Anomalous Meltwater from Ice Sheets and Ice Shelves is a Historical Forcing

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Key Points:

- Anomalous meltwater from ice sheets and shelves is sufficiently large to be included as a forcing in historical climate model simulations.
- When the GISS model includes these drivers, Southern Ocean SST and sea ice trends better match observations.
- Steric and dynamic impacts on regional sea level in the western North Atlantic and coastal Antarctica are significant.

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Abstract

Recent mass loss from ice sheets and ice shelves is now persistent and prolonged enough that it impacts downstream oceanographic conditions. To demonstrate this, we use an ensemble of coupled GISS-E2.1-G simulations forced with historical estimates of anomalous freshwater, in addition to other climate forcings, from 1990 through 2019. In this ensemble there are detectable differences in zonal-mean sea surface temperatures (SST) and sea ice in the Southern Ocean, and in regional sea level around Antarctica and in the western North Atlantic. These impacts mostly improve the model's representation of historical changes, including reversing the forced trends in Southern Ocean surface temperature and Antarctic sea ice. The changes in SST may have implications for estimates of the SST pattern effect on climate sensitivity and for cloud feedbacks. We conclude that the changes are sufficiently large that these drivers should be included in all-forcing historical simulations in coupled model intercomparisons.

Plain Language Summary

Simulations of recent historical periods are a key test of climate model reliability and skill. These model simulations require an accounting of all the drivers of climate change. We show that the impact of historical changes in freshwater fluxes from ice sheets and ice shelves on the ocean (through changes in salinity and stratification) are detectable in sea surface temperature and sea ice trends, and help improve the match between the modeled climate changes and observations. We recommend that these drivers be included in all climate simulations that do not explicitly model ice sheets and ice shelves.

1 Introduction

While coupled climate models have skillfully predicted global mean sea surface temperature (SST) trends since the 1970s (Hausfather et al., 2020), and successfully represented them in hindcasts over the historical period (e.g. Miller et al., 2021), there are nonetheless persistent regional biases. Notably, cooling trends since the 1980s in the Eastern Tropical Pacific and in the Southern Oceans are significantly different from the expectations drawn from the Coupled Model Intercomparion Project, Phase 6 (CMIP6) multi-model ensemble (Eyring et al., 2021) (Fig. 1) even when the models are screened for the likely range of Transient Climate Response (TCR) (Hausfather et al., 2022). Whether these departures from the expected forced pattern derived from a multi-model mean are due to internal variability, unrepresented or poorly represented climate feedbacks, or misspecifications or incompleteness of the forcings, is a subject of much current research (Dong et al., 2022; Wills et al., 2022; Kang et al., 2023).

Additionally, trends in Antarctic sea ice have been anomalous with respect to the multi-model ensembles (Roach et al., 2020). From 1979 to 2014, Antarctic trends were in fact slightly positive, in contrast to the situation in the Arctic and to the expectations of the CMIP5/CMIP6 models (Rye et al., 2020; Roach et al., 2020). Internal variability in the region is however high, and in recent years (2015 onward), Antarctic sea ice anomalies have been significantly negative, with 2022/2023 being the lowest austral summer sea ice amounts on record (Gautier, 2023).

Many explanations have been proposed for the departures in the Southern Ocean - such as impacts of changes in the Southern Annular Mode (driven by ozone depletion and rising greenhouse gases (Miller et al., 2006; Kostov et al., 2017, 2018; Hartmann, 2022)), problems associated with coarse resolution in ocean models that don't permit or resolve eddies (Rackow et al., 2022; Yeager et al., 2023), and/or Southern Ocean cloud feedbacks (Kim et al., 2022; Dong et al., 2022). One specific forcing that was not included in the CMIP5/6 models is the freshwater from historical changes in the mass balance of the Antarctic ice sheet and surrounding ice shelves (Bintanja et al., 2013). Note that for models

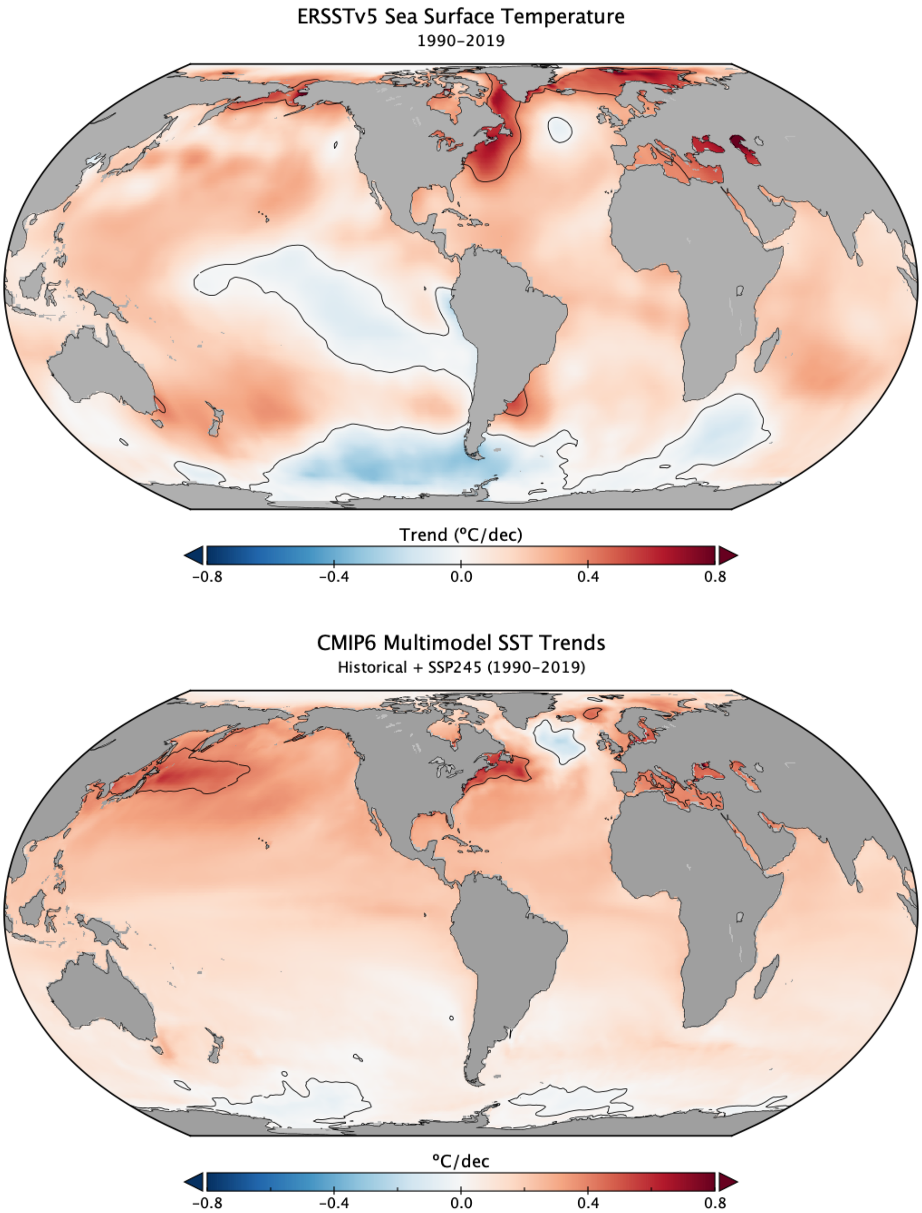

Figure 1. Annual mean sea surface temperature trends (1990–2019) from a) ERSSTv5 observations (Huang et al., 2017) and b) a screened multi-model ensemble mean from CMIP6 using historical simulations to 2014 and SSP245 scenarios from 2015 to 2019 (see Table S1 for details).

without a representation of the dynamics of ice sheets and ice shelves, which includes all of the models in the standard CMIP6 historical ensemble, anomalous freshwater or ice inputs from the ice sheets should be regarded as a forcing, even if in the fully coupled ice-sheet climate system those fluxes might arise as a response to ongoing climate changes. Hereafter, we therefore refer to the freshwater as a forcing in this context.

Multiple lines of observational evidence have demonstrated net mass loss from ice sheets and ice shelves in both hemispheres over the last few decades (Watkins et al., 2015; Velicogna et al., 2020; Slater et al., 2021; Mankoff, Fettweis, Langen, et al., 2021). The mass loss from grounded ice sheets has been a critical component of the closure of the sea level budget from 1993 onward (Dieng et al., 2017; Bartholet et al., 2021) contributing 1.2 mm yr^{-1} on average over that time (around 22 mm since 2003). The additional freshwater from the loss of ice shelves is quite variable from year to year, but has roughly doubled the cumulative amount of freshwater additions into this region over the last 30 years (Slater et al., 2021; Andreasen et al., 2023). Even though the loss of floating ice does not have a large direct effect on sea level (only due to halosteric effects (Jenkins & Holland, 2007; Noerdlinger & Brower, 2007)), it may have a large effect on oceanographic processes, such as stratification and sea ice formation/melt, and can indirectly affect sea level through increasing discharge from upstream grounded ice (Scambos et al., 2004; Rignot et al., 2004).

There have been a number of idealized Southern Ocean freshwater hosing simulations published (Pauling et al., 2016; Hansen et al., 2016; Rye et al., 2020; Li, Marshall, et al., 2023; Dong et al., 2022) and efforts are underway to build an understanding of the robustness of these results (Swart et al., 2023). However, due to an understandable desire to find a strong signal, the amounts of freshwater added in these simulations have often been much larger than the estimated observed cumulative anomalous mass flux from the 1990s to the present. For instance, 2000 Gt yr^{-1} was required to see a signal in a single run with CESM1 (Pauling et al., 2016), roughly six times larger than the estimated real world flux (Slater et al., 2021). These amounts may be more relevant for simulations focused on the future implications of potentially greater amounts of anomalous freshwater in the 21st Century (Gomez et al., 2015; Golledge et al., 2019; Sadai et al., 2020; Gorte et al., 2023; Li, England, et al., 2023; Purich & England, 2023).

Similarly, the majority of hosing experiments focused on the North Atlantic have used hosing rates one or two orders of magnitude greater than recent observed fluxes (e.g. Manabe & Stouffer, 1995; Rind et al., 2001; LeGrande et al., 2006; Orihuela-Pinto et al., 2022). However, it is unclear whether these fluxes may be contributing to the inferred decreases in the overturning circulation (Frajka-Williams, 2015; Caesar et al., 2021).

In this paper we explore whether, in the GISS-E2.1-G model ensemble, the historical transients of anomalous ice sheets and ice shelf meltwater are sufficiently large to warrant inclusion in standard CMIP hindcasts, and what, if any, are the signatures of this flux on key observables. The GISS-E2.1-G model is particularly suitable for this exploration because it has a relatively skillful climatology of Southern Hemisphere ocean and ice distribution (Kelley et al., 2020). We describe the model experimental design in Section 2, the basic results in Section 3, and discuss the implications for understanding real world changes and model intercomparisons in Section 4.

2 Experimental design

We use the GISS-E2.1-G coupled climate model with the same configuration as the CMIP6 DECK experiments (Kelley et al., 2020). Historical forcings (from 1850 CE to 2014) in the original experiments included greenhouse gases, aerosols and ozone (by concentration), parameterized aerosol indirect effects, volcanic, solar, orbital and land use/land change (including irrigation) (Miller et al., 2021). We extended these simulations to 2019 using observed greenhouse gases and solar forcing, while keeping composition and land use/land change at 2014 levels. Updates to these last fields to more recent years are still pending.

Climatological ice sheet discharge in GISS-E2.1-G is derived assuming hemispheric ice sheet mass and energy balance. Greenland and Antarctic net accumulations over 1990–2019 are 504 and 2780 Gt yr^{-1}, respectively, close to that inferred from regional models, 338 Gt yr^{-1} and 2690 Gt yr^{-1} (Fettweis et al., 2017; Kittel et al., 2021), though there are larger differences in individual terms (Alexander et al., 2019). Decadal imbalances are distributed uniformly across a spatial mask that delineates coastal areas of major iceberg melt in the modern ocean (Fig. S1). Note that the ocean model uses natural boundary conditions (mass, energy and salt are fluxed at the ocean/ atmosphere /sea ice boundaries) and is fully mass and energy conserving, and so the climatological glacial melt acts to balance evaporative mass loss (and hence sea level). The ice discharge is distributed uniformly in the vertical from 0 to 200 m with the energy consistent with the accumulation over the ice sheet (Schmidt et al., 2014). Since the mass and energy accumulation effectively occur through net snow accumulation, the discharge has an enthalpy consistent with ice. The mass and enthalpy of this discharge is added to the mass and enthalpy of the ocean water, leading to direct increases in ocean mass, and a slight cooling to provide sufficient energy to melt the ice. If at any time the resulting enthalpy of the ocean would be below that needed for liquid water at the freezing point, marine ice is formed and added to the sea ice.

In these experiments we input additional, anomalous, freshwater in an analogous fashion, based on estimates of the post-1990 'ice imbalance' from melting ice shelves and ice sheets (Slater et al., 2021; Mankoff, Fettweis, Langen, et al., 2021), but applied over an expanded spatial area roughly 500 km wide around Antarctica and 100 km wide around Greenland (Fig. S1). Thus the glacial freshwater input to the ocean in these experiments comes from two sources: excess mass from each ice sheet from the surface mass balance (SMB) such that the ice sheet masses remain constant, and additionally the net mass loss from each ice sheet based on observed mass changes. Note that we are not accounting here for net mass losses from mountain glaciers which is also relevant for sea level rise, but is spread more diffusely through many continental river systems.

In total, from 1990 to 2019 we add 4890 Gt and 10414 Gt of water in from Greenland and Antarctica respectively as ice. The sea level rise in the model will not be exactly equal to this number because of modulation by regional steric effects and feedbacks to the hydrologic cycle from any forced change in climate. Additionally, in comparing absolute sea level rise to observations, we would need to remove the amount of seawater that was no longer being displaced by the (unresolved) floating ice (7251 Gt of the 10414 Gt Antarctic mass change, equivalent to roughly 19.6 mm). The average freshwater fluxes over the 30 years of the experiments are 0.005 and 0.011 Sv, in the Northern and Southern hemispheres respectively. Note that the contribution from Antarctic ice shelves is roughly half the total freshwater added, and 70% of the amount around Antarctica, and so cannot be neglected.

We performed two 10-member ensembles using the same initial conditions in 1850 as the original CMIP6 historical runs and continued to 2019 using observed greenhouse gas and solar inputs, but keeping atmospheric composition and land surface properties constant at 2014 levels. One ensemble additionally included the anomalous freshwater added around Greenland and Antarctic from 1990 onward. Results shown below are based on the difference between these two ensembles.

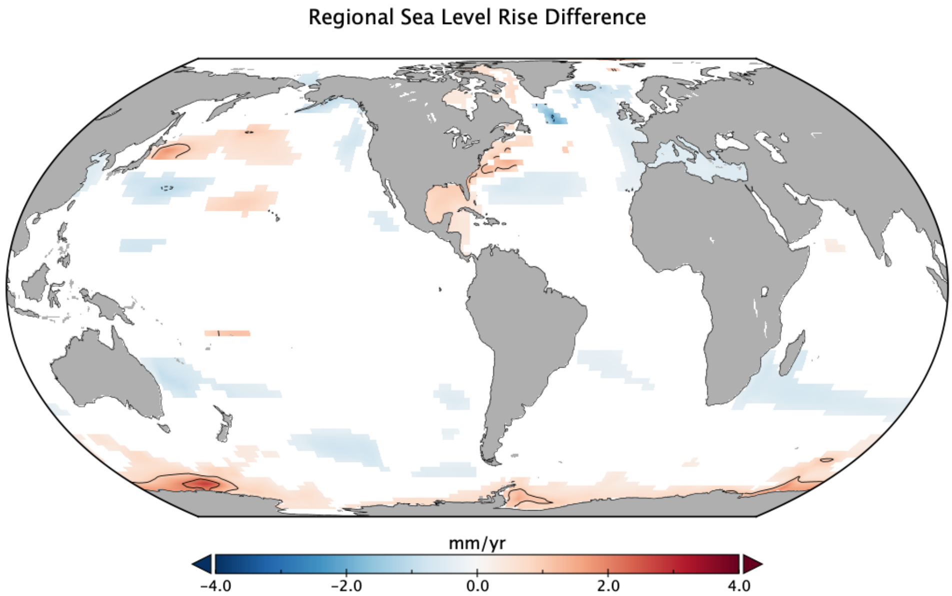

Figure 2. Impact of anomalous freshwater additions on regional sea level rise (1990–2019) (after adjusting for the global mean change in sea level). Only trends outside the 95% confidence interval on the linear trend are plotted.

3 Results

Globally, the ensemble mean sea level increases by 41.4 ±2.1 mm from 1990 through 2019 (95% confidence on the mean value) because of the anomalous freshwater flux (which includes barystatic and steric effects, climate feedbacks and residual internal variability), compared to 42.9 mm from just assuming that additional freshwater adds to sea level without climate feedbacks. The spread across the ensemble is [37.7, 46.9] mm, suggesting that internal variability can make a roughly 10 % difference in global impacts over this 30 year period. We define regional sea level rise anomalies as the difference in any particular area from the global mean sea level rise. There are local rises in regional sea level around coastal Antarctica and most notably along the Adelie coast (Rye et al., 2020; Li, Marshall, et al., 2023), but also in the North Atlantic, where the additional freshwater from Greenland results in almost 1 mm yr^{-1} higher sea level trends near the US East Coast (as also suggested by Stammer (2008)) and Gulf of Mexico (Fig. 2).

The zonal average differences in the ensembles show clear and significant forced cooling in Southern Ocean sea surface temperatures and increases in sea ice concentrations (Fig. 3) and in the ocean subsurface (Fig. 4). Notably, the sign of the forced trends in temperature and sea ice concentration have changed and are better aligned with observations in the Southern hemisphere. Subsurface temperatures around Antarctica also increase as the surface freshwater inhibits mixing though there is no detectable difference in net Antarctic Bottom Water production (Fig. 4 c and e). Simulated subsurface salinity trends show a freshening signal in the southern mid-latitudes (Fig. 4 d) along the subduction pathways of Subantarctic Mode Water and Antarctic Intermediate Water, which is not seen in the CORA5 dataset (Fig. 4 b) (Szekely et al., 2019). In the Northern Hemisphere, neither of the two ensembles have as much Arctic warming or decrease in sea ice as observed (Fig. 3), and the subsurface trends in temperature and salinity pen-

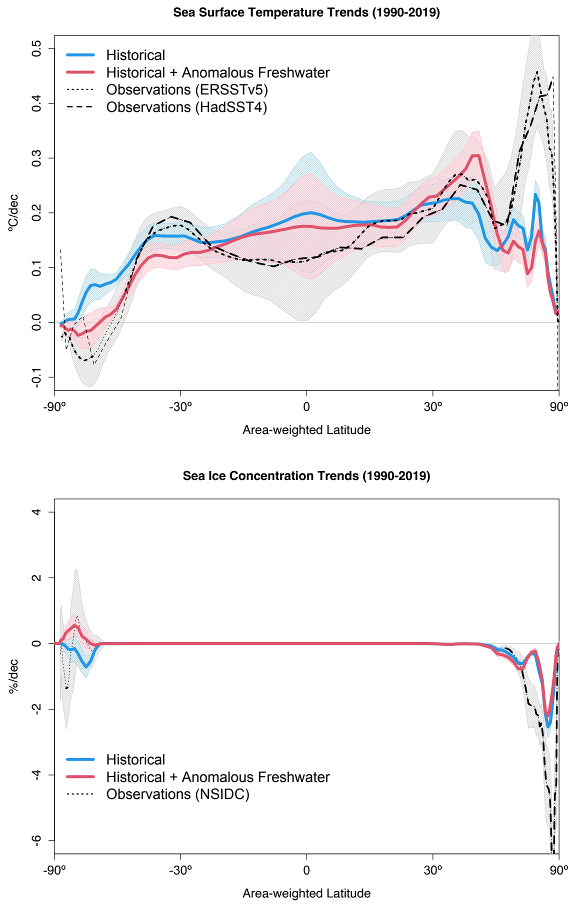

Figure 3. The 1990–2019 trends in zonal annual mean sea surface temperature and sea ice concentration in the two ensembles, together with the 95% confidence intervals on the trends in the ensemble mean. Observations in the SST plot are from HadSST4 (Kennedy et al., 2019) and ERSSTv5 (Huang et al., 2017) (emphasized where the trend exceeds the 95% confidence interval on the trend), and we use NSIDC CDRv4 for the sea ice concentration trend (Meier et al., 2014), with 95% confidence on the estimated trend.

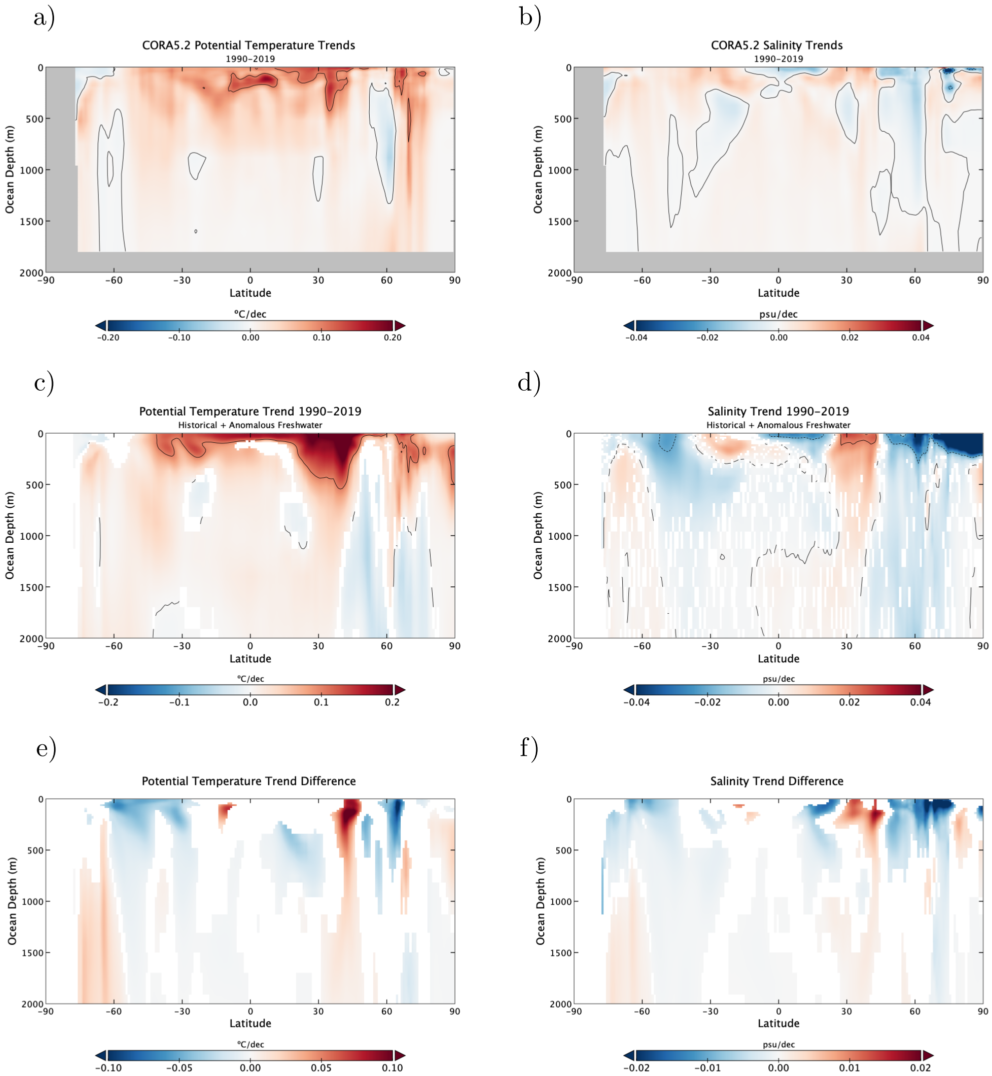

Figure 4. Trends (1990–2019) of zonally averaged potential temperature (left column) and salinity (right column) over 0–2000m depth: a) and b) in the Coriolis Ocean Dataset for Reanalysis v.5.2 (CORA5.2) (Szekely et al., 2019); c) and d) in the ensemble with anomalous freshwater; e) and f) the difference in the trends between the ensemble with anomalous freshwater and the ensemble without. In panels c–f, trends that are not significant at the 95% confidence level are masked out.

etrate deeper into the ocean than seen in the observations (Fig. 4). Tropical sea surface and subsurface temperature trends are too large in both model ensembles.

The differences between the ensembles in the Northern Hemisphere are mostly confined to around 45°N, where the additional freshwater causes a dipole pattern of warming to the south and cooling to the north (Fig. 3b). The impact in the NH is less than in the SH, and does not show any notable improvement when compared to observations, except perhaps in the regional sea level pattern.

Elsewhere regional impacts are less clear, though there are robust signals of cooling and freshening in SST and SSS around Antarctica, and in the northern North Atlantic, somewhat balanced by opposing temperature trends in the northern Pacific sector (Fig. 5). Mixed layer depths shoal in the Labrador and Irminger Seas, and increase in the Norwegian Sea (not shown), but there is no detectable change in the overall Atlantic Meridional Overturning Circulation (AMOC), possibly because the salinity and temperature trends roughly cancel in terms of density and there is no strong freshening trend in the subsurface. There are large salinity anomalies in the Ross and Weddell Seas near the Antarctic coast, which is consistent with sea ice changes there, that probably lead to reduced convection and warming of the subsurface Southern Ocean. Large warming in the Indian Ocean section of the Southern Ocean is mostly confined in the belt 60–65°S. There is a curious response in salinity in the tropics, with a decrease in the tropical Atlantic and Indian Oceans to the north of the equator, and an increase in the western Pacific, consistent with a shift northwards in the Intertropical Convergence Zone (ITCZ) in the Atlantic and Indian Oceans. In the subsurface, the main difference is an increase in warming in Antarctic Circumpolar Deep Water.

Altogether, we see a consistent set of responses in Southern Ocean salinity, surface and sub-surface temperatures, and sea ice area. This is in line with other estimates of the effects of anomalous freshwater in the Southern Oceans although the magnitude of response varies among studies. Note that with the level of forcings used here, and with the sensitivity to that forcing in this model, we see no detectable far field impacts on the tropical Pacific temperatures. There is a very slight decrease in net snow accumulation in Antarctica in the ensemble means (by about 30 Gt yr^{-1}), but it is not significant with respect to the internal variability.

4 Discussion

While the impacts of additional freshwater to climate models has been a topic of study for many decades (e.g. Manabe & Stouffer, 1993), the focus has often been to assess the existence of tipping points in the AMOC, and the magnitudes of fresh water inputs needed for that were orders of magnitude larger than current melt rates from Greenland (0.1 to 1.0 Sv). Similarly, efforts to explore the response of the Southern Ocean to increased meltwater since work by (Seidov et al., 2001; Stouffer et al., 2007), have generally used freshwater input rates that are much larger than current anomalous fluxes from Antarctica (Swart et al., 2023). This has been useful for seeing a signal emerge from the noise, particularly in single coupled model simulations, however, in the context of historical hindcasts, we need to assess the likely forced signal with realistic inputs. Our results suggest that the observed rates - especially once the impacts of ice shelf changes are included - are indeed sufficiently large to matter. The significance levels shown here are determined by the difference between two ten-member ensembles. If the number of ensemble members was larger, we would increase the significance of the changes. These significance levels are therefore useful for the attribution of the changes, but not necessarily the detection of the changes, which instead uses the ensemble spread to assess whether the observed changes are consistent with the unperturbed ensemble (or not) (Schmidt et al., 2023; Santer et al., 2008).

In other studies that have used qualitatively realistic Southern Ocean inputs (i.e. Golledge et al., 2019; Rye et al., 2020; Li, Marshall, et al., 2023; Bintanja et al., 2013; Beadling et al., 2022), the magnitude of the climate impacts have varied significantly. This is likely because of the different biases in Southern Ocean climate in different models, different processes at play (such whether the impacts of eddies are resolved or parameterized), and/or different implementations of the freshwater flux (horizontally, vertically, and phase) (L. Zhang et al., 2018; Singh et al., 2019; Thomas et al., 2023). The proposed SOFIA project may be able to unravel those issues (Swart et al., 2023), but an improved spatial distribution of the anomalous melt is an obvious target. However,

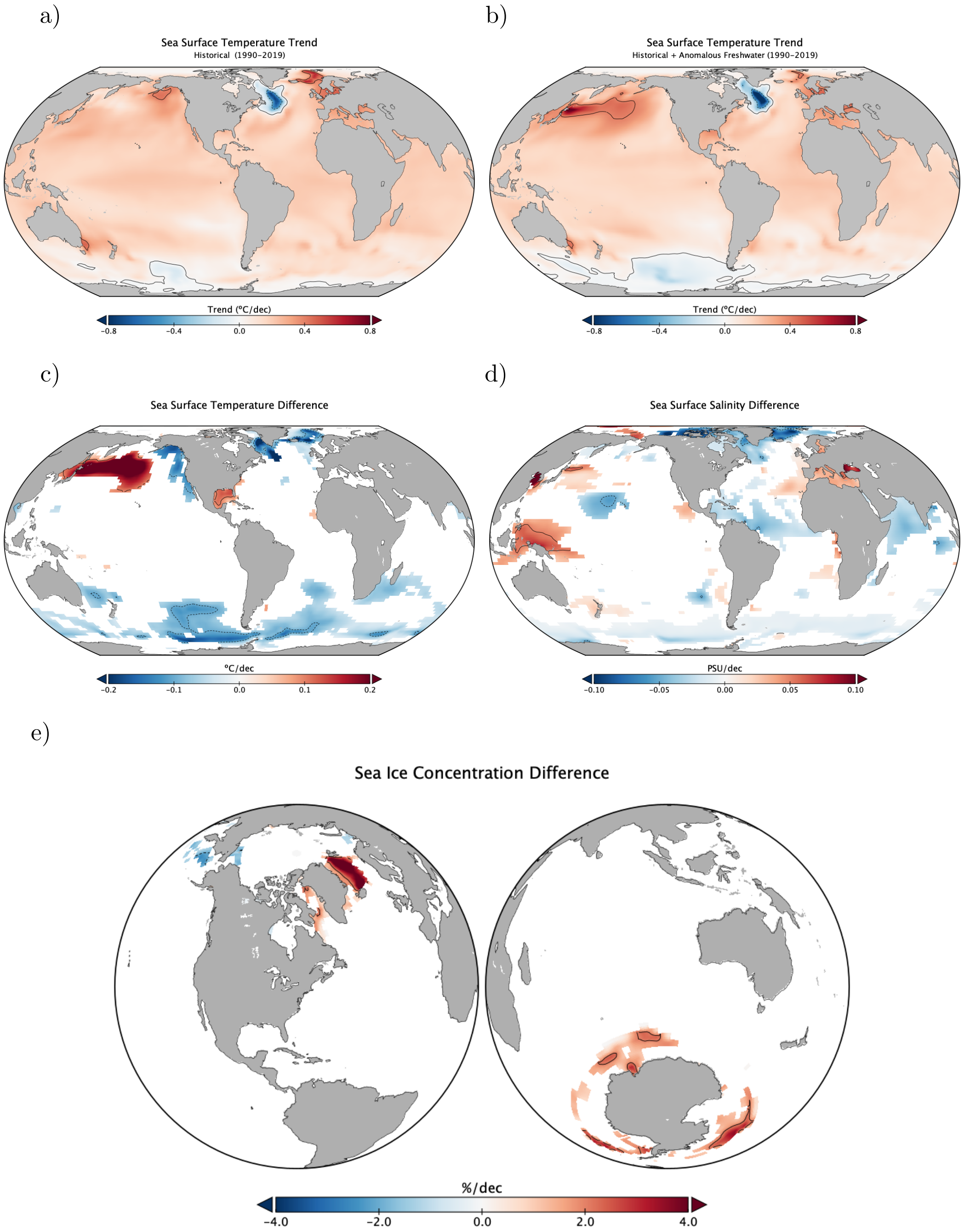

Figure 5. Ensemble mean trends 1990–2019 in a) the control historical ensemble, and b) the ensemble including anomalous freshwater (to be compared to Fig. 1a). The impact from the anomalous freshwater on 1990–2019 trends of: c) sea surface temperature; d) sea surface salinity; and e) sea ice concentration differences. The fields in the difference plots have been masked for 95% confidence intervals in the trend of the difference between the two ensembles.

given the importance of the CMIP historical simulations in constraining projections (Tokarska et al., 2020; Ribes et al., 2021), and estimating ocean thermal expansion (Kopp et al., 2023) etc., we think it will be necessary to have the impacts of freshwater fully integrated into the next round of CMIP simulations even with these structural uncertainties.

Notably, constraints on climate sensitivity based on historical changes rely on these model simulations for estimates of the SST pattern effect (Sherwood et al., 2020; Dong et al., 2022). Since the Southern Ocean SST anomaly is one of the clearest departures from the multi-model historical trend (Fig. 1) (the others being the Eastern Tropical Pacific cooling, and northern North Atlantic warming), model developments that bring the hindcasts into better agreement with the observations, will likely reduce the magnitude of the estimated pattern effect, and may lead to slightly lower constrained climate sensitivity estimates using this methodology (Andrews et al., 2018).

One key question is the extent to which the SST trends in the Southern Ocean and Eastern Tropical Pacific are connected (Kang et al., 2023; Kim et al., 2022; Kang et al., 2020; Meehl et al., 2016; X. Zhang et al., 2021; Chung et al., 2022). The magnitude of these effects may be dependent on the cloud feedbacks in the Southern Oceans or marine stratus decks, both of which have a large spread in climate models, but there is no indication that of a significant impact in our simulations.

Eventually, climate models will include a fuller representation of the atmosphere and ocean coupling to the ice sheets and ice shelves, though that is proving to be more of a technical challenge than was estimated a decade ago (Little et al., 2007). It is, however, only with this future functionality that we will be able to quantify the attribution of the ongoing mass loss to anthropogenic forcings, internal variability, or long-term ice sheet responses to the deglaciation or Holocene. Until then, there is an ambiguity, particularly for the Antarctic, as to whether (and with what precision) we can assign these inputs to anthropogenic or natural processes. This is not the only historical forcing so affected, for instance emissions from biomass burning have a similar ambiguity, but deciding what to do about the anomalous meltwater in DAMIP-type experiments requires further discussion and analysis. In the meantime, the use of observationally-constrained freshwater fluxes has the potential to at least partially represent the oceanographic impacts of these historical changes, and in future work we will similarly incorporate results from projections (e.g., Seroussi et al., 2020).

Finally, it is important to note that while this study covers the period through to the end of 2019 (including some extrapolation from 2016), Antarctic sea ice concentrations since 2015, and especially in 2022/2023, have plunged to record low levels for the satellite era, and since 2019, Antarctic grounded ice mass has increased slightly. It is as yet unclear what the proximate causes of these changes are and whether they are connected. It will be crucial to get better, and spatially resolved, estimates of the Antarctic freshwater fluxes past 2016 to test these hypotheses.

5 Open Research

GISS Model results (Table S1) are available from the NCCS portal and through ESGF. Ocean surface temperature observations are from ERSSTv5 (Huang et al., 2023) and HadSST4 (Kennedy et al., 2023), sea ice concentrations are from NSIDC (Meier et al., 2021), and the ocean reanalysis fields from CORA5 (Szekely et al., 2023). The multi-model CMIP6 ensemble SST trend was produced on the LEAP-Pangeo portal using code archived at Busecke (2023) and (Busecke et al., 2023), using the model simulations denoted in Table S2. Greenland and Antarctic mass balance data were sourced from Mankoff, Fettweis, Stendel, et al. (2021); Slater et al. (2023) and available directly from the NCCS portal (Mankoff, 2023).

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