Projected Impacts of Antarctic Meltwater Anomalies over the Twenty-First Century

Ariaan Purich*bc and Matthew H. Englandbce

* ARC Centre of Excellence for Climate Extremes, Sydney, New South Wales, Australia
b Climate Change Research Centre, University of New South Wales, Sydney, New South Wales, Australia
c Australian Centre for Excellence in Antarctic Science, Sydney, New South Wales, Australia

(Manuscript received 20 June 2022, in final form 19 December 2022)

ABSTRACT: Antarctic margin and Southern Ocean surface freshening has been observed in recent decades and is projected to continue over the twenty-first century. Surface freshening due to precipitation and sea ice changes is represented in coupled climate models; however, Antarctic ice sheet/shelf meltwater contributions are not. Because Antarctic melting is projected to accelerate over the twenty-first century, this constitutes a fundamental shortcoming in present-day projections of high-latitude climate. Southern Ocean surface freshening has been shown to cause surface cooling by reducing both ocean convection and the entrainment of warm subsurface waters to the surface. Over the twenty-first century, Antarctic meltwater is expected to alter the pattern of projected surface warming as well as having other climatic effects. However, there remains considerable uncertainty in projected Antarctic meltwater amounts, and previous findings could be model dependent. Here, we use the ACCESS-ESM1.5 coupled model to investigate global climate responses to low and high Antarctic meltwater additions over the twenty-first century under a high-emissions climate scenario. Our high-meltwater simulations produce anomalous surface cooling, increased Antarctic sea ice, subsurface ocean warming, and hemispheric differences in precipitation. Our low-meltwater simulations suggest that the magnitude of surface temperature and Antarctic sea ice responses is strongly dependent on the applied meltwater amount. Taken together, these findings highlight the importance of constraining projections of Antarctic ice sheet/shelf melt to better project global surface climate changes over the twenty-first century.

SIGNIFICANCE STATEMENT: Antarctic ice sheets and shelves are melting, adding meltwater to the Southern Ocean and changing the ocean circulation. Antarctic meltwater stratifies the upper ocean, resulting in cooling of the surface Southern Ocean but warming at depth that could accelerate ice shelf melting. Coupled climate models used to project twenty-first-century climate do not represent ice sheets or shelves, neglecting important climate impacts. Here we conduct meltwater simulations with a coupled climate model and find that the magnitude of climate responses is strongly dependent on the applied meltwater amount. This highlights 1) the importance of constraining Antarctic meltwater projections to better project global climate over the twenty-first century and 2) that it is important that Antarctic meltwater be represented in future-generation coupled climate models.

KEYWORDS: Southern Ocean; Ice shelves; Sea ice; Atmosphere–ocean interaction; Ocean dynamics; Coupled models

1. Introduction

Southern Ocean surface freshening has been observed over recent decades (Durack and Wijffels 2010; Durack et al. 2012; de Lavergne et al. 2014), with contributions from increased basal melting and iceberg calving from the Antarctic continent due to ice sheet and shelf melting (Paolo et al. 2015; Wouters et al. 2015; Konrad et al. 2018), as well as changes in sea ice transport (Haumann et al. 2016) and increased precipitation minus evaporation as storm tracks shift south in association with the positive Southern Annular Mode trend (Fyfe 2003; Frederiksen and Frederiksen 2007; Son et al. 2009; Fyfe et al. 2012; Purich and Son 2012; Fogt and Marshall 2020). Density stratification of the high-latitude Southern Ocean is dominated by salinity (de Lavergne et al. 2014) and as such, freshening at the surface increases stability, reducing convective overturning and mixing of warm subsurface waters into the surface layer, leading to surface cooling (Marsland and Wolff 2001; Liu and Curry 2010; Kirkman and Bitz 2011; de Lavergne et al. 2014; Morrison et al. 2015; Purich et al. 2018).

Understanding the role that Antarctic meltwater plays in global climate is a critical question. Present-day coupled climate models participating in phases 5 and 6 of the Coupled Model Intercomparison Project (CMIP5 and CMIP6, respectively) fail to include interactive ice sheets and ice shelves coupled to the atmosphere and ocean components (e.g., Pauling et al. 2016; Siahaan et al. 2022), and in doing so overlook the density stratification feedback in response to meltwater-induced freshening described above, with important climatic implications. Nonetheless, the role of Southern Ocean surface freshening in influencing Antarctic sea ice behavior from 1979 up until the sea ice maximum in 2014 has been examined extensively in coupled climate models (e.g., Bintanja et al. 2013, 2015; Swart and Fyfe 2013; Pauling et al. 2016, 2017; Purich et al. 2018; Rye et al. 2020); however,
differing experimental designs has obfuscated conclusions on the importance of meltwater in driving sea ice changes. The future influence of Antarctic meltwater on regional and global climate has also been investigated in studies where additional Antarctic meltwater has been added to the surface in coupled climate models under twenty-first-century forcing scenarios (Bronseelaer et al. 2018; Sadai et al. 2020). These studies found that global impacts in response to Antarctic meltwater include strong anomalous Southern Ocean surface cooling and subsurface warming, as well as negative surface air temperature anomalies over most regions globally, and changed global precipitation patterns, particularly in the tropics. Bronseelaer et al. (2018) focus on meltwater impacts under a high-emissions scenario (RCP8.5) while Sadai et al. (2020) consider meltwater impacts under both medium and high-emissions scenarios (RCP4.5 and 8.5), with both studies considering the meltwater impacts from high-end projections of Antarctic melt (taken from DeConto and Pollard 2016). However, there remains considerable uncertainty in projected Antarctic mass loss (Fox-Kemper et al. 2021). In addition to examining the sensitivity of the global climate response to meltwater additions under different emissions scenarios, it is also important to examine the response of the climate system to differing meltwater amounts under a given emission scenario. Using a coupled model of intermediate complexity, Schloesser et al. (2019) explore a range of future meltwater forcing scenarios under both RCP4.5 and 8.5 emissions scenarios and find that many of the regional and global changes in response to meltwater depend non-linearly on the amount of meltwater applied. Using a coarse resolution coupled climate model under idealized increasing greenhouse gas forcing, Park and Latif (2019) also conduct a range of meltwater simulations and find that changes to the large-scale ocean circulation, such as the meridional overturning circulation, also respond non-linearly to meltwater additions. Exploring the climate responses to a range of Antarctic meltwater projections in a typical CMIP6 coupled climate model with a 1°-horizontal-resolution ocean component [as compared with the 3°-resolution model used in Schloesser et al. (2019) and the 2°-resolution model used in Park and Latif (2019)] is a pertinent next step.

Here, we use the Australian Community Climate and Earth-System Simulator, Earth System Model, version 1.5 (ACCESS-ESM1.5), to investigate the global climate response to low and high Antarctic meltwater additions over the twenty-first century. Our meltwater simulations produce anomalous surface cooling, increased sea ice, hemispheric differences in precipitation and ocean warming at depth. Given the uncertainty in Antarctic melt projections over the twenty-first century, it is important to compare the climate responses to varying meltwater additions. We do this by exploring the climate response to both low- and high-projected meltwater additions under the high-emissions scenario (SSP585). We find the magnitude of climate response to be strongly dependent on the applied meltwater amount; namely, more meltwater leads to stronger surface freshening, stronger anomalous surface cooling both locally and remotely, a greater inter-hemispheric temperature gradient, and larger changes to global precipitation patterns. These demonstrate the sensitivity of future climate change to the magnitude of Antarctic meltwater additions.

2. Methods

a. Model description

To conduct our meltwater experiments we use ACCESS-ESM1.5, a fully coupled global climate model with land and ocean carbon cycle components, developed by the Commonwealth Scientific and Industrial Research Organization for participation in CMIP6 (Ziehn et al. 2020). ACCESS-ESM1.5 is based on ACCESS1.3, which was identified as one of the best CMIP5 models in terms of simulating Antarctic sea ice extent and regional Southern Hemisphere climate (Naughten et al. 2018). The atmospheric component of ACCESS-ESM1.5 is UMv7.3 (Martin et al. 2010, 2011) with N96 horizontal resolution and 38 vertical levels. The ocean component is MOM5 (Griffies 2012) with 360 longitude by 300 latitude points on a rectangular grid and enhanced horizontal resolution at the equator and over the Southern Ocean, along with 50 z vertical levels. The ocean model is Boussinesq with a free surface, and a K-profile parameterization and Langmuir mixing scheme are both implemented for the vertical mixing and surface mixed layer. The sea ice component is CICE4.1 (Hunke and Lipscomb 2010), with a horizontal grid that matches the ocean component and five thickness classes. A complete description of ACCESS-ESM1.5 and its sub-components can be found in Ziehn et al. (2020).

ACCESS-ESM1.5 simulates an equilibrium climate sensitivity of 3.9°C (Ziehn et al. 2020), close to the CMIP6 multimodel mean of 3.7°C (Meehl et al. 2020). As noted above, ACCESS-ESM1.5 is based on one of the better CMIP5 models in terms of simulating Antarctic sea ice and Southern Hemisphere climate, so we might again expect reasonable skill in this model version. This turns out to be the case, with ACCESS-ESM1.5 performing well in its simulation of the Southern Hemisphere westerly wind jet, with an equatorward bias of just 0.4° (one of the best-performing CMIP6 models in this regard; Table 4 in Bracegirdle et al. 2020a) and an intensity bias of 1 m s\(^{-1}\) [above the CMIP6 multimodel mean bias but well within the spread across models; Table 4 in Bracegirdle et al. (2020a)]. Particularly relevant to this study, ACCESS-ESM1.5 simulates an Antarctic sea ice extent within 1×10\(^6\) km\(^2\) of the observed extent over the seasonal cycle [also one of the best-performing CMIP6 models in this regard; see also Figs. S1a and S1b in the online supplemental material for sea ice area in Roach et al. (2020)]. However, ACCESS-ESM1.5 also exhibits a Southern Ocean SST warm bias associated with the atmospheric component (Ziehn et al. 2020), which is typical of CMIP6 models (Beadling et al. 2020). In terms of lateral and meridional Southern Ocean circulation, ACCESS-ESM1.5 simulates an Antarctic Circumpolar Current transport of 153 Sv (1 Sv = 10\(^6\) m\(^3\) s\(^{-1}\)), which is at the lower end of the observational estimate (Beadling et al. 2020), with some spurious deep convection simulated in both the Weddell and Ross Seas, and abyssal meridional overturning circulations of 3.6 ± 1.0 Sv in the Atlantic Ocean, 1.9 ± 3.3 Sv in the
In summary, ACCESS-ESM1.5 is one of the better-performing CMIP6 models in terms of the representation of Southern Hemisphere climate and Antarctic sea ice, but it also exhibits typical CMIP6 model biases, such as a warm bias in Southern Ocean SST (Beadling et al. 2020) and overly deep convective mixed layers in the Weddell and Ross Seas (Heuzé 2021).

b. CMIP6 Antarctic runoff

To motivate our meltwater experiments, we consider the representation of runoff from Antarctica in ACCESS-ESM1.5 and other CMIP6 models. As was also the case for CMIP5 models (de Lavergne et al. 2014; Pauling et al. 2016), CMIP6 models do not include interactive ice sheets nor do they resolve ice shelf cavities (Siahaan et al. 2022). As discussed in detail in Pauling et al. (2016), to maintain a mass balance over Antarctica, excess precipitation minus evaporation over the continent is routed to the coast and runs off as liquid and in some cases solid freshwater. To assess the amount of freshwater entering the Southern Ocean from Antarctic runoff we analyze liquid runoff for the 24 CMIP6 models with these data available, listed in Fig. 1. These models can be divided into four groups: 1) models that represent all Antarctic runoff as liquid runoff and do not include icebergs, including ACCESS-ESM1.5; 2) models that partition Antarctic runoff into liquid and solid phases with iceberg data available; 3) models that partition Antarctic runoff into liquid and solid phases but without iceberg data available; and 4) models for which the treatment of solid runoff could not be determined from the model documentation. We consider the total runoff (liquid, plus solid when available) in all grid cells around the Antarctic margins over the periods 1981–2000 and 2081–2100 (Fig. 1a). In this study we run simulations over the period 2000–2100 (described below in section 2c), and consider the two 20-yr time periods 1981–2000 and 2081–2100 consistently to represent the end of the twentieth century (as a pre-simulation reference) and the end of the twenty-first century, respectively.

For comparison with ACCESS-ESM1.5 and CMIP6 models, we make use of end of twentieth century and end of
We choose SSP585 to compare with previous simulations run over 1990–2010 (combining basal ice melt and entire ice sheet dynamic mass loss from their Figs. 1c,d). For the end of the twenty-first century, we focus on meltwater additions under the scenarios with high anthropogenic emissions (i.e., RCP8.5 and SSP585) for comparison with Bronselaer et al. (2018). We consider the simulations of Golledge et al. (2019) with additional meltwater feedbacks under RCP8.5, and we also consider the simulations of DeConto and Pollard (2016), which include additional ice dynamics that lead to high melt rates (taken from their “Extended Data Figure 8”) for RCP8.5.

Over the historical period the range in Antarctic total runoff across CMIP6 models in groups 1 and 2 is ~1000–3000 Gt yr$^{-1}$ (Fig. 1, dark-blue bars), with a multimodel mean of 2300 Gt yr$^{-1}$, which is within the uncertainty of the combined observation-constrained basal ice melt plus dynamic ice loss simulated by Golledge et al. (2019) (shown here in Fig. 1, dark-purple bar), namely, ~2500 Gt yr$^{-1}$ over 1990–2010 (from their Figs. 1c,d). ACCESS-ESM1.5 simulates 2900 Gt yr$^{-1}$ of Antarctic runoff over the historical period, which is at the higher end of the range of CMIP6 models and slightly outside the upper uncertainty of the estimate of Golledge et al. (2019, 2820 Gt yr$^{-1}$), but is of a comparable magnitude. Considerably less runoff is shown for those models in groups 3 and 4 with incomplete data available.

Precipitation over the Southern Ocean and Antarctic continent is projected to increase over the twenty-first century as a result of a warming atmosphere (Frieler et al. 2015; Palerme et al. 2017; Bracegirdle et al. 2020b), and Southern Ocean surface freshening is simulated in response to this increase in precipitation. Based on the treatment of excess precipitation over the Antarctic continent in the models (e.g., as discussed in Pauling et al. 2016), this results in an increase in Antarctic runoff over the twenty-first century (Fig. 1, light blue bars). ACCESS-ESM1.5 simulates an increase of 880 Gt yr$^{-1}$ by 2100 relative to the historical period, within the range of ~350–1400 Gt yr$^{-1}$ simulated across models in groups 1 and 2. However, this increase in runoff is considerably less than the increase in basal melt and dynamic loss seen in modest increasing-meltwater simulations (~5600 Gt yr$^{-1}$ by 2100; Golledge et al. 2019, Fig. 1, light purple bar) and an order of magnitude less than that of high-melt simulations (DeConto and Pollard 2016, Fig. 1, light purple bar), motivating the experiments conducted in this study with additional meltwater added around the Antarctic margins to make up this discrepancy over the twenty-first century (Fig. 1, light blue plus light purple bars on far right).

c. Experimental design

Using ACCESS-ESM1.5 in fully coupled configuration, simulations with additional freshwater fluxes added to the ocean component are branched from an ensemble of historical runs in the year 2000. Simulations are run under historical atmospheric forcings over 2000–14 and under SSP585 forcings over 2015–2100. We choose SSP585 to compare with previous simulations run under RCP8.5 (Bronselaer et al. 2018; Golledge et al. 2019). We apply a transient increasing anomaly in freshwater around the Antarctic margins in the Ross, Amundsen, Bellingshausen and Weddell Seas (160°E–360°), as the majority of Antarctic meltwater entering the Southern Ocean is projected in these regions (Golledge et al. 2019). We apply freshwater with a 3–2–1 tapering in grid cells adjacent to the coast (dark blue) and 75% spread northward (light blue), (b) Meltwater time series over 2000–2100 for the CTRL (no meltwater) in orange, ANT-MW-LOW in blue, ANT-MW-HIGH in purple, and ANTMW-HIGH-80% in dashed purple.
of the Southern Ocean surface cooling and reduced precipitation anticipated in response to the additional meltwater. We thus take these runoff increases into account when determining how much additional freshwater to add in the meltwater simulations (Table 1).

We run three main perturbation experiments each with a five-member ensemble with additional meltwater starting at zero at initialization in 2000 and increasing linearly as shown in Fig. 2b and described in Table 1. They are
1) ANT-MW-LOW: additional meltwater increasing to 4810 Gt yr⁻¹ by 2100, motivated by the meltwater projections from Golledge et al. (2019) with meltwater feedbacks (5600 Gt yr⁻¹ by 2100; N. Golledge 2021, personal communication).
2) ANT-MW-HIGH: additional meltwater increasing to 16650 Gt yr⁻¹ by 2100, motivated by the meltwater projections from DeConto and Pollard (2016, 0.55 Sv in their Extended Data Figure 8), and
3) ANT-MW-HIGH-80%: additional meltwater increasing by ~80% of ANT-MW-HIGH to 13600 Gt yr⁻¹ by 2100, motivated by the uncertainty in the high-end meltwater projections of DeConto and Pollard (2016) and providing a high meltwater scenario comparable to DeConto et al. (2021).

We focus on ANT-MW-LOW and ANT-MW-HIGH, but make use of ANT-MW-HIGH-80% to understand the sensitivity of the Southern Ocean response to very high meltwater additions.

The meltwater anomaly is applied as a precipitation minus evaporation correction to the surface layer of the ocean model component. In reality, basal melt in ice-shelf cavities occurs at depth, so this represents a simplification in our experimental design. Our spatial distribution of meltwater (Fig. 2a) distributes ~25% of the meltwater flux adjacent to the Antarctic coast with the remaining ~75% being applied farther north, the latter sitting within the range of 62°–87° solid ice discharge reported in Sadai et al. (2020) in experiments with hydrofracturing and ice-cliff calving. Basal and iceberg melting also result in substantial latent heat loss from the surrounding ocean, but this is not accounted for in our experiments, representing another simplification in our experimental design.

d. Meltwater analysis

We compare our meltwater simulations with the corresponding ACCESS-ESM1.5 simulations without additional freshwater, specifically, the 10 runs for the historical and SSP585 projection experiments submitted to CMIP6. Hereinafter, we refer to these ensemble runs as the CTRL, noting that this CTRL runs into the future and can be thought of as a climate change CTRL without the additional added effects of Antarctic meltwater.

When examining model differences, we show the total twenty-first-century climate change pattern as the CTRL ensemble average over 2081–2100 (SSP585 experiment) different from the CTRL ensemble average over 1981–2000 (historical experiment). In contrast, meltwater-induced climate impacts at the end of the twenty-first century are shown as the meltwater ensemble average over 2081–2100 different from the CTRL ensemble average over this same time period, 2081–2100. Statistical significance of the ensemble averaged difference is assessed using a Student’s t test at the 95% confidence level, using the variances of the 10 CTRL members and the five meltwater members.

3. Surface salinity, temperature, and sea ice response

Under increasing greenhouse gases and without the impact of Antarctic meltwater, the surface Southern Ocean is projected to freshen (Fig. 3a) and warm at a rate below the global average (Fig. 3b). In response to surface freshening from additional Antarctic meltwater, anomalous surface cooling of the Southern Ocean is expected, as surface freshening increases the stratification, reducing convective overturning and upwelling of warmer subsurface waters into the surface ocean (e.g., Purich et al. 2018; Bronselaer et al. 2018). The meltwater additions in ANT-MW-LOW increase the surface freshening in the regions where freshwater is applied (Ross, Amundsen, Bellingshausen and Weddell Seas) and in the Antarctic Circumpolar Current region in the Atlantic and Indian sectors (Fig. 3c). Given the lower freshwater additions in ANT-MW-LOW, it is not surprising that the anomalous surface freshening in ANT-MW-LOW is relatively weak and largely restricted to the Southern Hemisphere. This contrasts the expansive surface freshening seen in ANT-MW-HIGH (Fig. 3c), which shows strong
freshening of the Southern Ocean and freshening extending throughout the Indian Ocean, portions of the Pacific Ocean, and the Atlantic northward to 30°N. By the end of the century ANT-MW-LOW shows an average Southern Ocean anomalous surface freshening of 0.15 psu, while ANT-MW-HIGH shows anomalous surface freshening of 0.58 psu relative to the CTRL (south of 40°S, Fig. 4a).

Surface cooling is seen in response to the Southern Ocean surface freshening (Figs. 3d,f). The anomalous cooling in ANT-MW-LOW extends across the Southern Hemisphere, with an area-averaged cooling of 0.42°C south of 40°S, relative to CTRL (Figs. 3d and 4a). ANT-MW-HIGH shows a stronger anomalous cooling of southern high latitudes (0.83°C south of 40°S), with statistically significant cooling extending throughout the Southern Hemisphere as well as the Northern Hemisphere tropics (Figs. 3f and 4a). The pattern and magnitude of cooling in ANT-MW-HIGH largely matches that found in Bronselaer et al. (2018, their Fig. 1a), except that ACCESS-ESM1.5 does not simulate significant cooling in the Northern Hemisphere extratropics, as seen in Bronselaer et al. (2018). It is worth noting that ACCESS-ESM1.5 and GFDL-ESM2M both employ a MOM ocean model component (MOM5 and MOM4.1, respectively), which may contribute to the similarities seen in the surface temperature response of both models. On the other hand, the surface temperature anomaly pattern in response to high (DeConto and Pollard 2016) meltwater forcing presented in Sadai et al. (2020, their Fig. 3a) was simulated using an unrelated climate model, CESM1.2.2 with CAM5, and also lacks substantial cooling across the Northern Hemisphere extratropics. Golledge et al. (2019) also show the surface cooling in response to their lower meltwater additions to be largely restricted to the Southern Hemisphere; however, the magnitude of Southern Ocean surface cooling in their intermediate complexity simulations

Fig. 3. (left) Sea surface salinity (SSS; psu), and (right) surface air temperature (SAT; °C) anomalies for (a),(b) CTRL 2081–2100 average minus CTRL 1981–2000 average; (c),(d) ANT-MW-LOW 2081–2100 average minus CTRL 2081–2100 average; and (e),(f) ANT-MW-HIGH 2081–2100 average minus CTRL 2081–2100 average. Stippling indicates 95% significance.
(LOVECLIM v1.3) is considerably stronger than in our simulations (1.0°–1.5°C in their Fig. 4a). This highlights the need to assess the climate impacts of Antarctic meltwater across a suite of climate models.

When contrasting the surface temperature anomalies resulting from low and high Antarctic meltwater additions it is clear that the magnitude of response is strongly dependent on the amount of meltwater applied. Contrasting the surface responses to different Antarctic meltwater projections is important to understand the range of climate impacts that may occur from uncertain meltwater additions (Fox-Kemper et al. 2021); however, it is also important to note that it is anticipated that further additional meltwater will likely have a diminishing cooling effect, as the Southern Ocean becomes more strongly stratified. This was noted in the temporal evolution of global-mean SAT to meltwater additions in Bronselaer et al. (2018) and was also seen in Schloesser et al. (2019).

Across our meltwater ensembles, Southern Ocean surface cooling anomalies do not scale linearly with the amount of additional meltwater applied: for example, relative to ANT-MW-LOW, applying ~3.5 times as much meltwater in ANT-MW-HIGH yields an anomalous Southern Hemisphere extratropical cooling that is only 2 times as strong (Fig. 4a). This contrasts the salinity response to meltwater, which is fairly linear, with an anomalous Southern Ocean surface freshening ~4 times as strong in ANT-MW-HIGH. The nonlinearity in Southern Ocean surface cooling can be seen in the relationship between Southern Hemisphere extratropical area-averaged surface...
salinity and temperature across the CTRL and meltwater ensembles (Fig. 4a), where a strong correlation is found between salinity and temperature \((p < 0.001)\), but a nonlinear fit is evident (e.g., gray quadratic fit in Fig. 4a). When global metrics are considered, relationships appear to become more linear and Southern Hemisphere extratropical SSS is found to be significantly related with hemisphere-wide SAT (not shown, \(p < 0.001\)) and global SAT (Fig. 4b; \(p < 0.001\)), highlighting the strong influence Southern Ocean surface freshening plays on hemispheric and global temperature. Relationships between different SAT metrics appear to be fully linear: for example, Southern Hemisphere extratropical SAT is significantly correlated with global SAT (Fig. 4c; \(p < 0.001\)) and also with the global hemispheric SAT difference (i.e., Northern Hemisphere SAT minus Southern Hemisphere SAT, Fig. 4d; \(p < 0.001\)). The relationship between Southern Hemisphere extratropical SAT and the interhemispheric temperature gradient is intuitive but also noteworthy, because the hemispheric temperature gradient drives changes in global precipitation, including the latitude of the intertropical convergence zone (ITCZ, discussed below; see also Kang et al. 2008; Cabré et al. 2017).

The diminishing surface cooling effect in response to further added meltwater is evident by comparing ANT-MW-HIGH and ANT-MW-HIGH-80% in Figs. 4a and 4b: here the additional meltwater results in a stronger Southern Ocean surface freshening (0.46 psu in ANT-MW-HIGH-80% as compared with 0.58 psu in ANT-MW-HIGH averaged south of 40°S), but little change in Southern Hemisphere extratropical or global SAT (0.76°C in ANT-MW-HIGH-80% as compared with 0.83°C in ANT-MW-HIGH averaged south of 40°S, with considerable overlap between members across the two ensembles; Fig. 4c). Thus, when comparing end-of-twenty-first-century averages for the simulations of ANT-MW-HIGH and ANT-MW-HIGH-80%, the only separation between the two ensembles that can be seen clearly is for Southern Ocean salinity (Figs. 4a,b). In contrast, SAT responses between ANT-MW-HIGH and ANT-MW-HIGH-80% are almost indistinguishable (Figs. 4c,d). These results confirm the nonlinear response of surface temperature to high-end meltwater additions found in Schloesser et al. (2019), here using a state-of-the-art coupled climate model.

The meltwater-induced surface cooling (Figs. 3d,f) is accompanied by an anomalous increase in sea ice coverage by the end of the twenty-first century (Fig. 5), with a stronger anomalous increase in sea ice concentration (SIC) simulated in ANT-MW-HIGH than in ANT-MW-LOW. Both ensembles also show a weak (and nonsignificant) increase in Arctic sea ice [Figs. 5b,c and also reported in Sadai et al. (2020)], consistent with the weak cooling and weak increase in SSS seen in this region (Fig. 3).

Perhaps more interesting than the 2081–2100 average anomalies in SIC, which largely go alongside changes in surface temperature, is the temporal evolution of Antarctic sea ice extent (SIE; i.e., the areal-sum of grid cells with SIC > 15%) over 1981–2100, shown in Fig. 6. In the CTRL (Fig. 6, orange lines), as is generally seen across CMIP6 models (Roach et al. 2020), Antarctic SIE declines over the historical period (i.e., ~1990–2020). This contrasts the observed SIE behavior (Fig. 6, black line), which shows a multi-decade increase in SIE over 1979–2014 followed by a large decline in 2015/16 (Parkinson 2019). The meltwater additions in ANT-MW-LOW (Fig. 6, blue lines) are enough to offset the greenhouse gas-induced SIE decline seen in CTRL in the early twenty-first century, with Antarctic SIE relatively stable from approximately 2000 to 2030 and declining from 2030 at a similar rate to the CTRL. The high meltwater additions around the Antarctic margins in ANT-MW-HIGH (Fig. 6, purple lines) have a more substantial impact on Antarctic SIE. From 2000 to 2030, the additional meltwater in these ensembles offsets the
sea ice decline seen in CTRL and an increase in SIE is simulated, similar to the observed rate of increase from approximately 2000 to 2015. Declines of the magnitude observed in 2016 can also be seen in individual members of the ANT-MW-HIGH ensemble (although CMIP6 models are known to overestimate interannual variability in the sea ice maximum; Roach et al. 2020). By 2081–2100, Antarctic SIE loss is reduced by \( \frac{1.5}{3} \times 10^6 \text{ km}^2 \) under ANT-MW-HIGH relative to the CTRL in 2100. However, relative to the CTRL over 1981–2000, this still constitutes a reduction in annual-mean SIE of >30%, considerably more than that reported in Bronselaer et al. (2018). Our results complement those presented in Park and Latif (2019), where sea ice area responds to the amount of meltwater applied, but eventually declines under increasing greenhouse gas conditions under all meltwater scenarios.

The plateau and increasing trend in Antarctic SIE from 2000 to 2030 in ANT-MW-LOW and ANT-MW-HIGH, respectively, provides further support for Antarctic meltwater as a driver of observed Antarctic sea ice trends over the satellite era, in agreement with Bintanja et al. (2013, 2015), Pauling et al. (2017), Purich et al. (2018), and Bronselaer et al. (2018) and in contrast to Swart and Fyfe (2013) and Pauling et al. (2016). However, it is important to consider that observational estimates over 1997–2021 suggest that Antarctic ice shelves lost mass from calving and thinning at a combined rate of \( \sim 480 \pm 34 \text{ Gt yr}^{-1} \) (Greene et al. 2022), while our meltwater additions in ANT-MW-LOW correspond to 48 Gt yr\(^{-1} \) in 2000, increasing to 1000 Gt yr\(^{-1} \) in 2020, and those in ANT-MW-HIGH correspond to 164 Gt yr\(^{-1} \) in 2000, increasing to 3460 Gt yr\(^{-1} \) in 2020. This overestimate in added meltwater early in the twenty-first century occurs because our simplified meltwater additions increase linearly over the century, in contrast to the nonlinear additions in Golledge et al. (2019) and DeConto and Pollard (2016) that are gradual in the early twenty-first century and increase rapidly toward the end of the century. Thus, by 2020, even though our runs simulate a plateau or increasing trend in SIE, they do so by adding considerably more meltwater in both ensembles than is currently observed, particularly under ANT-MW-HIGH. This suggests that meltwater additions alone may not be responsible for the observed sea ice behavior, and points to the importance of considering other processes such as the influence from tropical variability (e.g., Li et al. 2014; Simpkins et al. 2014; Meehl et al. 2016; Purich et al. 2016; Chung et al. 2022) in tandem with meltwater effects when trying to disentangle the drivers of Antarctic sea ice behavior over recent decades. There is a clear need for a model intercomparison with consistent freshwater forcing to better understand the sensitivity to freshwater input on Antarctic sea ice trends (Pauling et al. 2017).

4. Global hydrological cycle response

Under increasing greenhouse gases without meltwater additions, ACCESS-ESM1.5 projects an increase in precipitation across the Southern Ocean, along with a strong increase in the equatorial Pacific (Fig. 7a). Decreased precipitation is projected across much of the Southern Hemisphere subtropics, including across southern Africa, Australia, and tropical South America (Fig. 7a). In response to Antarctic meltwater additions, Bronselaer et al. (2018) and Sadai et al. (2020) found a change in global precipitation patterns, namely, a drying of the Southern Hemisphere and a wetting of the Northern Hemisphere. Statistically significant changes in precipitation are seen in ANT-MW-HIGH relative to the CTRL, with an anomalous drying over the Southern Ocean (Fig. 7c) in response to the anomalous surface cooling. Anomalous drying of Southern Hemisphere land regions already projected.

![Fig. 6. Annual-mean Antarctic sea ice extent (SIE) time series over 1981–2020 (observations), 1981–2100 (CTRL), and 2000–2100 (meltwater ensembles). Observations (NSIDC SIE index; Fetterer et al. 2017) are shown in black, CTRL is shown in orange, ANT-MW-LOW is shown in blue, and ANT-MW-HIGH is shown in purple. Thick lines show observations and ensemble means smoothed with a 5-yr running average. For CTRL, ANT-MW-LOW, and ANT-MW-HIGH, SIE is calculated monthly as the area where SIC > 15% and is averaged annually.](http://example.com/fig6.png)
to dry under climate change (southern Africa, eastern Australia, and tropical South America) are also simulated. In response to the strengthened interhemispheric temperature gradient caused by the Southern Ocean surface cooling (Fig. 3f), a dipole change in precipitation is seen across the equatorial eastern Indian, Pacific and Atlantic Oceans, indicative of a northward shift in the ITCZ toward the warmer Northern Hemisphere (Kang et al. 2008, 2009; Cabré et al. 2017). Many of the precipitation changes seen in ANT-MW-HIGH agree with those presented in Bronsema et al. (2018), increasing confidence in the robustness of projected changes in large-scale precipitation patterns in response to high Antarctic meltwater additions. However, precipitation changes seen in ANT-MW-LOW largely lack significance (Fig. 7b). The clear anomalous reduction in precipitation seen across the Southern Ocean in ANT-MW-HIGH is absent in ANT-MW-LOW, except across the southeast Pacific and southwest Atlantic. The dipole change in precipitation across equatorial oceans is present in ANT-MW-LOW, suggesting that even low Antarctic meltwater additions have the potential to shift the ITCZ northward, but equatorial regional changes largely lack statistical significance (Fig. 7b). This demonstrates that the magnitude of global precipitation changes expected in response to Antarctic meltwater depends strongly on the amount of meltwater entering the Southern Ocean.

Hemispheric-scale precipitation scales linearly with the interhemispheric temperature difference (Fig. 8a; \( p < 0.001 \)), rather than with the amount of additional meltwater applied in the simulations, and so, while a larger change in precipitation is seen in ANT-MW-HIGH, it is not proportional to how much additional meltwater is added in these simulations relative to ANT-MW-LOW. This is further demonstrated by the similarity in precipitation changes in ANT-MW-HIGH and ANT-MW-HIGH-80%. The northward shift in the ITCZ in the Pacific (shown as precipitation in the NH ITCZ band minus the SH ITCZ band) is also linearly related to the interhemispheric temperature difference (Fig. 8b; \( p < 0.001 \)).

5. Subsurface temperature and overturning response

The Southern Ocean freshening-induced surface cooling is accompanied by a warming at depth (Fig. 9). The increased stratification leads to a reduction in convective overturning and upwelling of subsurface waters to the surface (as in Purich et al. 2018), retaining heat at depth. Around the Antarctic margins, this results in a zonal-mean subsurface warming extending from 100 m to below 2000 m in both ANT-MW-LOW and ANT-MW-HIGH (not shown). This is evident in the warm anomalies seen at 400-m depth (Figs. 9c,e) and 2000-m depth (Figs. 9d,f) across the Southern Ocean in both ANT-MW-LOW and ANT-MW-HIGH. ANT-MW-HIGH simulates the strongest warming in the Ross, Amundsen and Bellingshausen Seas \((-0.5^\circ C\), in regional agreement with the simulations of Golledge et al. (2019), although with a weaker amplitude than their simulations \((0.5^\circ -1.0^\circ C\); their Fig. 4c). The warm anomalies in ANT-MW-LOW around the East Antarctic margins are more substantial than in Golledge et al. (2019), despite our meltwater anomalies being added only around the West Antarctic margins. The anomalous high-latitude subsurface warming in ANT-MW-HIGH extends right around the continent. Midlatitude cool anomalies are seen at 400-m depth, where anomalously cool mode and intermediate waters are subducted (Figs. 9c,e). At 2000-m depth, statistically significant warm anomalies extend northward across all latitudes in the Atlantic sector in ANT-MW-LOW (Fig. 9d), and across the entire global ocean except the Arctic in ANT-MW-HIGH (Fig. 9f).

The Antarctic Bottom Water (AABW) meridional overturning cell (southernmost cell, south of \( \delta^\circ S \), e.g., Lago and England 2019) is shown in Fig. 10. A slowdown of AABW formation is seen under global warming without added
meltwater (i.e., for the CTRL; Fig. 10b, cf. Fig. 10a). This slowdown is accelerated in ANT-MW-LOW (Fig. 10c) and substantially accelerated in ANT-MW-HIGH (Fig. 10d). Examining the temporal evolution of the transport in Fig. 10e, AABW formation is seen to almost shutdown (plateau at \(0.5\) Sv) in ANT-MW-HIGH from \(2060\). The location of the maximum transport also deepens and shifts equatorward in ANT-MW-HIGH (not shown). Park and Latif (2019) also find a nonlinear response of the high-latitude meridional overturning cell to meltwater additions, with a gradual slowdown of AABW formation in their low meltwater ensemble, as compared with a rapid shutdown in the high meltwater ensemble. A strong reduction in the interannual variability in AABW is seen in all runs from 2000 relative to the CTRL over 1981–2000. ACCESS-ESM1.5, like many CMIP models, does not accurately represent dense water formation (Heuzé 2021) and it is likely that AABW transport is sensitive to open ocean convection. This reduction in variability in AABW formation suggests a reduction in open ocean convection in all runs over the twenty-first century, consistent with the findings of de Lavergne et al. (2014), and as found in response to meltwater additions in the simulations of Park and Latif (2019).

The rate of ventilation of the global abyssal ocean, controlled by AABW formation, has important implications for the cycling of heat, carbon and nutrients through the ocean. A large decrease in the volume of AABW in the Southern Ocean has already been observed between the 1980s and 2000s (Purkey and Johnson 2012), and a slowdown of AABW formation is simulated in response to Antarctic meltwater additions in both ocean–sea ice simulations (Lago and England 2019; Moorman et al. 2020) as well as coupled simulations (Mackie et al. 2020a,b), reducing the deep ocean ventilation. In our simulations, the global implications of the reduction in AABW formation relative to the CTRL, particularly in ANT-MW-HIGH where AABW formation is reduced substantially earlier in the century, are clearly evident in the anomalous ocean warming at 2000-m depth shown in Figs. 9d and 9f. In comparing the MOC changes (Fig. 10) and temperature anomalies at depth (Fig. 9) between ANT-MW-LOW and ANT-MW-HIGH, we see that the magnitude of Antarctic meltwater applied results in different global abyssal ocean properties simulated at the end of the twenty-first century.

6. Contextualizing meltwater-induced changes

To further emphasize the magnitude of meltwater-induced climate anomalies, we present surface temperature, sea ice, and 2000-m-depth temperature anomalies as a percentage of the standard (no added meltwater) climate change pattern over 2081–2100 (Fig. 11). With only a modest amount of meltwater applied around the Antarctic margins, ANT-MW-LOW reduces Southern Hemisphere extratropical surface warming by \(\sim 15\%\) (Fig. 11a) and reduces Antarctic SIC loss by \(\sim 20\%\) (Fig. 11b) by the end of the twenty-first century, relative to the CTRL (SSP585 forcing without meltwater additions). High meltwater additions reduce Southern Hemisphere extratropical surface warming by \(\sim 30\%\) and tropical warming by \(\sim 10\%\) (Fig. 11d) and reduce Antarctic SIC loss by up to \(\sim 60\%\) in some regions (Fig. 11e). These meltwater-induced reductions in surface climate changes are balanced by exacerbated ocean warming at depth: ANT-MW-LOW increases warming of the Southern Ocean at 2000 m by 5%–30% (Fig. 11c) and ANT-MW-HIGH increases warming of most regions of the global ocean by up to 30%, and the Southern Ocean by \(\sim 40\%\) relative to the CTRL (Fig. 11f). These meltwater-induced changes relative to the high-emission scenario climate change patterns provide further evidence that meltwater-induced changes make an important contribution to global climate change, and suggest that it is vital.
for Antarctic meltwater to be represented in future generation coupled climate models.

7. Conclusions

Antarctic meltwater is expected to have important climatic effects over the twenty-first century (Bronselaer et al. 2018; Sadai et al. 2020). While CMIP6 models do not include interactive ice sheets or ice shelves, here we show that the coastal runoff simulated by the models is comparable to observationally constrained simulations of Antarctic melt at the end of the twentieth century (Golledge et al. 2019). We also show that this runoff increases over the twenty-first century, due to increased precipitation over Antarctica (as for CMIP5 models; Pauling et al. 2016), but not at a rate that keeps up with the projected accelerating melt of ice sheets and ice shelves (Golledge et al. 2019; DeConto and Pollard 2016). To understand how the climate system responds to varying meltwater amounts, we run two ensembles of simulations with additional meltwater added to represent both low Antarctic melt and high Antarctic melt scenarios and examine the resulting climate anomalies at the end of the twenty-first century.

Our results, in combination with previous studies (Bronselaer et al. 2018; Schloesser et al. 2019; Sadai et al. 2020) show that meltwater-induced anomalies at the end of the twenty-first century are substantial. We find anomalous surface cooling across the Southern Hemisphere extratropics (and extending through to the Northern Hemisphere tropics in our high meltwater scenario), an anomalous increase in Antarctic SIE (and a net increase in SIE until ~2030 in our high melt scenario), and a drying of the Southern Hemisphere, wetting of the Northern Hemisphere and northward shift in the ITCZ. One of the key findings of our study based on assessing both low and high melt scenarios is that the magnitude of surface climate responses in our meltwater simulations (including surface freshening, cooling and changed precipitation patterns) are strongly dependent on the applied meltwater magnitude. This highlights the importance of constraining projections of Antarctic meltwater

---

**Fig. 9.** As in Fig. 3, but showing (left) 800-m-depth potential temperature (°C), and (right) 2000-m-depth potential temperature (°C) anomalies in (a),(b) CTRL; (c),(d) ANT-MW-LOW; and (e),(f) ANT-MW-HIGH over 2081–2100.
to better predict global climate changes over the twenty-first century.

The meltwater-induced reduction in convective overturning and weaker entrainment of warmer subsurface waters into the surface layer that result in a Southern Ocean surface cooling also cause a warming at depth (as in Purich et al. 2018). We find additional warming that exceeds the projected warming from standard climate change experiments in the Southern Ocean from ~100-m depth and extending downward (shown for 400-m depth in Figs. 9c,e). This additional warming occurs at the typical depth of ice-shelf cavities, and has the potential to lead to increased basal melt via a positive feedback. With previous studies finding that meltwater-induced subsurface temperature change around the Antarctic margin varies with ocean model resolution (Beadling et al. 2022), this is an important uncertainty in how future shelf warming will play out. Higher resolution models that resolve the Antarctic Slope Current exhibit a negative feedback mechanism wherein meltwater drives a stronger current, thus further isolating the Antarctic margin from warm Circumpolar Deep Water (Moorman et al. 2020; Beadling et al. 2022). This suggests that projected subsurface changes on the Antarctic shelf should be interpreted with caution. At 2000-m depth, warming of the Southern and Atlantic Oceans is seen under our low meltwater scenario. Under our high meltwater scenario, a shutdown of AABW formation occurs from around midcentury, and at 2000-m depth a statistically significant warming above the climate change signal is seen for the entire global ocean except the Arctic by the end of the twenty-first century, representing an important change to the global ocean.

Our simulations include simplifications that should also be considered. First, like many previous studies, our meltwater additions are applied at the surface. Pauling et al. (2016) compared the impacts of meltwater additions at the surface and at the depth of ice-shelf fronts and found that, while the surface response remained similar, there was a stronger warming below...
200 m in the simulations in which meltwater was added at depth, raising the possibility that the subsurface warming around the Antarctic margins and thus the potential for increased basal melt may be underestimated in our simulations. Second, again in common with many past studies, our meltwater simulations neglect the latent heat loss from the ocean associated with basal and iceberg melting. Schloesser et al. (2019) found considerably more surface cooling when the latent heat required to melt icebergs was taken into account, suggesting that the surface cooling and other surface climatic effects in our simulations may be underestimated because latent cooling is not accounted for. However, Schloesser et al. (2019) also found that accounting for the latent heat required to melt icebergs reduced the subsurface warming around the Antarctic margins, and thus the potential for the temperature-basal melt feedback. This demonstrates the complexity in estimating the climate impacts and feedbacks that will occur in response to Antarctic meltwater.

The results presented here are based on simulations run using one coupled climate model (ACCESS-ESM1.5). Single-model studies allow a process-based exploration of important concepts, but results are inherently limited by potential model dependency. Our results complement those of previous twenty-first-century meltwater studies using different models (e.g., Bronselaer et al. 2018; Schloesser et al. 2019; Sadai et al. 2020); however, these studies used different experimental designs and thus are not directly comparable to each other, or our study. A number of studies examining the role of Southern Ocean surface freshening in contributing to the satellite-era increase in Antarctic sea ice over the period from 1979 to the mid-2010s reached conflicting conclusions because of the different experimental designs and models used (Bintanja et al. 2013, 2015; Swart and Fyfe 2013; Pauling et al. 2016, 2017; Purich et al. 2018; Rye et al. 2020).

These examples and the results of this and previous studies demonstrate the critical importance of Antarctic meltwater additions to global ocean circulation and climate. This motivates a standardized meltwater intercomparison project to improve our understanding of how Antarctic meltwater will influence global climate over the twenty-first century. Our work also motivates some urgency for the climate modeling community to incorporate dynamic ice sheet and ice shelf sub-models into climate projection systems. It is critical to understand exactly how meltwater feedbacks onto ocean circulation and climate will play out over the coming decades and beyond.

Acknowledgments. This work was supported by the Australian Research Council (ARC) including the ARC Center of Excellence for Climate Extremes (CE17010023) and the ARC Centre for Excellence in Antarctic Science (SR200100008). This research was undertaken with the assistance of resources and services from the National Computational Infrastructure (NCI), which is supported by the Australian government. Figures were produced using the NCAR Command Language (https://doi.org/10.5065/D6WD3XH5). We thank the CMS team at the ARC Center of Excellence for Climate Extremes and Tilo Ziehn and Chloe Mackallah at CSIRO for their help in configuring ACCESS-ESM1.5. We thank Kaitlin Naughten and Nick Golledge for helpful discussions. We also thank Shaina Sadai and two anonymous reviewers for their constructive comments.

Data availability statement. CMIP6 data (models listed in the methods section) are publicly available and were accessed through NCI (https://esgf.nci.org.au/projects/cmip6-nci/). The NSIDC SIE index is freely available online (https://nsidc.org/data/G02135/versions/3). The Antarctic ice loss rate under
RCP8.5 with climate feedbacks from Golledge et al. (2019) was provided directly by Nick Golledge. ACCESS-ESM1.5 output from ANT-MW-LOW and ANT-MW-HIGH is available via NCI (contact Ariaan Purich for details).

REFERENCES


Siahaan, A., and Coauthors, 2022: The Antarctic contribution to 21st-century sea-level rise predicted by the UK Earth system


