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Anomalous Meltwater From Ice Sheets and Ice Shelves Is a Historical Forcing

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Key Points:

- The response to anomalous meltwater from ice sheets and shelves is large enough for it to be a forcing in historical climate 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 parts of the North Atlantic and coastal Antarctica are significant

Supporting Information:

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

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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. 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 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 model groups should strive to include more accurate estimates of these drivers in all-forcing historical simulations in future 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 more accurate estimates of 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 Intercomparison Project, Phase 6 (CMIP6) multi-model ensemble (Eyring et al., 2021) (Figure 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 mis-specifications or incompleteness of the forcings, is a subject of much current research (Dong et al., 2022; Kang et al., 2023; Wills et al., 2022).

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 (Roach et al., 2020; Rye 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 (Hartmann, 2022; Kostov et al., 2017, 2018; Miller et al., 2006)), 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 errors in Southern Ocean cloud

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feedbacks (Dong et al., 2022; Kim 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 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 can 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 (Mankoff, Fettweis, Langen, et al., 2021; Slater et al., 2021; Velicogna et al., 2020; Watkins et al., 2015). The mass loss from grounded ice sheets has been a critical component of the closure of the sea level budget from 1993 onward (Bartholet et al., 2021; Dieng et al., 2017) 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 (Andreasen et al., 2023; Slater et al., 2021). 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 (Rignot et al., 2004; Scambos et al., 2004).

There have been a number of idealized Southern Ocean freshwater hosing simulations published (Dong et al., 2022; Hansen et al., 2016; Li, Marshall, et al., 2023; Pauling et al., 2016; Rye et al., 2020) 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, 2,000 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) which may be more relevant for simulations focused on the future implications of anomalous freshwater in the 21st Century (Golledge et al., 2019; Gomez et al., 2015; Gorte et al., 2023; Li, England, et al., 2023; Purich & England, 2023; Sadai et al., 2020). 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., LeGrande et al., 2006; Manabe & Stouffer, 1995; Orihuela-Pinto et al., 2022; Rind et al., 2001). However, it is unclear whether these fluxes may be contributing to the inferred decreases in the overturning circulation (Caesar et al., 2021; Frajka-Williams, 2015).

In this paper we explore whether, in GISS-E2.1-G ensembles, 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). Extensions from 2015 to 2019 were performed using both the standard socio-economic shared pathways as described in Nazarenko et al. (2022) (10 runs), and also using observed greenhouse gases and solar forcing, while keeping composition and land use/land change at 2014 levels (10 runs).

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 2,780 Gt yr^{-1}, respectively, close to that inferred from regional models, 338 and 2,690 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

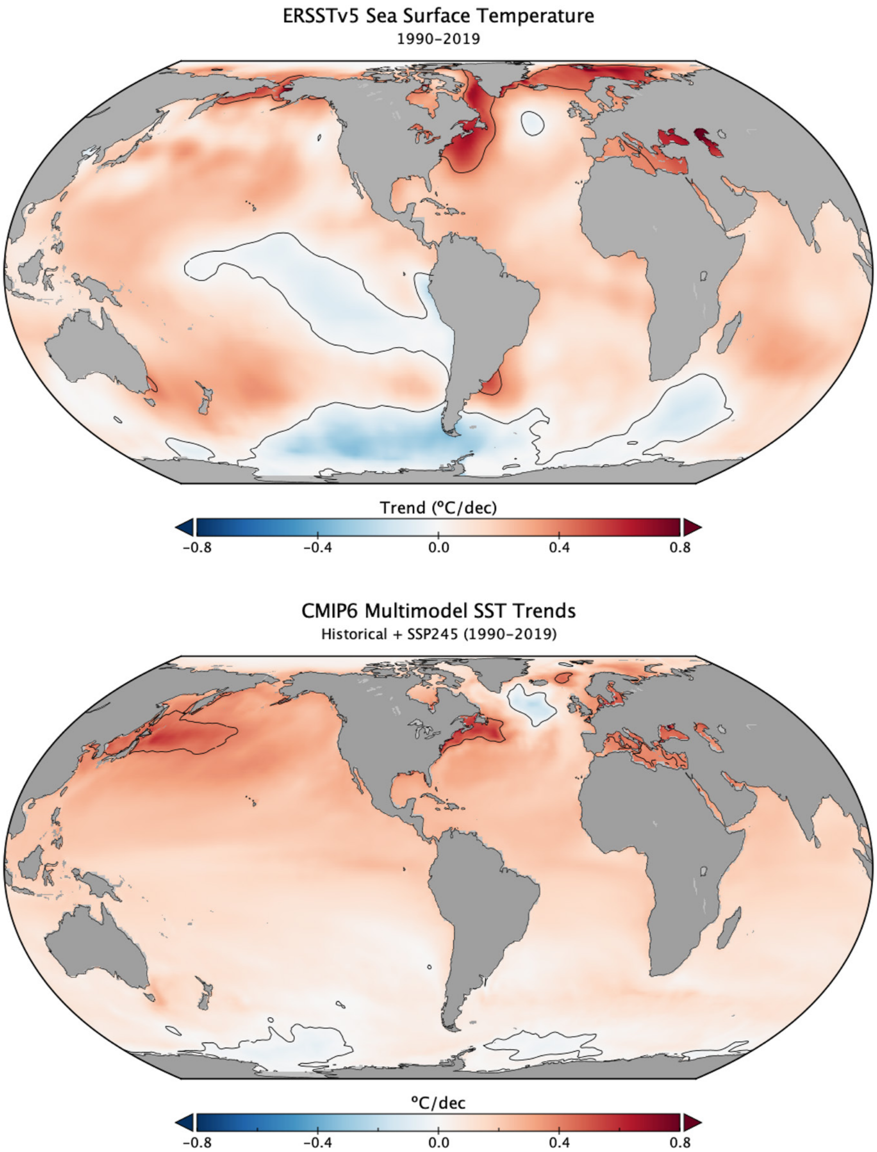

Figure 1. Annual mean sea surface temperature trends (1990–2019) from (a) ERSSTv5 observations (Huang et al., 2017) and (b) a screened multi-model ensemble mean from CMIP6 using historical simulations to 2014 and SSP245 scenarios from 2015 to 2019 (see Table S1 in Supporting Information S1 for details).

(Figure 2). 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 (Mankoff, Fettweis, Langen, et al., 2021; Slater et al., 2021), but applied over an expanded spatial area roughly 500 km wide around Antarctica and 100 km wide around Greenland (Figure 2). Thus the glacial freshwater input to the ocean in these experiments comes

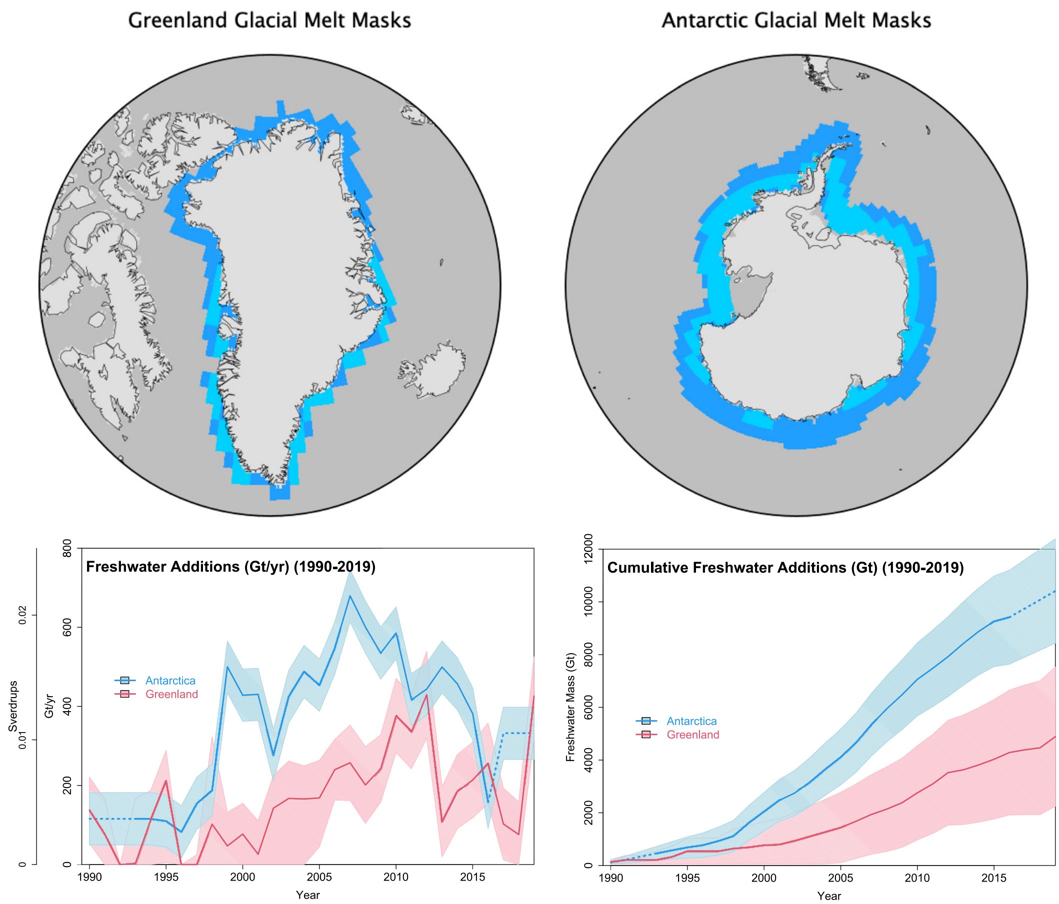

Figure 2. Top row: Glacial melt spatial masks around Greenland and Antarctica used in GISS-E2.1-G for adding climatological (light blue) and anomalous freshwater (dark blue plus light blue) from the ice sheets into the ocean. Bottom row: Anomalous total freshwater flux amounts used in these experiments (annual fluxes (Gt yr^{-1} or Sv) and cumulative fluxes (Gt) aggregated by hemisphere). Uncertainty bands are the spread in maximum and minimum plausible changes for each ice sheet. Antarctic values before 1994 and after 2015 are estimated using the mean of the post or prior 3-year period (dashed lines).

from two sources: excess mass from each ice sheet from the surface mass balance 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 4,890 and 10,414 Gt of water in from Greenland and Antarctica respectively as ice, equivalent to 42.9 mm of sea level rise. 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 (7,251 Gt of the 10,414 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.

We performed two sets of two 10-member ensembles, one using the same initial conditions in 1850 as the original CMIP6 historical runs and continued to 2019 using observed forcings, and a second using 1990 initial conditions from the CMIP6 ensemble and using the SSP2-4.5 forcing for the post-2015 period. The perturbation in both ensembles is just due to freshwater forcing, despite differences between the two ensembles in the post-2015 forcings. For our purposes here, we treat these simulations as exchangeable and assume that the differences can

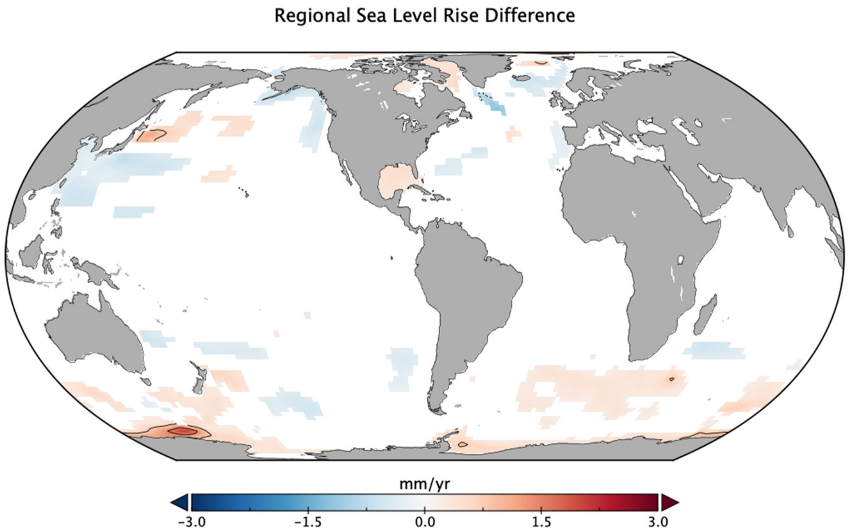

Figure 3. Impact of anomalous freshwater additions on regional sea level rise (1990–2019) (after adjusting for the global mean change in sea level). Only trends outside the 95% confidence interval on the linear trend are plotted.

be averaged together to get more precise estimates of the differences forced by the freshwater additions. This has only negligible impacts on the results.

3. Results

Globally, the ensemble mean sea level increases by 40.0 ± 1.8 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 standard deviation across the ensemble is 4 mm, suggesting that internal variability can make roughly 10% difference in global impacts over a 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 (Li, Marshall, et al., 2023; Rye et al., 2020), but also in the North Atlantic, where the additional freshwater from Greenland results in almost 1 mm yr^{-1} higher sea level trends in the Labrador Sea and Gulf of Mexico (Figure 3). There are increases all the way down the US East Coast (as also suggested by Stammer (2008)) but they are not significant at the 95% level.

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 (Figure 4) and warming in the ocean subsurface (Figure S1 in Supporting Information S1). 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, this is discussed further in Roach et al. (2023). Subsurface temperatures around Antarctica also increase as the surface freshwater inhibits mixing though there is no detectable difference in net Antarctic Bottom Water production (Figures S1c and S1e in Supporting Information S1). Simulated subsurface salinity trends show a freshening signal in the southern mid-latitudes (Figure S1d in Supporting Information S1) along the subduction pathways of Subantarctic Mode Water and Antarctic Intermediate Water, which is not seen in the CORA5 data set (Figure S1b in Supporting Information S1) (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 (Figure 4), and the subsurface trends in temperature and salinity penetrate deeper into the ocean than seen in the observations (Figure S1 in Supporting Information S1). 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 (Figure 4b). 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.

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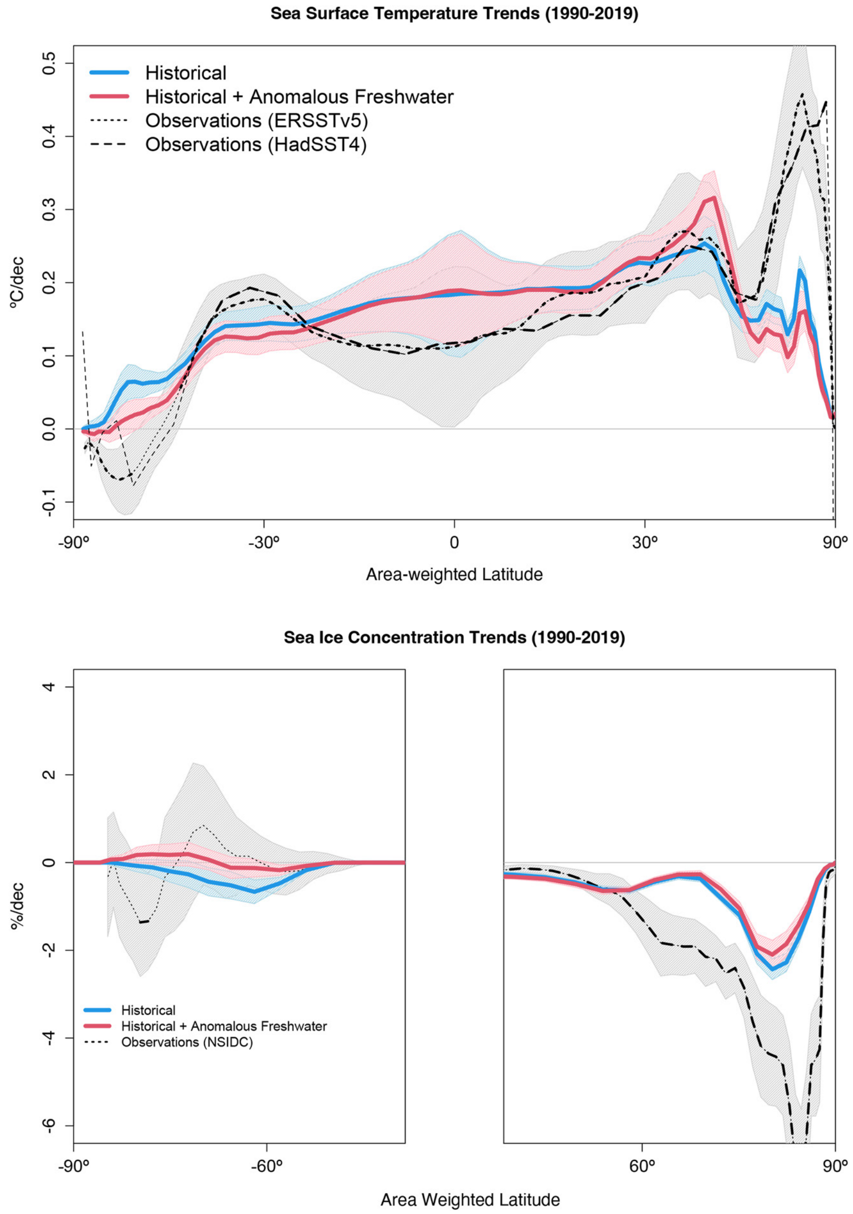

Figure 4. The 1990–2019 trends in zonal annual mean sea surface temperature and sea ice concentration in the two ensembles, together with the 95% confidence intervals on the trends in the ensemble mean. Observations in the SST plot are from HadSST4 (Kennedy et al., 2019) and ERSSTv5 (Huang et al., 2017) (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.

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 (Figure 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, 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, 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

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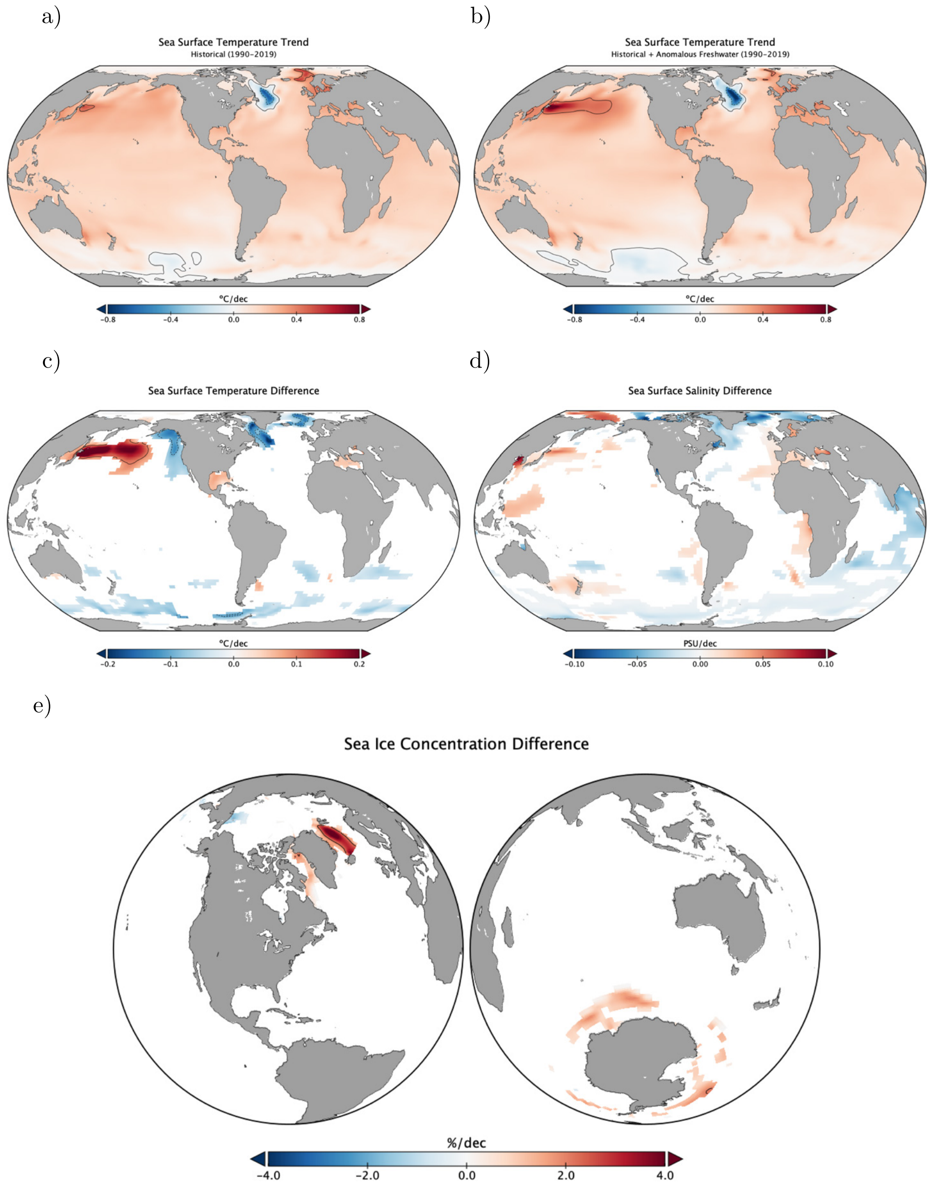

Figure 5. Ensemble mean trends 1990–2019 in (a) the control historical ensemble and (b) the ensemble including anomalous freshwater (to be compared to Figure 1a). The impact from the anomalous freshwater on 1990–2019 trends of: (c) sea surface temperature; (d) sea surface salinity; and (e) sea ice concentration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

with a shift northwards in the Intertropical Convergence Zone 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, there are 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}, equivalent to 2.5 mm SLE over the 30 year period), 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; Seidov et al., 2001; Stouffer et al., 2007), the focus has often been to assess the existence of tipping points in the ocean circulation, and the magnitudes of fresh water inputs needed for that were orders of magnitude larger than current melt rates from Greenland or Antarctica (Swart et al., 2023). This is 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 twenty-member ensembles. The larger the number of ensemble members, the greater 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) (Santer et al., 2008; Schmidt et al., 2023).

In other studies that have used qualitatively realistic Southern Ocean inputs (i.e., Beadling et al., 2022; Bintanja et al., 2013; Golledge et al., 2019; Li, Marshall, et al., 2023; Rye et al., 2020), 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) (Singh et al., 2019; Thomas et al., 2023; L. Zhang et al., 2018). The proposed SOFIA project may be able to unravel those issues (Swart et al., 2023), and an improved spatial distribution of the anomalous melt is an obvious target for future efforts. However, given the importance of the CMIP historical simulations in constraining projections (Ribes et al., 2021; Tokarska et al., 2020), and estimating ocean thermal expansion (Kopp et al., 2023) etc., we suggest it will be useful to have the impacts of anomalous freshwater integrated into the next round of CMIP simulations even with these structural uncertainties. Defining a consensus estimate of what that forcing should be (particularly prior to 1990, or in future scenarios using information from Seroussi et al. (2020) for example) is beyond the scope of this paper, but is the subject of ongoing community discussion in the runup to CMIP7.

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 clearly 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 detection and attribution-type experiments also requires further discussion and analysis.

We note that constraints on climate sensitivity based on historical changes rely on these model simulations for estimates of the SST pattern effect (Dong et al., 2022; Sherwood et al., 2020). Since the Southern Ocean SST anomaly is one of the clearest departures from the multi-model historical trend (Figure 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 (Chung et al., 2022; Kang et al., 2020, 2023; Kim et al., 2022; Meehl et al., 2016; X. Zhang et al., 2021). 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 while there is no indication of a significant impact in our simulations, this may change as models become more realistic.

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 (Roach et al., 2023), 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.

Data Availability Statement

Greenland and Antarctic mass balance data were sourced from Mankoff, Fettweis, Stendel, et al. (2021) and Slater et al. (2023) and available directly from the NCCS portal (Mankoff, 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 S1 of Supporting Information S1. 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). GISS ModelE results (Table S2 in Supporting Information S1) are available from the NCCS portal (GISS ModelE Team, 2023) and through ESGF.

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References

Alexander, P. M., LeGrande, A. N., Fischer, E., Tedesco, M., Fettweis, X., Kelley, M., et al. (2019). Simulated Greenland surface mass balance in the GISS ModelE2 GCM: Role of the ice sheet surface. *Journal of Geophysical Research: Earth Surface*, *124*(3), 750–765. https://doi.org/10.1029/2018jf004772

Andreasen, J. R., Hogg, A. E., & Selley, H. L. (2023). Change in Antarctic ice shelf area from 2009 to 2019. *The Cryosphere*, *17*(5), 2059–2072. https://doi.org/10.5194/tc-17-2059-2023

Andrews, T., Gregory, J. M., Paynter, D., Silvers, L. G., Zhou, C., Mauritsen, T., et al. (2018). Accounting for changing temperature patterns increases historical estimates of climate sensitivity. *Geophysical Research Letters*, *45*(16), 8490–8499. https://doi.org/10.1029/2018gl078887

Bartholet, A., Milne, G. A., & Latychev, K. (2021). Modelling sea-level fingerprints of glaciated regions with low mantle viscosity. *Earth System Dynamics*, *12*(3), 783–795. https://doi.org/10.5194/esd-12-783-2021

Beadling, R. L., Krasting, J. P., Griffies, S. M., Hurlin, W. J., Bronselaer, B., Russell, J. L., et al. (2022). Importance of the Antarctic slope current in the Southern Ocean response to ice sheet melt and wind stress change. *Journal of Geophysical Research: Oceans*, *127*(5), e2021JC017608. https://doi.org/10.1029/2021jc017608

Bintanja, R., van Oldenborgh, G. J., Drijfhout, S. S., Wouters, B., & Katsman, C. A. (2013). Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion. *Nature Geoscience*, *6*(5), 376–379. https://doi.org/10.1038/ngeo1767

Busecke, J. (2023). CMIP6 SST Trend Map: Initial release [Software]. Zenodo. (v0.1.0). https://doi.org/10.5281/zenodo.8335419

Busecke, J., Ritschel, M., Maroon, E., Nicholas, T., & readthedocs assistant. (2023). xMIP [Software]. Zenodo. (v0.7.1). https://doi.org/10.5281/zenodo.7519179

Caesar, L., McCarthy, G. D., Thornalley, D. J. R., Cahill, N., & Rahmstorf, S. (2021). Current Atlantic meridional overturning circulation weakest in last millennium. *Nature Geoscience*, *14*(3), 118–120. https://doi.org/10.1038/s41561-021-00699-z

Chung, E.-S., Kim, S.-J., Timmermann, A., Ha, K.-J., Lee, S.-K., Stuecker, M. F., et al. (2022). Antarctic sea-ice expansion and Southern Ocean cooling linked to tropical variability. *Nature Climate Change*, *12*(5), 461–468. https://doi.org/10.1038/s41558-022-01339-z

Dieng, H. B., Cazenave, A., Meyssignac, B., & Ablain, M. (2017). New estimate of the current rate of sea level rise from a sea level budget approach. *Geophysical Research Letters*, *44*(8), 3744–3751. https://doi.org/10.1002/2017gl073308

Dong, Y., Pauling, A. G., Sadai, S., & Armour, K. C. (2022). Antarctic ice-sheet meltwater reduces transient warming and climate sensitivity through the sea-surface temperature pattern effect. *Geophysical Research Letters*, *49*(24), e2022GL101249. https://doi.org/10.1029/2022gl101249

Eyring, V., Gillett, N., Achuta Rao, K., Barimalala, R., Barreiro Parrillo, M., Bellouin, N., et al. (2021). Human influence on the climate system. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Pean, S. Berger, et al. (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 423–552). Cambridge University Press. https://doi.org/10.1017/9781009157896.005

Fettweis, X., Box, J. E., Agosta, C., Amory, C., Kittel, C., Lang, C., et al. (2017). Reconstructions of the 1900–2015 Greenland ice sheet surface mass balance using the regional climate MAR model. *The Cryosphere*, *11*(2), 1015–1033. https://doi.org/10.5194/tc-11-1015-2017

Frajka-Williams, E. (2015). Estimating the Atlantic overturning at 26°N using satellite altimetry and cable measurements. *Geophysical Research Letters*, *42*(9), 3458–3464. https://doi.org/10.1002/2015gl063220

Gautier, A. (2023). *Antarctic sea ice extent sets a new record low*. NSIDC, Arctic Sea Ice News. Retrieved from https://nsidc.org/arcticseaicenews/2023/02/antarctic-sea-ice-extent-sets-a-new-record-low/

GISS ModelE Team. (2023). CMIP6 simulations with GISS ModelE. NASA Center for Climate Simulations [Dataset]. NASA Center for Climate Simulation. Retrieved from https://portal.nccs.nasa.gov/datashare/giss_cmip6/

Golledge, N. R., Keller, E. D., Gomez, N., Naughten, K. A., Bernales, J., Trusel, L. D., & Edwards, T. L. (2019). Global environmental consequences of twenty-first-century ice-sheet melt. *Nature*, *566*(7742), 65–72. https://doi.org/10.1038/s41586-019-0889-9

Gomez, N., Pollard, D., & Holland, D. (2015). Sea-level feedback lowers projections of future Antarctic ice-sheet mass loss. *Nature Communications*, *6*(1), 8798. https://doi.org/10.1038/ncomms9798

Gorte, T., Lovenduski, N. S., Nissen, C., & Lenaerts, J. T. M. (2023). Antarctic ice sheet freshwater discharge drives substantial southern ocean changes over the 21st century. *ESS Open Archive*, *50*(20). https://doi.org/10.22541/essoar.168771427.74160260/v1

Hansen, J., Sato, M., Hearty, P., Ruedy, R., Kelley, M., Masson-Delmotte, V., et al. (2016). Ice melt, sea level rise and superstorms: Evidence from paleoclimate data, climate modeling, and modern observations that 2°C global warming could be dangerous. *Atmospheric Chemistry and Physics*, *16*(6), 3761–3812. https://doi.org/10.5194/acp-16-3761-2016

Hartmann, D. L. (2022). The Antarctic ozone hole and the pattern effect on climate sensitivity. *Proceedings of the National Academy of Sciences*, *119*(35), e2207889119. https://doi.org/10.1073/pnas.2207889119

Hausfather, Z., Drake, H. F., Abbott, T., & Schmidt, G. A. (2020). Evaluating the performance of past climate model projections. *Geophysical Research Letters*, *47*(1), e2019GL085378. https://doi.org/10.1029/2019gl085378

Hausfather, Z., Marvel, K., Schmidt, G. A., Nielsen-Gammon, J. W., & Zelinka, M. (2022). Climate simulations: Recognize the 'hot model' problem. *Nature*, *605*(7908), 26–29. https://doi.org/10.1038/d41586-022-01192-2

Huang, B., Thorne, P. W., Banzon, V. F., Boyer, T., Chepurin, G., Lawrimore, J. H., et al. (2017). Extended reconstructed sea surface temperature, version 5 (ERSSTv5): Upgrades, validations, and intercomparisons. *Journal of Climate*, *30*(20), 8179–8205. https://doi.org/10.1175/jcli-d-16-0836.1

Huang, B., Thorne, P. W., Banzon, V. F., Boyer, T., Chepurin, G., Lawrimore, J. H., et al. (2023). Extended reconstructed sea surface temperature, version 5 (ERSSTv5) [Dataset]. National Oceanic and Atmospheric Administration. Retrieved from https://downloads.psl306.noaa.gov/Datasets/noaa.ersst.v5/sst.mnmean.nc

Jenkins, A., & Holland, D. (2007). Melting of floating ice and sea level rise. *Geophysical Research Letters*, *34*(16), L16609. https://doi.org/10.1029/2007gl030784

Kang, S. M., Ceppi, P., Yu, Y., & Kang, I.-S. (2023). Recent global climate feedback controlled by Southern Ocean cooling. *Nature Geoscience*, *16*(9), 775–780. https://doi.org/10.1038/s41561-023-01256-6

Kang, S. M., Xie, S.-P., Shin, Y., Kim, H., Hwang, Y.-T., Stuecker, M. F., et al. (2020). Walker circulation response to extratropical radiative forcing. *Science Advances*, *6*(47), eabd3021. https://doi.org/10.1126/sciadv.abd3021

Kelley, M., Schmidt, G. A., Nazarenko, L., Bauer, S. E., Ruedy, R., Russell, G. L., et al. (2020). GISS-E2.1: Configurations and climatology. *Journal of Advances in Modeling Earth Systems*, *12*(8), e2019MS002025. https://doi.org/10.1029/2019MS002025

Kennedy, J. J., Rayner, N. A., Atkinson, C. P., & Killick, R. E. (2019). An ensemble data set of sea surface temperature change from 1850: The Met Office Hadley Centre HadSST.4.0.0.0 data set. *Journal of Geophysical Research: Atmospheres*, *124*(14), 7719–7763. https://doi.org/10.1029/2018jd029867

Kennedy, J. J., Rayner, N. A., Atkinson, C. P., & Killick, R. E. (2023). Hadley Centre HadSST.4.0.1.0 data set [Dataset]. The UK Met Office. Retrieved from https://www.metoffice307.gov.uk/hadobs/hadsst4/data/netcdf/HadSST.4.0.1.0median.nc

Kim, H., Kang, S. M., Kay, J. E., & Xie, S.-P. (2022). Subtropical clouds key to Southern Ocean teleconnections to the tropical Pacific. *Proceedings of the National Academy of Sciences*, *119*(34), e2200514119. https://doi.org/10.1073/pnas.2200514119

Kittel, C., Amory, C., Agosta, C., Jourdain, N. C., Hofer, S., Delhasse, A., et al. (2021). Diverging future surface mass balance between the Antarctic ice shelves and grounded ice sheet. *The Cryosphere*, *15*(3), 1215–1236. https://doi.org/10.5194/tc-15-1215-2021

Kopp, R. E., Garner, G. G., Hermans, T. H. J., Jha, S., Kumar, P., Slangen, A. B. A., et al. (2023). The framework for assessing changes to sea-level (FACTS) v1.0-rc: A platform for characterizing parametric and structural uncertainty in future global, relative, and extreme sea-level change [preprint]. EGUsphere. https://doi.org/10.5194/egusphere-2023-14

Kostov, Y., Ferreira, D., Armour, K. C., & Marshall, J. (2018). Contributions of greenhouse gas forcing and the southern annular mode to historical Southern Ocean surface temperature trends. *Geophysical Research Letters*, *45*(2), 1086–1097. https://doi.org/10.1002/2017gl074964

Kostov, Y., Marshall, J., Hausmann, U., Armour, K. C., Ferreira, D., & Holland, M. M. (2017). Fast and slow responses of Southern Ocean sea surface temperature to SAM in coupled climate models. *Climate Dynamics*, *48*(5–6), 1595–1609. https://doi.org/10.1007/s00382-016-3162-z

LeGrande, A. N., Schmidt, G. A., Shindell, D. T., Field, C., Miller, R. L., Koch, D., et al. (2006). Consistent simulations of multiple proxy responses to an abrupt climate change event. *Proceedings of the National Academy of Sciences*, *103*(4), 837–842. https://doi.org/10.1073/pnas.0510095103

Li, Q., England, M. H., Hogg, A. M. C., Rintoul, S. R., & Morrison, A. K. (2023). Abyssal ocean overturning slowdown and warming driven by Antarctic meltwater. *Nature*, *615*(7954), 841–847. https://doi.org/10.1038/s41586-023-05762-w

Li, Q., Marshall, J., Rye, C. D., Romanou, A., Rind, D., & Kelley, M. (2023). Global climate impacts of Greenland and Antarctic meltwater: A comparative study. *Journal of Climate*, *36*(11), 3571–3590. https://doi.org/10.1175/jcli-d-22-0433.1

Little, C. M., Oppenheimer, M., Alley, R. B., Balaji, V., Clarke, G. K. C., Delworth, T. L., et al. (2007). Toward a new generation of ice sheet models. *Eos, Transactions American Geophysical Union*, *88*(52), 578–579. https://doi.org/10.1029/2007eo520002

Manabe, S., & Stouffer, R. J. (1993). Century scale effects of increased atmospheric CO_2 on the ocean atmosphere system. *Nature*, *364*(6434), 215–218. https://doi.org/10.1038/364215a0

Manabe, S., & Stouffer, R. J. (1995). Simulation of abrupt climate change induced by freshwater input to the North Atlantic Ocean. *Nature*, *378*(6553), 165–167. https://doi.org/10.1038/378165a0

Mankoff, K. D. (2023). Anomalous Freshwater from Greenland and Antarctica (1990–2019) [Dataset]. NASA Center for Climate Simulation. Retrieved from https://portal.nccs.nasa.gov/datashare/GISS_modelE/modelE_input_data/fw_anom/v1.0/

Mankoff, K. D., Fettweis, X., Langen, P. L., Stendel, M., Kjeldsen, K. K., Karlsson, N. B., et al. (2021). Greenland ice sheet mass balance from 1840 through next week. *Earth System Science Data*, *13*(10), 5001–5025. https://doi.org/10.5194/essd-13-5001-2021

Mankoff, K. D., Fettweis, X., Stendel, M., Noël, B., & Solgaard, A. (2021). Greenland ice mass balance from from 1840 through next week [Dataset]. GEUS Dataverse. Retrieved from https://dataverse01.geus.dk/dataverse/mass_balance

Meehl, G. A., Arblaster, J. M., Bitz, C. M., Chung, C. T. Y., & Teng, H. (2016). Antarctic sea-ice expansion between 2000 and 2014 driven by tropical Pacific decadal climate variability. *Nature Geoscience*, *9*(8), 590–595. https://doi.org/10.1038/ngeo2751

Meier, W. N., Fetterer, F., Windnagel, A. K., & Stewart, J. S. (2021). NOAA/NSIDC climate data record of passive microwave sea ice concentration [Dataset]. National Snow and Ice Data Center. https://doi.org/10.7265/efmz-2t65

Meier, W. N., Peng, G., Scott, D. J., & Savoie, M. H. (2014). Verification of a new NOAA/NSIDC passive microwave sea-ice concentration climate record. *Polar Research*, *33*(1), 21004. https://doi.org/10.3402/polar.v33.21004

Miller, R. L., Schmidt, G. A., Nazarenko, L. S., Bauer, S. E., Kelley, M., Ruedy, R., et al. (2021). CMIP6 historical simulations (1850–2014) with GISS-E2.1. *Journal of Advances in Modeling Earth Systems*, *13*(1), e2019MS002034. https://doi.org/10.1029/2019ms002034

Miller, R. L., Schmidt, G. A., & Shindell, D. T. (2006). Forced annular variations in the 20th century Intergovernmental Panel on Climate Change Fourth Assessment Report models. *Journal of Geophysical Research*, *111*(D18), D18101. https://doi.org/10.1029/2005JD006323

Nazarenko, L. S., Tausnev, N., Russell, G. L., Rind, D., Miller, R. L., Schmidt, G. A., et al. (2022). Future climate change under SSP emission scenarios with GISS-E2.1. *Journal of Advances in Modeling Earth Systems*, *14*(7), e2021MS002871. https://doi.org/10.1029/2021ms002871

Noerdlinger, P. D., & Brower, K. R. (2007). The melting of floating ice raises the ocean level. *Geophysical Journal International*, *170*(1), 145–150. https://doi.org/10.1111/j.1365-246x.2007.03472.x

Orihuela-Pinto, B., England, M. H., & Taschetto, A. S. (2022). Interbasin and interhemispheric impacts of a collapsed Atlantic Overturning Circulation. *Nature Climate Change*, *12*(6), 558–565. In press. https://doi.org/10.1038/s41558-022-01380-y

Pauling, A. G., Bitz, C. M., Smith, I. J., & Langhorne, P. J. (2016). The response of the Southern Ocean and Antarctic sea ice to freshwater from ice shelves in an Earth System Model. *Journal of Climate*, *29*(5), 1655–1672. https://doi.org/10.1175/jcli-d-15-0501.1

Purich, A., & England, M. H. (2023). Projected impacts of Antarctic meltwater anomalies over the twenty-first century. *Journal of Climate*, *36*(8), 2703–2719. https://doi.org/10.1175/jcli-d-22-0457.1

Rackow, T., Danilov, S., Goessling, H. F., Hellmer, H. H., Sein, D. V., Semmler, T., et al. (2022). Delayed Antarctic sea-ice decline in high-resolution climate change simulations. *Nature Communications*, *13*(1), 637. https://doi.org/10.1038/s41467-022-28259-y

Ribes, A., Qasmi, S., & Gillett, N. P. (2021). Making climate projections conditional on historical observations. *Science Advances*, *7*(4), eabc0671. https://doi.org/10.1126/sciadv.abc0671

Rignot, E., Casassa, G., Gogineni, P., Krabill, W., Rivera, A., & Thomas, R. (2004). Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf. *Geophysical Research Letters*, *31*(18), L18401. https://doi.org/10.1029/2004gl020697

Rind, D., Demenocal, P., Russell, G. L., Sheth, S., Collins, D., Schmidt, G. A., & Teller, J. (2001). Effects of glacial meltwater in the GISS Coupled Atmosphere-Ocean Model: Part I: North Atlantic Deep Water response. *Journal of Geophysical Research*, *106*, 27335–27354.

Roach, L. A., Dörr, J., Holmes, C. R., Massonnet, F., Blockley, E. W., Notz, D., et al. (2020). Antarctic sea ice area in CMIP6. *Geophysical Research Letters*, *47*(9), e2019GL086729. https://doi.org/10.1029/2019gl086729

Roach, L. A., Mankoff, K. D., Romanou, A., Blanchard-Wrigglesworth, E., Haine, T. W. N., & Schmidt, G. A. (2023). Winds and meltwater together lead to Southern Ocean surface cooling and sea ice expansion. *Geophysical Research Letters*. (in press). https://doi.org/10.1029/2023gl105948

Rye, C. D., Marshall, J., Kelley, M., Russell, G., Nazarenko, L. S., Kostov, Y., et al. (2020). Antarctic glacial melt as a driver of recent Southern Ocean climate trends. *Geophysical Research Letters*, *47*(11), e2019GL086892. https://doi.org/10.1029/2019gl086892

Sadai, S., Condron, A., DeConto, R., & Pollard, D. (2020). Future climate response to Antarctic ice sheet melt caused by anthropogenic warming. *Science Advances*, *6*(39), eaaz1169. https://doi.org/10.1126/sciadv.aaz1169

Santer, B. D., Thorne, P. W., Haimberger, L., Taylor, K. E., Wigley, T. M. L., Lanzante, J. R., et al. (2008). Consistency of modelled and observed temperature trends in the tropical troposphere. *International Journal of Climatology*, *28*(13), 1703–1722. https://doi.org/10.1002/joc.1756

Scambos, T. A., Bohlander, J. A., Shuman, C. A., & Skvarca, P. (2004). Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica. *Geophysical Research Letters*, *31*(18), L18402. https://doi.org/10.1029/2004gl020670

Schmidt, G. A., Jones, G. S., & Kennedy, J. J. (2023). Comment on "Advanced testing of low, medium, and high ECS CMIP6 GCM simulations versus ERA5-T2m" by N. Scafetta (2022). *Geophysical Research Letters*, *50*(18), e2022GL097716. https://doi.org/10.1029/2022GL102530

Schmidt, G. A., Kelley, M., Nazarenko, L., Ruedy, R., Russell, G. L., Aleinov, I., et al. (2014). Configuration and assessment of the GISS ModelE2 contributions to the CMIP5 archive. *Journal of Advances in Modeling Earth Systems*, *6*(1), 141–184. https://doi.org/10.1002/2013MS000265

Seidov, D., Barron, E., & Haupt, B. J. (2001). Meltwater and the global ocean conveyor: Northern versus southern connections. *Global and Planetary Change*, *30*(3–4), 257–270. https://doi.org/10.1016/s0921-8181(00)00087-4

Seroussi, H., Nowicki, S., Payne, A. J., Goelzer, H., Lipscomb, W. H., Abe-Ouchi, A., et al. (2020). ISMIP6 Antarctica: A multi-model ensemble of the Antarctic ice sheet evolution over the 21st century. *The Cryosphere*, *14*(9), 3033–3070. https://doi.org/10.5194/tc-14-3033-2020

Sherwood, S. C., Webb, M. J., Annan, J. D., Armour, K. C., Forster, P. M., Hargreaves, J. C., et al. (2020). An assessment of earth's climate sensitivity using multiple lines of evidence. *Reviews of Geophysics*, *58*(4), e2019RG000678. https://doi.org/10.1029/2019RG000678

Singh, H. A., Polvani, L. M., & Rasch, P. J. (2019). Antarctic sea ice expansion, driven by internal variability, in the presence of increasing atmospheric CO_2. *Geophysical Research Letters*, *46*(24), 14762–14771. https://doi.org/10.1029/2019gl083758

Slater, T., Lawrence, I., Otosaka, I., Shepherd, A., Gourmelen, N., Jakob, L., et al. (2023). Dataset for "Review article: Earth's ice imbalance" [Dataset]. Zenodo. (v1). https://doi.org/10.5281/ZENODO.7612514

Slater, T., Lawrence, I. R., Otosaka, I. N., Shepherd, A., Gourmelen, N., Jakob, L., et al. (2021). Review article: Earth's ice imbalance. *The Cryosphere*, *15*(1), 233–246. https://doi.org/10.5194/tc-15-233-2021

Stammer, D. (2008). Response of the global ocean to Greenland and Antarctic ice melting. *Journal of Geophysical Research*, *113*(C6), C06022. https://doi.org/10.1029/2006jc004079

Stouffer, R. J., Seidov, D., & Haupt, B. J. (2007). Climate response to external sources of freshwater: North Atlantic versus the Southern Ocean. *Journal of Climate*, *20*(3), 436–448. https://doi.org/10.1175/jcli4015.1

Swart, N., Martin, T., Beadling, R., Chen, J.-J., England, M. H., Farneti, R., et al. (2023). The Southern Ocean Freshwater release model experiments Initiative (SOFIA): Scientific objectives and experimental design. *EGUsphere*. https://doi.org/10.5194/egusphere-2023-198

Szekely, T., Gourrion, J., Pouliquen, S., & Reverdin, G. (2019). The CORA 5.2 dataset for global in situ temperature and salinity measurements: Data description and validation. *Ocean Science*, *15*(6), 1601–1614. https://doi.org/10.5194/os-15-1601-2019

Szekely, T., Gourrion, J., Pouliquen, S., & Reverdin, G. (2023). Global Ocean-Delayed Mode gridded CORA: In-situ Observations objective analysis in Delayed Mode [Dataset]. E.U. Copernicus Marine Service Information. (v5.2). https://doi.org/10.17882/4621

Thomas, M., Ridley, J. K., Smith, I. J., Stevens, D. P., Holland, P. R., & Mackie, S. (2023). Future response of Antarctic continental shelf temperatures to ice shelf basal melting and calving. *Geophysical Research Letters*, *50*(18), e2022GL102101. https://doi.org/10.1029/2022GL102101

Tokarska, K. B., Stolpe, M. B., Sippel, S., Fischer, E. M., Smith, C. J., Lehner, F., & Knutti, R. (2020). Past warming trend constrains future warming in CMIP6 models. *Science Advances*, *6*(12), eaaz9549. https://doi.org/10.1126/sciadv.aaz9549

Velicogna, I., Mohajerani, Y., Landerer, F., Mouginot, J., Noel, B., Rignot, E., et al. (2020). Continuity of ice sheet mass loss in Greenland and Antarctica from the GRACE and GRACE Follow-On missions. *Geophysical Research Letters*, *47*(8), e2020GL087291. https://doi.org/10.1029/2020gl087291

Watkins, M. M., Wiese, D. N., Yuan, D.-N., Boening, C., & Landerer, F. W. (2015). Improved methods for observing earth's time variable mass distribution with GRACE using spherical cap mascons. *Journal of Geophysical Research: Solid Earth*, *120*(4), 2648–2671. https://doi.org/10.1002/2014jb011547

Wills, R. C. J., Dong, Y., Proistosecu, C., Armour, K. C., & Battisti, D. S. (2022). Systematic climate model biases in the large-scale patterns of recent sea-surface temperature and sea-level pressure change. *Geophysical Research Letters*, *49*(17), e2022GL100011. https://doi.org/10.1029/2022GL100011

Yeager, S. G., Chang, P., Danabasoglu, G., Rosenbloom, N., Zhang, Q., Castruccio, F. S., et al. (2023). Reduced Southern Ocean warming enhances global skill and signal-to-noise in an eddy-resolving decadal prediction system. *npj Climate and Atmospheric Science*, *6*(1), 107. https://doi.org/10.1038/s41612-023-00434-y

Zhang, L., Delworth, T. L., Cooke, W., & Yang, X. (2018). Natural variability of Southern Ocean convection as a driver of observed climate trends. *Nature Climate Change*, *9*(1), 59–65. https://doi.org/10.1038/s41558-018-0350-3

Zhang, X., Deser, C., & Sun, L. (2021). Is there a tropical response to recent observed Southern Ocean cooling? *Geophysical Research Letters*, *48*(5), e2020GL091235. https://doi.org/10.1029/2020gl091235