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Reduced Deep Convection and Bottom Water Formation Due To Antarctic Meltwater in a Multi-Model Ensemble

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Key Points:

- Antarctic meltwater substantially reduces the strength of simulated Southern Ocean deep convection in climate models
- The additional meltwater induces Antarctic Bottom Water warming and contraction, with dense water classes converting to lighter ones
- Differences in the magnitude of these responses between models can be partly attributed to their different base states

Supporting Information:

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

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Abstract The additional water from the Antarctic ice sheet and ice shelves due to climate-induced melt can impact ocean circulation and global climate. However, the major processes driving melt are not adequately represented in Coupled Model Intercomparison Project phase 6 (CMIP6) models. Here, we analyze a novel multi-model ensemble of CMIP6 models with consistent meltwater addition to examine the robustness of the modeled response to meltwater, which has not been possible in previous single-model studies. Antarctic meltwater addition induces a substantial weakening of open-ocean deep convection. Additionally, Antarctic Bottom Water warms, its volume contracts, and the sea surface cools. However, the magnitude of the reduction varies greatly across models, with differing anomalies correlated with their respective mean-state climatology, indicating the state-dependency of the climate response to meltwater. A better representation of the Southern Ocean mean state is necessary for narrowing the inter-model spread of response to Antarctic meltwater.

Plain Language Summary The melting of the Antarctic ice sheet and ice shelves can have significant impacts on ocean circulation and thermal structure, but current climate models do not fully capture these effects. In this study, we analyze seven climate models to understand how they respond to the addition of meltwater from Antarctica. We find that the presence of Antarctic meltwater leads to a significant weakening of deep convection in the open ocean. The meltwater also causes Antarctic Bottom Water to warm and its volume to decrease, while the sea surface cools and sea ice expands. However, the magnitude of the response to meltwater varies across models, suggesting that the mean-state conditions of the Southern Ocean play a role. A better representation of the mean state and the inclusion of Antarctic meltwater in climate models will help reduce uncertainties and improve our understanding of the impact of Antarctic meltwater on climate.

1. Introduction

Recent observations show that the Antarctic Ice Sheet (AIS) (Forsberg et al., 2017; IMBIE, 2018; Rignot et al., 2019) and ice shelves (Adusumilli et al., 2020; Paolo et al., 2015; Scheuchl et al., 2016) are currently losing mass, which models suggest is likely to accelerate in the coming years under high emission forcing (Deconto et al., 2021; Edwards et al., 2021; Seroussi et al., 2020). The resulting meltwater discharge into the ocean influences regional and global climate (Bronselaer et al., 2018; Dong et al., 2022; Fyke et al., 2018; Purich & England, 2023; Rye et al., 2020), and has the potential to feedback onto the rate of basal ice shelf melting (Bronselaer et al., 2018; Flexas et al., 2022; Golledge et al., 2019), although this feedback is uncertain (Beadling et al., 2022; Moorman et al., 2020). However, the time-evolving interactions between the AIS, ice shelves, and the ocean are not included in Coupled Model Intercomparison Project phases 5 and 6 models (CMIP5 and CMIP6; Taylor et al., 2012; Eyring et al., 2016; Siahaan et al., 2022). These models employ specified ice sheets, where excess water from the ice/snow layer over Antarctica is rerouted to the ocean as runoff when snow depth exceeds a certain threshold. In cases where ice shelf cavities are present, the melt rates do not evolve in time (Mathiot et al., 2017). The absence of ice sheet processes and ocean–ice interactions in coupled climate models excludes

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potential feedbacks from meltwater discharge on regional and global climate, representing an unaccounted-for uncertainty in historical simulations and future projections (Swart et al., 2023).

The formation and recirculation of Antarctic Bottom Water (AABW) plays a crucial role in regulating the global climate by redistributing heat and carbon between the surface and deep ocean. In the real ocean, AABW is primarily formed by the sinking of dense waters on the Antarctic continental shelves (Orsi et al., 1999) with occasional contributions from open-ocean deep convection (Cheon & Gordon, 2019; Killworth, 1983). However, in most CMIP5 and CMIP6 models, AABW is formed by open-ocean deep convection (deep convection hereafter) with a large inter-model spread in the location and area of deep convection (Heuzé, 2021; Heuzé et al., 2013; Mohrmann et al., 2021). Simulated bottom water properties and transport are influenced by deep convection (Heuzé, 2021), which could be impacted by climate change. CMIP5 results suggest that Southern Ocean (SO) surface freshening caused by an enhanced hydrological cycle in a warming climate leads to a reduction in deep convection (De Lavergne et al., 2014). Additional surface freshening enhances the stratification by making surface waters less dense and thus the water column less prone to deep convection. Idealized model experiments also show that Antarctic meltwater forcing reduces convective depth (Fogwill et al., 2015) and suppresses the production of AABW (Lago & England, 2019; Li et al., 2023; Tesdal et al., 2023).

It remains unclear how the different representation of deep convection across models would affect the response of the SO climate to Antarctic meltwater. Inconsistent Antarctic meltwater forcing, and differing model configurations used in previous studies makes it challenging to quantify the uncertainty associated with the climate effects of Antarctic meltwater (Swart et al., 2023). For example, some studies suggest that simulated Antarctic sea-ice trends are highly sensitive to small amounts of Antarctic meltwater (10–250 Gt yr^{-1}) (Bintanja et al., 2013, 2015), while others show less sensitivity to significantly larger amounts of Antarctic meltwater (950–4,000 Gt yr^{-1}) (Pauling et al., 2016, 2017; Swart & Fyfe, 2013). A consistent experimental design applied across a wide range of climate models can help us discern robust, and model-dependent uncertainties to the meltwater forcing.

In this study, we present the first results from the new Southern Ocean Freshwater Input from Antarctica (SOFIA; Swart et al., 2023). We investigate the impacts of Antarctic meltwater on deep convection and relevant climate variables in seven different climate models following a consistent experiment protocol. We also evaluate the influence of the mean-state representation of deep convection on the modeled responses. By assessing the consistency and differences of the modeled response, this study highlights the need to understand and incorporate the effects of meltwater in future climate projections and the importance of refining and improving the representation of the Southern Ocean in climate models.

2. Methods

2.1. Models and Experimental Design

This study makes use of recent output from a novel multi-model ensemble of a coordinated Antarctic meltwater experiment, designed by the Southern Ocean Freshwater Input from Antarctica (SOFIA; Swart et al., 2023). We investigate the SOFIA Tier-1 *antwater* experiment, which imposes a temporally uniform additional freshwater flux of 0.1 Sv (1 Sv = 3.154×10^4 Gt yr^{-1}) at the ocean surface in the grid cells adjacent to the Antarctic coast, while all other forcing is taken from the CMIP6 pre-industrial control experiment (*piControl*; Eyring et al., 2016). While the observed freshwater volume associated with Antarctic ice sheet and shelves melt over 2010s is 0.017 ± 0.006 Sv (509 ± 186 Gt yr^{-1}) (Slater et al., 2021), primarily through basal melting and iceberg calving, the experiment utilizes a relatively strong but plausible freshwater forcing that may be achieved by mid-21st century under a high emission scenario (Golledge et al., 2019). Such a coordinated experimental design allows us to quantify the model similarities and differences in the climate response to Antarctic ice sheet melt among different models. Additional details about the configurations and experimental protocol can be found in Swart et al. (2023).

The simulations were run for at least 100 years, and data from seven models are currently available: ACCESS-ESM1-5 (Ziehn et al., 2020), GFDL-ESM4 (Dunne et al., 2020), GFDL-CM4 (Held et al., 2019), HadGEM3-GC31-LL (Kuhlbrodt et al., 2018), CanESM5 (Swart et al., 2019), GISS-E2-1-G (Kelley et al., 2020), and NorESM2-MM (Seland et al., 2020). These models all participated in CMIP6 and use the same configuration as in CMIP6 for the SOFIA experiment. The *piControl* run is taken from the CMIP6 output on the Earth System Grid Federation (ESGF) archive, except for GISS-E2-1-G, where the *piControl* outputs were provided directly

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along with SOFIA simulations. We only use the first ensemble member for each model and analyze the first 500 years for *piControl* and the concurrent first 100 years of *antwater* to examine the response to meltwater input.

2.2. Model Output Analysis

The monthly-mean mixed layer depth (MLD) we use is the CMIP6 output variable *mlotst* (Griffies et al., 2016) defined with a density threshold of 0.125 kg m^{-3}. Despite the modeled MLD computed in this way often being deeper than observed (Heuzé, 2015, 2021), its relative change presumably provides a reasonable measure for our purpose of process investigation. The deep convection area is defined as the total surface area south of 55°S with MLD exceeding 2,000 m (De Lavergne et al., 2014). To measure the SO deep convection strength, we compute the deep-mixed volume (DMV) south of 55°S by multiplying the grid cell area by its MLD, and summing for cells with MLD exceeding 2,000 m (Brodeau & Koenigk, 2016; Heuzé, 2021). The ventilated volume of each depth range is calculated in the same way, but with 100-m MLD increments, for example, the volume at 100 m is the volume with MLD between 100 and 200 m. While we compare the *antwater* outputs with parallel 100-year *piControl* data, we use 500-year *piControl* data to assess the variability beyond the selected 100 years. To maintain equal sampling, we divide the 500-year *piControl* time series into five non-overlapping 100-year chunks (periods), each representing an ensemble realization. Then, we calculate the statistic of interest for each chunk and average the results over five chunks for the entire 500-year period. These statistical methods are justified based on the large-variability and different climatological states possible in the SO across the suite of models given SO deep-convection.

2.3. Observation-Based Reference Data

Observed temperature and salinity data from the World Ocean Atlas (WOA18; Boyer et al., 2018) are used to estimate the climatological mean state of water mass properties in the SO. The *piControl* simulations represent a quasi-equilibrium climate state under pre-industrial forcing, while the WOA18 (1955–2017) climatology provides the historical state accounting for a warming ocean, therefore the two data sets are not directly comparable. However, WOA18 can be used as a reference to contextualize our simulation and analysis results, and to better understand the potential impact of Antarctic meltwater on the SO.

To assess the simulation of deep convection in the SO, we utilize the monthly-mean MLD obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) OCEAN5 ocean analysis-reanalysis (ORAS5: Ocean Reanalysis System 5) spanning from 1958 to 2022, with a horizontal resolution of approximately 0.25° × 0.25° (Copernicus Climate Change Service). This MLD metric is defined as the depth where the average sea water density exceeds the surface density plus 0.03 kg m^{-3}. The use of lower density criteria in reanalysis may result in shallower MLD compared to the criteria of 0.125 kg m^{-3} used in CMIP6 (Heuzé, 2015). While the ORAS5 data set provides an estimate of the historical evolution of the ocean representing a different period to the *piControl* simulations, it remains a useful reference for our analysis.

3. Results

3.1. Meltwater-Induced Reduction in Deep Convection

To examine the spatial variability of deep convection in the SO given its reported differences in location and strength across models (Heuzé, 2021; Heuzé et al., 2013), we first analyzed the maximum MLD in each model's *piControl* simulation. Deep convection, indicated by black contours of 2,000 m MLD (Figure 1), primarily occurs in the Weddell Sea and Ross Sea, varying in areal extents across models (from 0.38×10^5 km^2 in CanESM5 to 28.93×10^5 km^2 in ACCESS-ESM1-5; Table S1 in Supporting Information S1). Our focus is on how the models respond to the meltwater perturbation, which allows us to concentrate on the physics related to external freshwater forcing. This approach also permits us to assess the role of the model's mean state, but the underlying causes of climatological differences are beyond the scope of this paper.

In response to meltwater forcing, the maximum MLD decreases in all models. The reduction can be up to 4,000 m (blue shading in Figure 1). These changes suggest a near-complete cessation of deep convection in those regions except ACCESS-ESM1-5. In most deep convection regions in ACCESS-ESM1-5, the maximum MLD still reaches the bottom in *antwater*. Notably, models ACCESS-ESM1-5 and HadGEM3-GC31-LL show a positive

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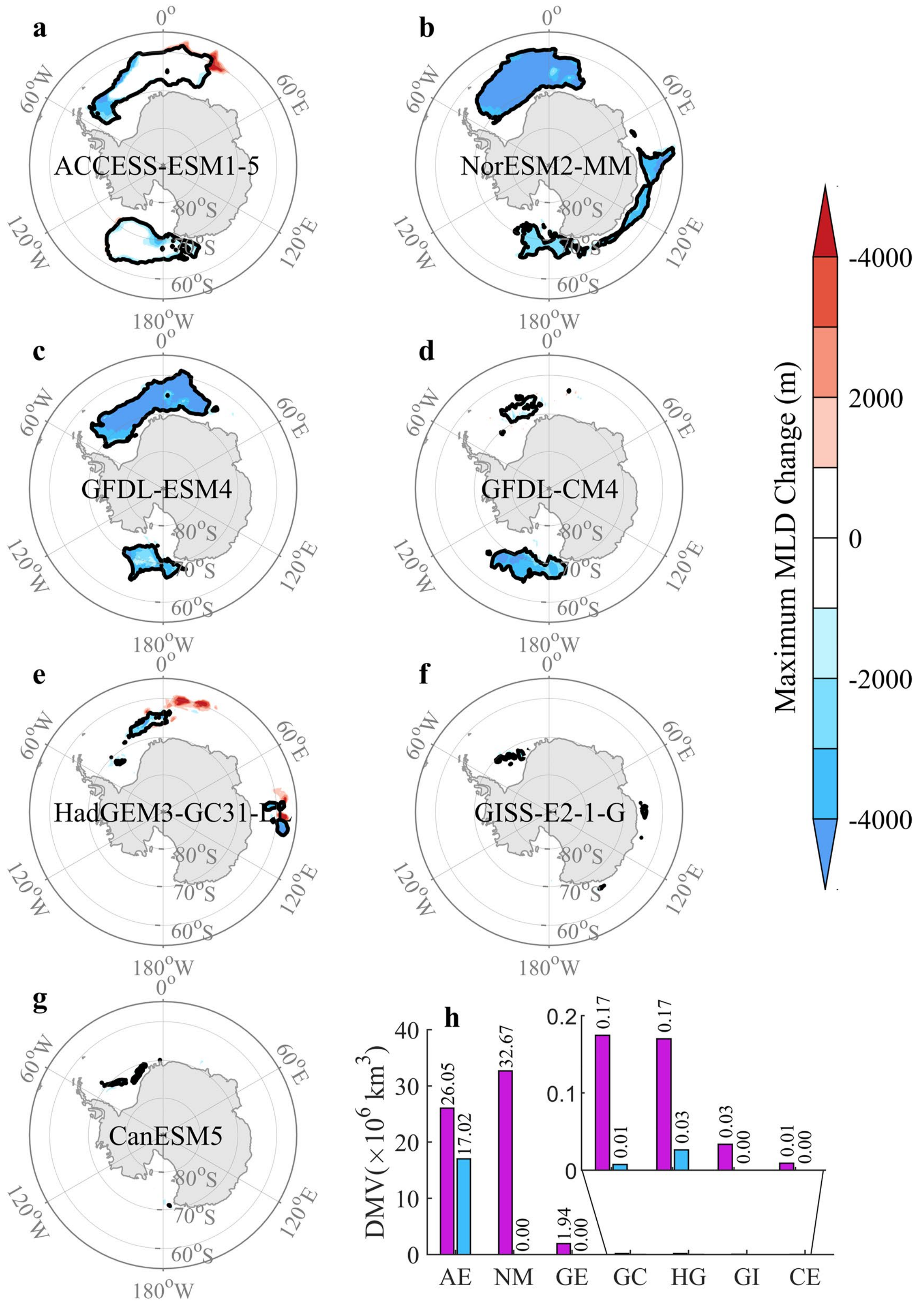

Figure 1. Response of Southern Ocean deep convection to meltwater. (a–g) Maximum mixed layer depth (MLD) change (shading; *antwater - picontrol*) south of 55°S across various models, each labeled in the center of its respective subplots. The black contour is 2,000 m of maximum MLD in *piControl*, delineating the location of deep convection. (h) Climatological annual deep mixed volume (DMV) south of 55°S for *piControl* (purple) and *antwater* (blue), with values at the top of each bar corresponding to models: ACCESS-ESM1-5 (AE), NorESM2-MM (NM), GFDL-ESM4 (GE), GFDL-CM4 (GC), HadGEM3-GC31-LL (HG), GISS-E2-1-G (GI), and CanESM5 (CE).

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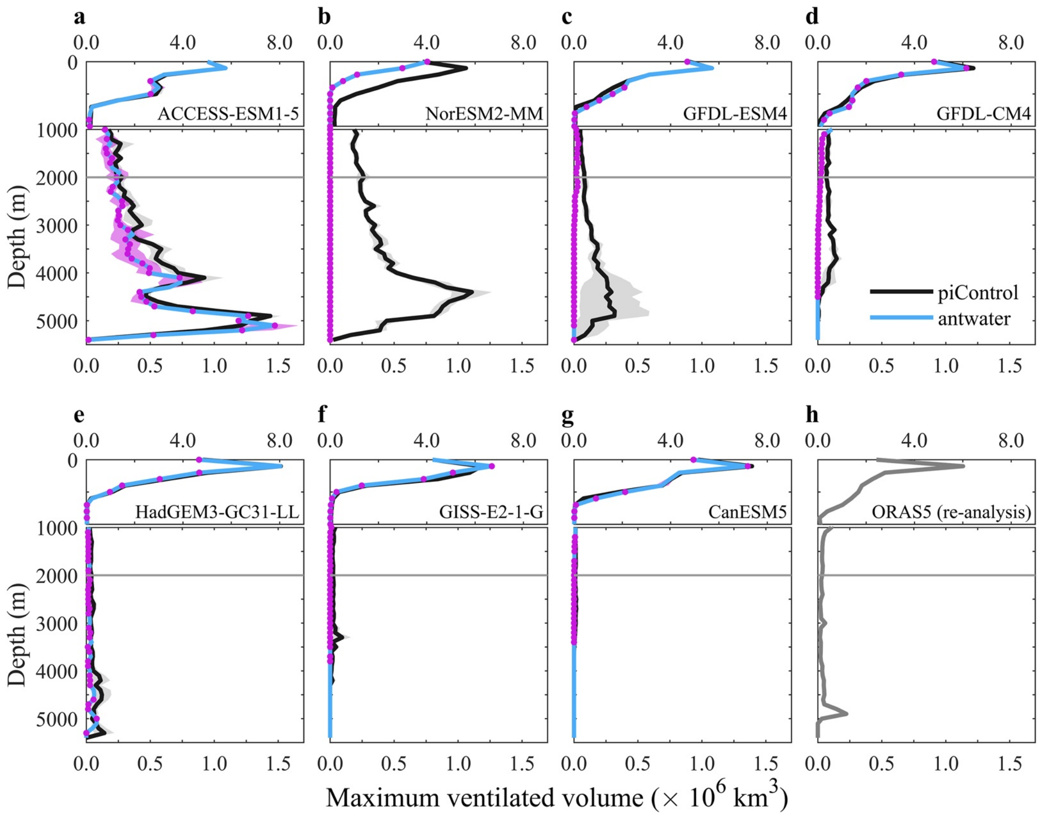

Figure 2. Vertical profiles of Southern Ocean convection: (a–g) Maximum ventilated volume in *piControl* (average, black; gray shading refers to one standard deviation) and in *antwater* (average, blue; purple dot where significant determined through a bootstrapping test, please refer to SI for details) across various models, each labeled within its respective subplots. For each column, the upper and lower panels represent the above 1,000 and 1,000–5,500 m depth ranges, respectively. Note that the horizontal and vertical scales changes between the upper ($0–9 \times 10^6$ km^3) and lower parts ($0–1.75 \times 10^6$ km^3) of each panel. (h) Maximum ventilated volume from ORAS5 re-analysis data over 1958–2022.

anomaly patch at the edge of the *piControl* deep convection region, possibly indicating a location shift of the deep convection. These findings indicate that meltwater forcing has a significant impact on the MLD and deep convection in the SO, but the response varies across models.

The maximum ventilated volume at each depth range provides a more detailed picture of how convective mixing responds to the meltwater forcing (Figure 2). All models exhibit a consistent vertical distribution in *piControl*, with relatively large volumes below 2,000 m and above 1,000 m, although the magnitudes differ among models. In *antwater*, all models, except ACCESS-ESM1-5, experience an extreme reduction in ventilated volume to nearly zero below 2,000 m, while the shallow (<500 m) mixed volume decreases by less than ∼30% or even increases at certain depths (Figure S1 in Supporting Information S1). This implies that the impact of the meltwater on the convective mixing varies with depth and is greater on deep ocean convection than on shallow mixing. Both ACCESS-ESM1-5 and NorESM2-MM have a significantly larger ventilated volume below 2,000 m in *piControl* compared to the other models and the re-analysis and display a larger change in response to meltwater. Averaged annual deep mixed volumes (DMV; Figure 1h) also exhibit substantial reduction to nearly zero in all models except ACCESS-ESM1-5, which still maintains strong deep convection. The magnitude of deep convection response has a high correlation with its mean-state value ($r^2 = 0.79$, $p < 0.01$). The additional freshwater further reduces the already low frequency of deep convection (Figure S2 in Supporting Information S1), with some models showing no occurrence for 100 consecutive years (Table S1 in Supporting Information S1). To account for potential sampling biases introduced by the meltwater simulations only performed for 100 years, and the long timescale variability of the SO, we conduct a bootstrapping test by randomly resampling 1,000 times from the *piControl* data (please refer to SI for details). The gray shading in Figure 2 represents the range of one standard deviation of the maximum ventilated volume obtained from the resampled data. The statistically

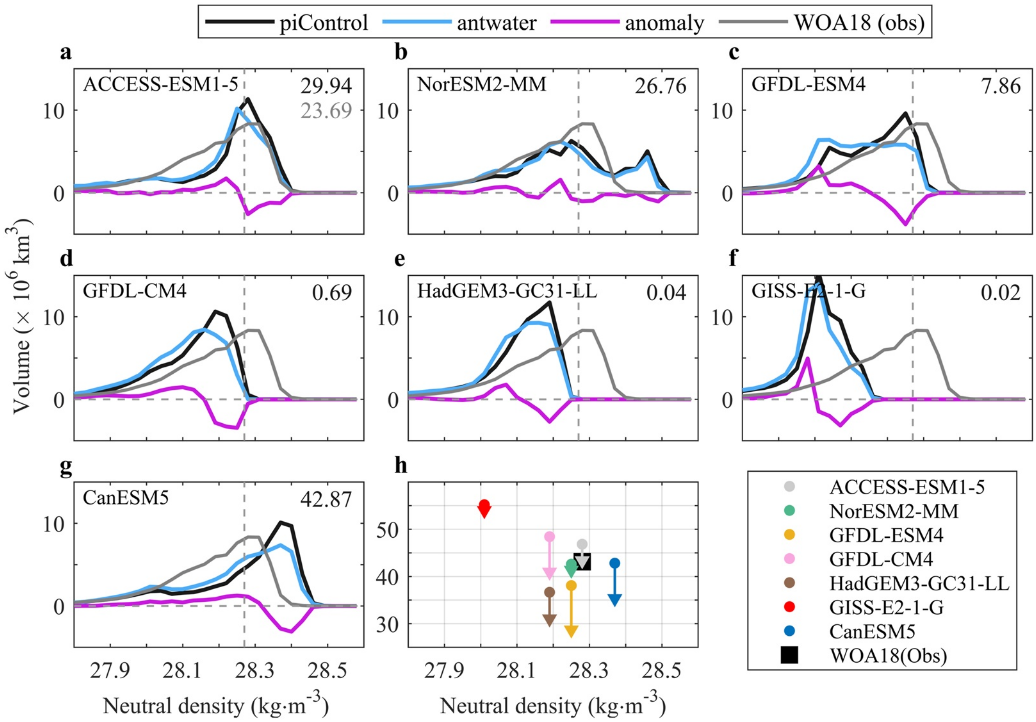

Figure 3. Volumetric distribution of water masses plotted by density south of 60°S from *piControl* (black), *antwater* (light blue), and the difference (purple). The observed distribution (light gray) from WOA18 is averaged from 1955 to 2017. The black number in the top-right corner of each panel is the simulated volume ($\times 10^6$ km^3) with density greater than 28.27 kg m^{-3}, indicated by a vertical gray line. The gray number in panel (a) represents the observed volume from WOA18. (h) Integrated volumes within a 0.18 kg m^{-3} range near the volume peak of each model are depicted as dots in *piControl*, arrows in *antwater*, and a black square for WOA18.

significant reduction in deep convection (Figure S3 in Supporting Information S1; purple dots in Figure 2) indicates that the result is not an artifact of the sampling uncertainty.

3.2. Reduced Antarctic Bottom Water Volume

Open-ocean deep convection is the main production mechanism of AABW in most CMIP6 models and reduced deep convection could have a large influence on simulated local and global climate by reducing the AABW formation rate (De Lavergne et al., 2014; Lago & England, 2019; Purich & England, 2023). However, it is not yet clear how the response of AABW formation and volume to Antarctic meltwater differs or is similar among different climate models.

AABW is typically defined by a neutral density greater than 28.27 kg m^{-3} (Orsi et al., 1999). We analyze the AABW properties south of 60°S, consistent with the established AABW cell definition (Lago & England, 2019), emphasizing the AABW signal. The AABW volume derived from WOA18 is about 23.69 × 10^6 km^3, roughly 32% of the total water volume in this region. The models display a wide variation in the distribution pattern of water masses density south of 60°S (Figure 3). This variability across models results in a wide range of AABW volume, spanning from 0.02 × 10^6 km^3 (GISS-E2-1-G) to 43.52 × 10^6 km^3 (CanESM5) across models (black curves and numbers in Figure 3) based on the observed-climatology criteria of 28.27 kg m^{-3}. The AABW volume change in response to meltwater has a high correlation with the AABW volume in the models' climatological mean state ($r^2 = 0.93$, $p < 0.01$; Figure S4c in Supporting Information S1). The AABW volume change ($\sigma = 3.50$) across models shows less variability than the climatological mean AABW volume ($\sigma = 17.74$) in *piControl*.

Despite large biases in the water mass properties, all models show a consistent contraction in the densest waters south of 60°S (purple curves in Figure 3), corresponding to a warming of the deep ocean (Figure 4). To better assess the volume changes of bottom water due to meltwater influence, a critical neutral density is determined at the position of maximum volume for each model. The integrated volume near this neutral density decreases across

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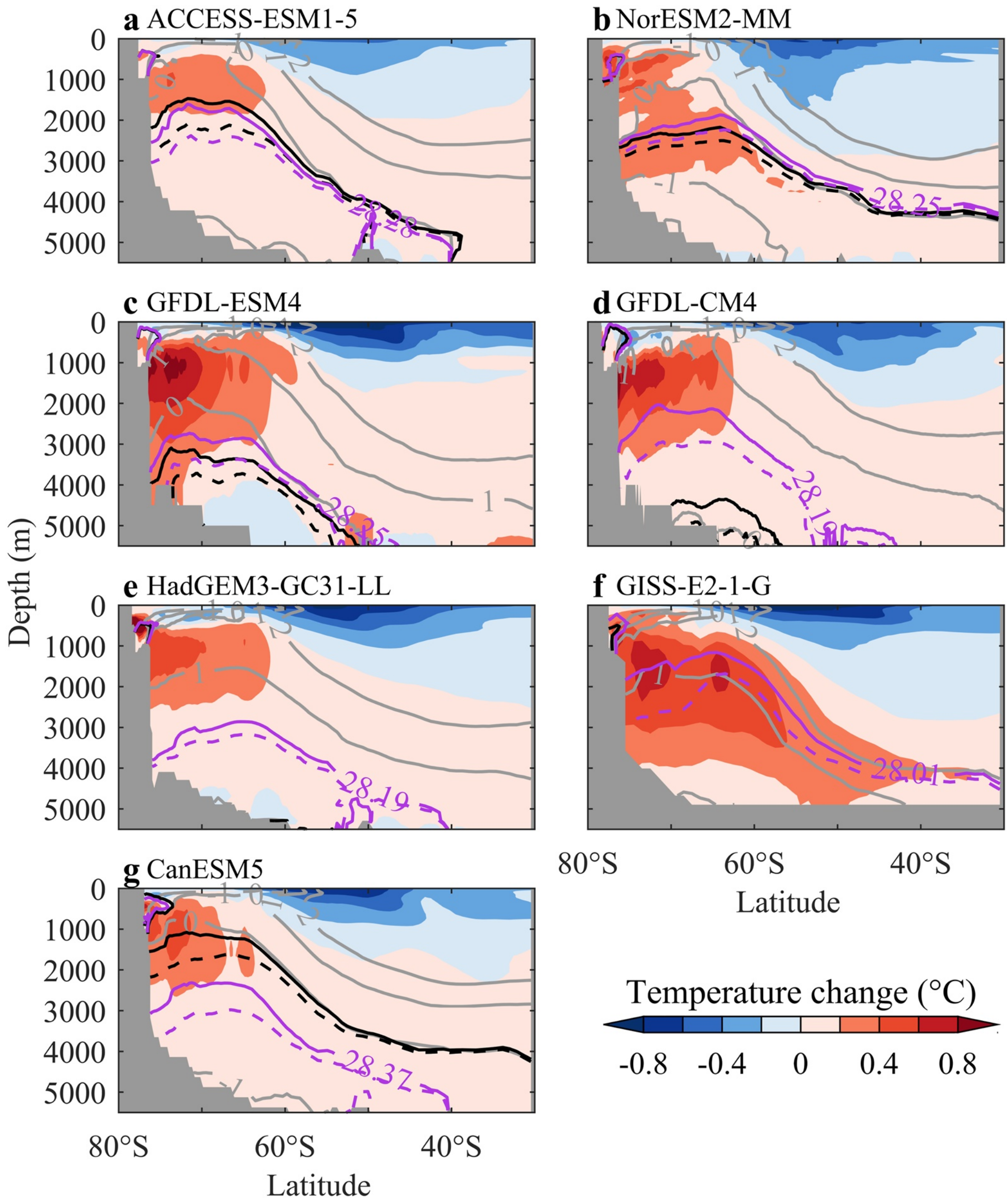

Figure 4. Zonal mean potential temperature change (°C; shading; *antwater - picontrol*). Solid gray contours show the climatological temperature in *piControl*. Black lines represent the 28.27 kg m^{-3} neutral density in *piControl* (solid line) and *antwater* (dashed line). Purple lines denote neutral density corresponding to the volume peak (see black line in Figure 3) observed in *piControl*.

all models (Figure 3h), with this neutral density being represented by the purple contours in Figure 4. The volume of the lighter water masses (e.g., around 28 kg m^{-3}) increases due to the upper ocean freshening. The consistent pattern of surface cooling and deep ocean warming at high latitudes might result from common processes and responses to the meltwater forcing shared among models, such as decreased deep convection discussed earlier. However, no significant linear relationship is found between the magnitudes of AABW contraction and the change or base state of deep convection (Figure S5 in Supporting Information S1). This suggests that other processes may also affect AABW. All models also show a reduced AABW overturning circulation and increased sea ice extent (Figure S5 in Supporting Information S1), possibly contributing to surface cooling and deep ocean warming. However, without further analysis of the associated processes, we cannot attribute the changes to any specific process.

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4. Discussion and Conclusions

This study analyzed the novel multi-model experiment *antwater*, which is specified as a part of the coordinated experimental designs proposed by SOFIA (Swart et al., 2023). Our analysis of seven climate models consistently shows a significant decrease in deep convection (Figures 1 and 2), contraction of Antarctic Bottom Water (AABW) (Figure 3) and warming of the deep ocean (Figure 4) in response to meltwater forcing. In *piControl*, all seven models exhibit deep convection in the Southern Ocean (SO), primarily in the Weddell and Ross Sea. Adding meltwater at the surface increases water column stratification at high latitudes, where density is dominated by salinity (De Lavergne et al., 2014; Purich & England, 2023), leading to reduction in deep convection. This finding is consistent with previous single-model studies (Fogwill et al., 2015; Lago & England, 2019; Li et al., 2023).

Observations suggest that Dense Shelf Water (DSW) overflow is the primary contributor to AABW (Orsi et al., 1999, 2002), and DSW formation is sensitive to the meltwater (Hattermann et al., 2021; Silvano et al., 2018). However, most CMIP6 models simulate AABW formation via deep convection due to the limitations of their coarse resolution (Heuzé, 2021; Mohrmann et al., 2021; Purich & England, 2021). Changes in deep convection may impact deep-ocean properties and circulation (Heuzé, 2021; Zanowski et al., 2015). The reduced deep convection hinders the sinking of cold surface water, contributing to deep-ocean warming and AABW volume contraction, consistent with previous studies on Antarctic meltwater effects (Li et al., 2023; Mackie et al., 2020; Park & Latif, 2019). However, we found no strong correlation between deep convection and deep-ocean warming across seven models (Figure S4 in Supporting Information S1), suggesting other factors like enhanced stratification, may also contribute to deep warming and surface cooling by limiting upward vertical mixing of subsurface heat (Chen et al., 2022). Furthermore, the meltwater-induced poleward shift of warm, saline Circumpolar Deep Water and the weakening of the lower cell of the overturning circulation (Figure S4 in Supporting Information S1) could also be associated with deep-ocean warming (Li et al., 2023; Moorman et al., 2020; Purich & England, 2021). These mechanisms may have already influenced SO climate, evident in observed AABW warming and contraction (Aoki et al., 2015; Purkey & Johnson, 2010, 2013; Shimada et al., 2022), overturning slowdown (Gunn et al., 2023; Zhou et al., 2023), as well as surface cooling or delayed warming south of the ACC (Armour et al., 2016; Haumann et al., 2020). It is noted that our results are based on an idealized experiment with meltwater input of greater magnitude than historically observed mass loss from Antarctic grounded and floating ice shelves (Slater et al., 2021), and thus cannot be directly applied to interpret observed changes in the SO. Nevertheless, our study suggests that inclusion of changing Antarctic meltwater in coupled climate models is important due to the far-reaching climate responses in the SO.

In addition to the robust responses, it is important to consider the variability among models. The magnitudes of changes in both deep convection and AABW volume varies strongly across models and are correlated with their respective mean state in *piControl* ($r^2 = 0.79$ and $r^2 = 0.93$, respectively; Figure S4 in Supporting Information S1) This indicates that the models' base state strongly influence deep convection and AABW volume anomalies. Differences in the ocean temperature changes (Figure 4) also exist among models, but no robust correlation is found between the anomalies and mean state magnitudes. Future research could benefit from including a larger model ensemble in intermodel comparisons to further evaluate the robustness of the results presented here.

We acknowledge that meltwater from Antarctica's ice shelves enters the ocean over a certain depth range instead of at the surface and also may be spatially distributed farther offshore by icebergs rather than only along the coast, both of which may have implications for the responses presented here. Unlike in reality, where the majority of mass loss occurs near Amundsen Sea (Davison et al., 2023; IMBIE, 2018), this study assumes a uniform distribution of meltwater surrounding the Antarctic coast. However, previous studies have not found substantial sensitivity to the different location of meltwater input (Park & Latif, 2019; Swart & Fyfe, 2013), which may be advected around the continent within about ten years (Dawson et al., 2023). Incorporating a more realistic representation of meltwater would enhance our understanding of its influence. These uncertainties are addressed in SOFIA Tier-2 and Tier-3 experiments (Swart et al., 2023), and could be examined once the model output becomes available. It is noteworthy that the intermodel differences in mean state are always larger than those in the response, particularly for deep convection volume and deep ocean temperature. This underscores the necessity for coupled climate models to accurately capture the SO's mean state, including a more realistic simulation of dense water formation, thereby reducing model uncertainty and improving models' performance in projecting future changes.

Data Availability Statement

The authors acknowledge the use of various data sets that significantly contributed to this research. The data of the freshwater experiments are available in Swart et al. (2023), the CMIP6 piControl experiments Eyring et al. (2016). The WOA18 data (potential temperature and salinity) are available in Boyer et al. (2018) and ORAS5 re-analysis data (mixed layer depth) are from Copernicus Climate Change Service (2021).

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