooling over the Southern Ocean has been accompanied by anomalous surface freshening, sub-surface warming, and an expansion of sea ice around Antarctica (Fan et al., 2014; De Lavergne et al., 2014; Armour et al., 2016; Parkinson, 2019; Roach et al., 2020), all of which remain puzzling features of the observed climate change in the Southern Hemisphere. Apart from its local impacts, Southern Ocean surface cooling has been found to have remote effects on the pattern of tropical surface warming (Hwang et al., 2017; Dong, Armour, et al., 2022; Kim et al., 2022), tropical atmospheric circulation (Kang et al., 2020, 2023), and estimates of the global warming rate and climate sensitivity (Dong, Pauling, et al., 2022).

Despite its broad impacts on both the local and global climate, the observed Southern Ocean SST trend remains poorly simulated by global climate models (GCMs) (Fig. 1c). GCM initial-condition large ensembles (Deser et al., 2020) generally produce too strong SO surface warming over recent decades (Wills et al., 2022), along with too weak surface freshening and positive trends in Antarctic sea-ice extent (Roach et al., 2020). These model deficiencies over the historical period thus call into question the reliability of model projections of future Antarctic climate change.

Several hypotheses have been put forward to explain the observed multi-decadal SO cooling, including SO natural variability driven by ocean convection (Polvani & Smith, 2013; Latif et al., 2013; Cabré et al., 2017; Zhang et al., 2019), freshwater input from Antarctic ice-sheet melt (Rye et al., 2020; Pauling et al., 2016; Bintanja et al., 2013; Purich et al., 2018; Purich & England, 2023) or from increased equatorward sea-ice melt (Haumann et al., 2020). These hypotheses, however, are mostly built on modeling evidence, and are thus potentially subject to model biases. An alternative hypothesis is that the observed SO cooling trends may be driven by trends in surface westerlies via the Southern Annular Mode (SAM) through northward Ekman transport (Hall & Visbeck, 2002; Lefebvre et al., 2004; Gupta & England, 2006; Ferreira et al., 2015). It has been robustly observed that the surface westerlies have strengthened and shifted poleward, associated with the positive trend in the austral-summer (DJF) SAM over the second half of the 20th century (Thompson & Solomon, 2002; G. J. Marshall, 2003) (also Fig. 1b). This trend in SAM has been in large part attributed to stratospheric ozone depletion (Polvani et al., 2011; Previdi & Polvani, 2014; Banerjee et al., 2020). The observed SAM trend is generally well captured in GCM simulations (Fig. 1d) (Waugh et al., 2020).

To link SST variability to SAM variability, Doddridge and Marshall (2017) carried out an observational study and reported a robust interannual relationship between the SAM and SO SST. Their results show that positive SAM anomalies in the austral summer lead to anomalous cold SST persisting to the following autumn, suggesting a possible contribution of ozone depletion to SO cooling. On the modeling side, the SAM-SST connection on multi-decadal time scales was supported by idealized model simulations with abrupt SAM or ozone forcing (e.g., Ferreira et al., 2015; Kostov et al., 2018; Seviour et al., 2016). Early "step-like" forcing experiments showed a two-time-scale feature of the SO SST response to wind/SAM anomalies – a fast time-scale SST cooling response driven by the northward Ekman transport of surface waters and a slow time-scale SST warming response driven by the upwelling of warmer waters from below. Although a comprehensive study of such idealized experiments showed a very weak relationship between SAM and SST cooling on decadal time scales (Seviour et al., 2019), the appeal of a simple physical mechanism, the observed interannual modulation of SO SST by the SAM – and thus the Antarctic ozone hole – remains popular as a potential explanation of the multi-decadal cooling trends in the SO (Hartmann, 2022).

On the other hand, the causal relationship between SO SST trends and SAM/wind trends is at odds with several studies which have suggested that stratospheric ozone depletion causes surface *warming*, not cooling, on multi-decadal time scale. Unlike the idealized abrupt-forcing simulations that show a "fast" SO cooling response, GCM simulations with realistic transient or time-averaged ozone forcing robustly simulate a SO warming response along with Antarctic sea-ice melting (Sigmond & Fyfe, 2014; Bitz & Polvani, 2012; Smith et al., 2012; Landrum et al., 2017). Additionally, a recent study by Polvani et al. (2021) re-examined the relationship between the SAM and Antarctic sea-ice extent (SIE) in observations and GCMs. They found that the interannual SAM modulation of Antarctic SIE only explains a small fraction of the year-to-year SIE variability, and thus does not account for multi-decadal SIE trends. These studies collectively suggest that SAM variability, associated with the ozone hole, is unlikely to be the main driver of the observed long-term trends in SO SST and Antarctic SIE, contradicting the conclusion of the idealized modeling studies.

Motivated by these discrepancies in previous findings, we aim to address two questions in this study: (i) Can GCMs simulate the observed interannual relationship between the SAM and SO SST? (ii) To what extent does the interannual SAM modulation of SO SST contribute to the multi-decadal cooling trends in observations?

2 Interannual SAM modulation of Southern Ocean SST

In this section, we first repeat the analysis in Doddridge and Marshall (2017) (hereafter "DM2017") and Polvani et al. (2021) to re-examine the interannual SAM-SST relationship in both observations and GCMs. By comparing the results between observations and models, we assess whether model biases in long-term SO SST trends stem in part from model biases in the short-term SAM-SST modulation.

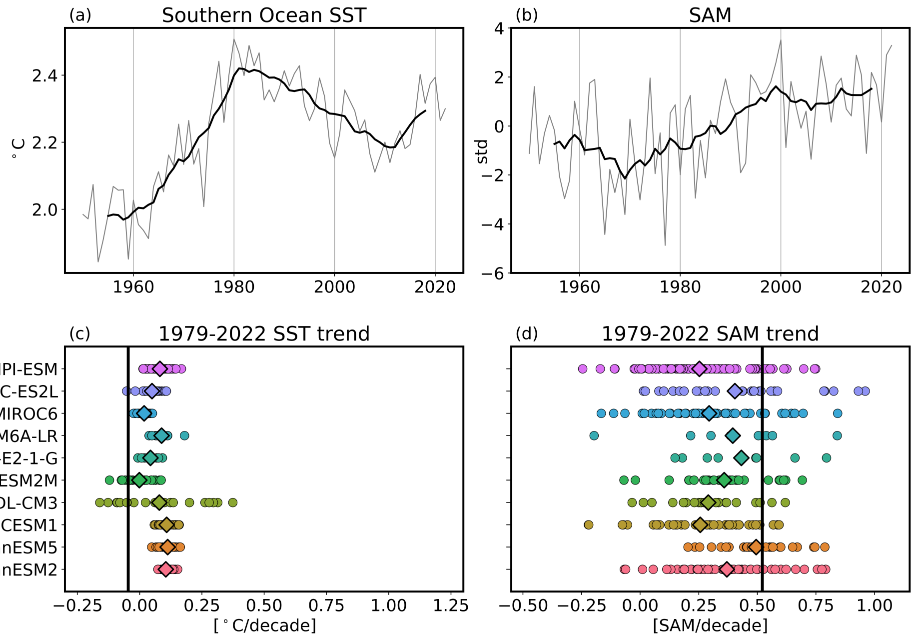

Figure 1. Observed and modeled Southern Ocean SST and SAM. (a – b) the observed annual-mean Southern Ocean SST and the DJF SAM index over 1950–2022. Black thicker lines denote 10-year running means. (c-d) the Southern Ocean SST trends and the SAM trend over 1979–2022 in observations (black line) and model large-ensembles. Circles denote each individual ensemble member; diamonds denote ensemble mean.

2.1 Data

For observations, we use SST from the NOAA Extended Reconstruction Sea Surface Temperature version 5 (ERSSTv5) dataset (Huang et al., 2017) and sea-level pressure (SLP) from the ERA5 Reanalysis dataset (Hersbach et al., 2020), both over the period of 1950–2022. For models, we use SST and SLP from 10 CMIP5 and CMIP6 models, including 5 models participated in multi-model large-ensemble project (Deser et al., 2020) and 5 CMIP6 models that have large ensembles (>10 members) of historical and SSP simulations. The main difference between the CMIP5 and CMIP6 ensembles is that the historical simulations extend to 2005 for CMIP5 but to 2014 for CMIP6. Thus, for the period up until 2022, we use RCP8.5 scenario for CMIP5 models and SSP245 or SSP370 scenario for CMIP6 models (see Table S1). Because forcing scenarios share similar trajectories early on in the 21st century, we expect this to cause little variation across model ensembles (Lehner et al., 2020).

We compute the SO SST index as the spatial average of the SST over 50°S – 70°S following DM2017. The DJF seasonal-mean SAM index is computed as the difference between zonal-mean SLP at 45°S and 60°S, normalized by the 1971-2000 average, following G. J. Marshall (2003). We focus on DJF SAM because the recent SAM trend is only significant in DJF (Swart & Fyfe, 2012; Waugh et al., 2020) and has been robustly attributed to stratospheric ozone depletion (Polvani et al., 2011; Banerjee et al., 2020). For both observations and GCM outputs, we remove the linear trend in DJF SAM and monthly SO SST timeseries over the entire period 1950–2022, before we perform the regression analysis.

2.2 Results

We begin with SO SST regressions against DJF SAM in observations, to examine whether DJF SAM anomalies are followed by anomalous SO SST. That is, we regress the timeseries of the DJF SAM index onto SO SST in every calendar month, ranging from the same year's December to next year's November. Fig. 2 clearly shows that positive DJF SAM anomalies lead to SO SST cooling, which peaks in the same season (DJF) and gradually weakens in the following two seasons before eventually vanishing at the end of the year. This independently confirms the findings of DM2017, who showed that the SAM impact on SO SST (derived from a shorter time period of 1981–2017 in that study) is highly seasonal and does not persist over a year. Furthermore, our analysis reveals that the annually-averaged SST anomaly following a unit of positive SAM is only -0.05 K (Fig. 2a) and the portion of SST variance explained (r^2) is merely 0.2 (Fig. 2b). Therefore, while positive SAM can indeed lead to SO SST cooling, we emphasize that this modulation occurs only on a seasonal timescale and can barely sustain at interannual or longer timescales. A similar result was reported by Polvani et al. (2021) for the DJF SAM modulation of Antarctic SIE.

Next, we repeat this regression analysis with model large ensembles. Perhaps surprisingly, models well reproduce the observed relationship between the DJF SAM and monthly SO SST (Fig. 2a, b grey lines), despite failing to simulate multi-decadal SO cooling (Fig. 1c). In fact, the multi-model mean regression even overestimates the maximum DJF SO SST cooling response and accounts for a higher SO SST variance (higher r^2)(also see Fig. S1 and S2 for individual models).

To further investigate how the SAM modulation of SO SST impacts model-simulated long-term SST trends, we separate all model ensemble members (365 in total) into two groups: one consisting of all the members that simulate a negative trend of SO SST over 1979–2022 (35 members, blue lines in Fig. 2) and the other consisting of the rest of members (330 members, orange lines in Fig. 2). Although the ensemble members that can simulate the long-term SO cooling all produce a stronger SST cooling response to SAM, the members that fail to simulate the long-term cooling are also able to capture or even

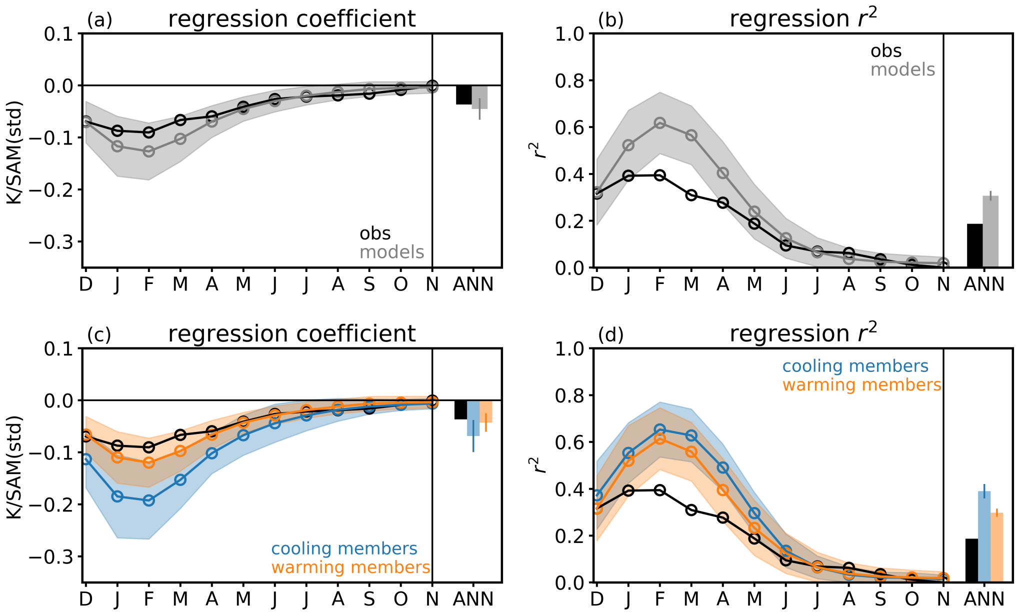

Figure 2. Regressions of monthly Southern Ocean SST (starting from DJF) onto same year's DJF SAM. (a-c) regression coefficient; (b-d) r^2 values of the regressions. Observations are shown in black, multi-model multi-ensemble means in grey, the ensemble members that simulate a negative SO SST trend over 1979–2022 ("cooling members") in blue, and the members that simulate a positive SO SST trend ("warming members") in in orange. All shadings denote one standard deviation across ensemble members.

overestimate the observed SST response to SAM. These results suggest that correctly simulating the seasonal-to-interannual SAM modulation of SO SST does not guarantee the model's performance on multi-decadal SO SST trends, implying that short-term and long-term SST variability may be caused by different processes in models.

3 Low-frequency variability in the Southern Ocean

In the previous section, we have shown that in both observations and models the SO SST cooling response to positive SAM anomalies only occurs in the same and following seasons. This raises a key question: Given the observed long-term SAM trend, to what extent does the short-term SAM-SST relationship contribute to the observed long-term SO cooling?

In the case of Antarctic SIE, Polvani et al. (2021) addressed this question by comparing the actual SIE trend in observation with the estimate based on the SAM-SIE regression. They found that the long-term SAM-regressed SIE trend is much smaller than the actual SIE trend, suggesting that the SAM is not the major driver of the observed long-term SIE trend. We performed the same analysis for the SO SST and found a similar result: the SAM-regressed annual-mean SO SST trend (1979–2022) is only 40% of the actual SO SST trend. However, such an analysis using the zonal-mean SAM index may overlook the spatial heterogeneity in the variability of winds and SST, and the reconstructed SST trend may also be sensitive to the time period selected (an issue reported by Polvani et al. 2021). Therefore, in this section, we revisit this question by employing a novel statistical method called low-frequency component analysis (LFCA; Wills et al., 2018), to identify modes of low-frequency variability in observed zonal winds and the SST changes associated with them.

3.1 LFCA method

LFCA (Wills et al., 2018) is a relatively new statistical technique – similar to the conventional principal component analysis – to compute a linear combination of empirical orthogonal functions (EOFs). LFCA maximizes the ratio of low-pass filtered variance to total variance, such that it isolates leading modes of low-frequency variability and extracts physically-based modes in spatial-temporal signals in climate fields. It has been applied to examine a wide range of climate quantities, including variability in global SST anomalies (Wills et al., 2022), Atlantic ocean heat transport (Oldenburg et al., 2021), and Arctic and Antarctic sea-ice concentration (Dörr et al., 2023; Bonan et al., 2023).

There are several advantages of using LFCA to investigate the relationship between long-term SAM and SST. First, it helps separate low-frequency (decadal to multi-decadal) and high-frequency (interannual) variability in SAM, allowing us to isolate the long-term contribution of SAM to SST trends. Second, instead of directly using the simpler zonal-mean SAM timeseries, we apply LFCA to the observed zonal winds at 850 hPa at each latitude and longitude and find the timeseries associated with the leading mode of wind variability. This gives us a more complete understanding of the relationship between winds and SST as it accounts for spatial variability of winds and SST. This is important because several recent studies have pointed out the non-zonal feature of the observed SAM-associated wind changes (Waugh et al., 2020) and its zonally asymmetric impacts on SO and remote SSTs (Dong, Armour, et al., 2022).

Our analysis uses the observed zonal winds at 850 hPa (U850) from the ERA5 Reanalysis dataset (Hersbach et al., 2020). As with the SAM index analyzed in section 2, we consider DJF U850 over 1950–2022. We apply LFCA to the observed U850 only over 40°S – 80°S, to avoid variability associated with tropical winds. Our LFCA uses a 15-year cutoff low-pass filter to isolate low-frequency variability, and we retain the 5 leading EOFs, which account for 77% of the total U850 variability (we find that increasing the number of EOFs does not lead to substantially more variance explained). The LFCA results remain the same regardless we choose a low-pass filter of 10 year, 15 year or 20 year (compare Fig. S3 to Fig. 3).

3.2 LFCA results

First, let us consider the leading anomaly patterns (i.e., low-frequency patterns, LFPs) and their associated timeseries (i.e., low-frequency components, LFCs) obtained by applying LFCA to the observed DJF U850 over the Southern Ocean. The first 5 LFPs and LFCs are shown in Fig. 3, in the left and right columns, respectively.

The leading mode (LFP1) features a SAM-like annular pattern of wind strengthening that has increased monotonically from 1970s to 2000s (see LFC1). This is well in line with the SAM trend caused by ozone depletion (Banerjee et al., 2020). This mode accounts for 58.3% of the low-frequency variance and has the highest signal-to-noise ratio of 0.4. The next four modes exhibit mostly non-zonal patterns (LFP2-5), where wind anomalies are confined to specific ocean sectors. The LFCs associated with LFP2 and LFP3 have some decadal-to-multi-decadal variability, while the LFCs associated with LFP4 and LFP5 are dominated by interannual variability, consistent with their low signal-to-noise ratio.

Next, we examine the U850 trend pattern (1979–2022) associated with each mode by projecting each LFC onto the corresponding LFP of U850 at each grid point over the SO. Fig. S4 confirms that the total reconstruction based on the five LFPs (Fig. S4b) well reproduces the observed U850 trend pattern (Fig. S4a), which is characterized by a strengthening of the westerlies at high latitudes in the Southern Ocean. Furthermore, the total reconstructed trend pattern remains the same using either the leading five or three LFPs, suggesting that LFP 1-3 are the major contributor to the total U850 trends over recent decades.

3.3 Long-term relationship between SO SST and winds

Having established that the leading modes obtained by LFCA well reproduce the observed U850 trend pattern, we next investigate the long-term relationship between U850 and SO SST by examining how each LFP and LFC influences SST across timescales.

First, we regress the observed DJF SST over the entire period (1950–2022) at each grid box onto the LFC timeseries associated with the three leading wind LFPs, respectively (Fig. 4 a-c). We focus on DJF SST as our earlier results suggest it is the season when the SAM, through surface winds, has the strongest impact on SST. Consistent with the SAM-SST regression result (Fig. 2), the wind LFC-SST regression also shows broad SST cooling anomalies around Antarctica associated with positive LFC anomalies. However, it is interesting that the patterns of SST cooling response do not quite match the wind anomaly patterns (compare Fig. 3 and Fig. 4): All three wind LFPs feature positive wind anomalies throughout the Southern Ocean (LFP1 even has stronger wind anomalies in the Atlantic basin than in the Pacific basin), yet their SST cooling responses are most significant in the Pacific basin. This mismatch in spatial patterns may give us a first hint that the proposed mechanism linking surface winds to SO SST through Ekman heat transport may not sufficiently explain the spatial patterns of wind-SST relationship.

Second, we estimate the long-term SST trends over the period 1979–2022 based on the above linear regression. Specifically, we multiply the regression between each LFC and SST at each grid box with the corresponding LFC, and then take the linear trend of the reconstructed SST timeseries at each grid box (Fig. 4). Although the LFC-based SST trends also occur in the Pacific basin – consistent with observations – one immediately sees that the magnitudes of wind-driven SST trends are much weaker than that observed (cf. Fig. 4 middle row vs. Fig. 4g). Taking a spatial average over the Pacific sector of the Southern Ocean where the observed SST cooling is strongest (150°E – 60°W, 50°S – 70°S), we obtain an SST trend of -0.98 $°C$/decade from the observation, and SST trends of -0.25, -0.14 and -0.02 $°C$/decade from LFC1-3 regressions respectively, which altogether account for less than half of the actual SST trend (Fig. 4i). To further illustrate the inability of winds to account for the time-evolution of SO SST, we plot the timeseries of DJF SO SST anomalies (relative to their climatology) for the observation and for the estimates using LFC1-3 regressions (Fig. 4h). Although each of the LFCs contributes to some SST variability, none of them can produce a multi-decadal SO SST variability as strong as the observed timeseries. Even the sum of all three LFC-regression-based SO SST timeseries fails to explain the much larger multi-decadal trends in the observed SO SST.

Furthermore, our SST trend estimates so far have been focused on DJF, in the same season with wind anomalies, so as to capture the strongest wind impacts on SST. We also repeated the analysis for annual-mean (instead of DJF only) SST (Fig. S5). The annual-mean SST anomalies following a unit of DJF wind LFC changes are even weaker, leading to almost negligible wind-driven annual-mean SST trends over recent decades, i.e., -0.16 $°C$/decade over 1979–2022 from all three leading-mode regressions, compared to -0.9 $°C$/decade of the actual SST trend (Fig. S5j).

Thus, by projecting SO SST onto the leading modes of observed wind variability, we find that although positive DJF wind anomalies can cause some SST cooling in the same season, this modulation does not survive more than a few months, and the resulting wind-driven SST cooling is *too weak* to explain the large multi-decadal trend in the

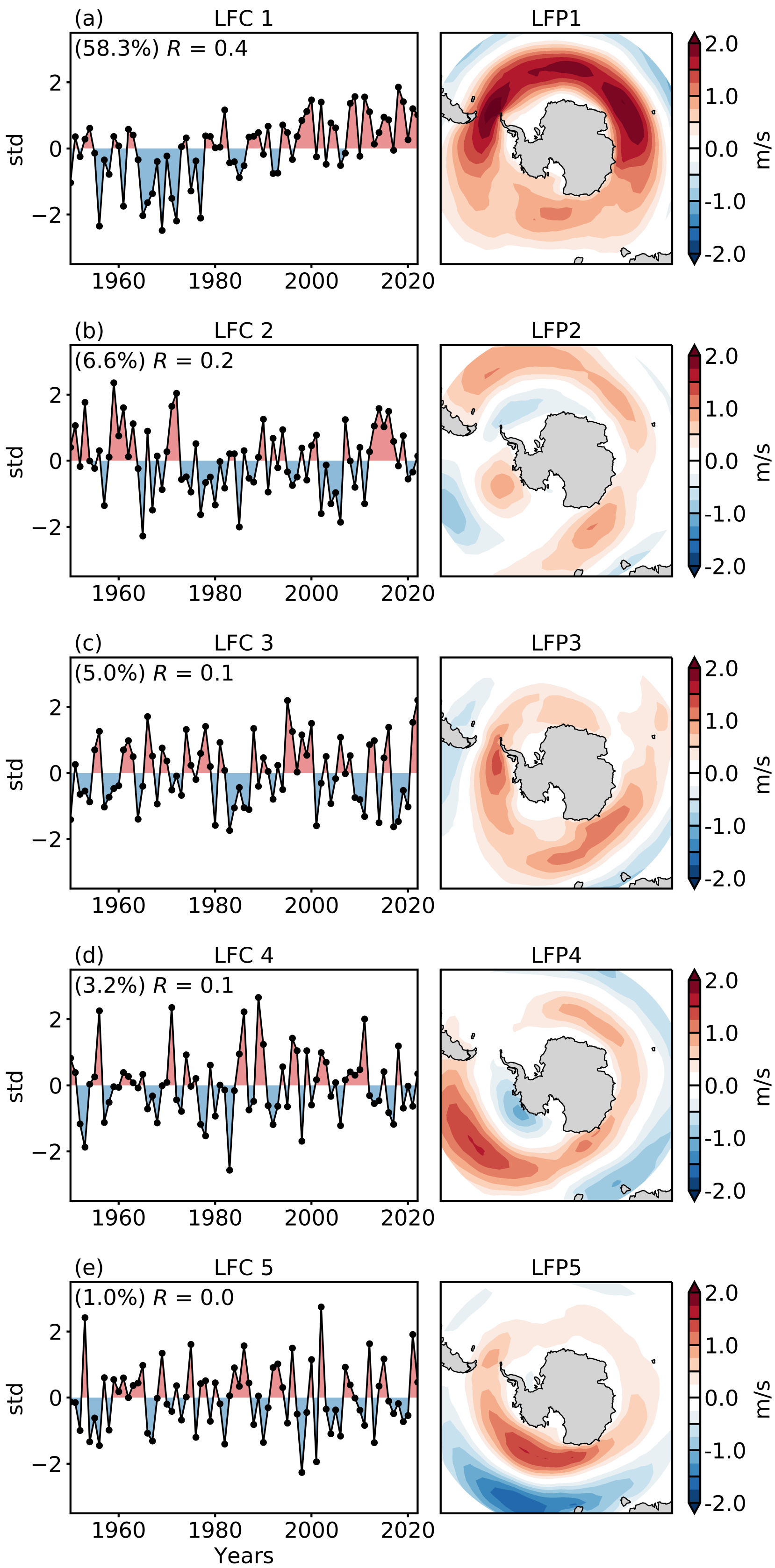

Figure 3. Low-frequency patterns (LFP; right column; unit: m/s) and their associated components (LFC; left column; unit: standard deviation) for the observed DJF U850 wind anomalies. Values in parentheses in the LFC panels denote the low-frequency variance explained by each mode. R values denote the ratio of low-frequency variance explained to the total variance, representing the signal-to-noise ratio.

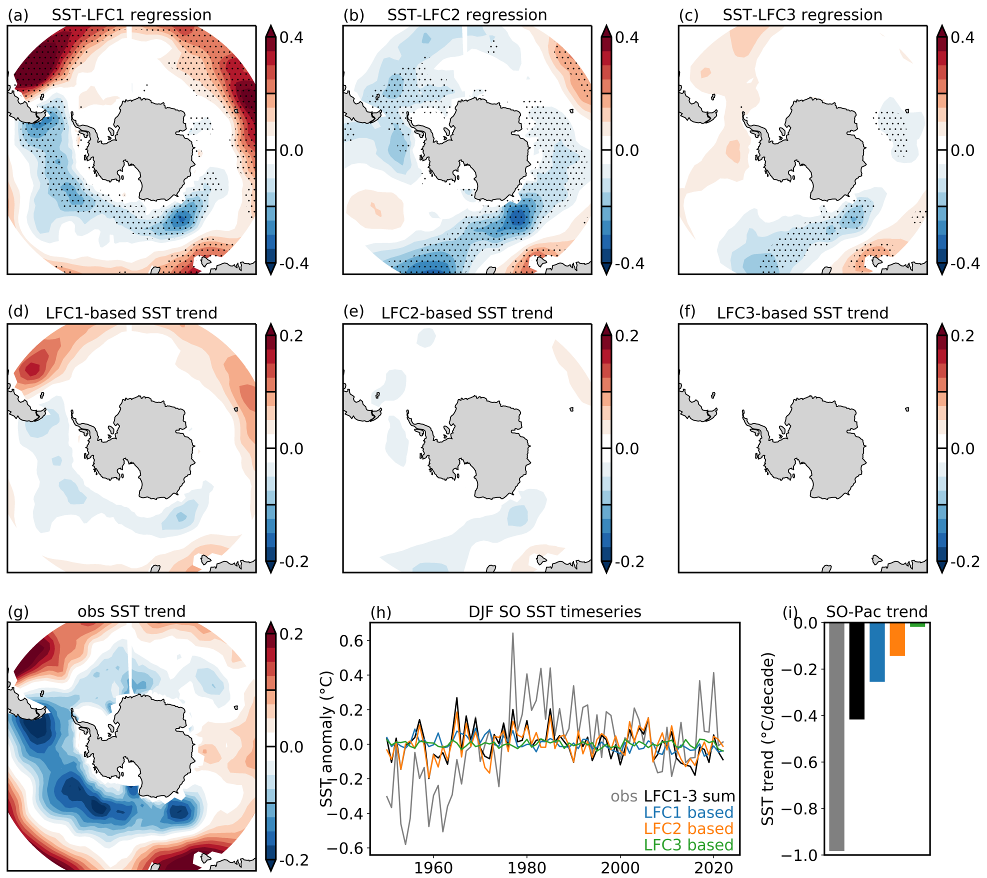

Figure 4. (a-c) DJF SST regression map onto LFC1-3 respectively (unit: $^\circ C$/std). Stippling indicates where linear regression is statistically significant at 95% level. (d-g) DJF SST trend patterns over 1979–2022 ($^\circ C$/decade) estimated from regressions with LFC 1-3 respectively and ERSSTv5. (i) Timeseries of SO SST anomalies relative to their climatology and (j) SST trends averaged over the Pacific sector over 1979–2022, from the observation (grey), the regressions with LFC1-3 respectively (colored), and all three leading LFCs (black).

observed Southern Ocean SST (Fig. 4). Hence, the recent wind strengthening over the Southern Ocean is unlikely the key driver of the long-term Southern Ocean cooling.

4 Summary and Discussion

In this study, we have re-examined a previously proposed idea that positive SAM anomalies in DJF, associated with a strengthening of the circumpolar westerlies, may in part explain the observed Southern Ocean cooling (J. Marshall et al., 2014; Ferreira et al., 2015; Doddridge & Marshall, 2017; Kostov et al., 2018; Hartmann, 2022). Using GCM large-ensembles, we have found that models are able to capture the observed seasonal-to-interannual modulation of SO SST by the SAM, regardless of whether they are able to simulate the long-term SO cooling. Focusing on observations, we have shown that although positive SAM anomalies and positive zonal wind anomalies in DJF can lead to some SST cooling anomalies in the same season, this mechanism only operates for a few months and does not persist from year to year. These results suggest that the SAM modulation of SO SST, via the strengthening of SO westerlies, is too weak to explain the observed multi-decadal Southern Ocean cooling.

One novel aspect of our study is that we used a low-frequency component analysis to isolate trends in SO zonal winds, rather than focusing on trends in the SAM. While the SAM index has been widely used as a metric to quantify zonal wind changes in the Southern Hemisphere, it only represents zonal-mean features and includes a wide range of variabilities from interannual to decadal timescales. Applying LFCA to the observed wind anomalies has allowed us to (1) obtain the timeseries (LFCs) of the leading modes of wind variability while retaining the spatial pattern of the wind anomalies, and (2) disentangle low-frequency from high-frequency variability.

It could be argued that the weak connection between long-term SAM and SST trends can be immediately deduced from the SAM and SST timeseries alone. A simple visual inspection of their smoothed timeseries (thick curves in Fig. 1a and b, respectively) suffices to note that the kinks in those curves do not match. The SST cooling starts after 1980 and persists past 2010, whereas the positive SAM trend starts well before 1970 and stops after 2000, as a consequence of the Montreal Protocol (Banerjee et al., 2020). Building on this, our new analysis, accounting for spatial-temporal variability, adds additional evidence corroborating the inability of the SAM and surface westerlies to explain the recent multi-decadal SO cooling.

Understanding the causes of the observed Southern Ocean cooling and biases in climate models remains a major challenge. By showing that the SAM-driven SST cooling is too weak to explain the long-term SO SST trends, our results point to a possibly limited role of stratospheric ozone depletion. This finding is also consistent with recent modeling evidence that nudging tropospheric wind anomalies around Antarctica towards observations in a GCM (CESM1) does not produce significant SO SST cooling over recent four decades (Blanchard-Wrigglesworth et al., 2021; Dong, Armour, et al., 2022). Thus, the impact of the Antarctic ozone hole on long-term SO SST via the SAM appears to be less robust than previously proposed. Even so, there is evidence that the ozone hole has caused remote climate impacts on lower latitudes, notably on subtropical precipitation (Kang et al., 2011; Gonzalez et al., 2014; Wu & Polvani, 2017). The Antarctic ozone hole, therefore, may have impacted SST in remote regions (e.g., the tropical Pacific), and those impacts could then have been communicated back to the Southern Ocean SST via atmospheric teleconnections (Ding et al., 2011; Meehl et al., 2016; Chung et al., 2022; Dong, Armour, et al., 2022). Such complex two-way teleconnections, however, remain largely unexplored.

Beyond potential remote impacts from the tropics, other local contributors to the recent SO cooling remain plausible, including freshwater input from Antarctic ice-sheet melt or more equatorward sea-ice melt (Purich et al., 2018; Bintanja et al., 2013; Rye et al., 2020; Dong, Pauling, et al., 2022; Haumann et al., 2020), and Southern Ocean natural variability (Latif et al., 2013; Cabré et al., 2017; Zhang et al., 2019). Whether the recent SO cooling was driven by historical forcings or simply reflects natural variability has important implications for SST trends in the near future. Accurately constraining future projections of Antarctic climate change thus requires a better understanding of the causes of the recent multi-decadal Southern Ocean SST trends.

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Data Availability Statement

ERSSTv5 SST data is available at https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html. ERA5 reanalysis SLP and U850 data is available from the Copernicus Climate Service at https://cds.climate.copernicus.eu/. CMIP5 and CMIP6 model multi-model large ensembles are available via the NCAR Climate Data Gateway and via the ESGF archive at: https://esgf-node.llnl.gov/search/cmip6/.

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Supporting Information for "Recent multi-decadal Southern Ocean surface cooling unlikely caused by Southern Annular Mode trends"

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1. Table S1
2. Figures S1 - S5

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Table S1. Model large-ensemble simulations used in this study

model	simulation	ensemble number
CanESM2	Historical, rcp8.5	50
CESM1	Historical, rcp8.5	40
GFDL-CM3	Historical, rcp8.5	20
GFDL-ESM2M	Historical, rcp8.5	30
MPI-ESM	Historical, rcp8.5	100
CanESM5	Historical, ssp245	25
GISS-E2-1-G	Historical, ssp370	10
IPSL-CM6A-LR	Historical, ssp370	10
MIROC6	Historical, ssp245	50
MIROC-ES2L	Historical, ssp245	30

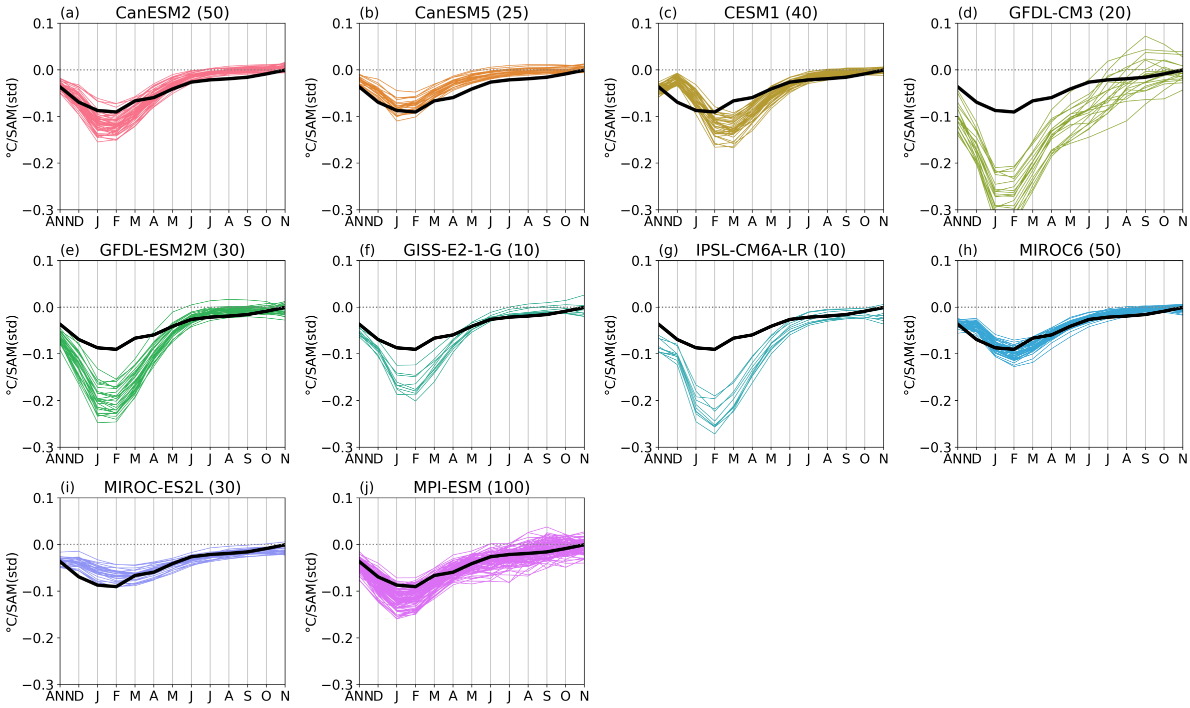

Figure S1. (a) Coefficients of monthly SST regressions onto DJF SAM for each individual model large-ensemble. Numbers in the title for each panel denotes the total number of ensemble members of the model.

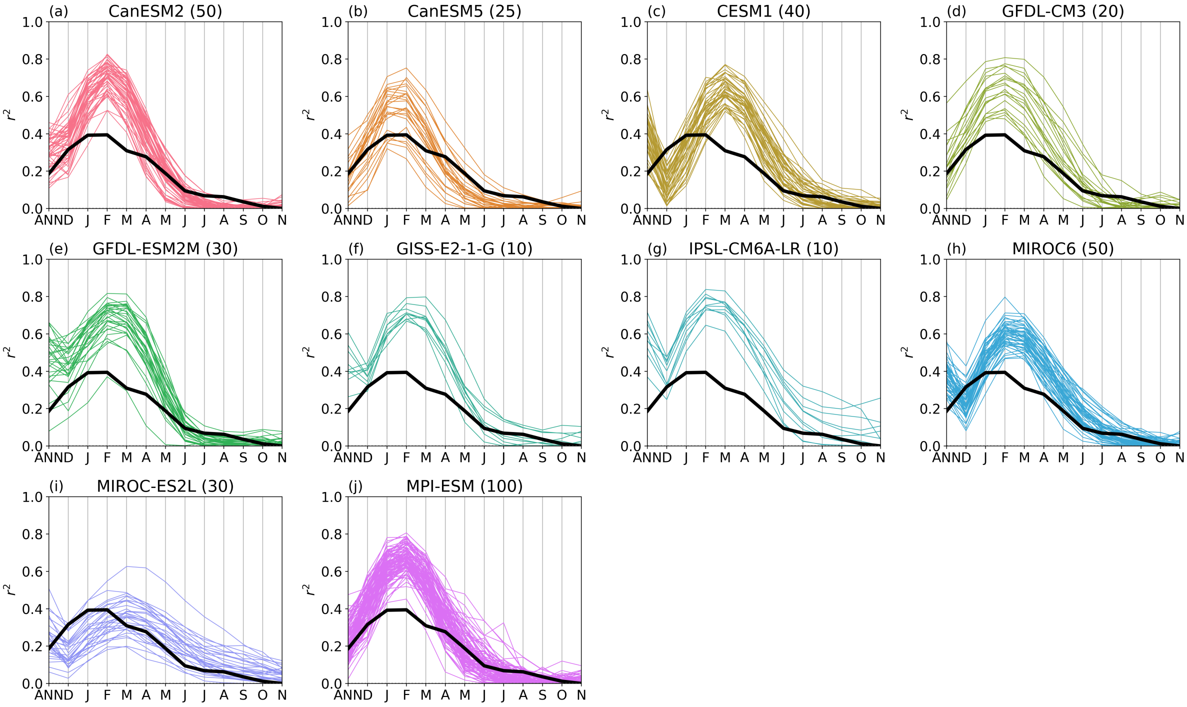

Figure S2. Same as Fig. S1, except for regression r^2.

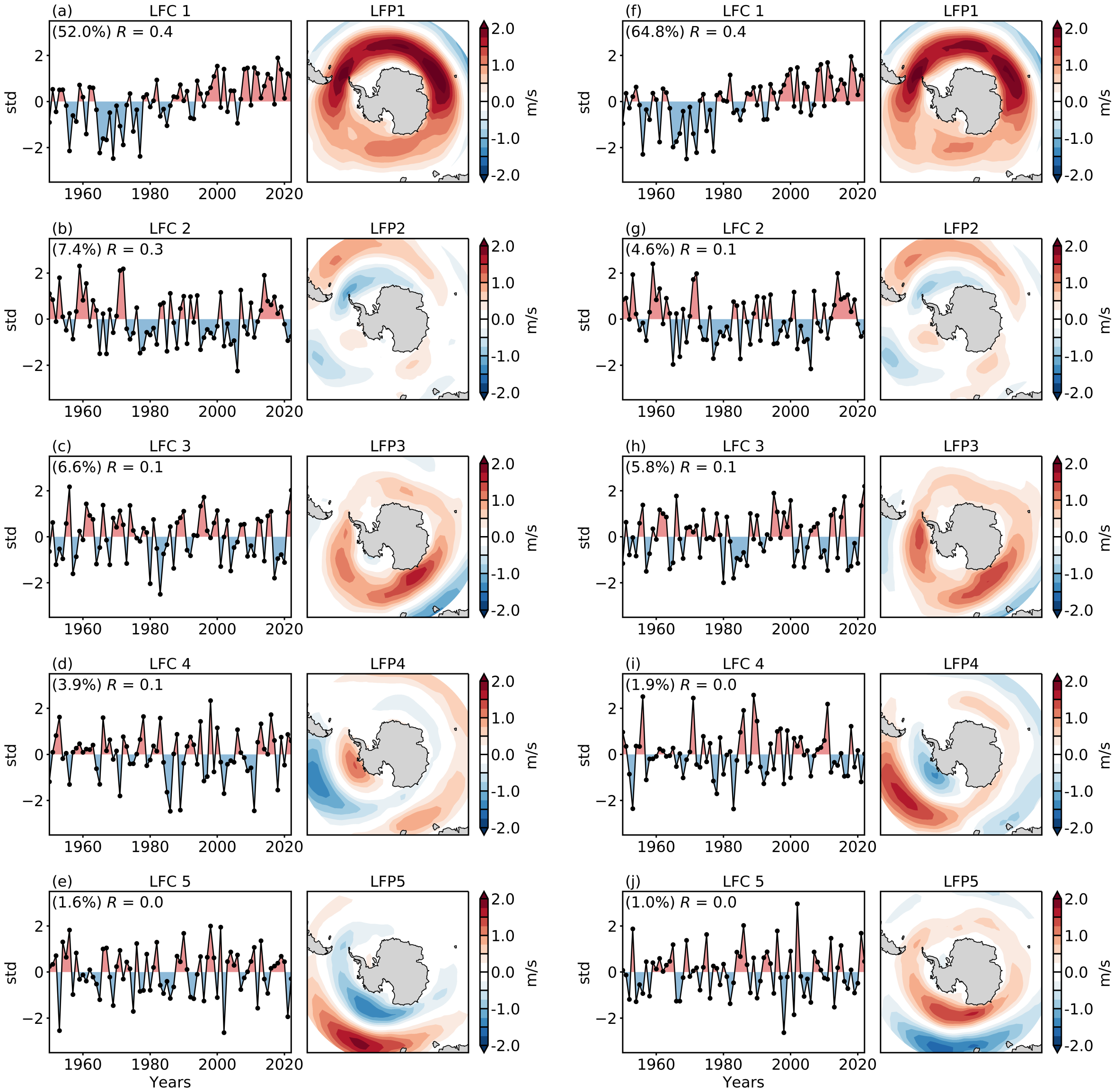

Figure S3. LFP and LFC results obtained using a cutoff of 10-year (left, a-e) or 20 year (right, f-j)

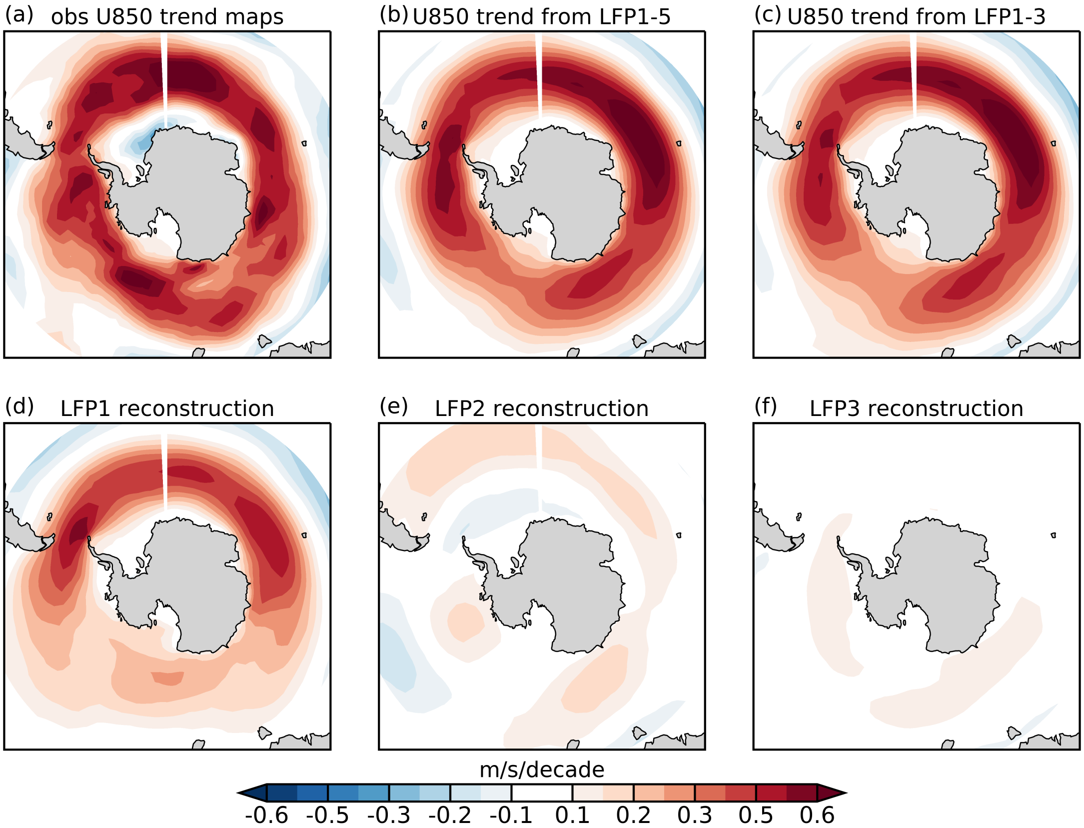

Figure S4. DJF U850 trend patterns over 1979-2022 (m/s/decade) from (a) ERA5 Reanalysis, (b, c) the reconstruction using all five LFPs or the leading three LFPs, and (d-f) the reconstructions using LFP 1-3, respectively.

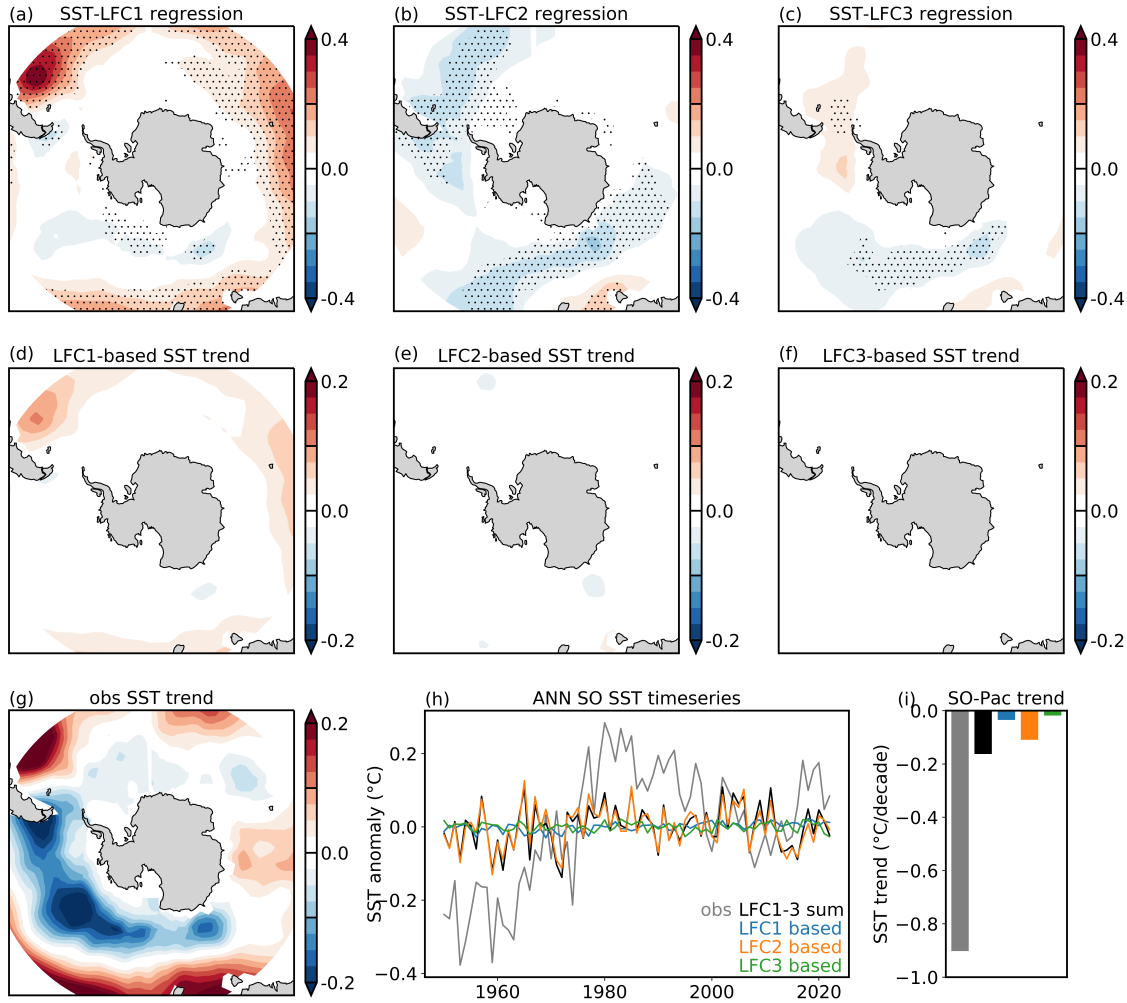

Figure S5. Same as Fig. 4, except for annual-mean SST regressions and trends.