

Supplementary Information to:
 Climate responses to Antarctic meltwater
 depend on the timing of meltwater release

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S1 Validity of 45:55 calving:basal melt scaling under future warming

Ice sheet projections from the Ice Sheet Model Intercomparison Project Phase 6 (ISMIP6) [1–3] are an attractive option for forcing Earth system models with future Antarctic freshwater fluxes, because these projections average across a wide ensemble of ice sheet models (see Introduction). However, because of differences in how different ice sheet models treat calving, only the ice shelf basal melting is reported by ISMIP6. Therefore, studies using this ensemble as a basis for future freshwater forcing [4–6] estimate calving using an observations-based historical estimate for the calving:sub-shelf melt ratio of 45:55 (following Rignot et al. [7]).

Using freshwater fluxes projected by Coulon et al. [8] we show that a fixed scaling is not appropriate under future warming, because sub-shelf melt rapidly accelerates while there is comparatively little change in calving, and additionally surface melting becomes important (particularly after 2100). This is illustrated in Fig. S1, where total projected freshwater fluxes from Coulon et al. [8] follow the black line. These are the sum of calving, sub-shelf melt and surface melt, which we here abbreviate as CLV, SSM, and SRF, respectively. Applying the 45:55 CLV:SSM scaling to estimate $\text{CLV} + \text{SSM} = \text{SSM}/0.55$ (red line) would greatly overestimate the projected $\text{CLV} + \text{SSM}$ (purple line), even by the late 21st century, because the projected CLV:SSM ratio rapidly decreases to near 11:55. Somewhat fortuitously in the scaled ISMIP6 approach, the overestimated $\text{CLV} + \text{SSM}$ compensates to some extent for the neglected surface melt, and so the freshwater fluxes estimated by scaling SSM (red line) do not appear unreasonable when compared with the projection (black line). Nevertheless, this apparent agreement emerges for the wrong reason and we cannot recommend using a constant 45:55 CLV:SSM scaling in freshwater forcings.

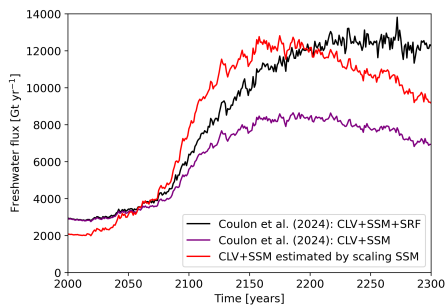


Fig. S1 Comparison of freshwater fluxes based on a full projection (calving plus sub-shelf melt plus surface runoff) and sub-shelf melt only. The full projection (black line) is from Coulon et al. [8], from which the calving plus sub-shelf melt contribution is shown in purple. Since calving and surface melt are not always reported, some freshwater studies scale sub-shelf melt to estimate calving, and in that case they would use freshwater fluxes following the red line.

S2 Handling of ice sheet freshwater fluxes in NorESM2

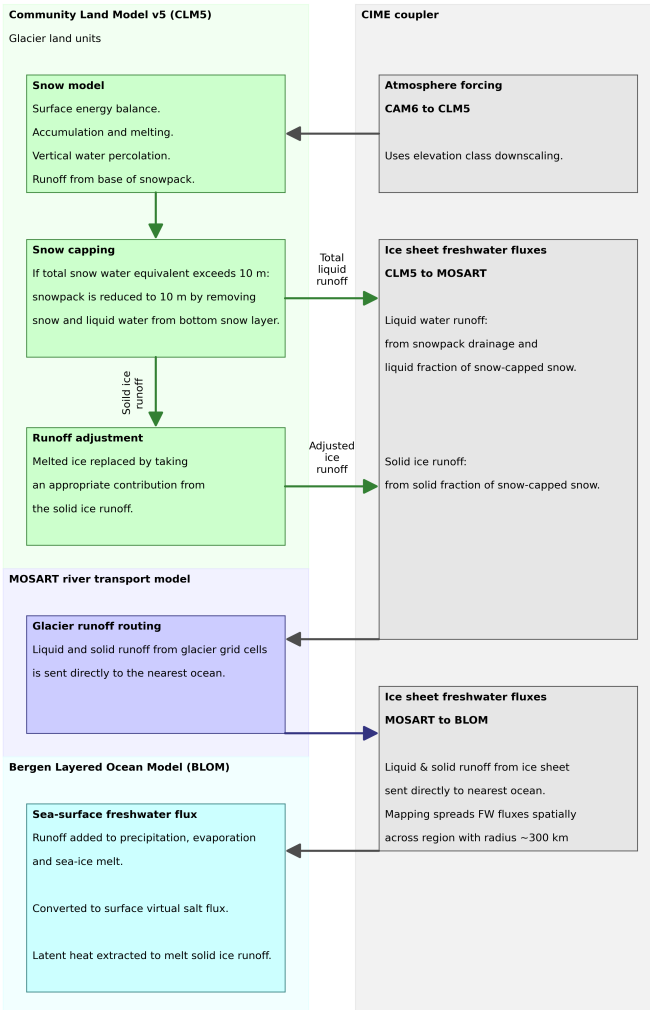


Fig. S2 Flowchart showing how ice sheet freshwater fluxes are generated in the land model (Community Land Model CLM5), and then passed to the ocean model (Bergen Layered Ocean Model BLOM) via the river routing model (Model for Scale Adaptive River Transport MOSART). Further details are provided in the Methods.

S3 NorESM2 freshwater budget in the Southern Ocean – an explanation of negative ice runoff

In NorESM2's ocean model (Bergen Layered Ocean Model: BLOM), the surface freshwater budget of the Southern Ocean comprises four components:

1. Precipitation, calculated by the Community Atmosphere Model (CAM), and passed to BLOM as solid and liquid freshwater fluxes. These fluxes are only passed to BLOM where there is open ocean – otherwise, they are passed to the sea-ice model, and eventually reach the ocean as sea-ice melt.
2. Evaporation, calculated by CAM.
3. Sea ice melt, calculated by the sea-ice model (CICE). This will comprise freshwater derived from frozen ocean, as well as freshwater derived from precipitation intercepted by sea-ice.
4. Surface runoff, calculated by the land model (CLM). In the Southern Ocean, all surface runoff is generated by surface melting or snow-capping in Antarctica.

Magnitudes of these fluxes averaged over the period 1960 to 2014 in the historical simulation are shown in Fig. S3. As explained in the Methods (Section 5) and Fig. S2, the ice sheet runoff comprises two components: liquid runoff (from surface melt and rainfall), and solid runoff (from snow-capping). The latter arises because NorESM maintains a constant ice sheet ice thickness, and must remove excess snow accumulation – this is sent directly to the ocean as solid ice runoff. In our modern climate (1960-2014), there is very little surface melt or rainfall in Antarctica, and so most of the precipitation falling in Antarctica is removed by snow-capping (Fig S4a,b). However, in a much warmer climate, there is considerable surface melting, particularly on the Antarctic Peninsula and in West Antarctica (S4c). In this scenario the surface melting exceeds annual snowfall, requiring that lost ice is replaced each year to maintain constant ice thickness. This lost ice is replaced with a negative ice discharge from the ocean, hence the regions with negative ice runoff in Fig. S4d.

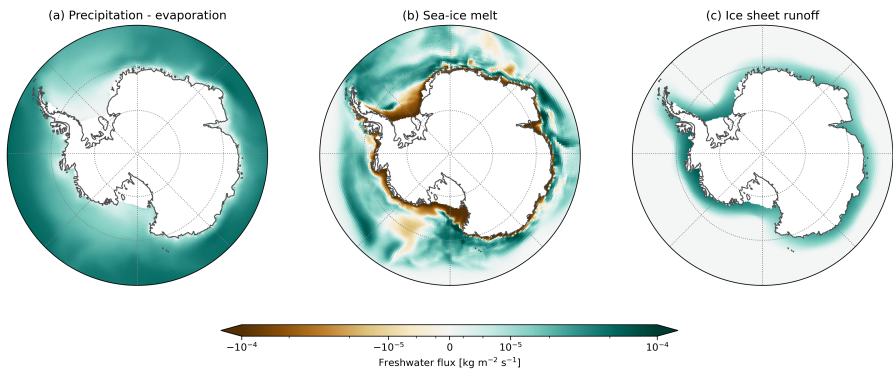
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Fig. S3 Annual mean freshwater fluxes in the NorESM2 historical simulation [9]. (a) Precipitation - evaporation, which is passed to the ocean model in three individual components (liquid precipitation, solid precipitation, and evaporation) where there is no sea-ice. (b) Sea-ice melt. (c) Ice sheet runoff, generated in Antarctica and passed to the ocean as two individual components (liquid runoff from surface melting, and solid runoff from snow-capping; see Methods and Fig. S4). The spatial mapping of Antarctic runoff to the ocean is indicated by the shaded band around the coast.

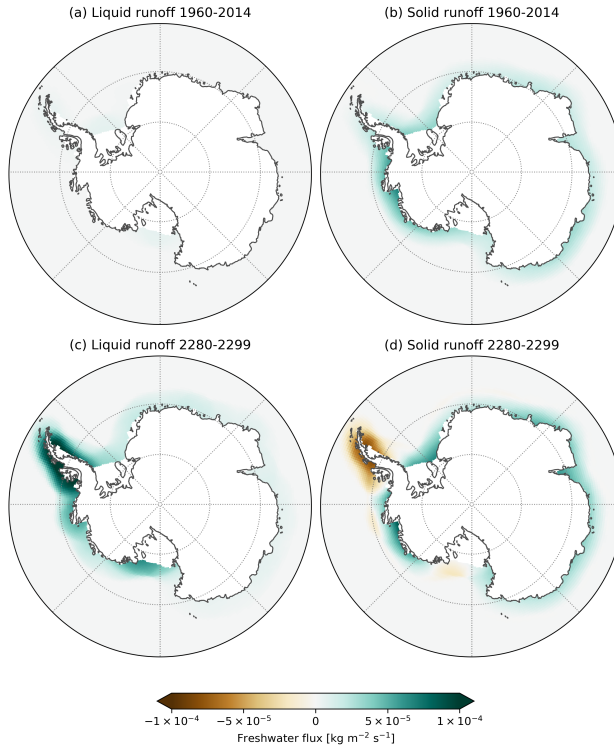


Fig. S4 Illustration of the split between liquid and solid runoff from Antarctica, in NorESM's treatment of freshwater fluxes with a fixed ice sheet. In the historical period, most runoff is in solid form, generated by snow-capping (panels a, b); see Methods for an explanation. In a warmer climate (ssp585-coulonfw, years 2280-2299), increases in surface melt and liquid precipitation lead to increasing liquid runoff (panel c). Since the increasing melt leads to net ice loss, this ice must be replaced by extracting mass from the ocean to ensure the ice sheet geometry remains fixed – hence the regions of negative solid runoff in panel (d).

S4 NorESM2 model bias

Here we quantify NorESM2 model bias under a modern climate by comparing the historical simulation [9] with observation-based datasets (primarily the World Ocean Atlas 2023: WOA23, Locarnini et al. [10]). We use the 1° statistically analysed annual mean temperatures averaged over the full period 1955 to 2022. We use the statistically analysed mean as it contains missing values in grid cells with no observations, rather than filling missing cells with interpolated values.

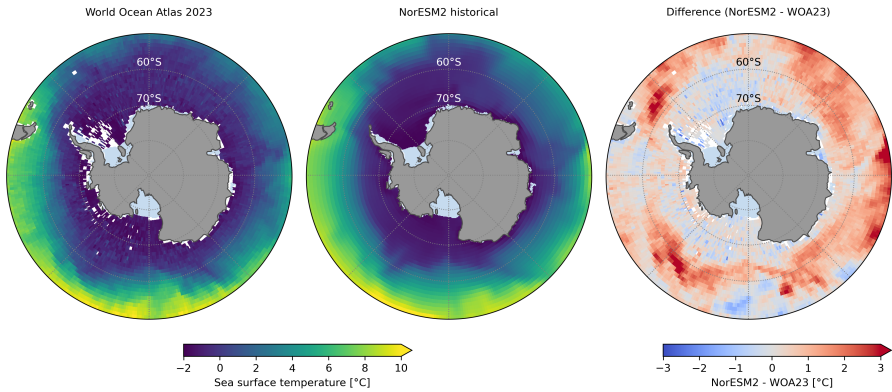


Fig. S5 Annual mean sea surface temperature (SST) in the World Ocean Atlas [10] and NorESM2 historical simulation [9].

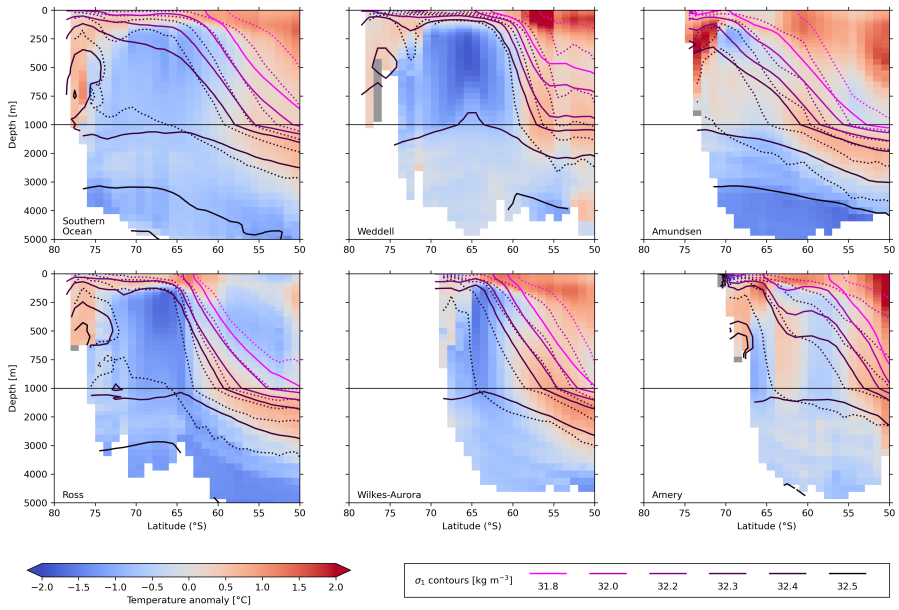


Fig. S6 Potential temperature bias in the NorESM2 historical simulation [9], relative to the observations-based World Ocean Atlas [WOA23: 10]. Plots are regional averages corresponding to the sections shown in Figs. 4, S17. σ_1 isopycnals are for WOA23 (dashed) and NorESM2 (solid).

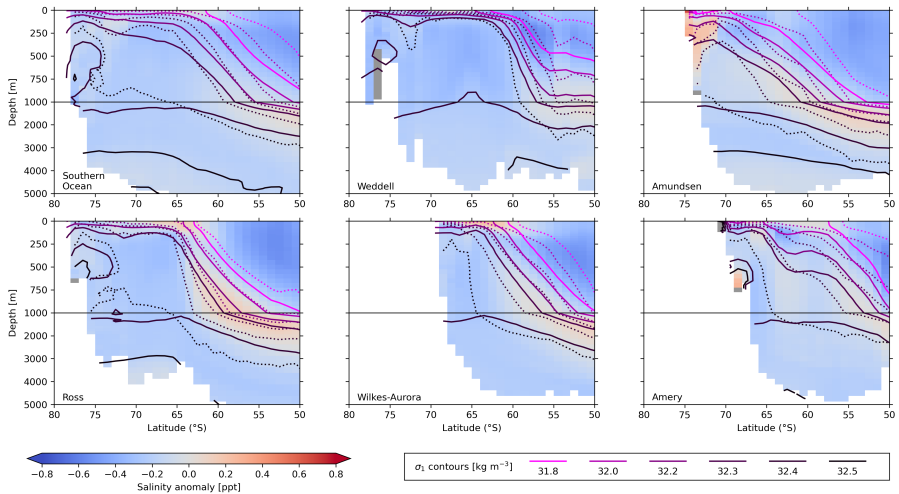


Fig. S7 Salinity bias in the NorESM2 historical simulation [9], relative to the observations-based World Ocean Atlas [WOA23: 10]. Plots are regional averages corresponding to the sections shown in Figs. 4, S17. σ_1 isopycnals are for WOA23 (dashed) and NorESM2 (solid).

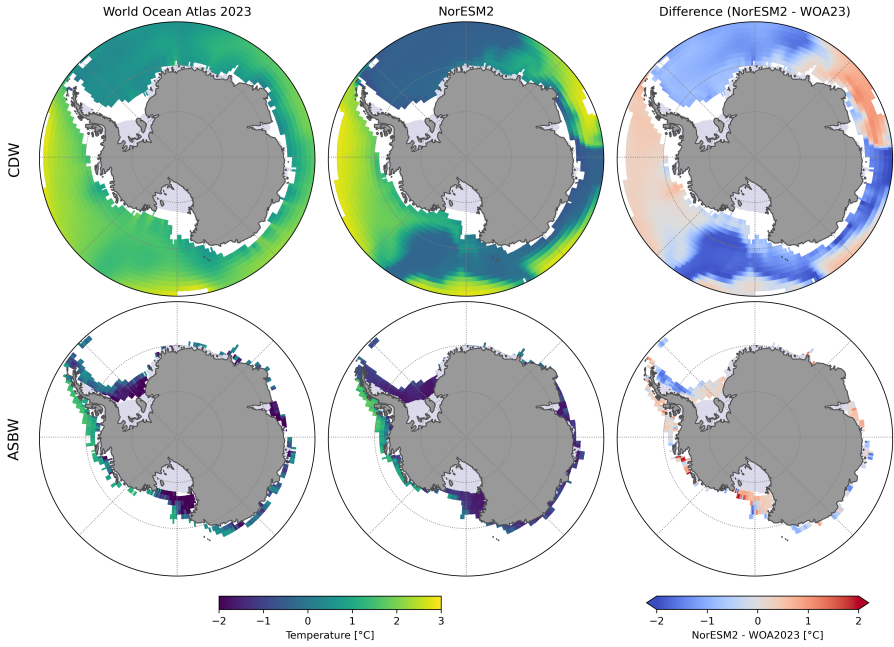


Fig. S8 Circumpolar Deep Water (CDW) and Antarctic Shelf Bottom Water (ASBW) temperatures in the World Ocean Atlas [10] and NorESM2 historical simulation [9]. Temperatures of both water masses are analysed following [11] (see Methods).

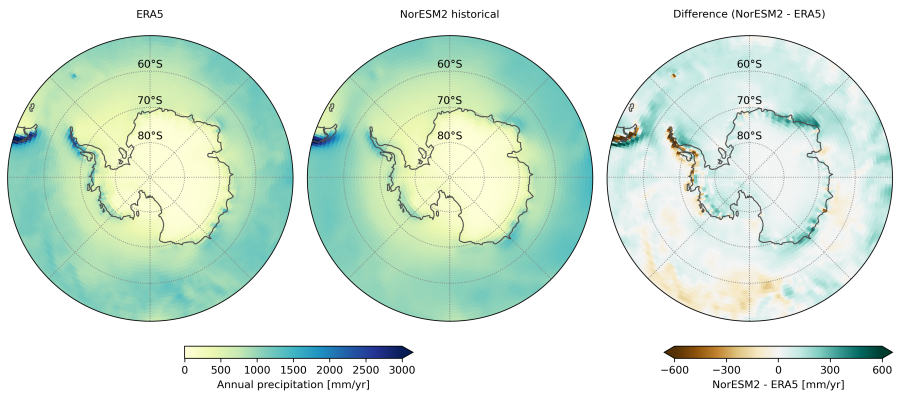


Fig. S9 Annual precipitation in ERA5 [12] and the NorESM2 historical simulation [9], averaged over the period 1995 to 2014.

S5 Missing latent heat flux

As noted in the main text (Methods), we add the additional freshwater forcing without correcting for the corresponding latent heat changes. Specifically, if we add an additional M kg/s of freshwater, we implicitly consume $M \times \rho_w \times L_f$ Watts of latent heat, where $\rho_w = 1000 \text{ kg m}^{-3}$ is the density of freshwater and $L_h = 334 \text{ kJ kg}^{-1}$ is the latent heat of fusion of ice. Since the additional freshwater forcing is primarily attributed to an increase in ice shelf basal melting (Fig. 1a), then the associated latent heat should mostly be extracted from the coastal Southern Ocean.

This correction was omitted for two reasons. First, we maximise consistency with SOFIA tier-1 (antwater), tier-2, and most tier-3 simulations (including antwater-60s), which prescribe no latent heat correction [4]. Second, we avoid numerical instability problems in the sea-ice model: extracting a latent heat flux from the surface layer of coastal grid cells caused excessive sea-ice growth in the first few years of the SOFIA tier-3 antwater-lh experiment with 0.1 Sv freshwater forcing. We acknowledge the possibility that reduced sea-ice growth in a warming climate could have mitigated this problem. Ideally the latent heat flux should be applied over a range of depths (as would also be ideal for the native and additional freshwater fluxes), but subsurface salinity and latent heat fluxes are technically challenging to implement in NorESM2. However, it will be possible in the upcoming NorESM3 (developed for CMIP7), so this correction can be more conveniently investigated in future studies.

For now, it is nevertheless important to consider the potential influence of the associated latent heat correction, or lack of. To do this, we compare its magnitude with other high-latitude ocean heat fluxes during the freshwater-forced SSP5-8.5 simulation (ssp585-coulonfw) (Fig. S10). Specifically, we calculate two quantities: (i) the meridional heat flux integrated across a given latitude Φ (here, 60°S or 67°S), and (ii) the ocean surface heat fluxes integrated over the entire region south of Φ . Without any other forcing terms, these two quantities represent the total Southern Ocean heat exchange south of latitude Φ .

For both latitudes 60°S and 67°S, the negative (southwards) meridional heat flux is not quite balanced by the negative (upwards) surface heat flux (Fig. S10a). Overall the ocean heat transport into the Southern Ocean exceeds the surface heat flux out. This excess heat (Fig. S10b) drives the ocean warming evident in Figs. S12 and S14. In comparison to these exchanges, the missing latent heat flux becomes increasingly important as the climate warms, due to an increase in the freshwater forcing particularly after 2100. This is consistent with modelling by Moorman et al. [13], who find that latent heat loss to sub-shelf melting under present-day conditions dominates the coastal ocean heat budget, leading to an average 0.1°C cooling at 400 to 800 m depth – see their Fig. 3a.

As sub-shelf melt accelerates in the late 21st century, a proportional cooling effect corresponding to that identified by Moorman et al. [13] could clearly have an important impact on our simulated subsurface warming, which averages 0.6°C (ASBW) or 0.3°C (CDW south of 60°S) by 2070-2100 (Southern Ocean

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means in Figs. 4, S17, respectively). Hence, we speculate that our simulated subsurface ocean warming is likely an upper bound, and in reality will be moderated to some extent by latent heat-driven cooling of the coastal ocean around Antarctica. Fully accounting for the latent heat exchange should be a priority in future work with ice sheet freshwater forcing.

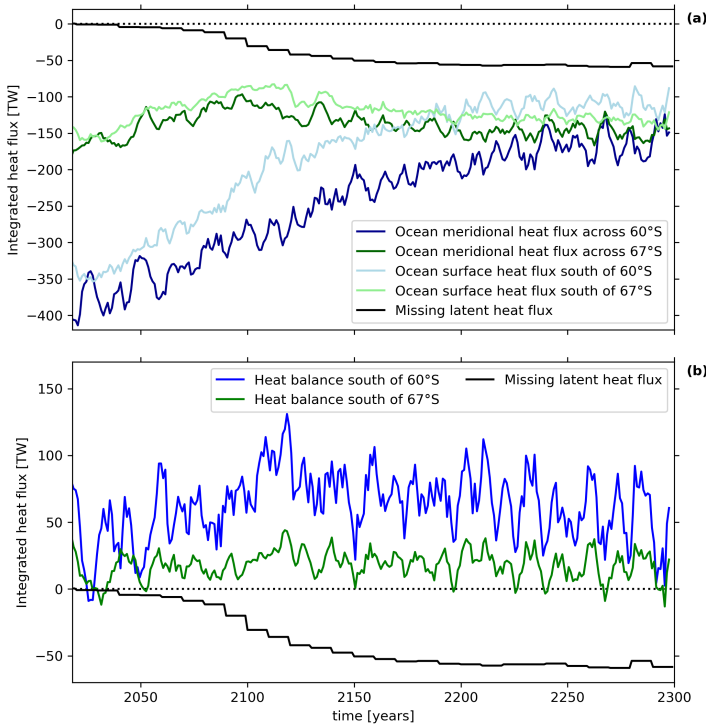


Fig. S10 Southern Ocean heat fluxes in the SSP5-8.5 simulation with added freshwater forcing (ssp585-coulon24). In (a) we show the individual heat exchanges, which are the integrated meridional heat flux across latitude Φ and integrated surface heat flux south of latitude Φ (here Φ is 60 or 67°S, shown as blue or green, respectively). These heat exchanges are compared with the total latent heat flux that is missing from the applied freshwater forcing (black). In (b) we plot the two heat exchanges as the net budget (surface heat flux minus meridional heat flux).

S6 Ice sheet tipping thresholds 553

In the main text we discuss whether our simulated Antarctic Shelf Bottom Water (ASBW) warming is likely to trigger tipping of major sectors of the Antarctic Ice Sheet. These sectors, of which we use Amundsen (West Antarctica) and Wilkes-Aurora (East Antarctica) as examples, are characterised by extensive regions grounded below sea-level and are vulnerable to rapid retreat driven by ocean warming. Several ice sheet modelling studies have estimated ocean temperature thresholds for tipping, as follows. Quoted thresholds are ocean temperature anomalies above present-day. 554
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- Golledge et al. [14] simulated collapse of main basins in West Antarctica but not in East Antarctica, under continued present-day climate. 563
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- Rosier et al. [15] estimated the temperature threshold for tipping of Pine Island Glacier as +1.2°C. We expect that collapse of Pine Island Glacier would lead to more widespread collapse of the Amundsen Sea sector. 565
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- Reese et al. [16] ran a 15-member ensemble of simulations under present-day climate. Collapse of main West Antarctic basins occurred in all 15 members, while there was no collapse of Wilkes-Aurora in any members. 568
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- Blasco et al. [17] estimated tipping thresholds of +0.5°C for West Antarctica, +3°C for Wilkes and +4°C for Aurora. 571
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- Chandler et al. [18] used a large ensemble of equilibrium simulations to show all basins are stable at -0.25°C, West Antarctic basins collapse at 0 to +0.25°C, and East Antarctic basins are still stable at +1.75°C. 573
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- van den Akker et al. [19] simulated collapse of main basins in West Antarctica but not in East Antarctica, under continued present-day climate. 576
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S7 Relevance of SSP5-8.5 results to less extreme warming scenarios

The CMIP6 SSP5-8.5 scenario we use for our warming experiments has been criticised as too pessimistic, and a less extreme top-end scenario has now been adopted for the forthcoming CMIP7 [20]. Given these developments, we comment here on the potential relevance of our results to less extreme warming scenarios.

Our choice of scenario was largely dictated by the freshwater flux projections from Coulon et al. [8], which are available for SSP1-2.6 and SSP5-8.5. In SSP1-2.6 there is relatively little change in projected freshwater fluxes, e.g., the 50th percentile increases by 374 Gt yr^{-1} (0.011 Sv) from the historical period to late 21st century. For comparison, if we estimate a 4 to 8% increase in Southern Ocean precipitation during that same period (see Fig. 4 in Bracegirdle et al. [21]), this would contribute an additional 0.02 to 0.03 Sv. Hence even in this low-end scenario we still expect Southern Ocean precipitation changes to lead ice sheet freshwater flux changes. We also expect even these relatively small precipitation changes to have some impacts that are qualitatively similar to those with stronger freshwater forcing. For example, Rye et al. [22] found the classic sea-ice expansion and SST cooling with as little as 200 Gt yr^{-1} (0.006 Sv) freshwater forcing under pre-industrial conditions. Both their approach and ours employ Earth system models with nominally 1° resolution ocean components. Therefore, we speculate that even in less extreme warming scenarios, the faster atmospheric response when compared to the deep ocean response will trigger the Southern Ocean stratification changes well in advance of the Antarctic freshwater flux changes. Similar to our ssp585-coulonfw experiment, this will lead to weak global impacts of Antarctic freshwater fluxes.

S8 Comparison between approaches with and without coupled Earth system - ice sheet models

In the main text we briefly discuss some main limitations of our NorESM2 simulations that lack a coupled Antarctic Ice Sheet. Primarily these relate to (i) lack of ice-ocean feedbacks, in particular the melt - subsurface warming feedback, and (ii) lack of realism with regards the distribution of freshwater fluxes and associated latent heat fluxes to the ocean. Although these issues can potentially be solved by coupled Earth system - Antarctic Ice Sheet models, the development of these models is generally at an early stage. Consequently, the realism of these models, in terms of resolution and/or ice-ocean coupling, in many cases still demands substantial compromises. This is highlighted in Table S1, where we compare representation of several aspects relevant to the implementation of ice sheet freshwater fluxes.

We then compare projected Antarctic freshwater fluxes from ice shelf basal melt as simulated by (i) stand-alone ice sheet modelling forced by Earth system models [8]; and (ii) coupled Earth system - ice sheet modelling (Fig. S11). The stand-alone ice sheet model projections are used in the present study as a basis for the additional forcing (see Methods), and the coupled model is from Siahaan et al. [23], at present representing the state-of-the-art in terms of the physical realism of Antarctic Ice Sheet - Southern Ocean coupling (see Table S1)

Table S1 Comparison of Antarctic Ice Sheet coupling in several models, including Earth system models (ESMs) [23, 24] and Earth system models of intermediate complexity (EMICs) [25–27]. We also include NorESM2-MM, used in the present study, which lacks a coupled Antarctic Ice Sheet (see Goelzer et al. [9] for the model description). Cell highlighting crudely indicates development stage. Green reflects a feature is present or well represented; reflects a feature that is absent or poorly represented; and yellow is intermediate.

	ESM	ESM with coupled Antarctic Ice Sheet			EMIC with coupled Antarctic Ice Sheet		
	This study	Sadal et al. 2025	Siahaan et al. 2022	Kreuzer et al. 2026	Li et al. 2024	Park et al. 2023	
Earth system model	NorESM2-MM	CESM1.2	UKESM	CM2Mc	Uvic-ESCM	LOVECLIM	
Coupled Antarctic Ice Sheet model	No	PSU3D	BISICLES	PISM	PSU3D	PSUIM	
Ocean resolution	1°	1°	1°	3°	3.6° lon x 1.8° lat		3°
Ocean vertical layers	70	60	75	28	19	20	
Ice sheet resolution	--	10 km	Adaptive 2 to 8 km		16 km	20 km	20 km
Ice sheet FWFs follow warming climate	Yes	Yes	Yes	Yes	Yes	Yes	
Spatial distribution of ice sheet FWFs	Idealised+coast	Coast	Realistic	Coast	Coast	Realistic	
Vertical distribution of ice sheet FWFs	Surface	Surface	Realistic	Surface	Surface	Surface	
Associated latent heat extracted	Partial	Yes	Yes	Yes	Partial	Yes	
Depth of ocean T passed to ice sheet	--	400 m	All	Deepest level	400 m	Subsurface	
Subshelf cavities in ESM	No	No	Yes	No	No	No	
Ocean sees evolving ice sheet geometry	No	No	Yes	No	No	No	
Warming scenarios reported	SSPs 8-5	RCPs 4.5, 8.5	SSPs 1-1.9, 5-8.5	2xCO2	SSPs 2-4.5, 5-8.5	SSPs 1-1.9, 2-4.5, 5-8.5	

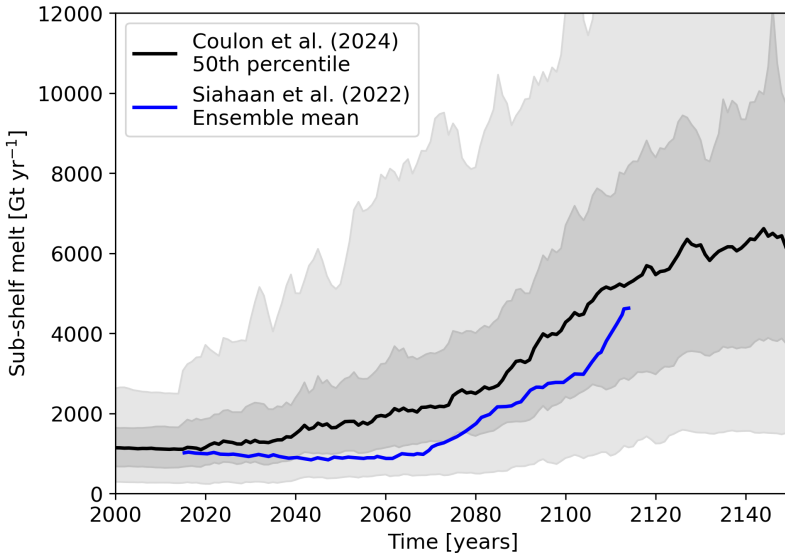


Fig. S11 Comparison between projected freshwater fluxes from sub-shelf melting in stand-alone ice sheet modelling [8] and a coupled Earth system model - ice sheet model [23]. The Coulon et al. [8] 50th percentile (black line) contributed to the freshwater fluxes in our study, and is shown here with 5th-95th (light grey) and 25th-75th (dark grey) percentile ranges. These are based on the Kori-ULB ice flow model [28], which was forced with SSP5-8.5 projections from four Earth system models (MRI-ESM2.0, IPSL-CM6A-LR, CESM2-WACCM, and UKESM1.0-LL). The coupled Earth system - ice sheet model is UKESM1.0-ice [29], which includes the BISICLES ice sheet model [30], and here we plot the ensemble mean (blue line) of a 4-member ensemble. Although UKESM1.0 was included as one of the four ESMs chosen to force Kori-ULB, the two studies are otherwise independent and the ice sheet models are substantially different in their numerical representation of ice sheet processes. For example if comparing Kori-ULB vs BISICLES: an 8 or 16 km spatial grid vs adaptive grid; a range of sub-shelf circulation and melt parameterisations vs explicit representation within an ocean model; power-law vs Tsai basal friction. Each of these could substantially influence ice sheet response to ocean warming. Despite the clear differences in the approaches of these two studies, we find their projected freshwater fluxes from sub-shelf melt are remarkably similar to 2110. Initially this similarity is inevitable from the initialisation/calibration to match historical ice loss and present-day ice geometry. However, if ice-ocean feedbacks are important we could have expected wider divergence between the stand-alone and coupled approaches. Instead, their similarity provides some support for employing Antarctic freshwater projections as a forcing in Earth system models lacking an interactive Antarctic Ice Sheet.

S9 Additional results

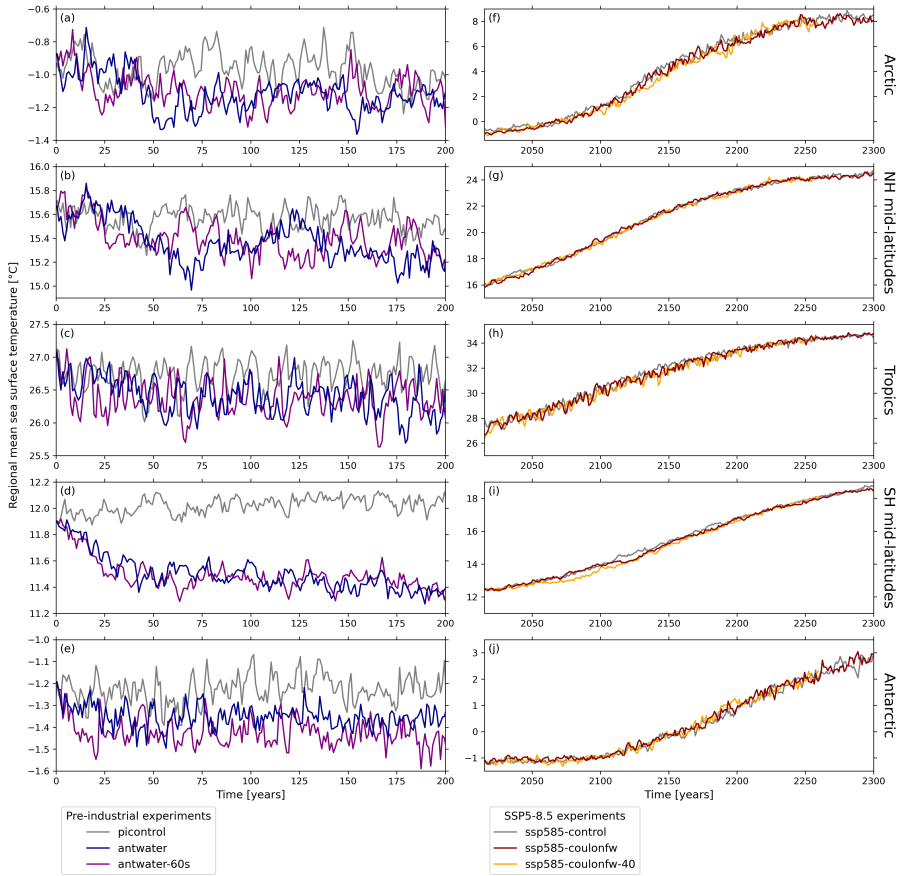


Fig. S12 Regional mean sea surface temperatures in simulations with and without additional Antarctic freshwater forcing. Left panels show the pre-industrial simulations (picontrol, antwater and antwater-60s); right-hand panels show SSP5-8.5 scenarios (ssp585-control, ssp585-coulonfw, ssp585-coulonfw-40). For SST anomalies (hosing - control), see Fig. 2.

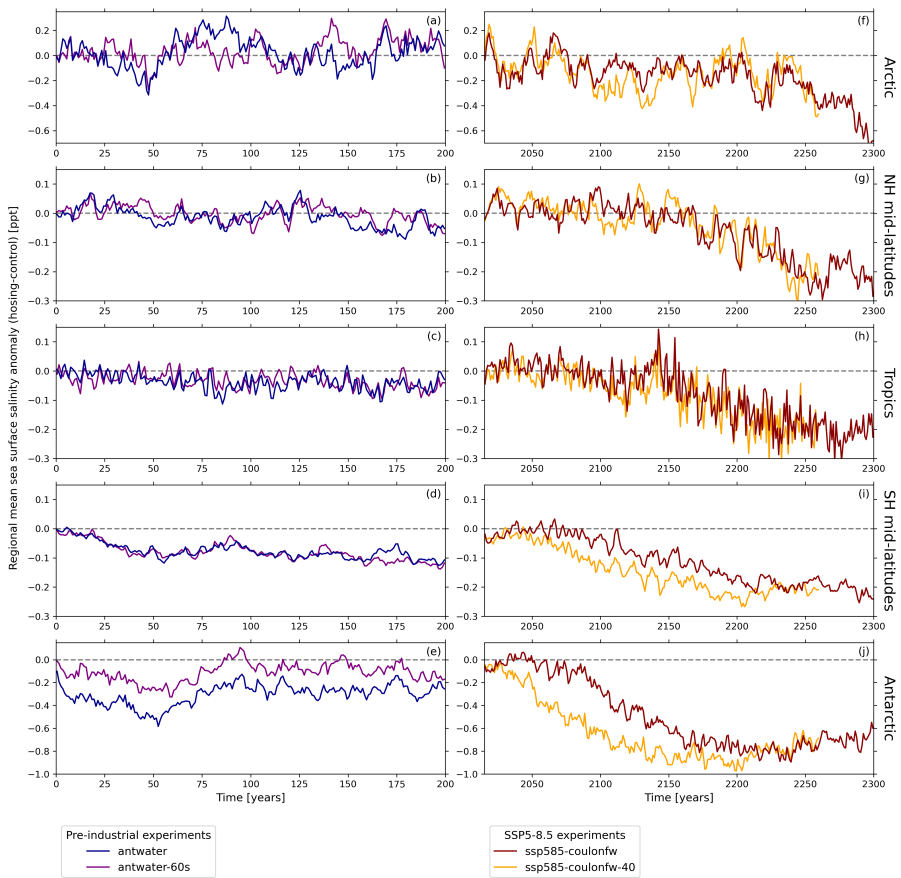


Fig. S13 Regional mean sea surface salinity anomalies in simulations with additional Antarctic freshwater forcing. Anomalies are relative to respective controls without additional freshwater forcing. Left panels show the pre-industrial simulations (antwater and antwater-60s) as anomalies relative to picontrol; right-hand panels show SSP5-8.5 scenarios (ssp585-coulonfw, ssp585-coulonfw-40) as anomalies relative to ssp585-control.

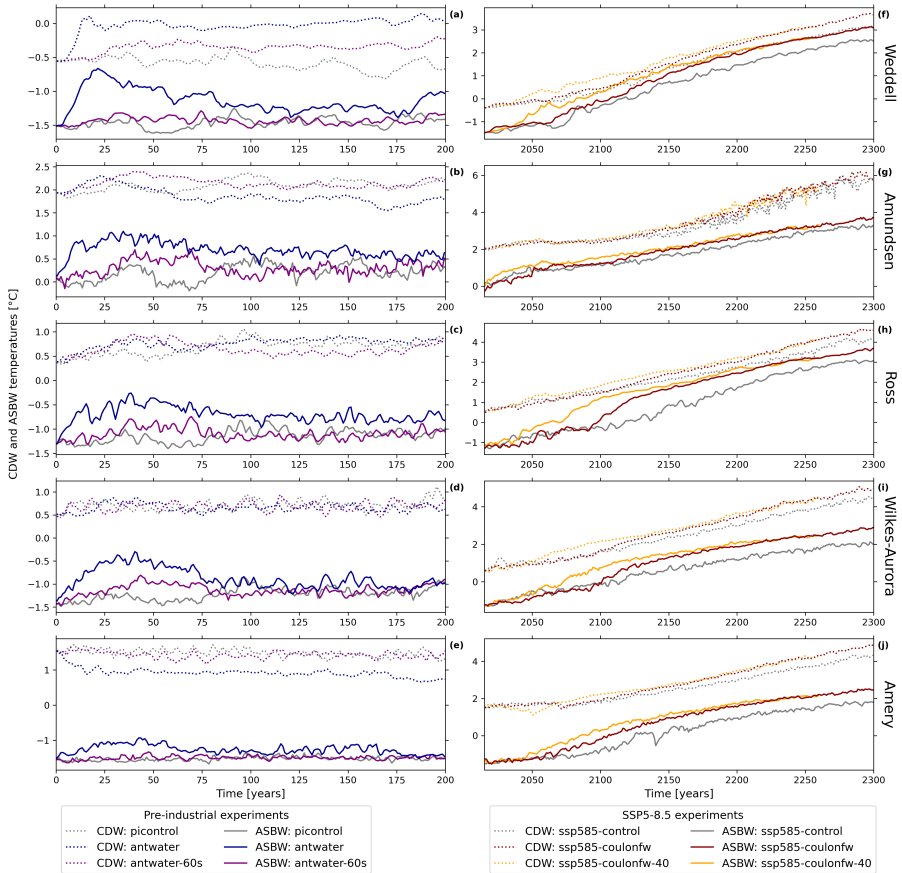


Fig. S14 Circumpolar Deep Water (CDW; dotted lines) and Antarctic Shelf Bottom Water (ASBW; solid lines) temperatures in simulations with and without additional Antarctic fresh-water forcing. Left panels show the pre-industrial-based simulations (picontrol, antwater and antwater-60s); right-hand panels show SSP5-8.5 scenarios (ssp585-control, ssp585-coulonfw, ssp585-coulonfw-40). CDW and ASBW temperatures are diagnosed following Schmidtko et al. [11] and are plotted as regional averages south of 60°S over the five sectors (Weddell, Amundsen Sea, Ross Sea, Wilkes-Auroa basins, Amery) shown in Fig. 4.

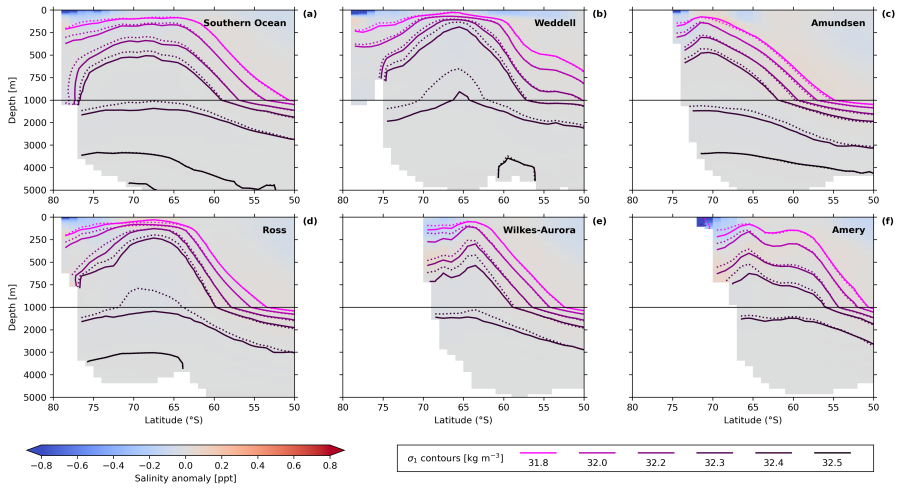
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Fig. S15 Vertical profiles of salinity averaged over the period 2100-2150 in the warming experiment with additional freshwater fluxes (ssp585-coulonfw). Salinities are anomalies relative to ssp585-control, in the Southern Ocean (a) and in five sectors (b-f, sector locations are shown in Fig. 4). Contours show potential density σ_1 with (solid) and without (dashed) additional freshwater.

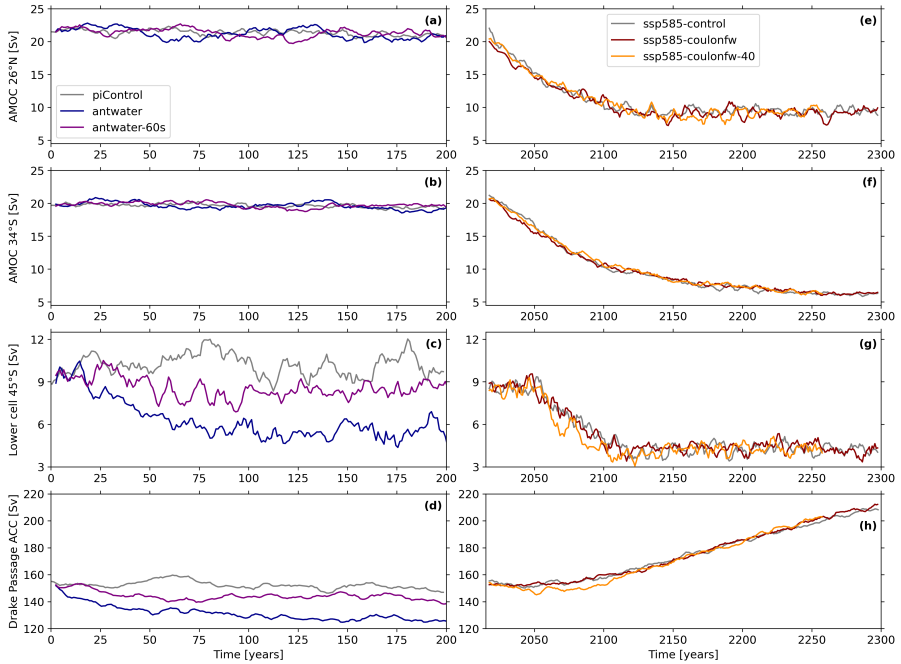


Fig. S16 Circulation changes in simulations with and without additional Antarctic freshwater forcing. Left panels (a-d) show the pre-industrial simulations (picontrol, antwater and antwater-60s); right-hand panels (e-h) show SSP5-8.5 scenarios (ssp585-control, ssp585-coulonfw, ssp585-coulonfw-40).

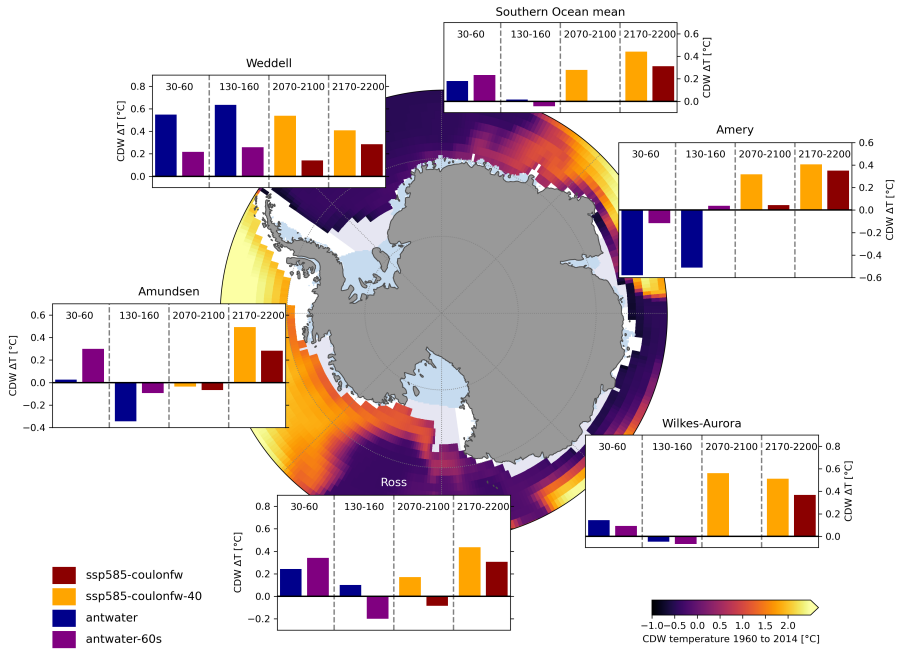


Fig. S17 Simulated circumpolar deep water (CDW) temperatures and temperature anomalies under different climates. Following Ref. [11], CDW is diagnosed as the temperature maximum below the winter water layer, in water deeper than 1500 m (in shallower water on the shelf, see the equivalent fig. 4 for Antarctic shelf bottom water). The shaded map shows CDW temperature in the historical simulation [9] averaged from 1960 to 2014. Insets show CDW temperature anomalies in key sectors of the Southern Ocean as indicated by the shaded regions. The three experiments shown in the insets are: antwater (blue bars) averaged over years 30 to 60 and 130 to 160, relative to piControl; and ssp585-coulonfw (red) and ssp585-coulonfw-40 (orange) averaged over years 2070-2100 and 2170-2200, relative to ssp585-control.

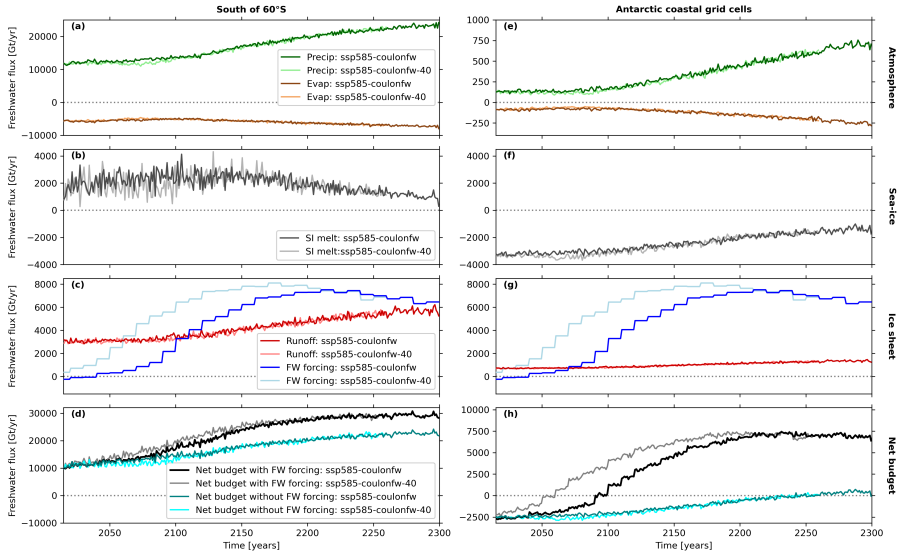


Fig. S18 Individual components of the Southern Ocean surface freshwater budget, in the SSP5-8.5 experiment with Coulon et al. [8] freshwater fluxes (ssp585-coulonfw) and in the sensitivity experiment with earlier freshwater fluxes (ssp585-coulonfw-40). Fluxes are grouped by domain: atmosphere (precipitation, evaporation) (a,e), sea ice melt (b,f), and ice sheet (runoff simulated by NorESM2, and the additional freshwater forcing) (c,g). Fluxes are annual means, which smooth substantial seasonal variability, particularly in the sea-ice melt/freeze. We integrate each flux over two regions: the Southern Ocean south of 60°S (a-d), and the coastal grid cells where we add freshwater (e-h). The total freshwater budget obtained by summing all components, either with (black) or without (cyan) the additional freshwater forcing, is shown in the bottom row (d,h). Note that the total simulated runoff from the ice sheet is smaller in the coastal-only cells than in the region south of 60°S because the ice sheet runoff is distributed across a coastal strip more than one grid cell wide (illustrated in Fig. S4).

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