Geophysical Research Letters

Key Points:
- Earth system model projections do not capture recent Southern Ocean climate trends
- The inclusion of plausible discharges of Antarctic meltwater provides a closer match to observations
- Results suggest interactive ice sheets should be included in model projections

Antarctic Glacial Melt as a Driver of Recent Southern Ocean Climate Trends

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Abstract Recent trends in Southern Ocean (SO) climate—of surface cooling, freshening, and sea ice expansion—are not captured in historical climate simulations. Here we demonstrate that the addition of a plausible increase in Antarctic meltwater to a coupled climate model can produce a closer match to a wide range of climate trends. We use an ensemble of simulations of the Goddard Institute for Space Studies Earth system model to compute "climate response functions" (CRFs) for the addition of meltwater. These imply a cooling and freshening of the SO, an expansion of sea ice, and an increase in steric height, all consistent with observations since 1992. The CRF framework allows one to compare the efficacy of Antarctic meltwater as a driver of SO climate trends, relative to greenhouse gas and surface wind forcing. The meltwater CRFs presented here strongly suggest that interactive Antarctic ice melt should be included in climate models.

Plain Language Summary Climate models do not capture recent Southern Ocean (SO) climate trends of surface cooling, freshening, and sea ice expansion. Here we demonstrate that including a realistic increase in Antarctic meltwater can improve a model's representation of SO trends. We use an ensemble of simulations of the Goddard Institute for Space Studies Earth system model. Model results suggest that Antarctic meltwater drives a cooling and freshening of the SO and an expansion of winter sea ice, all consistent with observations. Results suggest that a better representation of Antarctic ice melt should be included in climate models.

1. Introduction

Observed and modeled decadal trends in Southern Ocean (SO) sea surface temperature (SST) and sea surface salinity (SSS) shown in Figure 1 reveal marked discrepancies: At the surface the models are ~0.12 °C per decade warmer and ~0.03 PSU per decade saltier than observations during the period 1992–2014. Over the same period, models express around 4 km^2 per decade less Antarctic winter sea ice then observations, which show a small (2.4 km^2 per decade) increase (Comiso et al., 2017; Zwally et al., 2002), and Antarctic Subpolar sea surface height (SSH) has elevated by around 1 cm per decade above the SO rate (Rye et al., 2014). Hindcasting such trends in a consistent way is a difficult challenge and a notable deficiency of current coupled models used for climate change projections—see, for example, Wang et al. (2014) and Kostov et al. (2018).

Kostov et al. (2018) consider SO westerly wind forcing (as captured by the Southern Annular Mode, SAM, Marshall, 2003) and greenhouse gas (GHG) forcing as drivers of the observed SO SST cooling. They examine the sensitivity of SO SST in Coupled Model Intercomparison Project (Phase 5) (CMIP5) models to observed trends in SAM and GHG forcing by diagnosing wind and GHG climate response functions (CRFs) inferred from them. Linear convolution of the forcing with those CRFs implies an ensemble mean warming of 0.04 ± 0.01 °C per decade to GHG forcing and a cooling of 0.025 °C per decade to SAM forcing. This implies a net (SAM + GHG) *warming* of 0.015 °C per decade, across the 15 models considered, if GHG and winds were the only drivers. The observations (Figure 1), by contrast, reveal a *cooling* in excess of 0.05 °C per decade. Here we argue that the recent increase in Antarctic glacial melt (here referred to as the Antarctic Melt Anomaly, AAMA), although of uncertain magnitude, could induce such an additional cooling. Moreover, this cooling, and concomitant freshening, leads to sea ice growth around Antarctica and sea level rise in the Antarctic Subpolar ocean in broad agreement with observations (Comiso et al., 2017; Rye et al., 2014; Zwally et al., 2002).
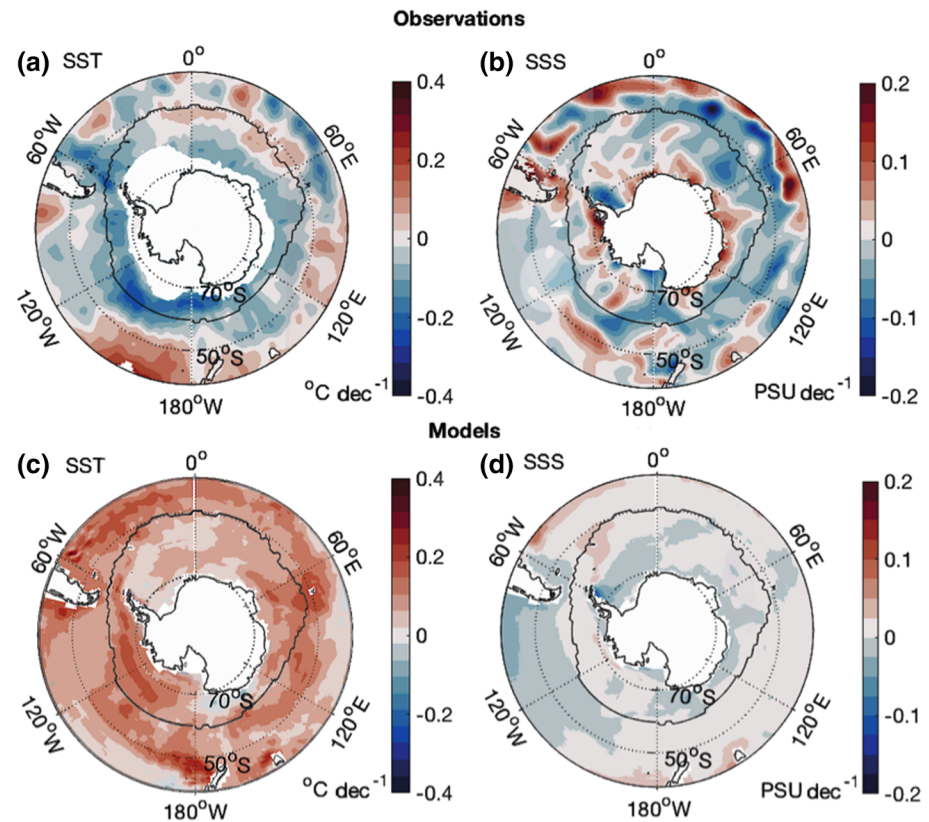
Figure 1. Simulated and observed trends in Southern Ocean surface properties 1990–2014. (a) Observed trend in SST (HadSST; Kennedy et al., 2019). (b) Observed trend in SSS (CORA5; Cabanes et al., 2013). (c) CMIP5 multimodel ensemble mean simulated trend in SST from the historical period 1990 to 2014. (d) CMIP5 multimodel ensemble mean simulated trend in SSS. The black contour denotes the extent of winter sea ice maximum in observations. Panels (c) and (d) show fields in which internal variability is smoothed by the multimodel ensemble mean. (a) In contrast, the observed fields, (a and b), contain internal variability.

CMIP5 Earth system models do not explicitly represent the increase in Antarctic glacial melt (AAMA) over recent decades. The Antarctic grounded ice sheet mass loss has increased to perhaps 250 Gt/yr in 2017 (Shepherd et al., 2018). The thinning and retreat of floating ice shelves are thought to have also contributed as much as 280 Gt/yr in recent years (2003–2015; Paolo et al., 2015). Furthermore, a series of large ice shelf retreats not included in the above estimates has contributed an additional flux of perhaps 210 Gt/yr over the period 1988 to 2008 (Shepherd et al., 2010).

A number of studies have recently explored the response of the SO to perturbations in Antarctic meltwater (AAMA) in a variety of coupled and ocean-only models (e.g., Bronselaer et al., 2018; Fogwill et al., 2015; Golledge et al., 2019; Hansen et al., 2016; Pauling et al., 2016; Rye et al., 2014). These suggest that the surface SO and subsurface Antarctic Subpolar Sea cool and warm respectively in response to an increase in AAMA. A number of studies have explored the response of Antarctic sea ice to an increase in AAMA with rather variable results. For example, Bintanja et al. (2013, 2015) find that an AAMA of around 180 Gt/yr is sufficient to reproduce the observed increase in sea ice between 1992 and 2015. In contrast, Pauling et al. (2016) suggest that a larger forcing of 3,000 Gt/yr is required. Pauling et al. (2017) find that an accelerating AAMA of 45 Gt/yr/yr up to 4,000 Gt/yr is sufficient to offset the decline in sea ice found in their model. Finally, Rye et al. (2014) highlight an anomalous trend in Antarctic subpolar SSH and finds that an AAMA of around 430 Gt/yr is sufficient to drive a steric height increase consistent with observations.

Here we use a novel CRF analysis to probe the role of AAMA in inducing recent climate trends in the SO, and its potency relative to other forcing such as GHG forcing and westerly wind trends. There is substantial uncertainty in the magnitude of the recent increase in AAMA; the CRF approach allows the response to any
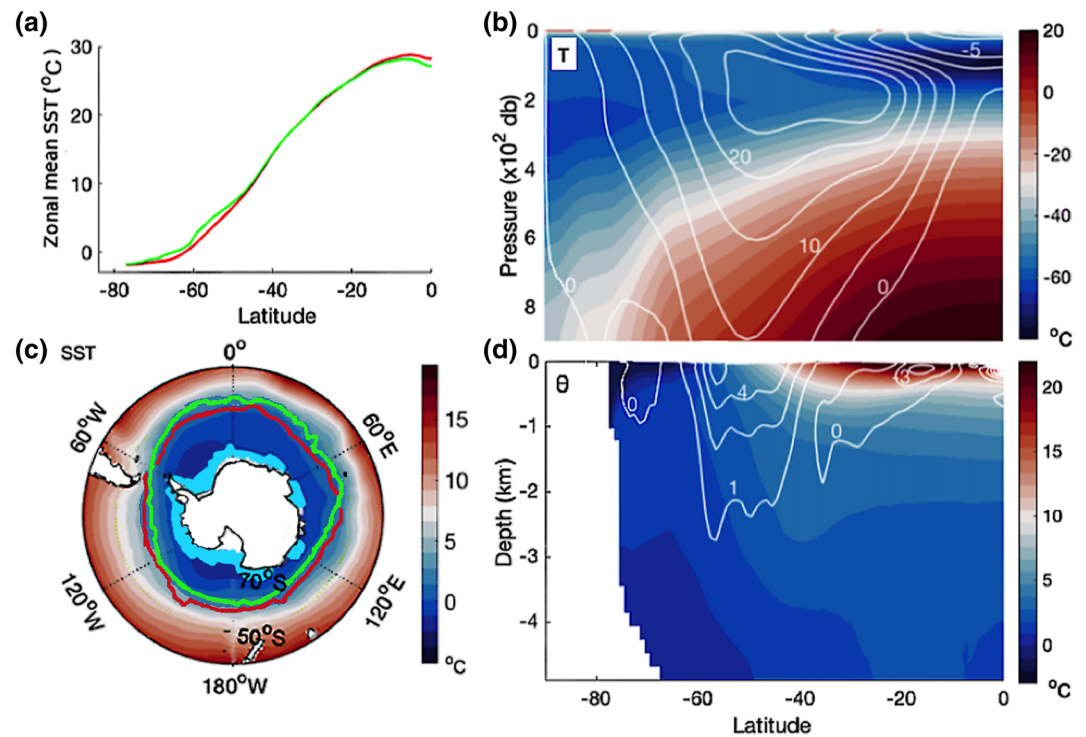
Figure 2. Southern Hemisphere Climatology of ModelE2.1-G. (a) Zonal mean Southern Ocean SST in observations (green) and from the model (red). (b) Modeled zonal mean atmospheric temperature. Contours denote the zonal mean zonal velocities (ms^{-1}). (c) Plan view of SST in the coupled model. The winter sea ice extent is denoted by contours, from observations (green) and the model (red). The light blue region surrounding Antarctica denotes the area where glacial meltwater is fluxed into the ocean. (d) Zonal mean potential temperature for the ocean. Contours denote zonal mean zonal velocities (cm/s).

chosen meltwater time history to be inferred, provided that the system response is linear. We conclude that glacial melt is likely an important missing component required to account for the magnitude and trend in all of the aforementioned climate signals and, in particular, it is consistent with the persistence of sea ice around Antarctica in a warming world.

2. Response of a Coupled Climate Model to Antarctic Glacial Melt

We utilize the Goddard Institute for Space Studies ModelE2.1-G Earth system model. The atmosphere and ocean components have a horizontal resolution of 2 × 2.5 and 1 × 1.25° with 40 vertical levels in pressure and mass, respectively. The preindustrial climatological state of the coupled model has an excellent climatology (Figure 2); details of the model can be found in the supporting information and Doddridge et al. (2019).

The response to a given scenario of AAMA is examined using ensemble perturbation experiments. Ensembles are created by initiating experiments at 50-year intervals from a long control run. The preindustrial state is perturbed by a 200 Gt/yr step change increase in glacial meltwater. The additional meltwater adds fresh, cold water (due to extraction of latent heat required to melt the ice) that is released in the upper 200 m of the ocean water column in a spatially uniform manner consistent with iceberg calving (Schmidt et al., 2014), indicated by Figure 2c. The perturbation experiments are run for 30 years with 20 ensemble members. Results are analyzed in terms of anomaly fields that are estimated by subtracting control runs from perturbation runs. Experimental design is described further in the supporting information.

Linear Convolution Theory (e.g., Kostov et al., 2018) allows one to construct the response for any given AAMA scenario, to the extent that the response is linear. Additional exploratory AAMA experiments suggest
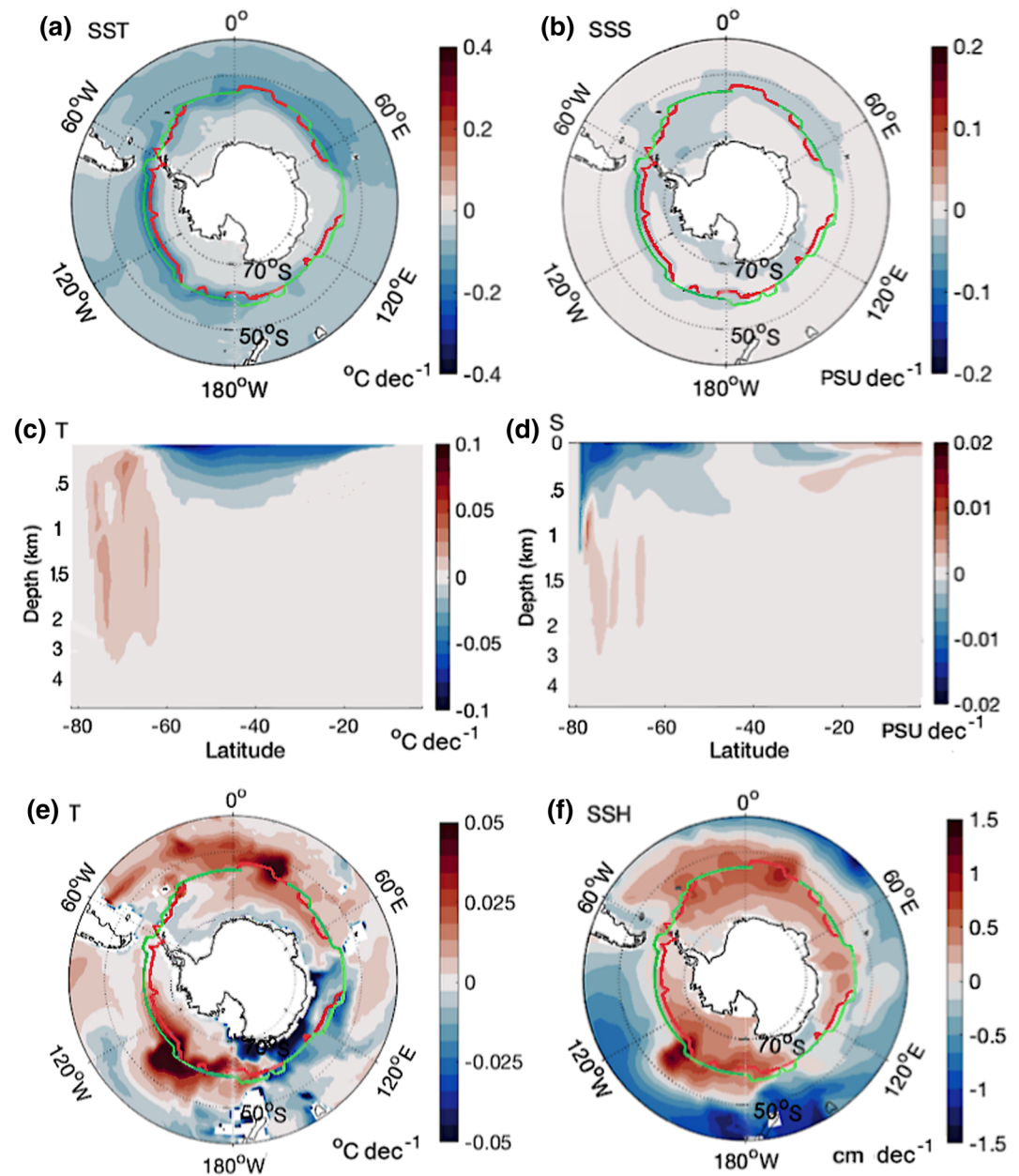
Figure 3. Modeled response to a 200 Gt/yr step change in AAMA. Decadal trends calculated over 30 year model runs from a 20-member ensemble in (a) SST, (b) SSS, (c) zonal-average potential temperature, (d) zonal-average salinity, (e) interior temperature, averaged between 500 and 3,000 m depths, and (f) SSH. Red and green contours denote the winter sea ice extent in the control run and after 30 years of perturbation experiment respectively.

that the response is linear for forcings below 1,000 Gt/yr; suggesting that contemporary climate change is in the linear regime.

The surface response of the model to a 200 Gt/yr step change in AAMA is shown in Figure 3. The meltwater induces a circumpolar band of cooling (0.03 °C per decade averaged 70–55°S) and freshening (0.004 PSU per decade averaged 70–55°S) together with an expansion of the winter sea ice extent (SIE; 1.2×10^5 km^2 per decade compared to an observed trend of around 2×10^5 km^2 per decade; Comiso et al., 2017). Cooling is concentrated around the northern extent of the winter sea ice. There is no trend under the sea ice where ice ocean fluxes keep the water near its freezing point.
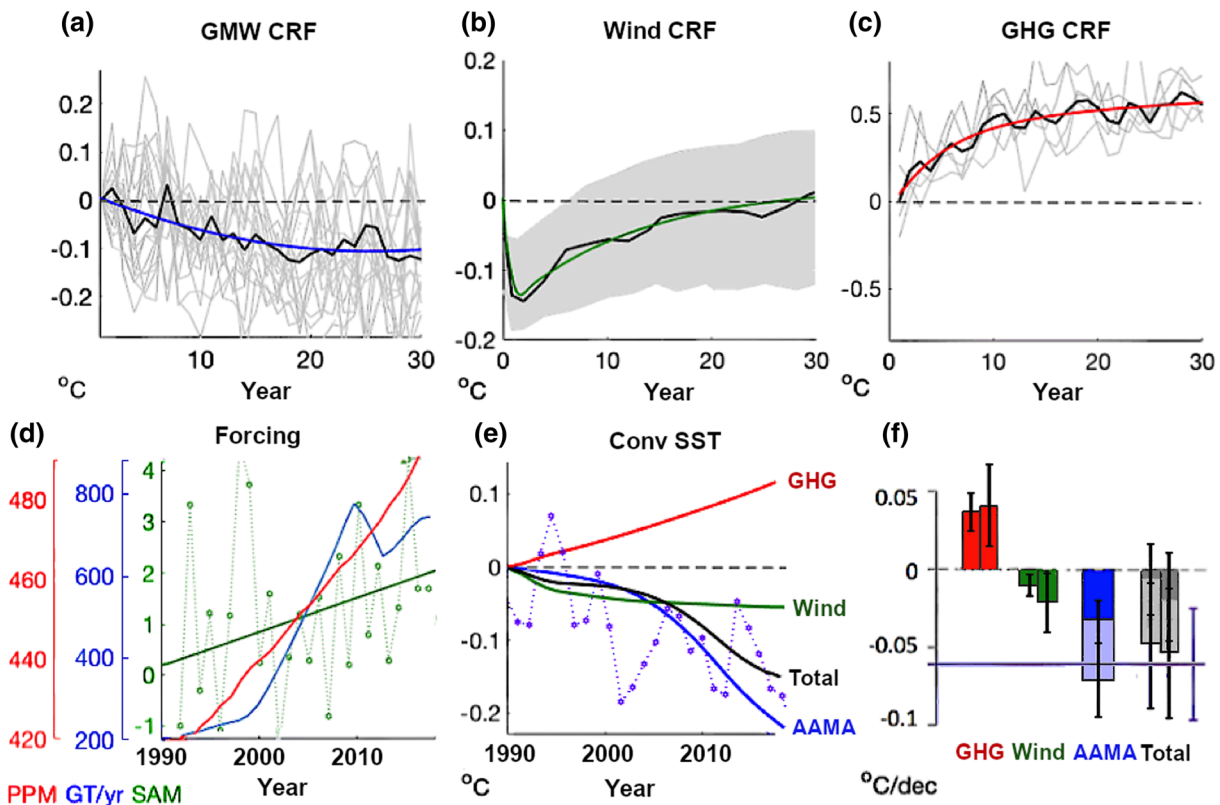
Figure 4. Linear convolution projections of Southern Ocean SST. ModelE Southern Ocean SST CRFs for (a) 200 Gt/yr step change in AAMA, (b) a 1-standard deviation step change in the Southern Annular mode (Doddridge et al., 2019). Gray area: CMIP-5 multimodel spread. (c) Double CO_2 forcing. In all plots: gray lines: Individual ensemble members. Black lines: ensemble means. Blue, green, and red lines: exponential fits. (d) Observed forcing histories. Red line: greenhouse gases (GHG; Butler et al., 1999). Blue line: combined AAMA (Shepherd et al., 2018; Paolo et al., 2015). Green line: Southern Annular Mode (SAM; Marshall, 2003). (e) The convolution of CRFs (a–c) with forcing histories (d). Red line: GHGs. Green line: SAM (wind). Blue line: AAMA. Black line: combined response. The purple dashed line and markers: observed Southern Ocean SST cooling (HadSST; Kennedy et al., 2019). (f) Summary of SST trends. Red bars: GHG. Green bars: SAM (wind). Blue bar: AAMA. Gray bars: Combined forcing. For GHG, wind and total, the left-side bar shows convolution results for ModelE and the right-side bar shows results for the CMIP-5 multimodel mean derived from Kostov et al. (2018) and Doddridge et al. (2019). For AAMA and total, the full bars denote convolutions for the time histories of grounded Antarctic mass loss anomaly; the shaded bars denote convolutions for the combined time history of grounded ice and floating ice shelves mass loss anomaly. The purple line: observed Southern Ocean cooling. Black whiskers: standard deviation.

In the upper 500 m, the water column cools and freshens between 70°S and 20°S. The upper 1,000 m of the shelf waters become fresher and the intermediate depth shelf waters slightly saltier. Between 50 and 3,000 m depths, Antarctic subpolar waters warm. The combined surface freshening and deep warming on the Antarctic Shelf produces a steric increase in SSH of 0.3 cm per decade. The sign and magnitude of these responses are broadly consistent with observed trends over the past decades (Comiso et al., 2017; Rye et al., 2014; Zwally et al., 2002).

3. Glacial Melt Response Functions: Implications for Understanding the Historical Record

The 200 Gt/yr AAMA perturbation experiment is now used to compute SST CRFs in response to glacial melt by integrating the time evolution of the SST response over the circumpolar region, 55°S to 70°S. It is shown in Figure 4a and should be compared to wind- and GHG-induced SST CRFs in Figures 4b and 4c, respectively, evaluated over the same area. The wind CRF from ModelE was obtained by computing lagged regressions between SAM and SST from a long control run (as described in Kostov et al., 2018) and—somewhat equivalently—by computing ozone-hole CRFs, which strongly project on to SAM (Doddridge et al., 2019). The GHG CRF of ModelE was computed by carrying out instantaneous 2xCO2 experiments, a common method of assessing and comparing the response of climate models to GHG perturbations.

In response to AAMA, SO SST decays over the first twenty years to reach a cooler equilibrium temperature. As suggested by, for example, Rintoul et al. (2001), fresh glacial melt is rapidly dispersed northward in the wind-driven Ekman layer and by the northward currents on the western edges of the Ross and Weddell gyres before it is carried eastward in the swiftly flowing surface expression of the Antarctic Circumpolar Current. The surface becomes more stably stratified, the mixed layers slightly shallower and thus, because of the pronounced temperature inversion typical of waters adjacent to Antarctica, colder water is brought to the surface. This cooling is very different from, and should be contrasted to, that induced by winds, shown in Figure 4b. This exhibits a two-timescale response discussed at length in Marshall et al. (2014), Ferreira et al. (2015), and Doddridge et al. (2019): a rapid, Ekman-driven initial cooling followed by a (much) slower warming tendency due to the upwelling of warm water from below. The GHG CRF is shown in Figure 4c and is a mirror image of the AAMA response, but with the familiar warming signal rising toward an equilibrium on timescales of 30 years. GHG forcing is understood to drive a change in the SAM; however, this is sufficiently small that it can be neglected (see the discussion in Kostov et al., 2018).

Having computed CRFs for these three key drivers of Antarctic climate change, we convolve them (equation (S1) in the supporting information) with historical time series of AAMA, SAM and GHG forcing (shown in Figure 4d). Here, the time series in AAMA is constructed from the combination of grounded ice melt (Shepherd et al., 2018), floating ice shelf melt (Paolo et al., 2015) and the breakup of floating ice shelves (Shepherd et al., 2010). AAMA from ice shelf melt and ice shelf calving after 2008 and 2012 respectively are assumed to continue at their preceding 10-year average rate. Results are given in Figures 4e and 4f. GHG forcing produces an almost linear trend in SO SST of around 0.04 °C per decade. The recent trend in SAM produces a small SO SST cooling of around 0.02 °C per decade. Finally, the combined Antarctic Glacial Melt Anomaly (AAMA) from the grounded ice sheet and floating ice shelves produces a cooling of around -0.07 ± 0.04 °C per decade. The combined response of GHG, SAM, and AAMA leads to an overall cooling of -0.05 ± 0.05 °C per decade that offsets the GHG-driven warming and provides the majority of the observed cooling trend between 1990 and present.

The 200 Gt/yr perturbation experiment can be used to compute CRFs for SSS, SIE, and SSH by integrating those quantities over the circumpolar region and plotting them as a function of time. They are shown in Figures 5a–5c along with Linear Convolution Theory projections for the recent time history of AAMA (Figures 5d and 5e). In response to the recent time history of AAMA, the modelE SIE and Antarctic SSH increase by 3 $\times 10^5$ km^2 per decade and 7 mm per decade, respectively, over 30 years. The response of SSS, SIE, and SSH is in broad agreement with observations (see, e.g., Cabanes et al., 2013, Rayner et al., 2003, Rye et al., 2014). The majority of the surface adjustment occurs in the initial 20 years.

4. Discussion and Conclusions

It is difficult to account for observed recent decadal trends in SST and SIE if one only invokes GHG and wind forcing. Most coupled climate models are unable to capture these trends. Here we have shown that including AAMA in GISS ModelE has a significant impact on the SO properties and may account for the majority of the observed cooling. That said, there is a large uncertainty in the current rate and future projections of Antarctic meltwater flux and there is a large spread in the response of models to a meltwater pulse. Furthermore, the Antarctic subpolar climate is highly challenging to represent in Earth system models and the root cause of large structural uncertainty. However, our results highlight the importance of quantifying the rates of glacial melt and improving the representation of those processes that govern the response of the polar climate to such perturbations.

Including AAMA in ModelE is also shown to drive an increase in SIE that can account for the majority (60%) of the difference between ModelE simulations and observations over recent decades. The ModelE2.1 (10 member) ensemble mean driven by historical GHG forcing expresses an Antarctic winter SIE decline of -2.0×10^5 km^2 per decade (1990–2015). Over the same period, the observed winter SIE increases by around 2.4×10^5 km^2 per decade (Comiso et al., 2017) and AAMA modelE runs convolved with historical forcing grow SIE by around 3×10^5 km^2 per decade. However, the decadal increase in AAMA (1990–2019) is not able to account for the rapid decline in SIE since 2015 (2015–2019). It is therefore likely that other forcing
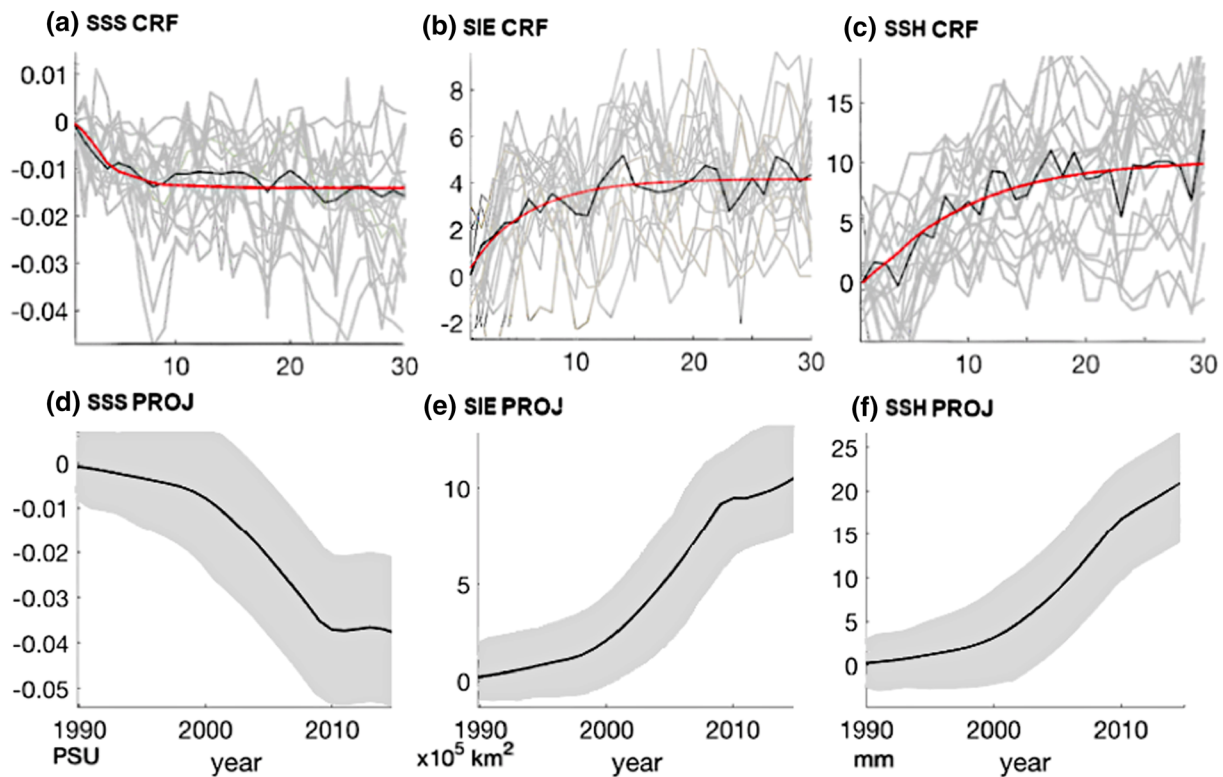
Figure 5. Southern Ocean climate response functions. ModelE CRFs for a 200 Gt/yr step change in Antarctic glacial melt. Gray lines: individual ensemble members. Black line: ensemble mean. Red lines: exponential or linear fit to ensemble mean. (a) Sea surface salinity averaged over 55°S to 70°S. (b) Winter sea ice extent. (c) Antarctic Subpolar Sea sea surface height averaged between the continent and 70°S. (d–f) convolutions of CRFs (a–c) with AAMA forcing shown in Figure 4d. (d) Response of Southern Ocean SSS. (e) Response of Southern Ocean SIE. (f) Response of Antarctic Subpolar Sea SSH.

mechanisms, such as wind variability (Doddridge & Marshall, 2017; Holland & Kwok, 2012) are also playing an important role.

Introduction of glacial meltwater simultaneously improves multiple SO trends consistent with observations (particularly in SST, SIE, and SSH). Moreover, the sense of the response of the SO climate to AAMA in models is broadly consistent across studies. For example, AAMA-driven SO SST cooling is found by Stouffer et al. (2007), Bintanja et al. (2013), Hansen et al. (2016), Bronselaer et al. (2018), Park and Latif (2018), and Golledge et al. (2019). AAMA-driven SO SIE expansion is found by Aiken and England (2008), Bintanja et al. (2013), Bintanja et al. (2015), Pauling et al. (2016), and Merino et al. (2018); finally, AAMA-driven Subpolar Sea SSH anomaly is found by Rye et al. (2014) and Merino et al. (2018). It is notable that the above modeling studies do not emphasize melt water flux associated with floating ice shelves and from the large ice shelve retreats discussed by Paolo et al. (2015) and Shepherd et al. (2010), respectively.

Although the sense of climate trends induced by Antarctic glacial melt appears to be broadly consistent across models, there is a wide spread in the magnitude of the response, particularly in respect of sea ice. For example, the work of Bintanja et al. (2013) found that an AAMA of 180 Gt/yr is sufficient to produce a small positive trend in sea ice, consistent with observations. In contrast, Pauling et al. (2016) argue that even large AAMA forcings of, for example, 2,000 Gt/yr are insufficient to account for the recent trend in sea ice expansion. The work of Zhang et al. (2019) suggests that differences between models may be associated with their ability to capture a conjectured natural cycle in SO convection, or due to intermodel differences in SO precipitation. Clearly, more work is required to explore the causes of these intermodel differences.

Finally, it should be said that in addition to meltwater, there are multiple other SO freshwater sources that complicate our discussion. For example, changes in precipitation are difficult to account for. Multiple

reanalysis data sets suggest that there is no significant trend in SO precipitation over recent decades (Bromwich et al., 2011). The freshwater perturbation associated with a standard deviation in SO precipitation is at least an order of magnitude larger than that currently produced by the grounded ice sheet. Purich et al. (2018) consider the response of the SO to a precipitation anomaly and finds broadly consistent results, in which additional precipitation leads to surface circumpolar cooling and freshening. Furthermore, wind-driven sea ice variability (Doddridge & Marshall, 2017; Holland & Kwok, 2012) also creates regional salinity perturbations that are an order of magnitude larger than those resulting from AAMA (Abernathey et al., 2016).

We conclude that AAMA is a leading candidate for the "missing process" implied by Figure 1. The match to multiple SO trends in disparate quantities, none of which appear in the CMIP5 ensemble, is suggestive that AAMA is not only active, but may be dominant and thus should be incorporated into future projections. Constraining the exact magnitude of the melt water rate is challenging but we judge that a range of between 300 and 800 Gt/yr in recent years is most consistent with observations.

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