



Decoded Antarctic snow accumulation history reconciles observed and modeled trends in accumulation and large-scale warming patterns

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Abstract. Increased snow accumulation on the Antarctic Ice Sheet mitigated global sea level rise by ~ 11 mm during 1901–2000 according to ice core reconstructions. However, in the most recent 40 years of more intense observation and warming, the trend in the Antarctic-wide accumulation rate has been negligible. We attribute these trends by evaluating Earth system model experiments in comparison with dynamically consistent reconstructions of surface climate. Single-forcing experiments reveal that rising concentrations of greenhouse gases (GHGs) have been the underlying driver of increased accumulation, yet acting alone would have caused twice the observed accumulation-related sea level mitigation during 1901–2000. Aerosol-driven cooling partially compensates this overprediction, but the reconstructions provide evidence that poorly modeled processes can explain observation-model trend discrepancies. In particular, these data support a hypothesis that high-latitude winds have been working together with ice-shelf meltwater fluxes to dampen Southern Ocean surface warming and suppress the GHG-driven accumulation increase since the initiation of West Antarctic ice shelf thinning in the mid-20th Century. The wind pattern associated with strengthening of the Southern Hemisphere westerlies and deepening of the Amundsen Sea Low distributes accumulation unevenly across the continent in an orographic pattern that is consistent across models and the reconstructions. In reconstructions, these same wind and accumulation patterns are associated with muted surface warming across the eastern Pacific and Southern Ocean, a pattern not captured in climate projections including the all-forcings large ensemble studied here. However, the westerly wind history constrained by paleoclimate data assimilation largely reconciles differences between the model's ensemble-mean response and the observed world for both Antarctic-wide accumulation and large-scale warming patterns. Although the large ensemble simulates similar wind histories to the real one – driven by internal variability and anthropogenic forcing – its corresponding responses in SSTs and Antarctic-wide snow accumulation are decoupled from the wind. We discuss how this significant observation-model discrepancy, which has implications for projecting regional climate change, likely arises from omitted meltwater forcing and/or resolution limitations. As a component of the sea level budget and a gauge of the magnitude and spatial pattern of climate change, Antarctic snow accumulation is a critical target for models to replicate.

1 Introduction

The Antarctic Ice Sheet (AIS) has been losing mass for at least the past four decades, primarily via enhanced ice discharge induced by ice-shelf basal melting, contributing to global sea level rise (e.g. Rignot et al., 2019; Velicogna et al., 2020; Fox-Kemper et al., 2021). The rate of mass loss has generally been accelerating since the 1980s (Rignot et al., 2019; Shepherd et al., 2019), but gravity anomalies from satellite data suggest that changes in snow accumulation have modulated this rate, even slowing it down during 2016–2019 (Velicogna et al., 2020). Record-high accumulation years have occurred in the early 2020s (Clem et al., 2023; Wang et al., 2025b), in part associated with the anomalous heat and moisture delivered during atmospheric river events (e.g. Blanchard-Wrigglesworth et al., 2023; Wille et al., 2025). However, the consensus among multiple studies employing observation-constrained physical models is that there has been no significant trend in the Antarctic-wide accumulation rate since 1980 despite significant climate warming (e.g. Lenaerts et al., 2019; Mottram et al., 2021; Clem et al., 2023; Jones et al., 2019). The lack of an accumulation trend may be linked to the surface cooling of the Southern Ocean (e.g. Fan et al., 2014; Kang et al., 2023), increased Antarctic sea ice extent during 1979–2014 (e.g. Fan et al., 2014; Blanchard-Wrigglesworth et al., 2021) or strengthening of the circumpolar westerly winds (Medley and Thomas, 2019), but the exact cause has not been determined.

Snow accumulation is the only mass input to the AIS; its time-averaged value is $\sim 2000 \text{ Gt yr}^{-1}$ over the grounded AIS (Mottram et al., 2021; Dunmire et al., 2022), or $\sim 6 \text{ mm yr}^{-1}$ of sea level equivalence (SLE; e.g. Medley and Thomas, 2019; Kittel et al., 2021). As such, modest changes to the accumulation rate, especially when sustained over multiple years, affect the overall mass balance of the AIS and its contribution to sea level. In the short term, an increase in accumulation represents an increase in mass storage on the AIS, thereby removing this mass from the ocean and causing a relative lowering of sea level. Although here we focus on the immediate potential sea level mitigation from increased Antarctic accumulation, over multiple decades to centuries, increased mass input may enhance the driving stress of outlet glaciers, accelerating their discharge of ice into the ocean (Winkelmann et al., 2012).

Given that AIS mass balance is the largest source of uncertainty in global sea level projections (Fox-Kemper et al., 2021), constraining the mass input from accumulation is a scientific imperative. Climate model projections suggest that annual Antarctic snowfall (the dominant term in snow accumulation) could increase by up to 43 % during the 21st Century (Palermo et al., 2016), in accordance with thermodynamics governing the increased moisture holding capacity of the atmosphere with warming. Yet, these projections

differ widely, and direct comparisons between observations and Earth system models are rare, with some studies suggesting that models underpredict accumulation trends (e.g. Medley et al., 2018) and others suggesting that they overpredict them (e.g. Dunmire et al., 2022). Reconstructions that combine temporal information from ice cores with spatial relationships from models or reanalysis offer a new opportunity for model evaluation over long time periods. Medley and Thomas (2019) find that increased accumulation mitigated sea level rise by $\sim 11 \text{ mm}$ during the 20th Century. Wang and Xiao (2023) report $\sim 14 \text{ mm}$ over the 1901–2010 period.

Beyond its central role in the AIS mass balance, Antarctic snow accumulation records the history of variations in the Southern Annular Mode (SAM; e.g. Medley and Thomas, 2019; Wang and Xiao, 2023; King and Christoffersen, 2024), teleconnections arising from the El Niño – Southern Oscillation (ENSO; e.g. Wang and Xiao, 2023; King and Christoffersen, 2024), and the strength and position of the Amundsen Sea Low (ASL, e.g. Raphael et al., 2016; Dalaiden et al., 2024), all prominent features of the Antarctic-Southern Ocean climate system that are affected by internal variability and anthropogenic forcing. These patterns are not necessarily independent – a positive SAM phase (which corresponds with strengthened and poleward shifted westerly winds) is typically associated with a deepened ASL and often occurs during the La Niña phase of ENSO (e.g. Schneider et al., 2012). Since instrumental observations in Antarctica began in the 1950s, the SAM has exhibited a multidecadal trend towards its positive phase (Marshall, 2003) while the ASL has deepened (Raphael et al., 2016), resulting in a snow accumulation trend dipole across the West Antarctic Ice Sheet (WAIS), with more anomalous accumulation in the Peninsula region and less on the Ross Ice Shelf side of the WAIS (Medley and Thomas, 2019; Wang and Xiao, 2023). Integrated Antarctic-wide, there has been a net negative trend in snow accumulation associated with the SAM trend (Medley and Thomas, 2019), damping the expected positive accumulation trend driven by atmospheric warming. Although the SAM trend is commonly attributed to stratospheric ozone depletion (e.g. Gillett and Thompson, 2003; Polvani et al., 2011), greenhouse gas increases also contribute to it (e.g. Kushner et al., 2001; Arblaster et al., 2011; Purich et al., 2025), while paleoclimate reconstructions indicate that a significant positive trend occurred in the mid-20th Century prior to the onset of ozone depletion, implying significant modulation by internal variability (Jones and Widmann, 2004; O'Connor et al., 2021a).

The primary aim of the present study is to evaluate the agreement between reconstructed snow accumulation and a current-generation climate model over the 20th Century, and to use the same model to identify the main drivers of historical change with a view towards constraining future pro-

jections. The single-model framework allows the drivers of the accumulation trend, including different external forcings (such as greenhouse gas concentrations, aerosols and stratospheric ozone), internal variability, and SST patterns (which can be internally and externally driven), to be more explicitly identified than is possible using multi-model analyses. It also enables observations to be directly used in the model framework in unique and complimentary ways, including SST and wind nudging, as well as paleoclimate data assimilation. By leveraging snow accumulation archives (Medley and Thomas, 2019) along with paleoclimate data assimilation products (O'Connor et al., 2021b, 2025b), this evaluation contributes to understanding systematic discrepancies between observed and modeled trends within the climate system (e.g. Wills et al., 2022; Simpson et al., 2025) over a century-long period. Resolving these discrepancies is imperative for gaining confidence in projections of accumulation, sea level, and regional climate patterns.

2 Data and Methods

2.1 Model description and primary metrics

Most experiments discussed here (Table 1) employ the Community Earth System Model, version 2 (CESM2), a comprehensive model with coupled land, atmosphere, sea ice and ocean components (Danabasoglu et al., 2020). CESM2 represents Antarctica surface climate and the processes that affect snow accumulation very well, improving upon its predecessor, CESM1 (Dunmire et al., 2022). Here, we use the term “snow accumulation” or simply “accumulation” for consistency with Medley and Thomas (2019) and to emphasize that accumulation is the only mass input to the AIS. “Surface mass balance (SMB)” has the same meaning as our formulation of accumulation, which is explained in Sect. 2.3 below. CESM2 does not have an interactive Antarctic Ice Sheet or interactive ice shelves.

Dunmire et al. (2022) report that CESM2 simulates an unrealistically large, upward trend in Antarctic accumulation for the 1979–2015 period, which they attribute to CESM2's equilibrium climate sensitivity (ECS) of ~ 5 K (Gettelman et al., 2019a), which is greater than observationally constrained estimates of ECS suggest (Armour et al., 2024). However, when observed SST warming patterns are accounted for, high-ECS models have a lower effective climate sensitivity (Armour et al., 2024). This is explained by the SST pattern effect, which describes the dependence of radiative feedbacks on the spatial pattern of surface warming (e.g. Andrews et al., 2022). In observations, the Southern Ocean and eastern Pacific have cooled in recent decades, in contrast to the warming simulated by CESM2 and many other CMIP6 models (Wills et al., 2022). In CESM1 (Hurrell et al., 2013) at least, introducing Antarctic observational data into the model via enhanced meltwater fluxes or wind nudging brings simulated SST and sea level pressure trends into better agree-

ment with observations (Dong et al., 2022a; Armour et al., 2024). However, it has yet to be demonstrated that reduced Southern Ocean warming lowers the Antarctic accumulation rate. To test this idea, we exploit the many realizations of internal variability within a large ensemble and examine accumulation trends in several experiments constrained by observations.

We compare snow accumulation simulated by CESM2 with the gridded reconstruction of Medley and Thomas (2019) (hereafter, “MT19” or “reconstruction”), favoring this reconstruction because it is accessible, well verified and has been used in previous work with CESM2 (Dunmire et al., 2022). It was calibrated to the spatial signature of precipitation minus evaporation (P minus E) in the MERRA2 atmospheric reanalysis (Gelaro et al., 2017), with a bias correction based on accepted *in-situ* measurements. We specifically use the version remapped by Dunmire et al. (2022) from its native resolution to the standard grid of CESM2's land and atmosphere components. It spans 1801–2000 at annual resolution.

Our primary metric of snow accumulation is the timeseries of cumulative mass change over the grounded AIS relative to a pre-industrial baseline, as explained in Sect. 2.3 below. This metric de-emphasizes the large temporal variability of precipitation (Previdi and Polvani, 2016) making for a less noisy data-model comparison, and permits the time-integrated signals of climate forcings (Casado et al., 2023) to be detected. The spatial patterns of snow accumulation trends are also indicators of the responsible climate drivers; pattern correlations (Appendix A) between reconstructed and modeled trends are adopted as secondary metrics for interpreting the Antarctic snow accumulation history. Signatures of atmospheric circulation variability are prominent in Antarctic accumulation records (e.g. Medley and Thomas, 2019; Genton et al., 2003), making it imperative to account for these impacts to uncover the underlying warming-driven trends. As such, we calculate a wind index that captures the dominant circulation variability and determine the trends in accumulation that are congruent with trends in this index (Appendix A).

2.2 CESM2 Experiments

Our evaluation leverages a suite of previously published CESM2 experiments (Table 1). The first four ensembles comprise the single-forcing large ensemble (Simpson et al., 2023), whose forcings added together are the same external forcings as in the half of the 100-member CESM2 Large Ensemble (CESM2-LE) that has smoothed biomass burning (Rodgers et al., 2021). The other half of the Large Ensemble, denoted as CESM2-LEcmip6, uses the standard CMIP6 historical forcing with a few exceptions (Rodgers et al., 2021; Danabasoglu et al., 2020). Hereafter the text will use “Large Ensemble” to generally refer to the whole ensemble.

Table 1. Summary of coupled CESM2 experiments used for cumulative mass gain calculations and spatial trend illustrations. All experiments use the standard $1^\circ \times 1^\circ$ horizontal resolution and all (except piControl) follow the SSP3-7.0 forcing scenario from 2015 onwards. Figure 2 and Table 3 display uncertainty estimates of the cumulative mass gain.

abbreviation	years integrated	evolving radiative forcing	SSTs, sea ice	purpose	ensemble members	ens. mean mass gain 1901–2000
GHG	1850–2050	anthropogenic greenhouse gases	coupled	evaluate forced response to greenhouse gases	15	7483 Gt, 21 mm SLE
AAER	1850–2050	anthropogenic industrial aerosols (CMIP6)	coupled	evaluate forced response to anthropogenic industrial aerosols	20 (15 for GHG + AAER)	–3156 Gt, –8.7 mm SLE (GHG + AAER = 4185 Gt, 11.6 mm SLE)
BMB	1850–2050	biomass burning aerosols (smoothed)	coupled	evaluate forced response to biomass burning aerosols	15	–281 Gt, 0.78 mm SLE
EE	1850–2050	stratospheric & tropospheric ozone; solar variability; volcanic aerosols; EE = “Everything Else”	coupled	evaluate forced response to natural and anthropogenic forcings not included in GHG, AAER or BMB	15	745 Gt, 2.1 mm SLE
CESM2-LE	1850–2100	all major natural and anthropogenic forcings from CMIP6 (with few exceptions, Danabasoglu et al., 2020), with smoothed biomass burning	coupled	evaluate response to combined forcings; separate forced response from internal variability	50	6079 Gt, 16.9 mm SLE
CESM2-LEcmip6	1850–2100	all major natural and anthropogenic forcings, including original CMIP6 biomass burning aerosols	coupled	as above; also used as prior for PDA	50	6434 Gt, 17.8 mm SLE
TPACE	1880–2019	as in CESM2-LEcmip6	coupled; nudged to SST anomalies (ERSSSTv5) in trop. Pacific	sync the model to evolution of observed variability in the tropical Pacific in the context of evolving radiative forcing	10	4167 Gt, 11.5 mm SLE
CESM2-LE*	1850–2100	as in CESM2-LEcmip6; members with same initial conditions as TPACE	coupled	baseline to isolate impacts of SST nudging in TPACE	10	6478 Gt, 17.9 mm SLE
piControl	1000 years	pre-industrial control; forcings fixed at nominal 1850 values	coupled	evaluate climate system behavior in the absence of anthropogenic forcing; calculate baseline Antarctic snow accumulation rate	1	mean of 24 century-length segments: –186 ± 1114 Gt

The tropical Pacific pacemaker experiment, TPACE, constrains the evolution of internal variability in the model by nudging it towards observed SST anomalies in the tropical Pacific (15° N to 15° S and from the west coast of the Americas to the dateline; west of the dateline, the wedge-shaped nudging mask tapers off to a point at ~0° N, 130° E) (Rosenbloom et al., 2025; O'Connor et al., 2025a). It generally follows the method of Kosaka and Xie (2013). SSTs outside of the nudged region are free to evolve. Given the ubiquitous role of tropical teleconnections in Antarctic climate variability (e.g. Li et al., 2021; Schneider et al., 2012), the pacemaker setup is an important way to constrain simulations with observations. In addition to the synching of internal variability, it can also help account for biases in the model's forced response, but it does not override the model's mean-state biases.

Stratospheric ozone depletion and recovery is represented in the Large Ensemble, TPACE and “everything else” (EE) ensembles, but its role cannot be isolated with these experiments, as was done in experiments with CESM1 (Lenaerts et al., 2018; Chemke et al., 2020; Schneider et al., 2020). There is no CESM2 single-forcing ensemble with stratospheric ozone depletion and recovery as the sole evolving forcing. Stratospheric ozone is however the dominant time-evolving forcing in EE during the latter part of the 20th Century, during which a strong accumulation signal appears. While the lack of an ozone-only ensemble is a limitation of this work, the greenhouse gas only (GHG), industrial aerosol-only (AAER), and biomass burning aerosols only (BMB) ensembles enable the novel analyses of accumulation responses to these forcings, which to our knowledge have not been previously presented.

We use the data-rich period since 1979 to evaluate multiple observation-constrained simulations (Table 2) and their depictions of the spatial patterns of snow accumulation change. These experiments include a coupled wind nudging experiment, uncoupled prescribed SST and sea ice experiments, and a coupled meltwater experiment to explore specific mechanisms of accumulation change.

Wind nudging is a technique that can override circulation biases in a model, for example associated with polar stratospheric vortex dynamics (e.g. Gettelman et al., 2019b), in addition to controlling for internal variability in the highly dynamic polar regions (e.g. Gilbert et al., 2025). In CESM2-WNUDGE the model's winds are nudged to winds from ERA5 (Hersbach et al., 2020) across the middle and high southern latitudes, following a protocol developed with CESM1 (Blanchard-Wrigglesworth et al., 2021) and recently applied to CESM2 (Espinosa et al., 2024). Zonal (U) and meridional (V) winds over January 1950 through November 2023 are nudged to 6-hourly ERA5 U and V from 850 hPa to the top of the model between 55 and 80° S. The model was free to evolve through the end of 2024. As the first few decades of CESM2-WNUDGE show signs of drift in the Antarctic accumulation values we use only the 21st Century

portion of this experiment. The difficulty in removing drift and the single ensemble member are the key limitations of this experiment.

Anomalous freshwater fluxes from thinning ice shelves are not included in standard CMIP6 historical experiments nor the CESM2 experiments in Table 1. Recent work argues that ice sheet and ice shelf meltwater is a climate forcing that should be included in such experiments to enhance their accuracy in simulating historical trends and predicting future change (e.g. Rye et al., 2020; Roach et al., 2023; Schmidt et al., 2023; Sadai et al., 2025). Pauling et al. (2016) and Dong et al. (2022a) describe a meltwater hosing ensemble with CESM1 that spans 1980–2013. We utilize this ensemble (using the ensemble mean of 7 members where total anomalous freshwater flux is set to 2000 Gt yr⁻¹, prescribed at the front of ice shelves at depths of 100–200 m) for insight into the possible influence of meltwater on snow accumulation. A caveat is that the magnitude of the freshwater fluxes imposed in this ensemble is much larger than observational estimates (Pauling et al., 2016). In the observational record since 1990, anomalous freshwater fluxes to the ocean from the AIS and its ice shelves have exceeded 2000 Gt yr⁻¹ in a few years (Schmidt et al., 2025), but the time-averaged value is around 500 Gt yr⁻¹ (Swart et al., 2023). In reality, anomalous ice-to-ocean freshwater fluxes are approximately equally distributed between ice shelf basal melting and iceberg discharge (e.g. Coulon et al., 2024; Schmidt et al., 2025). Pauling et al. (2016) present an iceberg freshwater flux experiment, but we do not include it here due to the small ensemble size and the precedent of previous climate dynamics studies in using the larger CESM1 ice shelf basal melt ensemble (Dong et al., 2022a; Armour et al., 2024). Advantages of the CESM1 basal meltwater experiment are that it captures the spatial pattern of anomalous meltwater forcing including its depth, and that it simulates significant responses in SSTs (Dong et al., 2022a), sea ice extent (Pauling et al., 2016) and transient climate sensitivity (Dong et al., 2022a). All CESM experiments conserve ocean mass and volume such that snow accumulating on the AIS in excess of 1 m is returned to the ocean, analogous to river runoff. The freshwater forcing in CESM1-AIS meltwater is implemented as an additional, negative salinity flux to estimate the climate impact of the mass imbalance of the AIS (Pauling et al., 2016).

To circumvent the challenges in modeling the roles of meltwater and winds on SSTs and accumulation, we directly link Antarctic accumulation with the observed SST and sea ice record by considering two uncoupled, atmosphere-land-only simulations (“AMIP” style) with prescribed SSTs and sea ice concentrations from observational datasets. The Global Atmosphere – Global Ocean (GOGA) experiment specifies time-varying SSTs and sea ice concentrations throughout the global ocean domain. The Tropical Ocean – Global Atmosphere (TOGA) uses time-varying SSTs in the tropical latitudes only and specifies monthly climatology for SSTs and sea ice concentrations elsewhere.

Table 2. Summary of observationally constrained CESM2 and CESM1 experiments used for evaluation of recent snow accumulation and circulation trends. All experiments use the models at their standard $1^\circ \times 1^\circ$ horizontal resolutions, except for CESM1-AIS meltwater, which uses a $\sim 2^\circ$ resolution.

abbreviation	model version	radiative forcing	SSTs, sea ice	primary purpose	ensemble members
CESM2-GOGA	CESM2	as in CESM2-LEcmip6; GOGA = “Global Ocean – Global Atmosphere”	prescribed from ERSSTv5; HadISST1 & OISSTv2 sea ice	find global atmospheric response to observed SST and sea ice anomalies globally	10
CESM2-TOGA	CESM2	as in CESM2-LEcmip6; TOGA = “Tropical Ocean – Global Atmosphere”	as in GOGA but using climatology polewards of $\sim 28^\circ$ N and $\sim 28^\circ$ S	find global atmospheric response to observed SST and sea ice anomalies in the tropics and subtropics	10
CESM2-WNUDGE	CESM2	as in CESM2-LEcmip6; winds nudged to ERA5 55–80° S, above 850 hPa	coupled	constrain model to Antarctic winds estimated by reanalysis	1
CESM1-AIS meltwater	CESM1	CMIP5 forcing as in CESM1-LE (Kay et al., 2015) plus Antarctic meltwater hosing	coupled	find atmosphere-ocean response to anomalous freshwater fluxes from Antarctic ice shelves	7 for accumulation; 10 for SST
CESM1-GOGA	CESM1	CMIP5 forcing as in CESM1-LE (Kay et al., 2015)	prescribed from ERSSTv4; HadISST1 sea ice	to compare with CESM1-AIS meltwater using the same atmospheric model and radiative forcing	10

2.3 Snow accumulation and cumulative mass gain calculation

The domain of our snow accumulation calculations is the grounded AIS, as defined by Zwally et al. (2012). Unlike Medley and Thomas (2019), we do not include Antarctic islands in our calculation of Antarctic-wide snow accumulation. For Antarctic-wide snow accumulation from MT19, grid-cell values in mm w.e. yr^{-1} are scaled by the area of the respective grid cell, and summed over the grounded AIS for each year of the dataset. This mass timeseries is converted to a relative mass timeseries by subtracting the long-term mean for 1801–1900 ($1927.4 \text{ Gt yr}^{-1}$) from the entire timeseries. Cumulative mass is calculated by integrating the relative mass timeseries with time, starting in 1901. SLE at the year 2000 is obtained by dividing the cumulative mass by 361 Gt mm^{-1} . This procedure was repeated for $+1\sigma$ and -1σ error timeseries; the gridded error fields are as provided by Medley and Thomas (2019) in their MERRA2 reconstruction. Here, the term “relative mass” has a distinct meaning from “Antarctic-wide accumulation rate”. Changes in the Antarctic-wide accumulation rate are assessed over specific time intervals, for example linear trends over 1901–2000. Relative mass refers specifically to how much the Antarctic-wide snow accumulation rate (expressed in Gt yr^{-1}) in a particular year is anomalous relative to the 1801–1900 baseline value.

From the output of CESM2’s land model component, SNOW and RAIN variables are used as the precipitation terms, while QSOIL and QRUNOFF are used as the ablation terms. Monthly data are summed to annual means by weighting each monthly value by the length of the month. The relative and cumulative mass timeseries are determined by the same method as for the MT19 reconstruction, except for the calculation of the preindustrial baseline value.

Crucial for the calculation of cumulative mass and its sea level equivalence from CESM2 is the estimate of the baseline accumulation rate that is representative of nineteenth-century values in a stable climate. We reference each ensemble member to the same baseline value from piControl, averaged over the 452-year period of 1000–1451, yielding 102.9 Gt yr^{-1} . All ensemble members of all historical experiments in Table 1 had their initial states drawn from this piControl segment, between the years 1001 and 1301, which was chosen because it has a stable control climate (Danabasoglu et al., 2020; Rodgers et al., 2021; Simpson et al., 2023). An ensemble member initialized from the piControl year 1301 at calendar year 1850 would reach calendar year 2000 150 years later, overlapping with piControl through year 1451. This overlap method is a way of ensuring that mass accumulated by year 2000 arises from forcing (or internal variability), minimizing the influence of drift. The same 1000–1451 piControl period was used for accumulating mass over 24, overlapping 100-year segments to determine how much mass gain or loss within a century could occur due to internal variability alone, in the absence of anthropogenic forcing.

2.4 Reconstructions using paleoclimate data assimilation

To help illustrate and quantify the role of atmospheric circulation and surface temperatures over the entire 20th Century, we employ annually resolved reconstructions of near-surface zonal winds, sea level pressure (SLP) and surface air temperature (SAT) generated by paleoclimate data assimilation (PDA). We first use the reconstruction presented in O’Connor et al. (2021a) that uses members of the CESM1 Large Ensemble (Kay et al., 2015) to form the prior, which is a physically based assumption about the state of the system without accounting for new information from observational

or proxy data. The global proxy network includes Antarctic ice core data used in the MT19 reconstruction. This reconstruction, while skillful in the regions of interest to this study, is not fully dynamically consistent with the CESM2 experiments evaluated here. We therefore utilize a newer PDA reconstruction following the same methodology and using the same global proxy network, but with the prior formed by the first seven members of CESM2-LEcmip6 (O'Connor et al., 2025a). Use of both CESM1-LE PDA and CESM2-LE PDA has some advantages. While both reconstructions skillfully estimate the ASL index (Fig. 1a) and other aspects of the dynamics represented by winds and sea level pressure (Fig. A1), there are marked differences in their surface temperature reconstructions (Figs. A2, A3). Based on considerations discussed in Appendix A, we regard the CESM1-LE PDA as the more reliable of the two surface temperature reconstructions.

2.5 Distinguishing responses to anthropogenic forcing from internal variability

The broad suite of experiments combined with results from PDA enable a multi-faceted strategy to characterize signals arising from external climate forcing and separate them from the effects of internal variability. For the forced response, the ensemble mean of a large ensemble smooths out the signals of internal variability arising from the initial conditions, revealing the model's response to the external radiative forcings (greenhouse gasses, aerosols, etc.) imposed in the experiment. In this text, the forced response is denoted by square brackets, for example “[GHG]” for the ensemble-mean of the greenhouse gas single forcing ensemble. The internal component of a given ensemble member is found by subtracting the forced response from that member.

Using large ensembles is only the first step towards a comprehensive accounting of internal variability. This step may not be sufficient because (a) models like CESM2 may simulate an unrealistic magnitude of internal variability (e.g. Casado et al., 2023); and (b) internal variability in free-running coupled experiments like the Large Ensemble is not synched with real-world internal variability. The second step is the use of nudged coupled experiments, TPACE and CESM2-WNUDGE, which constrain the coupled model by introducing observed anomalies. Third, we use a long segment of piControl to characterize the evolution of accumulation in the absence of anthropogenic forcing. Fourth, the PDA reconstructions of the major surface climate variables that we use are constrained both by well-calibrated proxy records and by the physical dynamical frameworks of CESM1 and CESM2. Finally, we evaluate accumulation trends in prescribed SST/sea ice experiments using again the same dynamical framework of the atmosphere and land component models of CESM. Importantly, results from all of these approaches, presented below, converge upon a single set of conclusions: The accumulation rate increase during

the 20th Century that mitigated sea level rise by ~ 11 mm can only be explained by external forcing, namely greenhouse gases. Real-world internal variability most likely has dampened the forced response. The follow-up question we discuss but ultimately leave open for future work is the extent to which internal variability is sufficient to account for observation-model trend discrepancies, or if there is an important role for poorly resolved processes such as the response to anomalous ice sheet and ice shelf meltwater and the sensitivity of SST anomalies to wind stress.

3 Results

The Results section is organized as follows: Sect. 3.1 verifies the sensitivity of the accumulation rate to temperature in the observations and the model, and then compares the cumulative mass changes in the MT19 reconstruction to the Large Ensemble, single-forcing large ensemble and TPACE experiments. Section 3.2 discusses the spatial patterns of accumulation change over the 20th Century, comparing the observed pattern to simulated patterns arising from anthropogenic forcing and internal variability. Next, the perspective is broadened to illustrate the large-scale surface warming patterns that accompany these accumulation patterns. Section 3.3 focuses on the observation-rich period since 1979 to more closely examine the roles of observed trends in atmospheric circulation, SSTs and sea ice on recent accumulation trends. Section 3.4 explores evidence that Antarctic meltwater has contributed to the accumulation trends and accompanying warming patterns. Section 3.5 presents a trio of conceptual diagrams to synthesize the results in the preceding sections.

3.1 Cumulative AIS mass change due to snow accumulation during 1901–2000

From the MT19 reconstruction, we find a cumulative mass gain over the grounded AIS of 10.5 mm SLE over the 20th Century (Fig. 2a), in agreement with the 10.6 mm previously reported (Medley and Thomas, 2019). The cumulative mass gain arises because the relative mass (the annual anomaly relative to the nineteenth century) increases in a stepwise fashion during the 20th Century (Fig. 1c). For 1901–1925, the relative mass is about 20 Gt yr^{-1} ; for 1976–2000 it is above 60 Gt yr^{-1} . The cumulative mass timeseries is highly correlated with global-mean temperature anomalies in the CESM1-LE PDA ($r = 0.92$; Fig. 3a). Since some common proxy data were used in MT19 and the PDA, we verify this relationship with the independent SAT dataset from ERA-20C (Poli et al., 2016), which similarly shows a high correlation with cumulative mass. Cumulative mass and global temperature anomalies are also highly correlated in CESM2 ($r = 0.83$ for [TPACE]). On the continental scale, both the reconstructions and the model experiments indicate a significant positive correlation between AIS-wide surface temper-

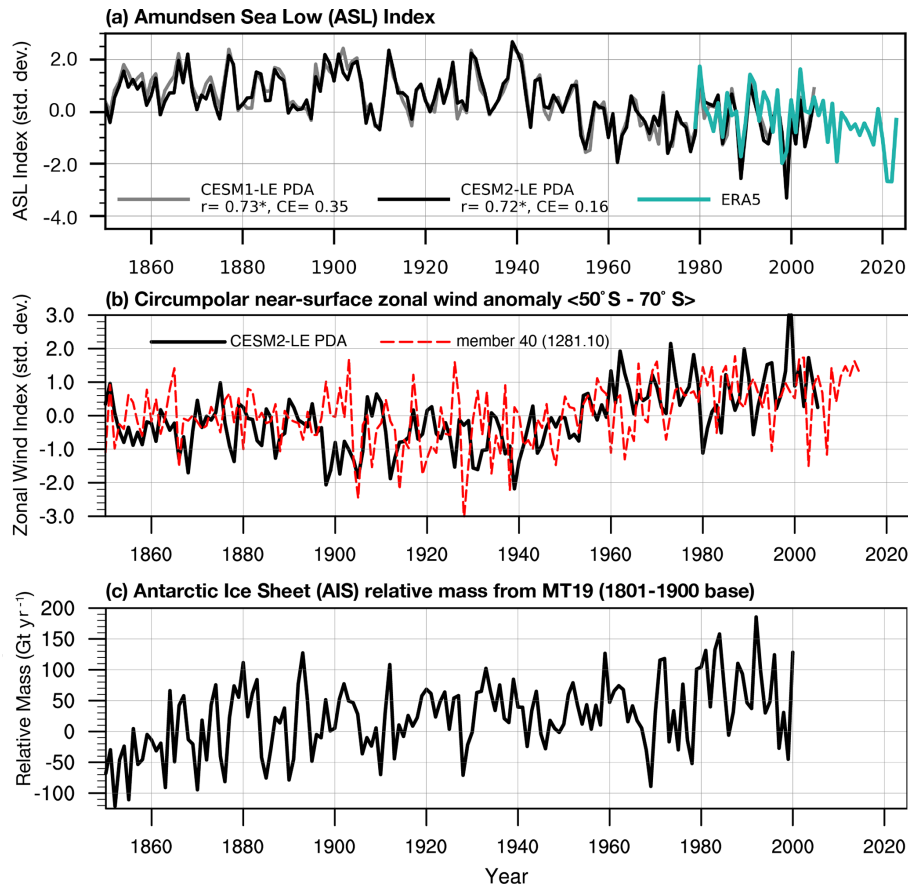


Figure 1. (a) Timeseries of annual-mean Amundsen Sea Low (ASL) index from two different instances of PDA, compared with ERA5. Anomalies relative to 1979–2005. The ASL Index is the standardized mean SLP over 60–75° S, 180–310° E; (b) Standardized, annual mean, near-surface zonal wind indices across 50–70° S from CESM2-LE PDA variable “uas” and member 40 of CESM2-LEcmip6 (using CESM variable “UBOT”). The 1901–2000 linear trend in the CESM2-LE PDA zonal wind index is statistically significant ($p < 0.01$); (c) Relative mass timeseries integrated over the grounded AIS from MT19 snow accumulation reconstruction. Base period is 1801–1900. The 1901–2000 linear trend in relative mass is statistically significant ($p < 0.05$). Over 1901–2000, detrended relative mass and the detrended zonal wind index from CESM2-LE PDA are significantly correlated ($r = -0.39$, $p < 0.01$).

ature anomalies and relative mass timeseries (Fig. 3b), consistent with previous work on the sensitivity of snow accumulation to temperature (Monaghan et al., 2008; Frieler et al., 2015; Dalaiden et al., 2020). Broadly, these results affirm the expectation from thermodynamics of more snow accumulation with warming (e.g. Frieler et al., 2015). However, the exact sensitivity depends on the choice of averaging period, specific experiment, and/or whether an ensemble mean or individual ensemble member is used. Global- or Antarctic-mean temperatures provide only a weak constraint on the magnitude of the snow accumulation increase and are not diagnostic of the forcings that are driving it. To understand the role of these forcings, we evaluate the suite of ensembles listed in Table 1.

As shown in Fig. 2 and Table 1, [CESM2-LE] has a mass gain of 16.8 mm SLE from 1901 to 2000, well above the MT19 reconstruction. The original members of the Large Ensemble with the CMIP6 biomass burning protocol exhibit a

slightly higher ensemble-mean value of 17.8 mm SLE, physically consistent with the spurious warming that arises from CMIP6 biomass burning emissions (Fasullo et al., 2022). Ensemble spread is indicated in the box-whisker plots (Fig. 2b, d). The 5 % lower bound of the CESM2-LE lies within the $+1\sigma$ error of MT19, while two outlier ensemble members are within MT19’s -1σ error. Interpreting the [CESM2-LE] value of 16.8 mm SLE as the forced response to all forcings combined, a mass loss of 6.3 mm SLE is required to match the value of 10.5 mm SLE from MT19. This mass loss can be interpreted as driven by internal variability as 10.5 mm lies within the ensemble spread of CESM2-LE, but falls on the extreme end of the ensemble distribution outside of the 5 % lower whisker (Fig. 2b). A similar distribution occurs in CESM2-LEcmip6, with 10.5 mm SLE lying on the extreme end (Fig. 2d).

Mass accumulated over century-length segments of pi-Control suggests that internal variability alone cannot ac-

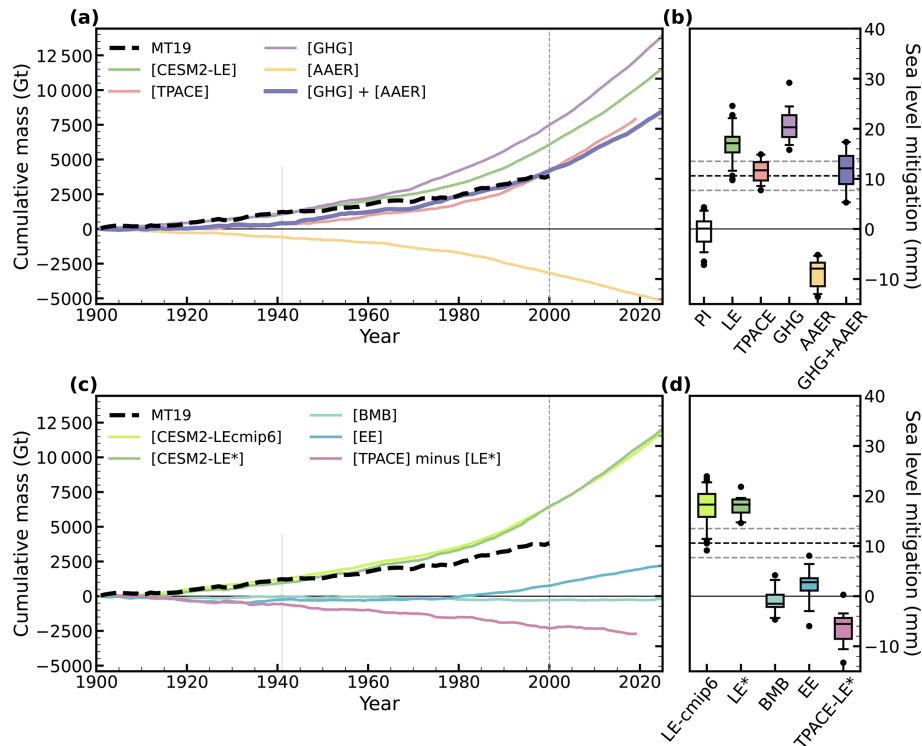


Figure 2. Cumulative mass and equivalent sea level mitigation due to accumulated snow on the grounded Antarctic Ice Sheet (AIS) in MT19 and CESM2: **(a)** Cumulative mass timeseries from MT19 compared with timeseries from selected ensemble means; **(b)** Box plot indicating ensemble spread of cumulative mass at the year 2000 for each of the ensembles and the pseudo ensemble generated by summing 15 individual members of GHG and AAER. The boxes indicate the interquartile range; the median is shown by a horizontal line. Whiskers represent the 5 % and 95 % bounds of the ensemble, with the values lying outside of these bounds indicated by closed black circles. “PI” refers to the piControl simulation: mass was accumulated over 24 overlapping, 100-year segments. Dashed black horizontal line indicates the mean value of MT19; gray dashed lines indicate its $\pm 1\sigma$ uncertainty bounds; **(c)** As in **(a)**, but for different ensembles and [TPACE] – [CESM2-LE*] to isolate the effect of nudging to observed tropical Pacific SST anomalies; **(d)** As in **(b)**, but for the ensembles shown in **(c)**.

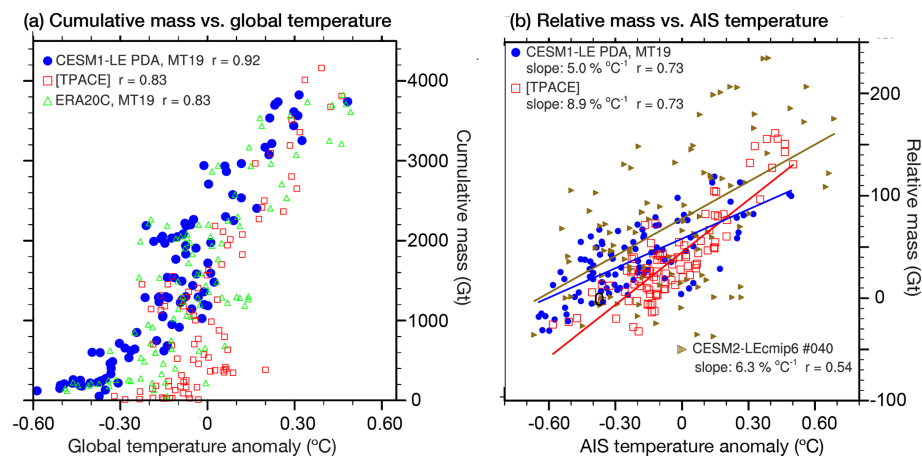


Figure 3. **(a)** Scatter plot of annual-mean, global-mean surface temperature anomalies versus cumulative mass timeseries over 1901–2000 with no smoothing applied; **(b)** Scatter plot of AIS relative mass (annual accumulation anomalies relative to 1801–1900 baseline) versus annual AIS surface temperature anomaly, estimating the Antarctic-wide sensitivity of accumulation to temperature for selected reconstructions and CESM2 experiments. A 5-year running mean was applied to the annual-mean timeseries before computing the regression coefficients and correlation values. The slope and correlation values without the running mean applied are: $4.9\% \text{ } ^{\circ}\text{C}^{-1}$, $r = 0.65$ for CESM1-LE PDA; $7.4\% \text{ } ^{\circ}\text{C}^{-1}$, $r = 0.73$ for [TPACE]; and $4.4\% \text{ } ^{\circ}\text{C}^{-1}$, $r = 0.40$ for CESM2-LEcnp6 #040.

count for the observed mass gain (Fig. 2b). Yet, as the ensemble spreads show, internal variability can partially counteract the forced response in [CESM2-LE] or [CESM2-LEcmip6] and bring model results in agreement with MT19. In the constrained TPACE experiment, mass gain is only 11.5 mm SLE, just 1 mm greater than MT19 and within its 1σ error (Fig. 2b). The observed trends and variability captured in TPACE reduced 20th-Century cumulative mass by 6.4 mm SLE, roughly matching the magnitude of internally driven mass loss in the Large Ensemble that is required to fit the observations.

The single-forcing ensembles uncover the two major components of the forced response (Figs. 2b, d). Greenhouse gases are the dominant driver of the cumulative mass gain, with [GHG] giving a value of 21 mm SLE, twice the value from the reconstruction. Aerosols offset this; mass change in [AAER] is -9 mm SLE. The sum of [GHG] and [AAER], 12 mm SLE, is within the $+1\sigma$ error of MT19 (Fig. 1b). The other forced responses are smaller, at 2.1 mm SLE for [EE] and -0.78 mm SLE for [BMB]. Although the response in [EE] does not strictly isolate the role of stratospheric ozone depletion, the mass gain in [EE] occurs after 1980 (Fig. 2c), consistent with the timing of ozone depletion and qualitatively consistent with ozone-driven accumulation increases found in previous work (Lenaerts et al., 2018; Schneider et al., 2020). The sum of the four separate ensemble means (13 mm SLE) is near the top of the $+1\sigma$ error range of MT19 and in line with the ~ 14 mm SLE from the reconstruction of Wang and Xiao (2023). The result that [CESM2-LE] is ~ 4 mm SLE larger than the sum of the single-forcing ensemble means could be due to aerosol forcing alone causing a large increase in Antarctic sea ice area, but not when it acts in concert with greenhouse gas forcing (Simpson et al., 2023).

The results thus far, while showing general consistency between the CESM2 and the MT19 reconstruction, suggest two interpretations for the cumulative mass gain in MT19. Namely, the single-forcing ensembles suggest that the 10.5 mm SLE from MT19 is only due to external forcing, dominated by opposing responses to GHGs and aerosols. In contrast, the Large Ensemble and TPACE suggest a smaller role for aerosols, but a large role for internal variability in counteracting the mass gain due to GHGs. We therefore turn to the spatial patterns of snow accumulation and atmospheric circulation change to help inform the most likely interpretation of the trends. This analysis will lead to a third possibility: A portion of the mass loss that is internally driven according to the Large Ensemble and TPACE may indicate a missing and/or misrepresented external forcing.

3.2 Spatial patterns of snow accumulation trends and their relationships with atmospheric circulation and surface temperatures

For spatial analysis, we survey the pattern correlations between the 20th-Century trend in MT19 accumulation and each ensemble member of the Large Ensemble and TPACE, along with the ensemble means of all historical experiments from Table 1 (Figs. B1, B3). Similarly, pattern correlations for the sea level pressure (SLP) trend across 40 – 90° S are computed with the same model experiments and using the CESM2-LE PDA as the benchmark (Figs. B2, B4). For illustration, we select the ensemble member whose trend patterns in snow accumulation and atmospheric circulation exhibit the best pattern correlations to the MT19 and CESM2-LE PDA reconstructions, respectively. Specifically, member 40 from CESM2-LEcmip6 has a pattern correlation with the reconstructed SLP trend over 40 – 90° S of 0.92 and with the reconstructed accumulation trend on Antarctica of 0.52, giving an average correlation of these two metrics of 0.72. This is the highest average correlation out of 110 individual members from the CESM2-LE, CESM2-LEcmip6, and TPACE ensembles. The following discussion uses member 40 to illustrate spatial patterns but these same relationships are found in several other ensemble members.

Like the reconstructed patterns (Fig. 4a), member 40 (Fig. 4b) exhibits an accumulation trend dipole across the WAIS, consistent with the deepened ASL and stronger on-shore flow onto the eastern WAIS and offshore flow from the western WAIS. On a larger scale, both member 40 and the reconstruction feature a pressure dipole between the middle and high southern latitudes, consistent with the strengthening and poleward shift of the westerlies (O'Connor et al., 2021a; Dalaiden et al., 2022). Using the Large Ensemble, member 40 is separated into its forced (Fig. 4c) and internal (Fig. 4d) components. The increased accumulation rate is entirely explained by external forcing, with only a minor offset from internal variability. Using the single-forcing ensembles, the forced response patterns associated with individual forcings are also evaluated (Figs. B3, B4). [GHG] and [EE] are best correlated with the reconstructed SLP and accumulation patterns, but not better than the all-forcings response in [CESM2-LEcmip6].

The accumulation pattern in member 40, including the dipole across the WAIS, is shaped by internal variability (Fig. 4d). In the forced response, snow accumulation increases nearly everywhere on the continent but is especially enhanced on the coasts of the WAIS and Queen Maud Land (Fig. 4c). The forced atmospheric circulation pattern indicates a strengthening and poleward shift of the westerlies, especially in the Indian Ocean sector and Drake Passage. The internally driven circulation pattern is also consistent with a strengthening of the westerlies, displaying the characteristic pressure dipole between the middle and high southern latitudes. Neither of the two circulation patterns are perfectly

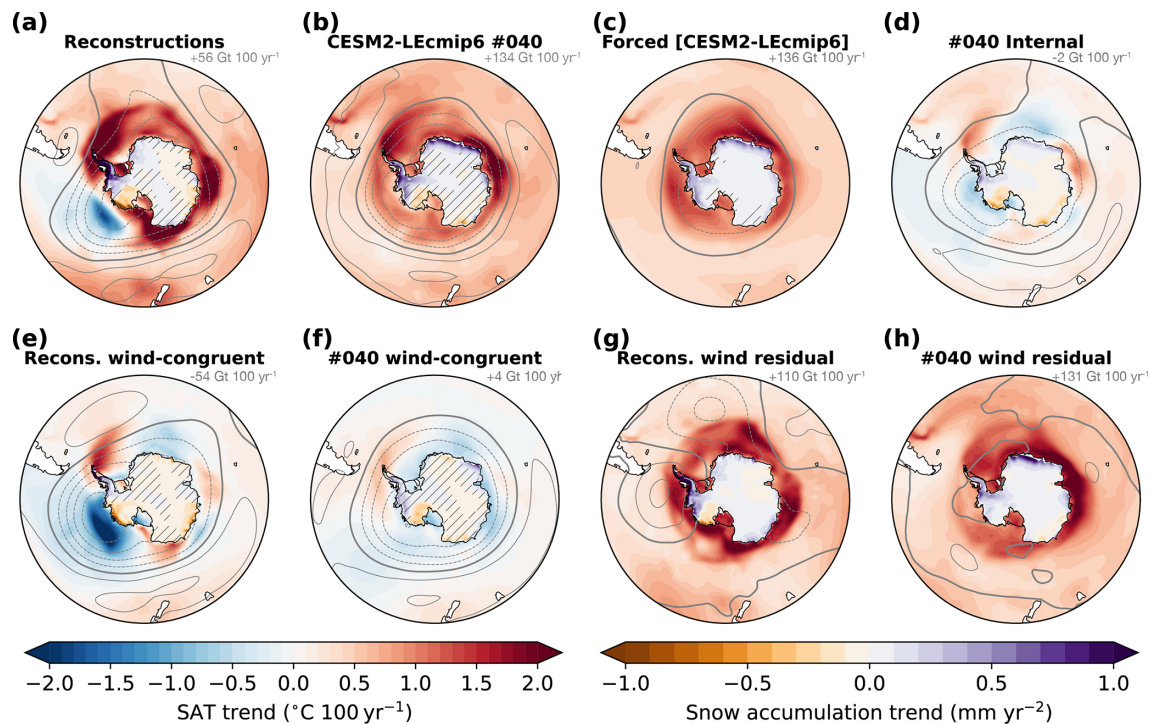


Figure 4. Linear trend patterns for 1901–2000 in annual-mean Antarctic snow accumulation rate (mm water equivalent per year), sea level pressure, and surface air temperature over the ocean from reconstructions and multiple model-based estimates. The change in the Antarctic-wide accumulation rate over the century (1976:2000 minus 1901:1925) is given in the upper right of each plot: (a) PDA and MT19 reconstructions; (b) Ensemble member 40 of the CESM2-LEc mip6 ensemble; (c) The forced component of member 40; (d) The internal component of member 40; (e) Trends in the reconstructions linearly congruent with the CESM2-LE PDA zonal wind index; (f) Trends in member 40 linearly congruent with its zonal wind index; (g) Residual trends in the reconstructions after removal of wind-congruent trends; (h) Residual trends in member 40 after removal of wind-congruent trends. SLP contours (gray lines) are in intervals of 1 hPa 100 yr⁻¹. Negative SLP values are dotted lines and positive values are solid lines; the zero contour is a heavier solid line. For the PDA reconstructions, CESM1-LE PDA is used for SAT and CESM2-LE PDA is used for SLP and the zonal wind index. On panels (a), (b), (c), (e), and (f) hatching indicates where the accumulation trend is not significant at the $p < 0.05$ level or better; note that panels (d), (g), and (h) are simple differences of other panels without formal significance testing.

zonally symmetric. The forced pattern features lobes of low pressure jutting out into the eastern Ross Sea and into the south Atlantic, whereas the internal pattern features a deepened ASL, marked by low pressure anomalies in the south-eastern Pacific. As discussed below, these zonally asymmetric pressure patterns are associated with zonally asymmetric SST trends in lower latitudes.

How have the strengthening westerly winds, associated with the positive phase of the SAM, affected accumulation? Medley and Thomas (2019) use the SAM index (Marshall, 2003) to show a reduction in accumulation related to the positive phase of the SAM for 1957–2000. Here, we use the zonal winds directly and for the full century, as provided by CESM2-LE PDA and member 40 (Fig. 1b). In the MT19 reconstruction, there is a large reduction in the Antarctic-wide accumulation rate that is linearly congruent with the significant trend in the zonal wind index (Fig. 4e). Spatially, the accumulation rate is reduced nearly everywhere on the continent except for the Peninsula. This pattern is more weakly

expressed in member 40 and there is only a small change in the Antarctic-wide accumulation rate associated with the winds (Fig. 4f). With wind-congruent trends removed from the reconstructions, the residual pattern exhibits a large increase in the accumulation rate associated with increased accumulation over East Antarctica, accompanied by a weaker ASL (Fig. 4g). This wind correction brings the reconstructed Antarctic-wide accumulation trend closer to the forced response given by [CESM2-LEc mip6].

The effect of tropical SST nudging in TPACE is to weaken the ASL and reduce the magnitude of the westerly wind trend (Figs. B2, B5a), resulting in a worse fit of modeled and reconstructed trend patterns than in [CESM2-LE*] (Figs. B1, B2). Nudging also drives a reduction in the Antarctic-wide accumulation rate, bringing the cumulative mass gain in [TPACE] closer to the reconstruction than in [CESM2-LE*]. This suggests that it is not the winds or deepened ASL *per se* which reduce the accumulation rate. A key differentiator of the reconstructed (Fig. 4a) and modeled trend pat-

terns (Fig. 4b) is their surface temperature trends. According to regression, reconstructed and modeled accumulation have similar sensitivities to temperature of $5\%–6\% \text{ }^{\circ}\text{C}^{-1}$ on an Antarctic-wide basis (Fig. 3b), consistent with CMIP6 multi-model consensus (Nicola et al., 2023). In the reconstruction, there is a surface cooling trend in the Pacific Sector of the Southern Ocean, especially in the Amundsen Sea near the center of the ASL. The cooling region covers the major moisture source region for snowfall on the WAIS (Sodemann and Stohl, 2009). In member 40, the Pacific Sector warms less than other regions of the Southern Ocean, but only slightly less. The wind patterns are also associated with surface cooling in the mid-latitude Indian Ocean, the major moisture source region for East Antarctic precipitation (Sodemann and Stohl, 2009). [TPACE] is also associated with muted Southern Ocean warming, but it is maximized in the Atlantic and Indian Ocean sectors rather than the Pacific (Fig. 5o). Comparing Fig. 4g and h, even after the wind corrections, there are stronger surface warming trends in the free-running model than in the reconstruction; TPACE appears to account for some of this difference.

To provide context for the polar wind and surface temperature trends, we zoom out to the entire globe (Fig. 5). The observed SST pattern from the independent ERSSTv5 dataset (Fig. 5a) is not obviously La Niña – like or El Niño – like, but it does feature less warming in the central-eastern Pacific than in the western Pacific, consistent with the strengthening Walker circulation during this time period (Lee et al., 2022) that is reflected in the zonal gradient in the SLP trend simulated by [CESM2-GOGA]. The zonal wind index from CESM2-LE PDA is congruent with cooling in the central-Eastern Pacific (Fig. 5b), in an overall pattern that closely resembles “Pattern 1” associated with observed-modeled SST trend discrepancies since 1979 (Wills et al., 2022, their Fig. 3). The wind-residual pattern is associated with enhanced eastern equatorial Pacific warming (Fig. 5c). The PDA reconstructions capture these large-scale patterns, showing muted warming in the central-eastern Pacific and enhanced warming in the western Pacific (Fig. 5d). This zonal temperature contrast is enhanced by the winds (Fig. 5e). Like in ERSSTv5, if the wind-congruent trends are removed from the reconstruction, the residual pattern shows an El Niño – like equatorial warming pattern with a weakened ASL (Fig. 5f). Considering the dynamics of poleward propagating Rossby waves, a weakened ASL is typically associated with an El Niño – like SST pattern in the tropics, while a deepened ASL is typically associated with a La Niña – like SST pattern (e.g. Raphael et al., 2016).

The observed and reconstructed patterns can be compared to the forced responses to all forcings (Fig. 5j), aerosols only (Fig. 5k), and GHGs only (Fig. 5l) ([EE] exhibits a similar pattern to [GHG] but of much weaker magnitude, not shown). [GHG], with its El Niño – like warming pattern and north Atlantic cooling, is a good fit to the wind-residual patterns in the observations and reconstructions. Cooling

in [AAER] is concentrated in the north Pacific and eastern equatorial Pacific, in disagreement with the cooling patterns associated with winds. Aggressive aerosol-driven cooling is evident in the all-forcings forced response, [CESM2-LEcmip6], which has too weak of a warming trend compared to observations and reconstructions. The Pacific zonal SST gradient is improved in member 40 (Fig. 5g), along with the representation of the deepened ASL. However, in member 40, the winds are only associated with weak SST anomalies (Fig. 5h), and the wind-residual pattern is not El Niño like (Fig. 5i), possibly because the aerosol response in the tropics overwhelms the GHG response (Heede and Fedorov, 2021). The stronger zonal SST contrast and deeper ASL in member 40 are driven by a pattern of internal variability that resembles the negative phase of the Interdecadal Pacific Oscillation (IPO; Fig. 5n) defined by Henley et al. (2015). The response to nudging in TPACE (Fig. 5o) is a near mirror image to the internal component of member 40 (Fig. 5n) except that both have a patch of cooling in the central tropical Pacific, consistent with the muted warming there in observations (Fig. 5a).

In summary, modeling a good fit to the reconstructed accumulation trend pattern requires (a) A deepened ASL; (b) Stronger circumpolar westerlies; and (c) A strong zonal SST gradient in the subtropical Pacific, with more warming in the western than eastern part of the basin. Holland et al. (2022) similarly find that western subtropical Pacific warming accompanies ASL deepening, which they hypothesize is part of a negative IPO-like pattern of internal variability. Consistently, member 40's internal component is a negative IPO pattern. Note that the pattern congruent with reconstructed winds (Fig. 5e) differs from the canonical negative IPO in that it has its strongest loadings in the Amundsen Sea region.

3.3 Recent patterns of change

For 1979–2019, we adopt [CESM2-GOGA] as the reference pattern (Fig. 6a). [CESM2-GOGA] has no trend in the Antarctic-wide accumulation rate, consistent with results from reanalysis and regional models (e.g. Clem et al., 2023; Mottram et al., 2021). Like the pattern during the 20th Century, a trend dipole occurs across the WAIS, consistent with the deepened ASL (Fig. 1a). Significant negative accumulation trends occur in Wilkes Land over the Totten Glacier and in West Antarctica over the Thwaites and Pine Island Glaciers, two regions where independent observational studies show strong evidence for circulation-driven variability in snow accumulation that affects year-to-year variations in the mass balance of these basins (King and Christoffersen, 2024). Nonetheless, long-term mass loss in these basins has been predominantly driven by ice-ocean interactions and grounding line discharge, not by surface processes (e.g. Shepherd et al., 2019; Lu et al., 2025). The accumulation trend magnitudes are weaker and less significant in [CESM2-TOGA] (Fig. 6b), which does not simulate the

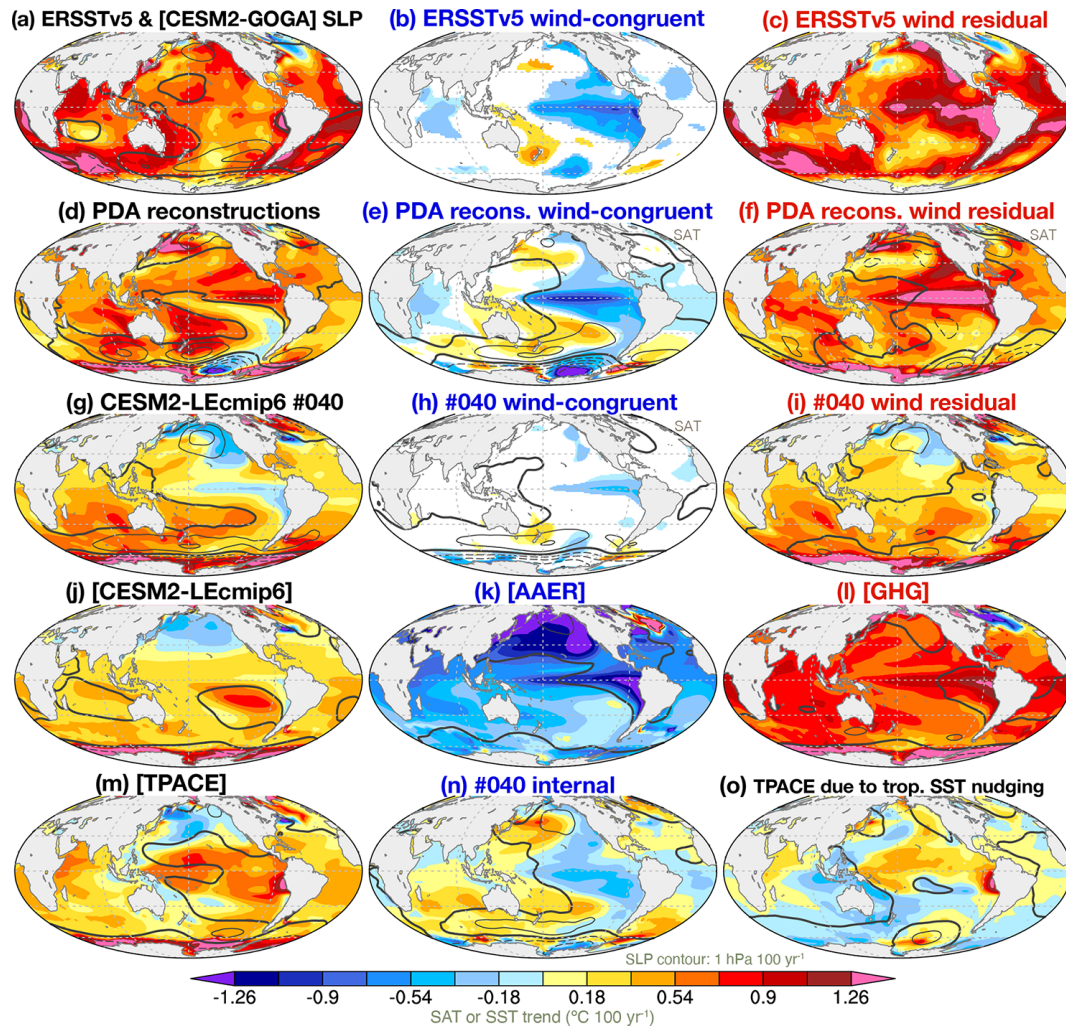


Figure 5. Near-global linear trend patterns (1901–2000) in annual-mean SST (or SAT, as indicated) and SLP in observed, reconstructed, and simulated datasets. In the left column, the original trends are shown without any filtering applied. In the middle column panels (b), (e), (h), (n) the trends congruent with the zonal wind index or associated with internal variability are shown (only those grid boxes where the wind-surface temperature regression coefficient is significant at the $p < 0.05$ level or are shown). In the right column panels (c), (f), (i), residual trends after removal of the wind-congruent trends are shown. In the middle rows, the forced responses to all forcings in panel (g) CESM2-LEcmip6 are compared with responses to aerosols alone in panel (k) and greenhouse gases alone in panel (l). The SST (or SAT) trends are in $^{\circ}\text{C } 100 \text{ yr}^{-1}$. SLP contours (gray lines) are in intervals of $1 \text{ hPa } 100 \text{ yr}^{-1}$. Negative SLP values are dashed lines and positive values are solid line; the zero contour is a heavier solid line. For the PDA reconstructions, CESM1-LE PDA is used for SAT and SLP in panel (d); for panels (e) and (f) CESM1-LE PDA is used for SAT and CESM2-LE PDA is used for SLP and the zonal wind index; see comparison of the reconstructions in Appendix A. Radiative surface temperature is used for the model results in panels (g)–(o) unless otherwise indicated.

negative trend over Totten. This suggests that regional accumulation trends are responsive to extratropical SST and sea ice trends, consistent with mid-to-high latitude moisture sources of precipitation for near-coastal Antarctic regions (Sodemann and Stohl, 2009).

The coupled experiments, [CESM2-LEcmip6] (Fig. 6c) and [TPACE] (Fig. 6d) exhibit significant upward accumulation trends across much of the continent, inconsistent with the observation-constrained [CESM2-GOGA]. Spatially, [TPACE] fits the reference pattern given by [CESM2-GOGA] better than does [CESM2-LEcmip6]. Although trop-

ical pacemaker experiments can simulate ASL deepening for the period since 1979, they do not simulate Antarctic sea ice expansion and Southern Ocean surface cooling (Schneider and Deser, 2017), which explains why [TPACE] simulates too strong of an accumulation trend. A temporal perspective on these recent trends is provided in Fig. 6e. In MT19 and the prescribed SST experiments, most of the accumulation increase occurs between about 1970 and 1990, during a period of Southern Ocean warming (Zhang and Deser, 2024). In the coupled experiments, the accumulation rate steadily increases from about 1970 through the end of the timeseries,

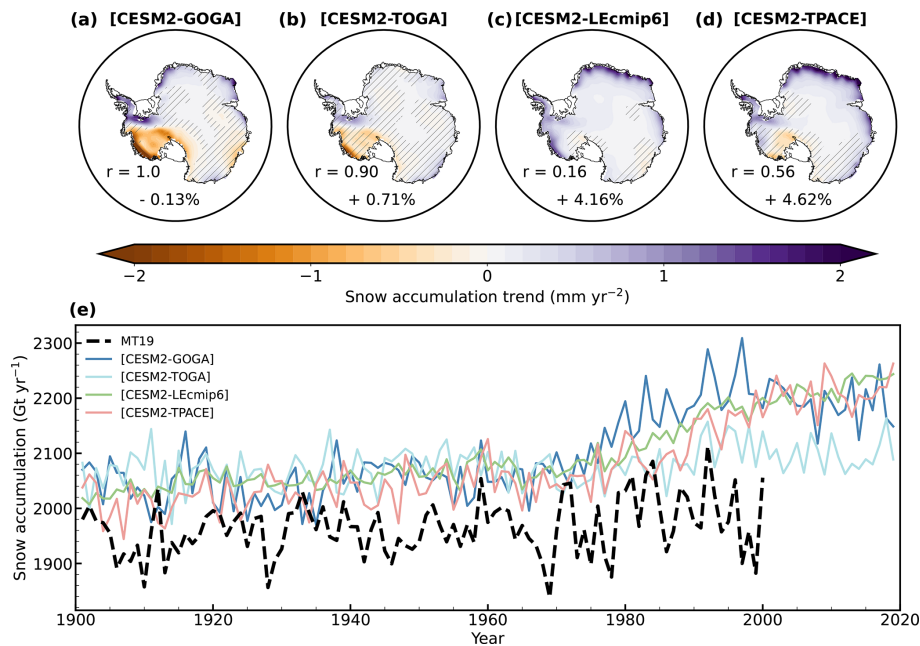


Figure 6. Maps of 1979–2019 linear trends in snow accumulation for (a) [CESM2-GOGA], (b) [CESM2-TOGA], (c) [CESM2-LEcmip6], and (d) [CESM2-TPACE]. The percentages indicate changes of the Antarctic-wide snow accumulation rate averaged over 2005–2019 compared with 1979–1993. The r values represent the pattern correlation of the simulated trend with the trend given by [CESM2-GOGA]. Hatching indicates where the accumulation trend is not significant at the $p < 0.05$ level or better. (e) Timeseries of annual snow accumulation over the grounded AIS from MT19 and various model simulations.

physically consistent with stronger-than-observed ocean surface warming and sea ice loss.

The ASL has continued to deepen in the 21st Century (Fig. 1a), as reflected in the 2001–2022 SLP trend pattern in ERA5 (Fig. 7a). The ASL deepening is embedded within a larger-scale trend pattern associated with the positive phase of the SAM. The ERA5 SLP and snow accumulation patterns are well captured in CESM2-WNUDGE (Fig. 7b). Underlying the nudged pattern is a steady upward trend in the forced response (Fig. 7c) associated with background warming. Figure 7d isolates the effect of the wind nudging, which drives cooling in the Amundsen Sea but strong warming in the western Ross Sea, reminiscent of the pattern associated with wind-congruent trends in the reconstructions (Fig. 4e). While the forced response drives significant accumulation trends in the interior of East Antarctica and Queen Maud Land (Fig. 7c), the wind pattern is associated with significant drying over Wilkes Land and a significant accumulation increase in the Peninsula region (Fig. 7b, d).

Large-scale orographic effects are evident in the wind-driven accumulation pattern. The WAIS divide separates the positive and negative snow accumulation trends, with Elsworth Land on the windward side and Marie Byrd Land on the lee side with respect to the ASL. In East Antarctica, Queen Maud Land receives high snowfall as it faces the winds, and its climatological moisture transport pathway (Naakka et al., 2021) is enhanced by the trend pattern.

The positive snow accumulation trend extends inland to the South Pole, qualitatively consistent with observations there (Zhai et al., 2023). At least some of the increased cyclonic activity in the Amundsen Sea and south Atlantic, associated with positive snow accumulation trends in the Peninsula region and Queen Maud Land, respectively, is driven by the forced response (Fig. 7c). A negative snow accumulation trends occurs across most of the terrain that lies downwind of the main East Antarctic ice divide. The largest negative trends occur in Wilkes Land. A recent observational study (Wang et al., 2025a) found a significant decrease in the 2005–2020 accumulation rate along a transect from Zhongshan Station (69°S , 76°E) to Dome A (80°S , 77°E), associated with trends in the large-scale atmospheric circulation and consistent with the accumulation trend pattern in CESM2-WNUDGE.

3.4 Potential roles for meltwater and two-way teleconnections

While atmospheric circulation explains spatial accumulation patterns, temperature in and around Antarctica is the main driver of the accumulation rate. The most pronounced period of Southern Ocean surface cooling and increasing sea ice extent in recent years was 1980–2013, which corresponds with the period covered by the meltwater experiment. For comparison, we include [CESM2-GOGA] (Fig. 8a) and the older [CESM1-GOGA] (Fig. 8b), which uses the same CAM5 at-

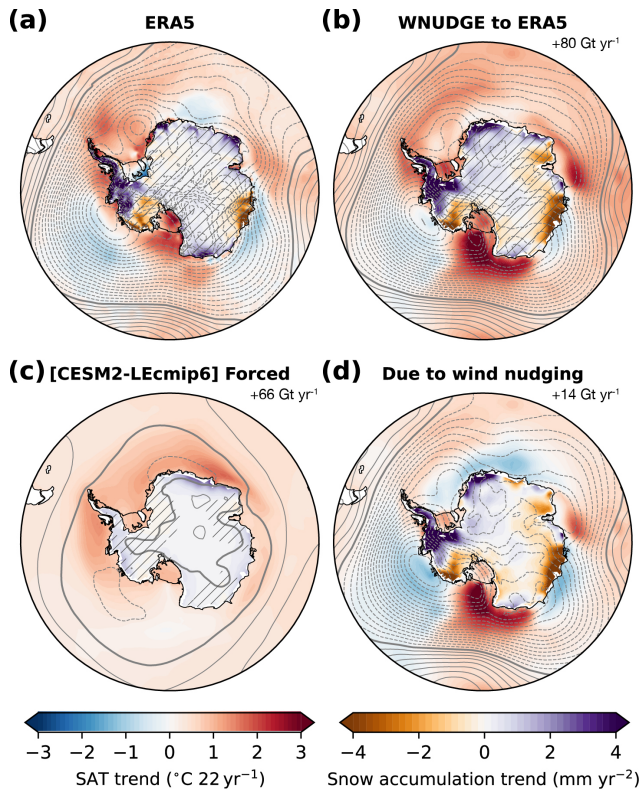


Figure 7. Maps of 2001–2022 linear trends in snow accumulation, SAT and SLP for (a) ERA5 (precipitation minus evaporation used to estimate the snow accumulation pattern); (b) CESM2-WNUDGE; (c) [CESM2-LEcmip6]; (d) internal pattern due to wind nudging (forced response from panel c subtracted). SLP contours (gray lines) are in intervals of $0.015 \text{ hPa yr}^{-1}$. Negative SLP values are dotted lines and positive values are solid lines; the zero contour is a heavier solid line. Values in the upper-right of (b), (c), and (d) indicate the change in Antarctic-wide accumulation rate for 2019:2022 minus 2001:2005. Hatching on panels (a), (b), (c) indicates where the accumulation trend is not significant at the $p < 0.05$ level or better.

mospheric model as [CESM1-AIS meltwater] (Fig. 8c). The snow accumulation pattern in the meltwater experiment exhibits good agreement with the pattern in [CESM1-GOGA] ($r = 0.62$), while having a less than 1 % increase in the Antarctic-wide accumulation rate during 1979–2013. Thus, the accumulation response to meltwater is consistent with the response to the observed SSTs. This result of an accumulation decrease in response to Antarctic meltwater is qualitatively supported by Zhang et al. (2026), who find meltwater-driven precipitation decreases on the Antarctic continent across multiple CMIP6-era models. Additionally, Sadai et al. (2025) find a similar precipitation decrease in a set of CESM1 experiments driven by meltwater fluxes from an offline ice sheet model. Observational uncertainties and model limitations make a highly realistic meltwater simulation very challenging, but there is a multi-model consensus that melt-

water leads to Southern Ocean surface cooling and a precipitation decrease over Antarctica (Zhang et al., 2026).

As discussed in previous work (Dong et al., 2022a; Armour et al., 2024), Antarctic meltwater reduces global-mean warming and reduces effective climate sensitivity via the SST pattern effect. A key piece of the SST pattern effect is the zonal SST gradient in the subtropical south Pacific, which CMIP6 models systematically do not replicate (Wills et al., 2022). In the reconstructions for 1901–2000, there is less warming in the subtropical and mid-latitude eastern Pacific than in the western part of the basin even if the wind-congruent trends are removed (Fig. 9a). This is a stronger gradient than can be explained by GHGs alone (Fig. 5l), suggesting that another signal is present. The meltwater-induced pattern (Fig. 9b) could be this missing signal, as it features more cooling in the eastern than western Pacific. If the meltwater signal is added to [GHG], the resulting pattern (Fig. 9c) is strongly correlated ($r = 0.91$ over 30° – 70° S) with the wind-residual pattern in the PDA reconstruction (Fig. 9a).

The meltwater-induced SST anomaly pattern in Fig. 9b was originally estimated by Dong et al. (2022a) as a decadal trend; here we multiply their decadal trend by five to account for 50 years during which Antarctic meltwater has plausibly been a relevant forcing. Ice shelf thinning and grounding line retreat in West Antarctica commenced in the mid-20th Century, several decades prior to the modern satellite era (Smith et al., 2016; Clark et al., 2024). Since the mid-20th Century, an anomalous contribution of freshwater to the ocean has been sustained by ice shelf thinning and glacier retreat driven by northerly wind anomalies in the Amundsen Sea Embayment associated with the ASL deepening trend (O'Connor et al., 2025a). For snow accumulation, it is around 1950 when the cumulative mass gain in [CESM2-LE] begins to outpace the gain in the MT19 reconstruction (Fig. 2a), and when the signal in [TPACE] noticeably counteracts the signal in [CESM2-LE*] (Fig. 2c). It is plausible that a meltwater-driven cooling signal could be propagated towards the subtropics via atmospheric advection and a chain of amplifying wind-SST-cloud feedbacks (Dong et al., 2022a, b; Kim et al., 2022; Kang et al., 2023) and be embedded in the observed SST record and the proxy records. ERA5 trends over 1950–2024 show cooling around 60° S, 180° W (Fig. C1) that is consistent with the meltwater response in Fig. 9b–c. The pattern due to tropical SST nudging in TPACE (Fig. 9d) shows a central Pacific El Niño-like state (resembling “El Niño Modoki”, e.g. Ashok and Yamagata, 2009) that is consistent with the CESM1 response to meltwater (Fig. 9b). As discussed above, the Southern Ocean cooling response to meltwater is supported by a well-established multi-model consensus. However, the tropical Pacific response depends upon model physics such as the strength of subtropical shortwave cloud feedbacks and the structure of the intertropical convergence zone (ITCZ) (Zhang et al., 2026; Dong et al., 2026; Kim et al., 2022).

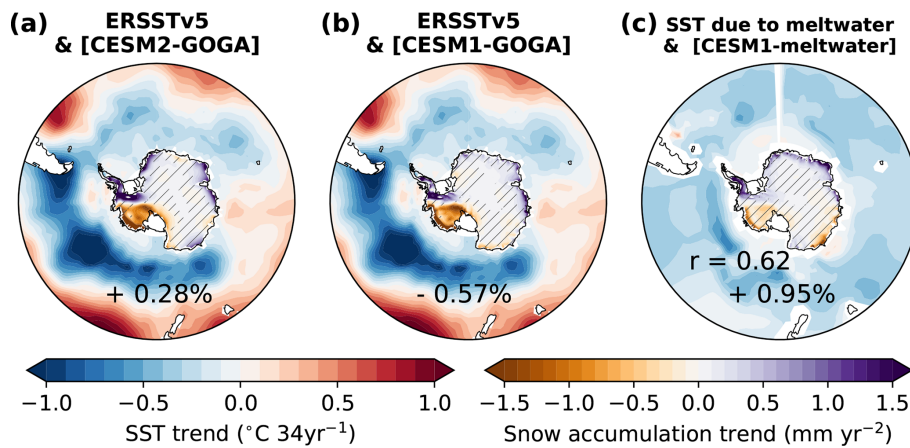


Figure 8. Maps of 1980–2013 linear trends in snow accumulation and SST for (a) [CESM2 – GOGA] and ERSSTv5; (b) [CESM1 – GOGA] and ERSSTv5; (c) [CESM1 – AIS meltwater], with the SST trend due to meltwater hosing (forced response from CESM1-LE removed; see Armour et al. (2024) for SSTs with the radiatively forced response included). Also shown is the percentage change in the Antarctic-wide accumulation rate between the averages of (2000:2013) and (1980:1993), as well as the pattern correlation of [CESM1 – AIS meltwater] with [CESM1 – GOGA]. The CESM1-GOGA ensemble prescribed ERSSTv4 but ERSSTv5 data are displayed here for illustration purposes. Hatching indicates where the accumulation trend is not significant at the $p < 0.05$ level or better.

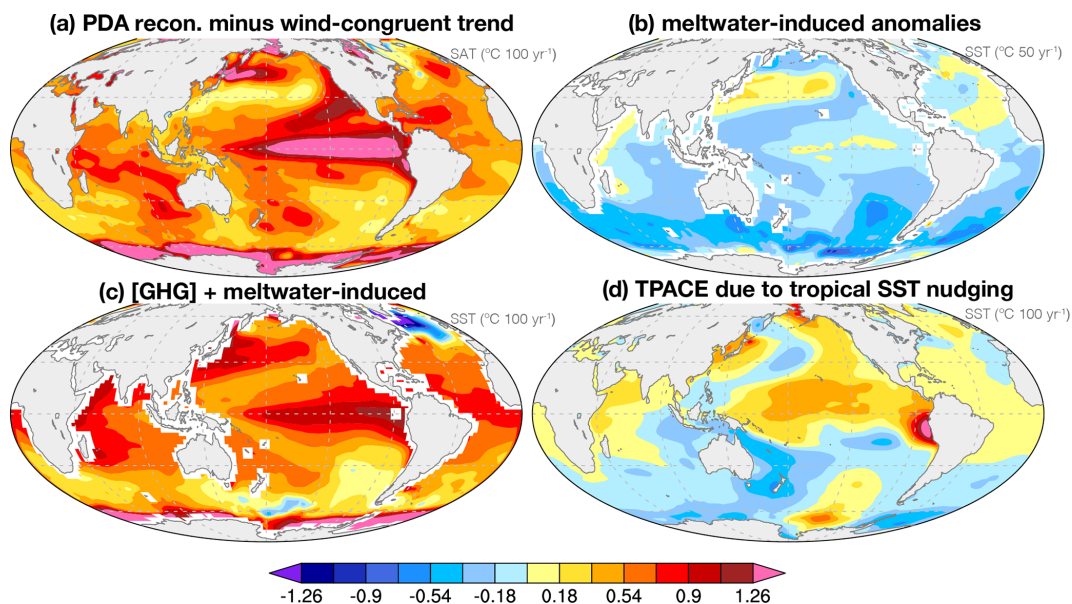


Figure 9. (a) Map of 1901–2000 trend in CESM1-LE PDA SAT after removal of the wind-congruent trends (as in Fig. 5f); (b) SST anomalies due to historical Antarctic meltwater anomalies from the CESM1-AIS meltwater experiment (decadal trend multiplied by five to estimate meltwater’s role over the second half of the 20th Century); (c) SST anomalies formed from [GHG] (as in Fig. 5l) added to the meltwater-induced anomalies in panel (b). (d) 1901–2000 trend in TPACE due to tropical SST nudging. To ensure that the anomalies in (d) are not aliasing interannual ENSO variability, an 8 year lowpass filter was applied to annual timeseries in [TPACE] – [CESM2-LE*] before computing the trend. Radiative surface temperature is used for [GHG]. Note that the SAT pattern in (a) likely contains an aerosol signature, especially in the north Pacific and north Atlantic.

3.5 Narrative and graphical summary

The foregoing results are summarized in graphical form in Fig. 10, which compares accumulation trends and their large-scale contexts across the reconstructions (Fig. 10a), the GHG-only scenario (Fig. 10b), and associated with the

proxy reconstructed wind timeseries (Fig. 10c). The maps use a pseudo Spilhaus projection (e.g. Chen et al., 2023) to place Antarctica and the Southern Ocean near the center of the map and emphasize connections across the ocean basins. In Fig. 10a, the 10.5 mm of sea level mitigation occurs in

the context of a deepened ASL and strong warming around most of Antarctica except for the Amundsen Sea. The ice-albedo feedback makes these warming/cooling trends larger than anywhere else except for the Arctic. Cold-air advection and the wind-evaporation-SST (WES) feedback propagate the Amundsen Sea cooling signal towards the tropics as the south Pacific subtropical high strengthens. However, this signal is blocked from reaching the eastern equatorial Pacific by the ITCZ and by the competing effects of greenhouse gases (Fig. 10b). Although the eastern tropical Pacific SSTs look El Niño like, the overall SST anomaly pattern results in Rossby waves propagating towards Antarctica that deepen the ASL, reinforcing this pattern (see [CESM2-GOGA] simulated SLP pattern, Fig. 5a), which promotes ice shelf thinning and glacier retreat in the Thwaites and Pine Island region (King and Christoffersen, 2024; O'Connor et al., 2025a). Under greenhouse gases only (Fig. 10b), the tropics are decidedly El Niño like and poleward propagating Rossby waves act to weaken rather than reinforce the ASL deepening trend. The south Pacific subtropical high strengthens, promoting the WES feedback, but it does not extend to the coast of South America where it could help stabilize the stratocumulus cloud deck, enhance coastal upwelling, and alter the trajectory of the tropics.

Greenhouse gases explain the widespread warming and accumulation increase evident in the proxy reconstructions but do not explain the important dynamical details that suppress the accumulation rate increase, give rise to a dipole in snow accumulation across the WAIS, and reshape the warming patterns. The Southern Hemisphere westerly winds are the major source of momentum forcing of the global ocean (e.g. Wunsch, 1998). Their potential impact on surface climate is depicted in Fig. 10c. In this depiction, the cooling signal originating in the Amundsen Sea is communicated all the way to the equatorial Pacific along the reverse teleconnection pathway. The subtropical shortwave cloud feedback (Kim et al., 2022) and the ITCZ (Dong et al., 2026) are the key mediators of this connection. Recent studies argue that strengthening winds forced by stratospheric ozone depletion contribute to the La Niña like SST trend in the tropics (Hartmann, 2022; Dong et al., 2025). Similarly, Antarctic meltwater can contribute to a La Niña like SST trend pattern (Dong et al., 2022a; Zhang et al., 2026; Dong et al., 2026). However, none have argued that these high latitude signals are the sole cause of the observed La Niña like trend. It is important to keep in mind that the wind timeseries (Fig. 1b) used in Fig. 10c includes signals arising from internal variability. During the 20th Century, a trend towards the negative phase of the IPO (which favors La Niña) preceded strong forcing from greenhouse gas increases and stratospheric ozone depletion (Dalaiden et al., 2024). As such, this IPO trend is part of the wind-congruent map in Fig. 10c. Nonetheless, the presence of internal signals within this IPO-like pattern does not rule out the possibility of anthropogenic forcing driving a multidecadal shift towards the negative phase of the IPO

(Klavans et al., 2025). Regardless of the exact origins of this pattern, as shown it exhibits the mutually reinforcing two-way teleconnections discussed in Dong et al. (2022b). This reinforced circulation pattern enhances meltwater production by the mechanism of O'Connor et al. (2025a). To the extent that the meltwater-driven cooling signal reaches the tropics, it is communicated back to the Southern Ocean via the two-way teleconnection.

For brevity, Fig. 10 omits the cooling patterns explicitly associated with aerosols and meltwater. Figure 5k shows that aerosols drive Southern Ocean cooling, which reduces accumulation across Antarctica (Fig. B3). Meltwater also cools the Southern Ocean and reduces the accumulation rate (Figs. 8c, 9b). Both the aerosol-only and meltwater experiments have limited utility as explanations for the 20th-Century history. The strong cooling in [AAER] may be partially spurious because of the experimental design in which aerosol forcing acts alone on a cold pre-industrial background state, triggering ice-albedo feedbacks to amplify the cooling more than it would be when greenhouse gases increase at the same time (Simpson et al., 2023). The meltwater experiment suffers from its unrealistic total magnitude of forcing and from its distribution of this forcing all around the continent. More realistically, 20th Century meltwater forcing was small and concentrated in the Amundsen Sea, where it could locally alter sea ice formation and SST anomalies, ultimately strengthening the westerlies in the southeast Pacific, to which the ocean would have to adjust (e.g. Kang et al., 2026). In turn, this cooling signal could be propagated towards the eastern Pacific tropics along the reverse teleconnection pathway. Some combination of high-latitude winds and meltwater signals have likely contributed to the wedge-shaped pattern of cooling or muted warming in the proxy reconstruction that extends into the central tropical Pacific (Fig. 10a); this pattern is remarkably similar to recent results from high-resolution model simulations forced by the standard suite of external forcings (greenhouse gases, aerosols, stratospheric ozone, etc.) without the meltwater feedback (Kang et al., 2026).

4 Discussion

4.1 Anthropogenic increase in snow accumulation reduced by Southern Ocean cooling

The first part of our analysis focuses on attributing the 20th-Century history of Antarctic snow accumulation using the single-forcing large ensemble and the all-forcings Large Ensemble from CESM2. We evaluate what combination of external forcing and internal variability explains the historical trends and therefore may be applied towards more accurate projections of snow accumulation into the future. Greenhouse gases have been the primary driver of increased snow accumulation on the AIS, leading to a cumulative mass gain of 21 mm SLE for 1901–2000 due to their role in warming

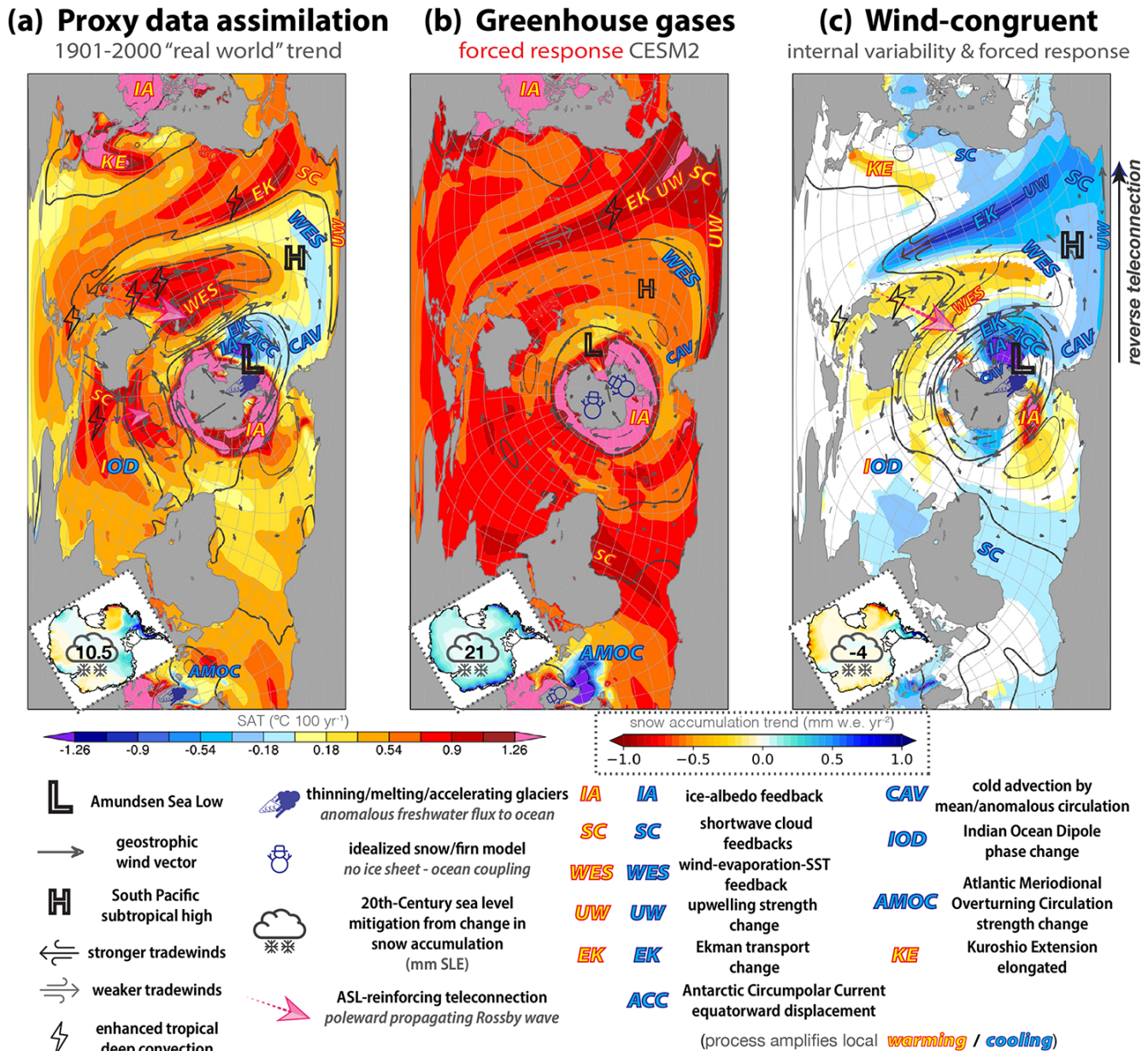


Figure 10. Conceptual diagrams illustrating key processes that connect Antarctic snow accumulation trends with large-scale warming patterns: (a) As observed according to proxy data assimilation (CESM1 – LE PDA) and the MT 19 reconstruction; (b) under greenhouse gas forcing only in CESM2; and (c) connected with the proxy reconstructed zonal wind trend across 50–70° S (as in Fig. 5e using the wind index from Fig. 1b). Geostrophic wind vectors polewards of 15° S were computed from the SLP fields. SLP contouring as in Fig. 5. The indicated processes and feedbacks are qualitatively inferred from the warming patterns and from previous diagnostic studies cited in the text, with additional verification from a freely available large language model (i.e., Google Search AI Mode); this schematic is offered for conceptual understanding rather than as a complete list and quantification of relevant processes. Credit: The cloud, snow model, tradewind, lightning bolt and ice cream icons are used under a Creative Commons license (CC BY 3.0) from Noun Project; see complete credit in the Acknowledgements section. All other content generated in NCL, python, and Adobe Illustrator by David P. Schneider and Ziqi Yin.

the atmosphere and ocean surface. Internal variability over the 20th Century cannot explain the observed cumulative mass gain, but internal variability could combine with the forced response to greenhouse gases and aerosols (when used together in the same Large Ensemble experiment) to reduce

the magnitude of the cumulative mass gain. This contrasts with Previdi and Polvani (2016), who argue that internal variability has completely masked the anthropogenic increase in Antarctic snow accumulation. Their study did not have the long observational perspective of the MT19 reconstruction

to work with, nor the single-forcing large ensemble. By employing these datasets and applying the cumulative mass gain metric, the anthropogenic signal in snow accumulation can be detected.

Table 3 summarizes our interpretation of the cumulative mass gain results, and how a missing meltwater forcing in conjunction with the “reverse” tropical teleconnection could reconcile results among the experiments and the reconstructions. What this does not resolve is the portion of the wind-congruent accumulation trends that are attributable to external forcing vs. internal variability, nor the question of whether West Antarctic ice shelf thinning (the source of the meltwater forcing) was naturally triggered. These questions are explored in Holland et al. (2022). From their study, the pattern of internal variability that fits PDA-reconstructed atmospheric circulation trends is the negative phase of the IPO, which concurs with our analysis. However, the pattern we uncover differs from the canonical IPO pattern in that it is not symmetrical about the equator; it has stronger loadings in the Southern Hemisphere. This is consistent with the idea of the Southern Ocean rather than the tropics as the true pacemaker (e.g. Kang et al., 2023, 2026; Zhang and Deser, 2024). The ASL is part of the negative IPO pattern; Dalaiden et al. (2024) attribute ASL deepening trends to a combination of internal variability and anthropogenic forcing. Holland et al. (2022) suggest that while ice-shelf thinning may have been naturally triggered in the mid-20th Century, it has been sustained by anthropogenic forcing. The ASL deepening trend is consistent with northerly wind anomalies in the Amundsen Sea Embayment that are driving ongoing ice shelf thinning and WAIS retreat, supplying the meltwater forcing (O’Connor et al., 2025a).

Results presented here agree with the previous attribution work. Much of the reconstructed circulation trend can be explained by the forced responses to greenhouse gases and “everything else” but there is considerable spread across the Large Ensemble arising from internal variability (Fig. B4). The ensemble member that best matches the reconstructed circulation history and accumulation spatial pattern, member 40, does not exhibit the strong relationship between winds and surface temperature trends that is evident in reconstructions and observations (Figs. 4, 5); this is also seen in other members (Fig. A4). This decoupling has major consequences for the simulated Antarctic-wide accumulation rate and the corresponding SST trends. It suggests either misrepresented processes or a missing forcing.

In the context of anthropogenic warming, the lack of an observed increase in Antarctic-wide accumulation for 1980 to near present has been puzzling. Surface cooling (or muted warming) of the Southern Ocean is the solution to this puzzle. In a prescribed SST and sea ice experiment, CESM2-GOGA, no trend in the Antarctic-wide accumulation rate occurs, in contrast to the coupled Large Ensemble in which accumulation steadily increases. In the coupled CESM1, the snow accumulation trend is reduced by prescribing ice shelf

meltwater fluxes. Qualitatively similar results are obtained from a CESM2 experiment nudged to observed Southern Ocean SST anomalies (Fig. B6; Kang et al., 2023).

4.2 Towards constrained future projections

Accurate projection of future changes in snow accumulation is hampered by uncertainty in the evolution of SST and atmospheric circulation trends. To tentatively project potential sea level mitigation from increased accumulation to 2050, we use the lower bound of the GHG + AAER ensemble at 2050 in reference to the value given by [GHG] + [AAER] at the year 2000 (Fig. 11d–e). This is based on the idea that [AAER] has too strong of a cooling and effectively does the work of both aerosols and omitted meltwater to suppress the GHG-driven accumulation increase. Using the 5 % lower bound at 2050 gives an average rate of 0.5 mm yr^{-1} of snowfall-related sea level mitigation for 2001–2050. This is less than the widely used CESM2 Large Ensemble projects, and less than the ice sheets’ current rate of contribution to sea level rise (Stokes et al., 2025). If meltwater continues to dampen surface warming (Sadai et al., 2020, 2025) snow accumulation will have a hard time keeping up with ocean-driven dynamic mass loss. While the uptick in intense atmospheric river events, recent sea ice loss and warm Southern Ocean conditions could indicate that increased snow accumulation will provide significant sea level mitigation, strong warming will mean more mass lost to surface melting and runoff (Gilbert and Kittel, 2021) especially after 2050 (e.g. Kittel et al., 2021; Jourdain et al., 2025). As warming continues, some precipitation will fall as rain (Vignon et al., 2021). The observed uptick in atmospheric river events that bring intense heat and moisture to the ice sheet (e.g. Blanchard-Wrigglesworth et al., 2023; Wille et al., 2025) is a worrying trend that may mean that rainfall and mass loss processes become important sooner than model simulations would suggest (Mottram et al., 2025).

Spatially, the wind and snow accumulation patterns that were dominant in the recent past should continue, marked by relatively more snow in the Peninsula and Queen Maud Land, and relatively less snow in Wilkes Land and a positive SAM pattern in the pressure field (Fig. 11a–c). Although these maps (and the all-forcings CESM2-LE, not shown) indicate that the westerlies will continue to strengthen through the mid- 21st Century due to continued greenhouse gas increases, this could be a model-dependent result stemming from CESM2’s high climate sensitivity and a scenario-dependent result associated with the high-emissions SSP3.7 scenario. Under a lower emissions scenario and/or in a model with lower climate sensitivity we might expect stratospheric ozone recovery to lead to a weakening of the westerlies by the mid- 21st Century (Arblaster et al., 2011). However, on the annual-mean basis the positive SAM trend is projected to continue across many models in intermediate- to high-emissions scenarios (Purich et al., 2025).

Table 3. 1901–2000 cumulative mass gain from increased snowfall on the AIS in MT19 and various CESM2 experiments (standard deviation arises from the ensemble spread). Right column summarizes the interpretation discussed in the text.

	Cumulative mass gain	Summary interpretation
MT19	3824 ± 1046 Gt (10.5 mm SLE)	response to greenhouse-gas driven warming, offset by aerosol-driven cooling and SST trends (internal and anthropogenic) associated with winds and meltwater
[CESM2-LEcmip6]	6434 ± 1242 Gt (17.8 mm SLE)	combined response to all forcings, with biased response to biomass burning aerosols, but meltwater missing
[CESM2-LE]	6079 ± 1186 Gt (16.9 mm SLE)	combined response to all forcings, with corrected biomass burning forcing, but meltwater missing
[TPACE]	4167 ± 855 Gt (11.5 mm SLE)	combined response to all forcings, the tropical response to Antarctic wind and meltwater, and Antarctic response to tropically induced Rossby waves
[AAER]	−3156 ± 960 Gt (−8.7 mm SLE)	mass loss arising from aerosol-driven cooling that is too strong due to spurious Antarctic sea ice – albedo feedbacks
[GHG]	7483 ± 1220 Gt (20.7 mm SLE)	response to greenhouse gases, plus too-strong aerosol response that approximates the responses to aerosols and meltwater combined
[GHG] + [AAER]	4185 ± 2231 Gt (11.6 mm SLE)	
[EE]	745 ± 1293 Gt (2.1 mm SLE)	mass gain largely due to late-20th-Century stratospheric ozone depletion with other minor influences

4.3 Limitations and future work

This work has several limitations, the most prominent being that it features a single low-resolution model, CESM2. The advantage of relying on CESM2 is that it enables a robust assessment of the roles of anthropogenic forcing and internal variability across a hierarchy of experiments from free-running fully coupled to nudged coupled to prescribed SST/sea ice experiments. We are not aware of comparable studies that have used CMIP6 or other models to make similar assessments of Antarctic accumulation trends across a hierarchy of experiments. As such, we encourage future coordinated efforts like CMIP7 and beyond to facilitate this type of study across multiple models.

Higher resolution modeling might change some details of our results and the relative importance of meltwater and winds, but should not change our overall interpretation. Regional high resolution would resolve finer details of the orographic patterns in accumulation, better represent snowfall in coastal regions and may change the response of processes like surface melting to warming (Datta et al., 2023; Noël et al., 2023; Yin et al., 2025). Regional atmospheric grid refinement over the recent historical period in an atmosphere-only configuration produces differences in the simulated snow accumulation conforming strongly to topography and enhanced poleward moisture transport (Datta et al., 2023). Global high resolution enhances the linkage of the Southern Ocean with the tropical Pacific (Chang et al., 2020; Yeager et al., 2023; Kang et al., 2026), which is too weak in most low-resolution models (Chung et al., 2022; Dong et al., 2026). The linkage is

relatively strong in CESM2 due to its strong shortwave cloud feedbacks (Kim et al., 2022; Zhang et al., 2026) and improved representation of the ITCZ (Dong et al., 2026). Low resolution and/or weak shortwave cloud feedbacks could be reasons why CESM1 is not very responsive to meltwater fluxes, requiring a perturbation of 2000 Gt yr^{−1} to produce a significant response (Pauling et al., 2016). Alternatively, if the model’s SSTs are more sensitive to winds at high resolution, meltwater may not need to be invoked to explain observation-model discrepancies, as suggested by Kang et al. (2026). Our results imply that the ability of a model to reproduce Antarctic accumulation trends is an important benchmark for any high-resolution experiment that purports to solve observation-model trend discrepancies. We propose adding Antarctic evaluation metrics to high-resolution model intercomparisons such as Dhame et al. (2025) and meltwater intercomparisons like Zhang et al. (2026).

Observations and/or reconstructions underpin any model evaluation study. We have based our model evaluation on the MT19 reconstruction, which is similar to the kriging reconstruction of Wang and Xiao (2023). Applying two distinct methodologies to the same proxy network, Wang and Xiao (2023) find significant differences between reconstructions. This methodological dependence might be alleviated if more ice core data were available, especially on the East Antarctic plateau (Eswaran et al., 2024) and West Antarctic coastal margin (Neff, 2020). More observations would avoid the need to indirectly infer what trends have occurred in these regions. We have also used CESM2-LE PDA, which is

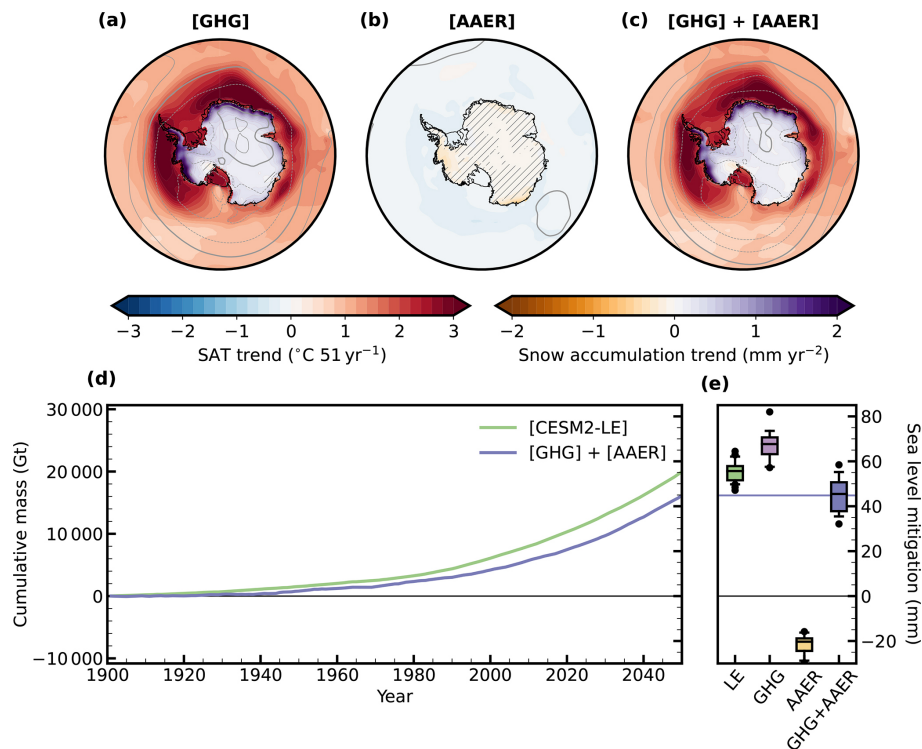


Figure 11. Linear trends in snow accumulation, SLP and SAT during 2000–2050 for (a) [GHG]; (b) [AAER]; (c) [GHG] + [AAER]. SLP contours (gray lines) are in intervals of 0.015 hPa yr⁻¹. Negative SLP values are dotted lines and positive values are solid lines; the zero contour is a heavier solid line. Hatching indicates where the accumulation trend is not significant at the $p < 0.05$ level or better. (d) Cumulative mass timeseries like in Fig. 2a, but timeseries are extended to 2050. (e) Box-whisker plot like in Fig. 2b, but for mass accumulated over 1901–2050, relative to the piControl baseline. By comparison with Fig. 2b, this indicates that [GHG] + [AAER] projects ~ 28 mm of sea level mitigation over 2001–2050, or an average rate of 0.56 mm yr⁻¹. Applying the 5 % lower bound of the GHG + AAER ensemble at 2050 (to account for stronger meltwater/weaker aerosol forcing than in the 20th Century), there would be ~ 23 mm of sea level mitigation during 2001–2050, continuing from ~ 12 mm for 1901–2000, or an average rate of ~ 0.5 mm yr⁻¹.

dynamically consistent with the CESM2. Long-term (1950–2024) trends in the ERA5 reanalysis qualitatively support the overarching interpretation we have made from these datasets (Fig. C1).

5 Conclusion

Greenhouse gases from anthropogenic activities emerge as the primary contributor to both the long-term Antarctic accumulation rate increase and the larger-scale warming patterns. Other factors have dampened this accumulation rate increase and warming trend. Using observational (or proxy) evidence and a suite of model experiments, we conclude that the most important damping factors are (a) anthropogenic aerosols; (b) strengthening westerly winds and deepened ASL; and (c) Antarctic meltwater. Each of these factors cool the Southern Ocean surface, which can be viewed as the proximate cause for reducing the continental accumulation rate. The latter two factors, winds and meltwater, likely have both anthropogenic and internal components. We also emphasize that winds on their own redistribute accumulation in a pre-

dictable orographically shaped pattern, but must be accompanied by lower surface temperatures to reduce the Antarctic-wide accumulation rate. In reaching this conclusion, this study bridges the gap between modeled and observed Antarctic snow accumulation trends, with relevance to the failure of models to reproduce SST trends in the Southern Ocean and eastern Pacific (Simpson et al., 2025; Wills et al., 2022; Kang et al., 2026).

The effects of wind and meltwater on SSTs (and in turn accumulation) stand out as processes that may not be modeled very well. In particular, this work highlights a discrepancy in the relationship between wind and SST anomalies between observational/proxy datasets and the free-running model. The observations suggest a tighter relationship between Southern Ocean surface cooling, Antarctic accumulation rate decrease, and tropical eastern Pacific cooling than does the free-running model. In contrast to previous attributions of Antarctic trends that have emphasized that what happens in Antarctica depends on the evolution of the tropical Pacific (e.g. Holland et al., 2022), this work adds to the growing body of literature emphasizing a significant influ-

ence of Antarctica and the Southern Ocean on the tropics (e.g. Hartmann, 2022; Dong et al., 2022b, 2025, 2026; Kim et al., 2022; Kang et al., 2023, 2026; Yeager et al., 2023; Zhang et al., 2026). One key piece of evidence we add is that spatial trends in Antarctic accumulation and atmospheric circulation over the 20th Century cannot be explained by tropically driven teleconnections – the nudged TPACE experiment worsens the replication of these trends compared with the unconstrained Large Ensemble. From the Large Ensemble and single-forcing large ensemble we infer that the high-latitude circulation trends are explained by a combination of greenhouse gas increases, stratospheric ozone depletion, and internal variability. The “internal” component does not fit the response to the observed tropical SST trend. Rather, we have discussed evidence that the reverse is true – the observed tropical SST trend pattern is consistent with the influence of the Southern Ocean on the tropics. Although the nudged TPACE experiment does not help to explain the spatial pattern of accumulation or atmospheric circulation trends, it dampens the Antarctic-wide accumulation rate, suggesting that cooling signals from the high latitudes have reached the tropics, consistent with results from high-resolution models that have relatively strong shortwave cloud feedbacks and explicit treatment of heat transport by ocean eddies (Kang et al., 2026).

Improved projections of Antarctic accumulation change will require a multi-pronged strategy, ranging from using prescribed meltwater forcing in existing low-resolution model frameworks (e.g. Mottram et al., 2024; Swart et al., 2023; Schmidt et al., 2025; Sadai et al., 2025), to high-resolution model development (e.g. Chang et al., 2020; Yeager et al., 2023; Kang et al., 2026), to fully coupled ice sheet-ocean-atmosphere models, which sometimes have a high-resolution grid only over the domains of the ice sheets (e.g. Yin et al., 2025). With any of these configurations, it is important to keep a model’s representation of large-scale warming patterns in mind when downscaling or otherwise using its output for Antarctic studies or projections of climate change in other regions. We have shown that prescribing the observed SST and sea ice anomalies over 1979–2019 flattens the Antarctic accumulation rate trend, in sharp contrast to the unrealistic accumulation rate increase in the free-running CESM2 model (Dunmire et al., 2022). Similarly, SST nudging in the TPACE experiment reduces the 20th Century cumulative mass gain by 6.4 mm SLE compared with the free-running Large Ensemble. These are major differences related to the question of how much an increase in Antarctic snow accumulation could offset the dynamic mass loss from ice-berg calving and grounding line retreat.

Appendix A: Additional methods and verification and comparison of PDA reconstructions

A1 Calculating pattern correlations and wind-congruent trends

In evaluating the agreement of simulated and reconstructed trend patterns, we use the pattern correlation metric. Pattern correlations are the Pearson correlation coefficient of the linear correlation between two maps of the same variable. We use the uncentered (no mean value removed) pattern correlation of the trend fields. We calculate trends in snow accumulation, surface temperature, and SLP that are linearly congruent with the trend in the Southern Hemisphere westerly winds as estimated both by the PDA reconstructions and an ensemble member (member 40) of the Large Ensemble. First, the zonal wind index (near-surface zonal wind area-weighted average across 50–70° S; Fig. 1b) is standardized, while the accumulation, SLP or temperature fields at each grid point are expressed as anomalies relative to 1901–2000. All time-series, including the wind index and anomaly fields at each grid point are linearly detrended. Then, the linear regression coefficient is calculated between the detrended fields and the detrended wind timeseries. These regression coefficients are multiplied by the 1901–2000 trend in the wind index to give the wind-congruent trends in accumulation, surface temperature or SLP.

A2 Verification and comparison of PDA reconstructions

Figure A1 shows the reconstruction skill statistics for the CESM2-LE PDA zonal wind (uas) and SLP fields; details on these statistics are in O’Connor et al. (2021a). When CESM1-PDA 20th-Century SLP trends are subtracted from CESM2-LE trends, CESM2-LE PDA exhibits an enhanced zonal wavenumber-3 pattern across the Southern Ocean compared to CESM1-LE PDA (Fig. A2). Figure A2 reveals more noticeable differences in the SAT field. These differences likely arise from different warming patterns in CESM2 vs CESM1 associated with shortwave cloud and surface albedo feedbacks (Schneider et al., 2022), which affect high-latitude atmospheric circulation (Schneider et al., 2020). Given these strong feedbacks, we postulate that with meltwater forcing, the sign of the horseshoe-shaped pattern linking the Amundsen Sea to the tropics would be reversed. This could help reconcile the CESM2-LE PDA global-mean temperature reconstruction with observations, as discussed below.

In the global-mean (Fig. A3), CESM2-LE PDA warms about 0.2 °C more than CESM1-LE PDA during the 20th Century. The warming of ~ 0.55 °C (1976:2000 minus 1901:1925) in CESM1-LE PDA is close to the ~ 0.6 °C from comprehensive land-ocean datasets like HadCRUT5 (Morice et al., 2021) and GISTEMP (Lenssen et al., 2019). In contrast, global-mean warming in CESM2-LE PDA is almost identical to that in [GHG]. The CESM2-LE PDA apparently

disregards information from aerosol forcing in the Large Ensemble, a sign that this forcing may be incorrect and/or there is a missing high-latitude forcing like meltwater. Based on these considerations, we regard the CESM1-LE PDA as the more reliable of the two surface temperature reconstructions, as it is less affected by strong feedbacks that are triggered by aerosol forcing and/or missing meltwater forcing.

Figure A4 shows that the choice of CESM1-LE PDA or CESM2-LE PDA for calculating the wind-congruent trends results in only minor differences to the associated spatial patterns. Both PDA reconstructions indicate stronger wind-SAT relationships than in the free-running Large Ensemble.

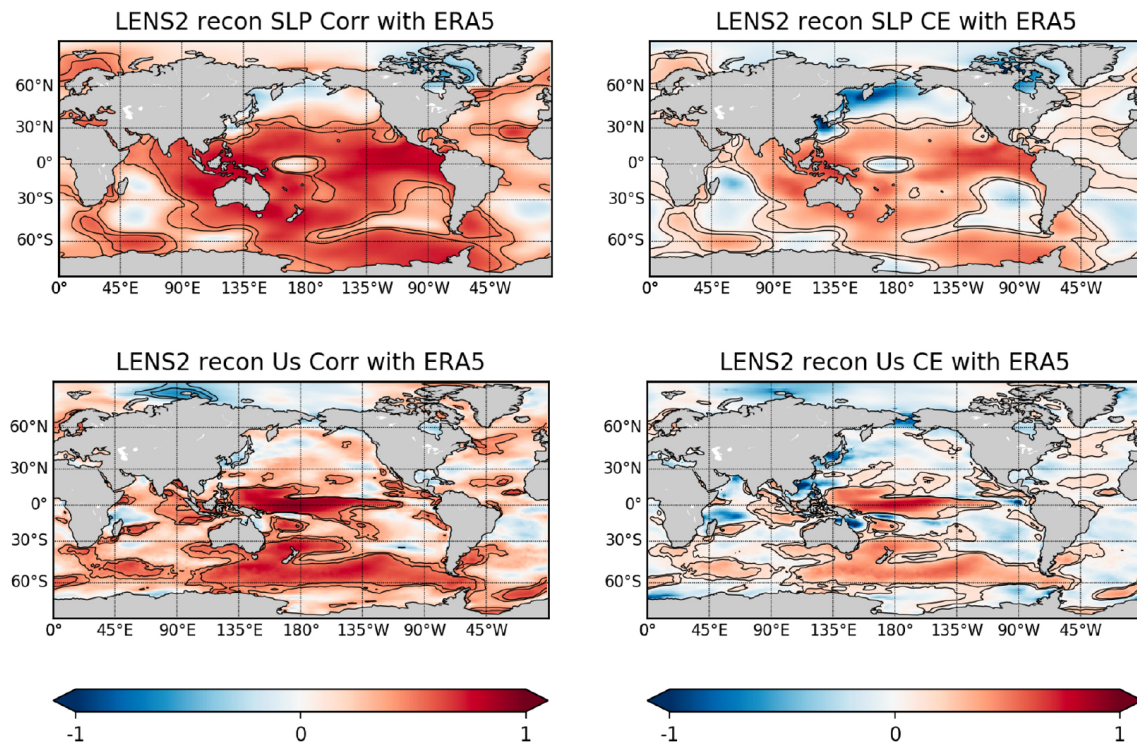


Figure A1. Verification statistics for the CESM2-LE PDA reconstruction SLP (top row) and uas (bottom row), compared to ERA5 reanalysis for the period of overlap, 1979 to 2005 (anomaly reference period used in this analysis is 1979 to 2005). Correlations are shown on the left, with contours highlighting p -values of 0.01 and 0.05. Coefficient of efficiency (CE) is shown on the right (> 0 demonstrates skill). See further verification and discussion in O'Connor et al. (2025a). From <https://jortuck.github.io/PaleoclimateVisualizer/> (last access: 15 June 2026), the 50–70° S near-surface zonal wind index that we use from CESM2-LE PDA is correlated with ERA5's zonal winds for 1979–2005 at $r = 0.62$ ($p < 0.01$). This zonal wind index is more skillfully reconstructed than the SAM index (O'Connor et al., 2021a).

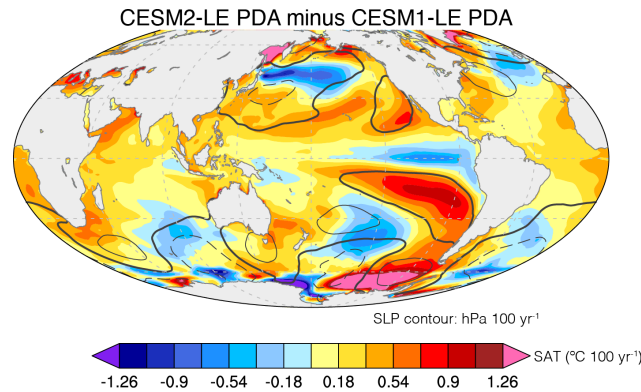


Figure A2. Differences in reconstructed SAT and SLP trends during 1901–2000 between the PDA reconstruction using CESM2-LE as the prior and the reconstruction using CESM1-LE as the prior. For SLP, the dashed black lines represent negative differences, (interval of 1 hPa) the thin solid black lines represent positive differences (interval of 1 hPa), and the zero line is represented by the heavy solid black line. Note the horseshoe-shaped pattern linking the Amundsen Sea region to the eastern subtropical Pacific. We hypothesize that this pattern is primarily caused by shortwave cloud and ice albedo feedback differences between CESM1 and CESM2 (Schneider et al., 2022; Kim et al., 2022). Hypothetically, meltwater forcing could make these feedbacks dampen rather than amplify warming.

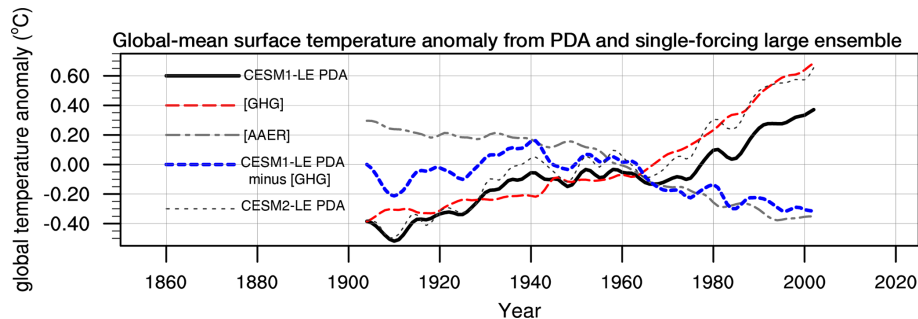


Figure A3. Timeseries of global-mean surface air temperature anomalies during the 20th Century from two different instances of PDA and the ensemble-mean responses in the greenhouse gas and aerosol single-forcing ensembles. All temperature timeseries smoothed with a 7 year low-pass filter with anomalies relative to 1901–2005.

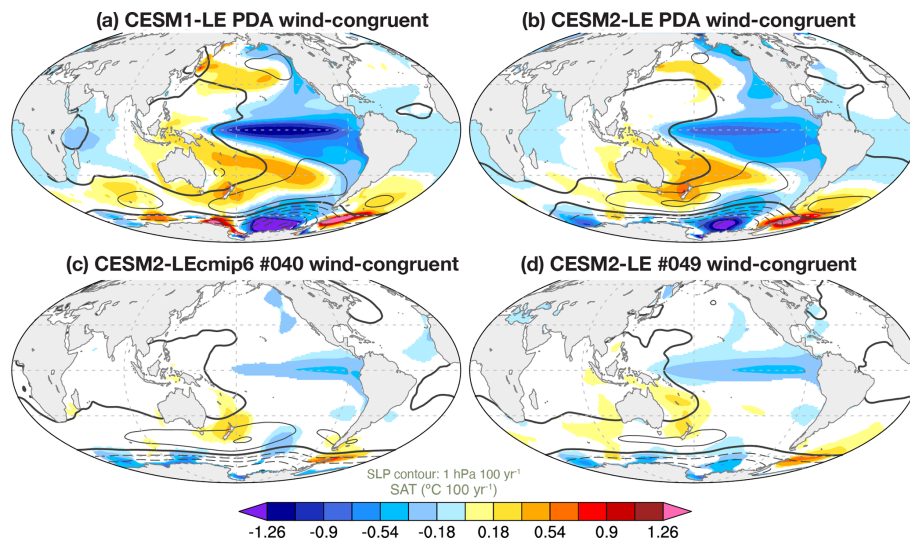


Figure A4. (a) As in Fig. 5e, but using only zonal wind timeseries, SLP and SAT fields from CESM1-LE PDA; (b) As in Fig. 5e, but using only zonal wind timeseries, SLP and SAT fields from CESM2-LE PDA; (c) As in Fig. 5g; (d) As in Fig. 5g, but using only zonal wind timeseries, SLP and SAT fields from member #049 of CESM2-LE (aka 1301.19) instead of member #040 of CESM2-LEcmip6 (aka 1281.10).

Appendix B: Results across members of the Large Ensemble and TPACE, with supporting results from other experiments



Figure B1. “Postage stamp” maps displaying the 20th-Century snow accumulation (SMB) trend in [CESM2-LE], [CESM2-LE*], and [TPACE], along with all 50 ensemble members of the CESM2-LE and the 10 members of TPACE. Included in the top row is the trend in the MT19 snow accumulation. At the bottom-center of every model map, the spatial pattern correlation coefficient with MT19 over the grounded AIS is shown. Trends are calculated as epoch differences of 1976:2000 minus 1901:1925 annual means.

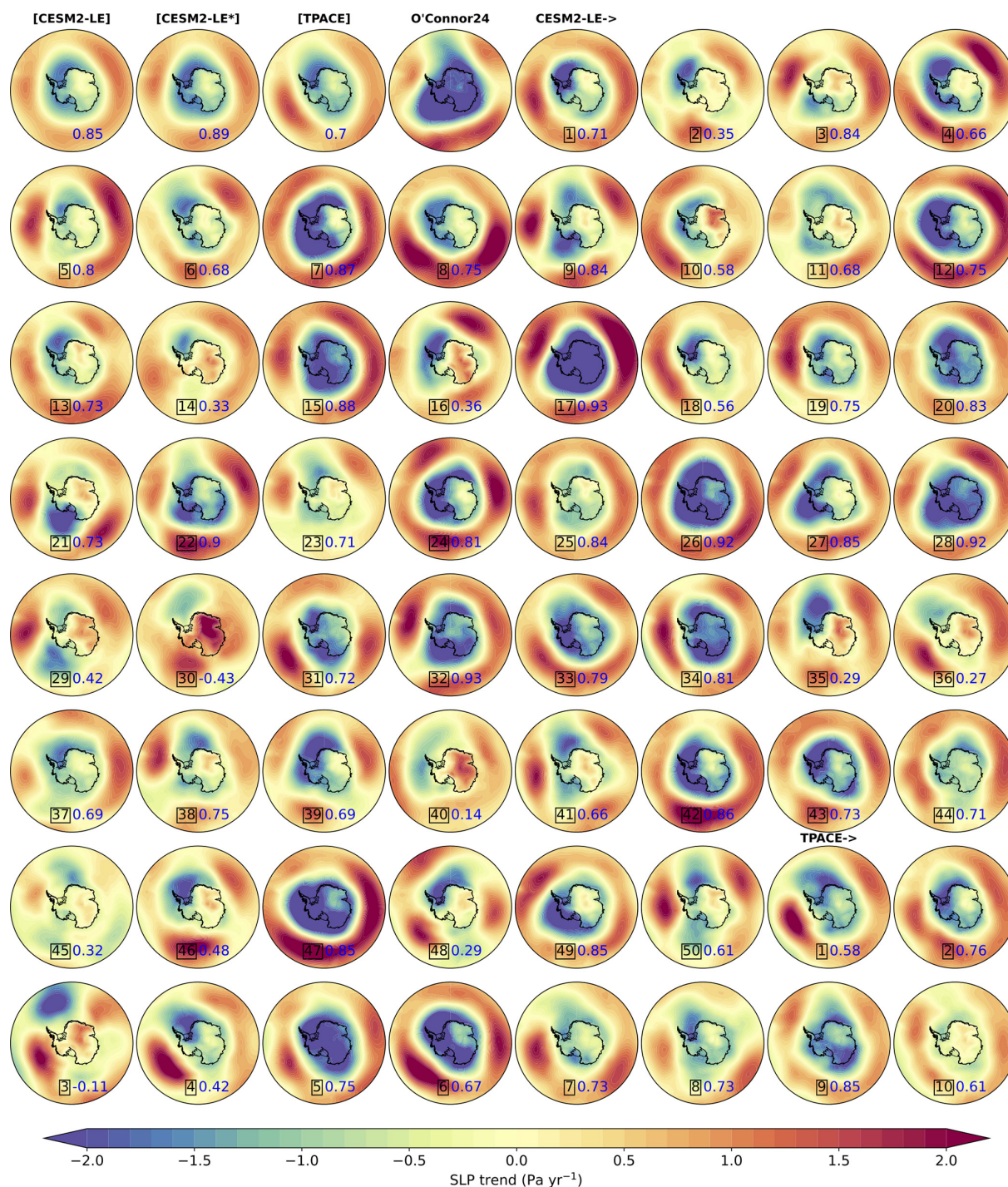


Figure B2. As in Fig. B1, but for SLP and using the CESM2-LE PDA reconstruction (labeled O'Connor24) as the benchmark for the pattern correlation over 40–90° S, a domain that covers the footprint of the ASL and most of the footprint of the SAM (e.g. Marshall, 2003).



Figure B3. “Postage stamp” maps displaying the 20th-Century snow accumulation (SMB) trend in [CESM2-LEcmip6], [AAER], [GHG], [EE], and [BMB], along with all 50 ensemble members of the CESM2-LEcmip6. Included in the top row is the trend in the MT19 snow accumulation. At the bottom-center of every model map, the spatial pattern correlation coefficient with MT19 over the grounded AIS is shown. Trends are calculated as epoch differences of 1976:2000 minus 1901:1925 annual means.

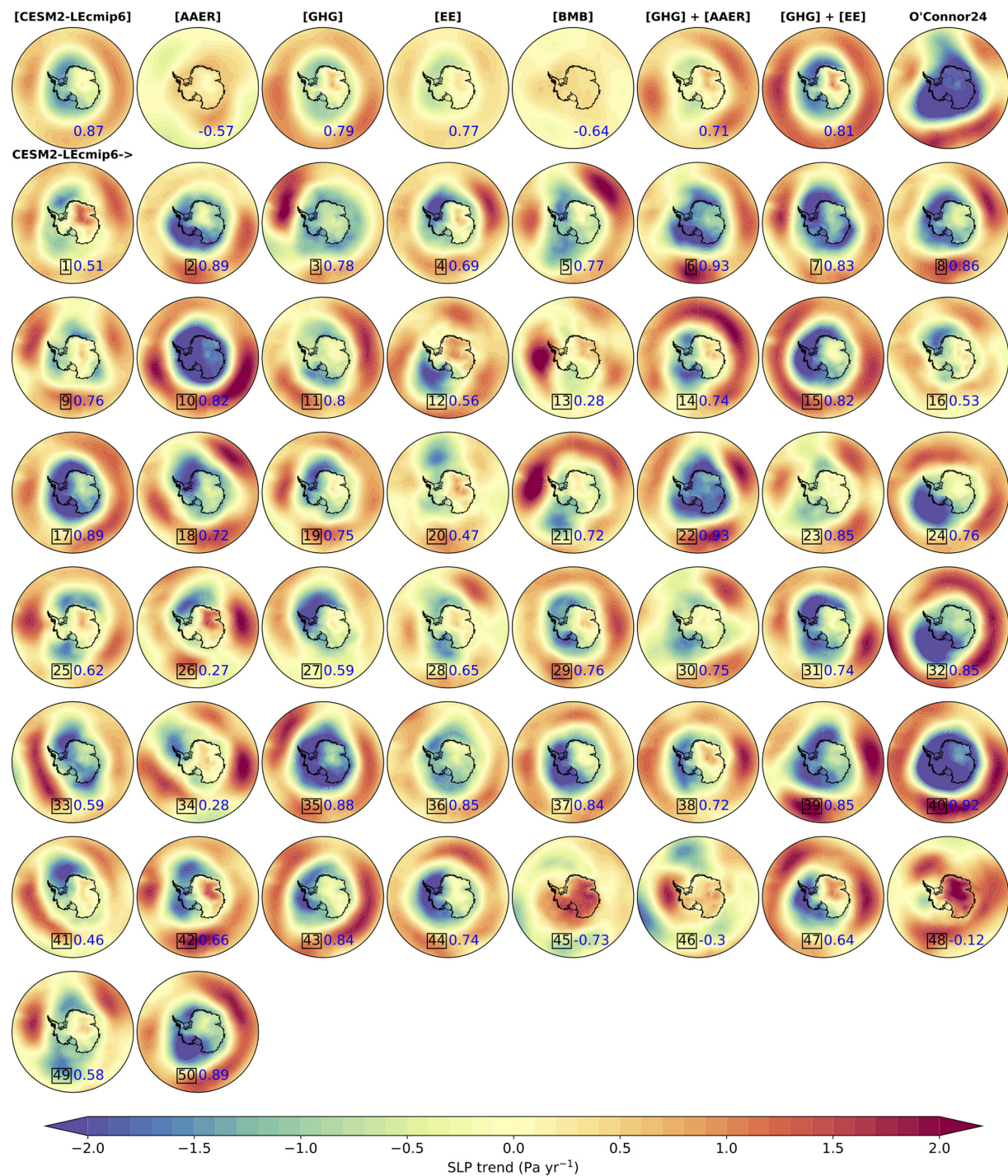


Figure B4. As in Fig. B3, but for SLP and using the CESM2-LE PDA reconstruction (labeled O'Connor24) as the benchmark for the pattern correlation over 40–90° S.

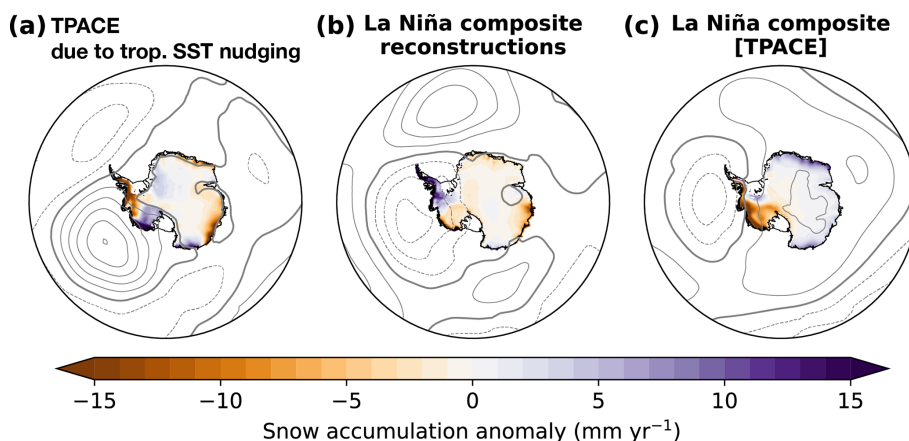


Figure B5. (a) Tropically driven ([TPACE] – [CESM2-LE*]) trend patterns in SLP and snow accumulation (1976:2000 minus 1901:1925). (b, c) Composites of snow accumulation and SLP anomalies during La Niña years over 1901–2000. Accumulation and SLP timeseries were linearly detrended before forming the composites. La Niña years are defined from NOAA’s extended multivariate ENSO index, using austral autumn (MAM) values (<https://psl.noaa.gov/enso/mei.ext/>, last access: 28 July 2025). The years composited are 1902, 1904, 1907, 1908, 1909, 1910, 1911, 1913, 1916, 1917, 1921, 1950, 1955, 1956, 1963, 1971, 1974, 1975, 1976, 1982, 1985, 1989, 1991, 1999, and 2000. SLP contours (gray lines) are in intervals of 0.25 hPa. Negative SLP values are dotted lines and positive values are solid lines; the zero contour is a heavier solid line.

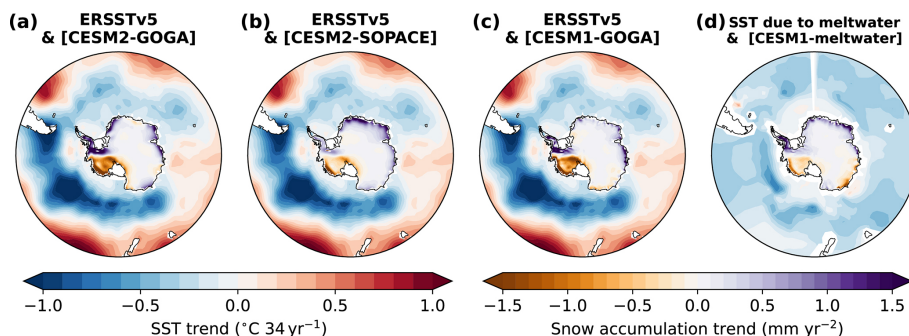


Figure B6. As in Fig. 8 but including results from the CESM Southern Ocean Pacemaker experiment that was nudged to SST anomalies from ERSSTv5 over the Southern Ocean (Kang et al., 2023). Data from CESM2 Southern Ocean Pacemaker provided by Yue Yu and Sarah Kang.

Appendix C: Trends in ERA5 since 1950

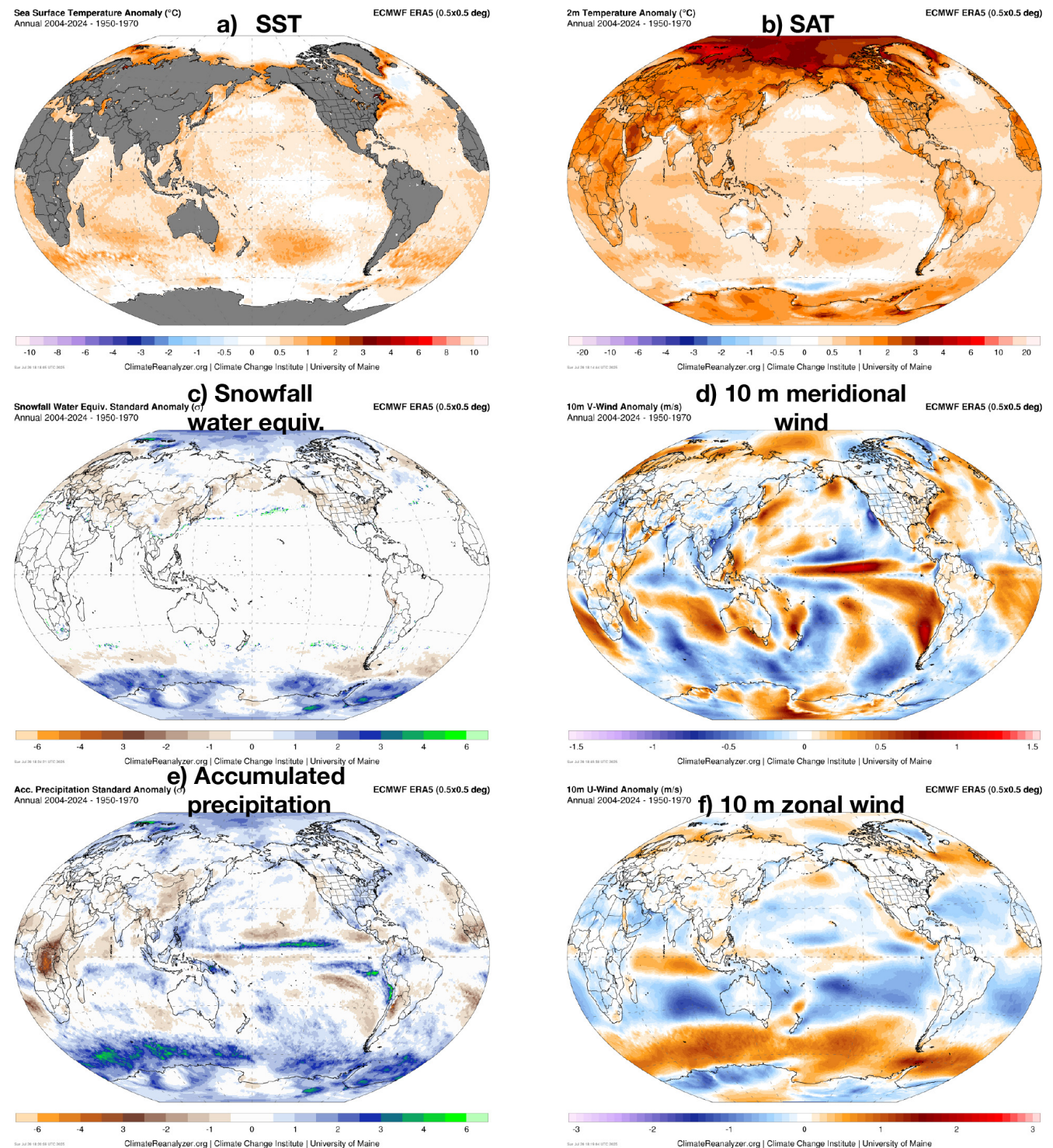


Figure C1. 1950–2024 epoch difference maps (2004:2024 minus 1950:1970) in annual fields from ERA5 (Hersbach et al., 2020) courtesy of the Climate Reanalyzer (https://climatereanalyzer.org/research_tools/monthly_maps/, last access: 28 July 2025). These maps support the trends and relationships inferred from paleoclimate data assimilation and CESM2 discussed in the main text, and the argument that these patterns have been in motion since the mid-20th Century. Variables include SST, SAT, snowfall (standardized), 10 m meridional wind, accumulated precipitation (standardized) and 10 m zonal wind.

Code and data availability. Links to public archives of the data analyzed in this study are provided in the list below. Code for creating the key figures has been deposited on Zenodo (<https://doi.org/10.5281/zenodo.16541813>, Yin, 2026). An interactive visualizer of the PDA reconstructions with different model priors is available at <https://jortuck.github.io/PaleoclimateVisualizer/> (last access: 15 June 2026).

Data availability and references for the CESM experiments analyzed in this study.

- GHG, AAER, BMB, and EE: <https://doi.org/10.26024/yw4w-1w27> (Simpson et al., 2023; Simpson and Rosenbloom, 2023)
- CESM2-LE and CESM2-LEcmip6: <https://doi.org/10.26024/KGMP-C556> (Rodgers et al., 2021; IBS Center for Climate Physics et al., 2021)
- CESM2-TPACE: <https://doi.org/10.26024/GTRS-TF57>; <https://www.cesm.ucar.edu/working-groups/climate/simulations/cesm2-pacific-pacemaker> (last access: 15 June 2026; Rosenbloom et al., 2025)
- CESM2-GOGA and CESM2-TOGA: <https://doi.org/10.26024/800d-nj44> (Phillips and Simpson, 2024)
- CESM2-WNUDGE: <https://doi.org/10.5281/zenodo.16459492> (Espinosa et al., 2024; Espinosa, 2025)
- CESM1-AIS meltwater: <https://doi.org/10.5281/zenodo.7072847> (Pauling et al., 2016; Dong et al., 2022a; Dong, 2022)
- CESM2 piControl: <https://doi.org/10.22033/ESGF/CMIP6.7733> (Danabasoglu et al., 2019, 2020)
- CESM1-GOGA <https://www.cesm.ucar.edu/working-groups/climate/simulations/cam5-prescribed-sst> (last access: 28 July 2025)

Data availability and references for observational datasets, reconstructions and reanalysis products analyzed in this study.

- MT19 snow accumulation: <https://earth.gsfc.nasa.gov/cryo/data/antarctic-accumulation-reconstructions> (last access: 28 July 2025) (Medley and Thomas, 2019)
- CESM1-LE PDA: <https://doi.org/10.5281/zenodo.5507606> (O'Connor et al., 2021a, b)
- CESM2-LE PDA: <https://doi.org/10.5281/zenodo.15243743> (O'Connor et al., 2025a, b)
- ERSSTv5: <https://doi.org/10.7289/V5T72FNM> (Huang et al., 2017a, b)
- ERA5: <https://doi.org/10.24381/cds.f17050d7> (Hersbach et al., 2020; Copernicus Climate Change Service, 2023)
- ERA20C: <https://doi.org/10.5065/D6VQ30QG> (Poli et al., 2016; European Centre For Medium-Range Weather Forecasts, 2014)

Author contributions. DPS conceptualized the overall study, obtained primary funding, curated datasets and led the writing of the paper. ZY was the primary contributor to the analysis code and figures, with contributions from DPS. EBW and ZE conceptualized and produced the wind-nudged experiment. RTD contributed

to analysis and interpretation. DPS, ZY, EBW and RTD mentored students involved in the project. All authors discussed results and reviewed the manuscript.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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Credit for the icons in Fig. 10: Cloud snowflake by barurezeki from <https://thenounproject.com/icon/cloud-snowflake-2939171/> (last access: 15 June 2026), Noun Project (CC BY 3.0). Ice cream by Rab from <https://thenounproject.com/icon/ice-cream-7213092/> (last access: 15 June 2026), Noun Project (CC BY 3.0). Snow man by Muhammad Zulkifly Suradin from <https://thenounproject.com/icon/snow-man-8201860/> (last access: 15 June 2026), Noun Project (CC BY 3.0). Wind by Syaeful Amri from <https://thenounproject.com/icon/wind-8390620/> (last access: 15 June 2026), Noun Project (CC BY 3.0). Lightning bolt by perilous graphic from <https://thenounproject.com/icon/lightning-bolt-6309438/> (last access: 15 June 2026), Noun Project (CC BY 3.0).

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