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Key Points:

- Up to a four-fold increase in the magnitude of Antarctic freshwater discharge is projected by 2300 for an extreme climate scenario
- We project a shift in the form and depth of Antarctic freshwater export, as sub-shelf (and potentially surface) melt outpaces solid calving
- Our key findings align with satellite-based observations and are robust despite uncertainties in climate and ice-dynamical response

Supporting Information:

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

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Future Freshwater Fluxes From the Antarctic Ice Sheet

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Abstract Surface freshening of the Southern Ocean driven by meltwater discharge from the Antarctic ice sheet has been shown to influence global climate dynamics. However, most climate models fail to account for spatially and temporally varying freshwater inputs from ice sheets, introducing significant uncertainty into climate projections. We present the first historically calibrated projections of Antarctic freshwater fluxes (sub-shelf melting, calving, and surface meltwater runoff) to 2300 that can be used to force climate models lacking interactive ice sheets. Our findings indicate substantial changes in the magnitude and partitioning of Antarctic freshwater discharge over the coming decades and centuries, particularly under very-high warming scenarios, driven by the progressive collapse of the West Antarctic ice shelves. We project a shift in the form and location of Antarctic freshwater sources, as liquid sub-shelf melting increases under the two climate scenarios considered, and surface meltwater runoff could potentially become a dominant contributor under extreme atmospheric warming.

Plain Language Summary Melting Antarctic ice releases freshwater into the Southern Ocean, which can have profound impacts on the regional and global climate. In a warming world, the freshwater input into the ocean is expected to increase. However, climate models often poorly represent ice-sheet mass loss, leading to uncertainty in climate predictions. This study provides new projections of Antarctic freshwater discharge, including contributions from melting at the base of the floating ice shelves, iceberg calving and surface meltwater runoff, up to the year 2300. These projections can be integrated into climate models that lack interactive ice sheets. The results indicate substantial changes in the amount and nature of freshwater discharge from Antarctica in the coming decades and centuries, especially under extreme warming scenarios. We show that liquid melting beneath the floating ice shelves will increase under the two climate scenarios considered, and that surface meltwater runoff could become a major source of freshwater under very high atmospheric warming conditions.

1. Introduction

The Antarctic ice sheet gains mass from snow accumulation in its interior (~2500 Gt yr^{-1}; Mottram et al., 2021) and loses mass mainly through ice discharge across the grounding line into the ocean, where ice shelves form. These ice shelves, the floating extensions of the ice sheet in direct contact with the ocean, progressively melt or calve icebergs, releasing freshwater into the Southern Ocean. Currently, this freshwater discharge primarily occurs through ocean-induced basal melting underneath the ice shelves (liquid discharge) and iceberg calving at the ice-shelf front (solid discharge). More specifically, approximately half of the ice-sheet surface mass gain is lost through oceanic melting before reaching the calving front (Adusumilli et al., 2020; Davison et al., 2023; Depoorter et al., 2013; Greene et al., 2022; Paolo et al., 2023). Basal melting under ice shelves is an important source of freshwater at depth, influencing Antarctic Bottom Water formation (Silvano et al., 2018), a key component of the global ocean circulation. Icebergs, on the other hand, transport freshwater far beyond the continent, slowly releasing it into the ambient ocean. This contributes to both thermodynamic and dynamic effects on the ocean, which feedback into the atmosphere and influence climate variability (Schloesser et al., 2019). Although all Antarctic ice shelves experience surface melting (Trusel et al., 2013, 2015), only a small amount of mass is currently lost by surface meltwater runoff (Bell et al., 2017). Further minor freshwater contributions from Antarctica are subglacial melt by geothermal and deformational heat underneath the grounded ice sheet (estimated at 65 Gt yr^{-1}; Pattyn, 2010), as well as blowing snow that is transported by the wind from the ice-sheet margin onto the ocean (Lawrence et al., 2023).

Surface freshening of the Southern Ocean has been observed in recent decades (de Lavergne et al., 2014). This could in part be due to the Antarctic ice sheet and ice shelves losing mass at an accelerating rate, particularly in

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West Antarctica (Adusumilli et al., 2020; Davison et al., 2023; Otosaka et al., 2023; Smith et al., 2020), releasing increasing amounts of meltwater into the ocean. Antarctic mass loss is projected to further accelerate in the future (Edwards et al., 2021; Payne et al., 2021; Seroussi et al., 2020, 2024), making the resulting freshwater input a major contributor to global mean sea-level rise in the coming decades and centuries (Fox-Kemper et al., 2021). Especially, Antarctic ice-shelf basal melt, iceberg calving, and surface runoff are all expected to increase in a warming climate (Coulon, Klose, et al., 2024; Golledge et al., 2019; Trusel et al., 2015).

Such meltwater and ice discharge from the Antarctic ice sheet have been shown to impact global climate dynamics and influence the trajectory of future climate change (Bronselaer et al., 2018; Golledge et al., 2019; Purich & England, 2023; Sadai et al., 2020). This underscores the need to integrate these feedbacks into climate model projections. However, fully coupled climate—ice sheet models have only recently been developed (Pelletier et al., 2022; Siahaan et al., 2022), and most existing climate models do not have interactive ice sheets. Even for CMIP6 models, it is either assumed that ice sheets are in mass balance, or that discharge from the ice sheets remains constant in time (Swart et al., 2023). As a result, most climate projections lack a representation of spatiotemporal trends in ice-sheet freshwater fluxes and, consequently, the impact of (changes in) meltwater and ice discharge from Antarctic ice sheets and ice shelves on the global climate system is not reliably represented. Those who have addressed the critical question of understanding the future influence of Antarctic meltwater on regional and global climate have often used idealized freshwater perturbation experiments (Swart et al., 2023), for example, by approximating the future spatiotemporal evolution of the Antarctic freshwater sources in a warming climate by scaling of observed ratios (e.g., Gorte et al., 2023; Swart et al., 2023; Thomas et al., 2023). This introduces unquantified biases and uncertainties into future climate and sea-level projections (Bronselaer et al., 2018; Golledge et al., 2019; Purich & England, 2023; Sadai et al., 2020). Furthermore, given the significant uncertainty in projected Antarctic mass loss (Fox-Kemper et al., 2021), it is crucial to explore the response and sensitivity of the climate system to a range of realistic (in space and time) changes in meltwater amounts in a warming climate (Purich & England, 2023).

To address this, we present historically calibrated projections of the spatial variability of sub-shelf melt, iceberg calving, and surface runoff from the Antarctic ice sheet under two climate scenarios (a low and a very-high emission scenario) from present-day to 2300. These distributions of future Antarctic freshwater fluxes were produced by considering a wide range of climate and ice-dynamical uncertainties, including ice-shelf melting, iceberg calving, basal sliding and ice damage. The resulting data set hence provides estimates of the future spatiotemporal evolution of the main Antarctic freshwater sources in a warming climate. It can be used to force climate models that do not include interactive ice sheets, improving their representation of freshwater export and thus representing a significant advancement in accounting for the missing freshwater forcing associated with future Antarctic ice loss in climate projections.

2. Methods

Our Antarctic freshwater flux projections are derived from a 240-member ensemble of historically calibrated standalone ice-sheet model projections, comprehensively exploring a range of uncertain processes and parameters (Coulon, Klose, et al., 2024, see Table S1 in Supporting Information S1). All simulations were generated with the Kori-ULB ice flow model (Coulon, Klose, et al., 2024; Kazmierczak et al., 2024), which is based on the former f.ETISh model (Pattyn, 2017). The 1990–2300 pan-Antarctic simulations are forced by atmospheric and oceanic projections inferred from a subset of models from the sixth phase of the Coupled Model Intercomparison Project (CMIP6) under the low- and very high-emission scenarios SSP1-2.6 and SSP5-8.5. Although more climate scenarios are available within CMIP6, only a few models and scenarios are available until 2300.

To resolve sub-shelf processes and generate basal melt rates in such a standalone framework, we rely on a panel of physically based parameterizations that approximate the local thermal forcing based on far-field ocean properties provided by the General Circulation Models (GCMs; Jourdain et al., 2020; Favier et al., 2019; Reese et al., 2018; Lazeroms et al., 2019, Table S1 in Supporting Information S1). Similarly, freshwater discharge through iceberg calving is parameterized using semi-empirical calving laws (Morlighem et al., 2016; Pollard et al., 2015; Wilner et al., 2023). These calving laws, and in particular crevasse-depth laws, do not always produce realistically looking ice fronts and more work on iceberg calving is therefore needed. Finally, surface melt and runoff are determined within the ice-sheet model as a function of monthly air temperatures and precipitations from GCMs, using a positive degree-day (PDD)-based melt-and-runoff model to capture the basic physical processes of refreezing versus runoff in the snow column (Coulon, Klose, et al., 2024, see Supporting Information S1). PDD-based projections have shown good agreement with climate models in terms of both pattern and magnitudes (Coulon, Klose, et al., 2024). The melt–elevation feedback is incorporated through the use of a lapse rate correction of the air temperatures with changes in ice-sheet surface elevation. In turn, near-surface air temperatures alter the amount of rainfall as well as the surface meltwater production and refreezing, so that the evolving ice-sheet topography dynamically alters the surface mass balance. Estimates of subglacial meltwater discharge across the grounding line and of blowing snow are not included here. Initially, the simulated rate of subglacial meltwater production underneath the grounded ice sheet is around 50 Gt yr^{-1}, which is comparable to Pattyn (2010). This rate increases to up to 200 Gt yr^{-1} during the model runs. While this amount is not negligible compared to the other freshwater fluxes, it remains difficult to constrain this as the amount of subglacial meltwater that reaches the sub-shelf cavities is unknown.

Our ice-sheet simulations start in 1990 to allow for comparisons with observations over the satellite era (Davison et al., 2023; Otosaka et al., 2023). Initial ice-sheet conditions are provided by a spin-up simulation nudging toward present-day ice-sheet geometry (Bernales et al., 2017; Coulon, Klose, et al., 2024; Pollard & DeConto, 2012a) from Bedmachine v3 (Morlighem, 2022). A historical simulation over the period 1990–2014 is then produced using surface mass balance and air temperature conditions based on the Regional Atmospheric Climate MOdel (RACMO2.3p2; van Wessem et al., 2018) and a present-day climatology of ocean temperature and salinity fields of the coastal ocean around Antarctica taken from Jourdain et al. (2020). This two-step approach allows us to construct a present-day ice-sheet state that reproduces both the observed geometry and changes in mass balance. The historical calibration then consists of a Bayesian calibration of our ensemble, which results in the most likely (posterior) distribution of input parameters given measured mass balance estimates and associated errors. Here we use regional mass balance estimates from the latest Ice Sheet Mass Balance Inter-comparison Exercise (IMBIE; Otosaka et al., 2023, see Supporting Information S1 and Table S2 in Supporting Information S1), which is an independent data set not used in the spin-up process. This allows a higher predictive weight to be attributed to model simulations that closely reproduce observations (Coulon, Klose, et al., 2024; Nias et al., 2019; Wernecke et al., 2020).

As of 2015, changes in atmospheric and oceanic properties derived from four CMIP6 climate models (MRI-ESM2-0, IPSL-CM6A-LR, CESM2-WACCM, and UKESM1-0-LL) are used as forcing until the year 2300. The forcing applied is derived from the Shared Socioeconomic Pathway (SSP) 1–2.6 and 5–8.5 scenarios to estimate the possible evolution of Antarctic freshwater fluxes in response to a wide range of climate forcings. Similar to Coulon, Klose, et al. (2024); Klose et al. (2024), climate forcing is implemented by applying atmospheric and oceanic anomalies to present-day climatologies, and detailed in Supporting Information S1.

To account for parametric uncertainty in our projections, we designed a perturbed parameter ensemble including 12 uncertain model parameters (see Table S1 in Supporting Information S1) that govern ice dynamics (e.g., calving, basal sliding, ice-shelf damage), ice-climate interactions (e.g., sub-shelf melting, surface melt, and runoff) and climate forcing. We adopted a two-step approach using Latin hypercube sampling to generate a comprehensive ensemble of 240 simulations. First, we generated a 120-member ensemble by uniformly sampling the multi-dimensional parameter space. Based on the resulting posterior distributions, we refined the parameter space to encompass the highest probability densities, adjusted to cover 75% cumulative probability. The posterior distributions of the parameter space for the final 240-member ensemble are displayed in Figure S1 in Supporting Information S1.

3. Freshwater Fluxes Projections

We provide historically calibrated yearly estimates of freshwater export from the Antarctic ice sheet from 1990 to 2300 separated into 27 drainage basins, with quantified uncertainties. Here, we analyze the results by aggregating each flux component over 5 regions of interest (Weddell Sea, Indian Ocean, western Pacific Ocean, Ross Sea and Amundsen/Bellingshausen Sea; Figure 1). However, the data for the 27 basins is available (Coulon, De Rydt, et al., 2024a).

3.1. Hindcasts Over the Observational Period

The 1990–2020 average of the calibrated median total freshwater discharge from the Antarctic ice sheet is ~3140 Gt yr^{-1} (Table 1). If the ice sheet were in steady state, this freshwater discharge should be balanced by the total

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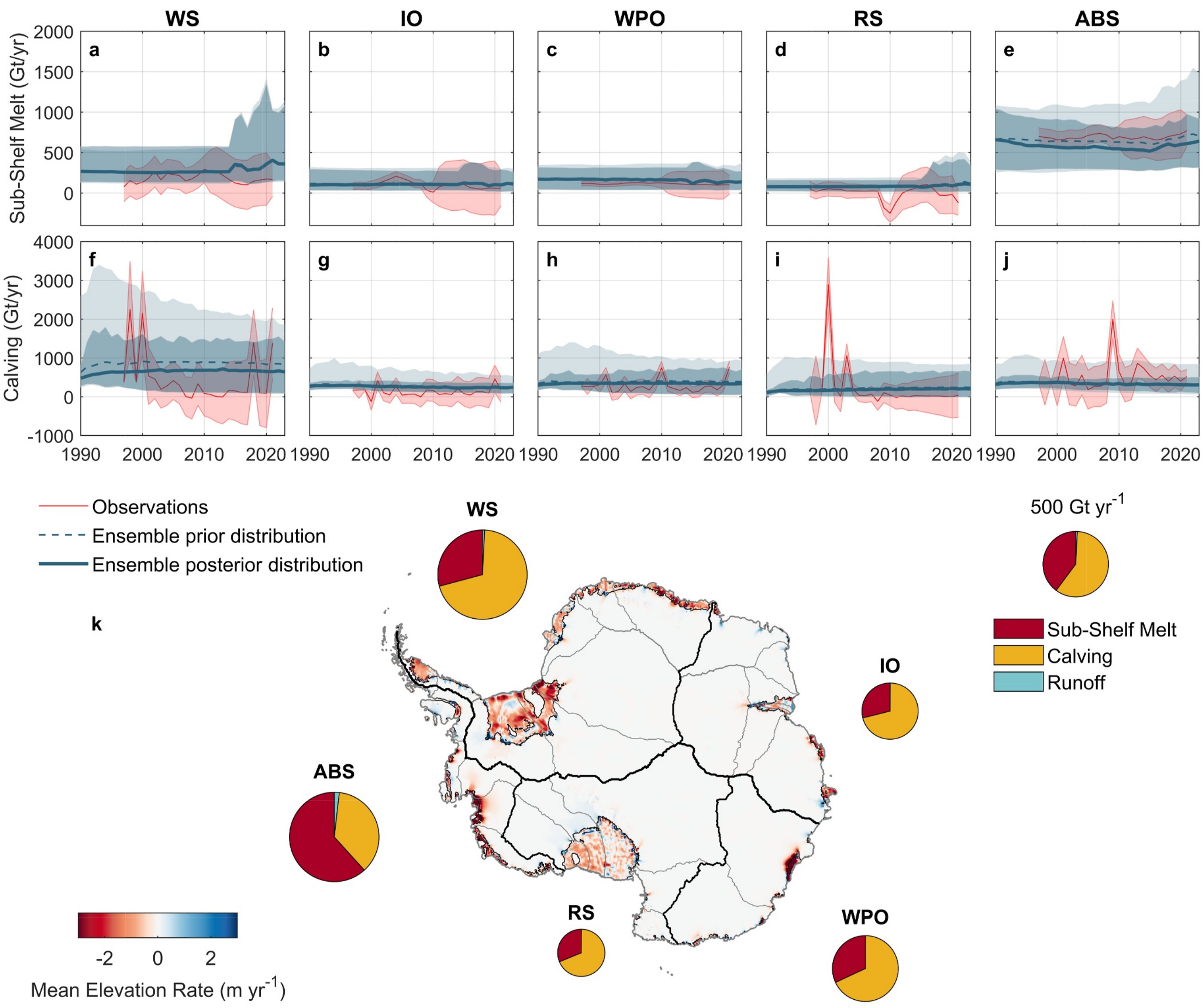

Figure 1. Modeled Antarctic freshwater fluxes over the historical period (1990–2020). (a–j) Evolution of the regional sub-shelf melt (a–e) and calving (f–j) fluxes over the historical period and comparison with observational estimates from Davison et al. (2023) (red lines - shaded areas represent the uncertainty of the observations, shown as ± 1.64 σ, with σ the observational error) for the Weddell Sea (WS), Indian Ocean (IO), Western Pacific Ocean (WPO), Ross Sea (RS) and Amundsen and Bellingshausen Sea (ABS) sectors. Dashed lines and pale blue-shaded areas represent the ensemble prior distributions (medians and 5%–95% probability intervals) while solid lines and dark blue-shaded areas represent the posterior (Bayesian calibrated medians and 5%–95% probability intervals) distributions. (k) Bayesian calibrated median regional freshwater fluxes averaged over the 1990–2020 period overlain on the 1990–2020 ensemble calibrated mean elevation rate. The boundaries of the 27 drainage basins and the 5 sectors discussed in this study are shown in gray and black, respectively.

surface accumulation. A difference between both leads to an ice sheet imbalance, with a higher discharge leading to ice mass loss. According to our model estimates, this loss is about six times the average Antarctic contribution to global mean sea-level rise over the observational period as reported in Otosaka et al. (2023), showing that much of the ice and water discharge is not contributing to sea level rise. The dominant contributor to this total mass loss is solid ice discharge from iceberg calving (59%), while liquid discharge through sub-shelf melting accounts for 40% of the total freshwater export. The modeled present-day pattern of sub-shelf melt rates is shown in Figure S2 of Supporting Information S1. In contrast, surface runoff remains a negligible contributor, accounting for less than 1% of the freshwater entering the Southern Ocean, consistent with estimates from regional climate models (Figure S3 in Supporting Information S1). This partitioning of the pan-Antarctic freshwater export aligns well with satellite-based estimates (Davison et al., 2023).

Table 1
Antarctic Freshwater Fluxes $(\mathrm{Gt\ yr^{-1}})$ *Estimates Under Low- and Very-High Emission Scenarios*

	Time periods				
	1990–2020	2040–2050	2090–2100	2190–2200	2290–2300
Observations (Davison et al., 2023)					
Sub-shelf melt	1086.2 [711.8, 1460.6]				
Iceberg calving	1542.0 [638.6, 2445.5]				
Scenario SSP1-2.6					
Total	3139.0 [1312.0,5359.0]	3767.0 [1209.3,6468.1]	3513.6 [1128.9,7243.7]	3265.9 [1055.9,8372.1]	3869.8 [939.7,9551.6]
Sub-shelf melt	1242.4 [639.0,1878.1]	1866.6 [908.9,3061.8]	1888.9 [964.3,4046.1]	1780.0 [977.0,4651.2]	2360.0 [946.7,5240.1]
Iceberg calving	1873.1 [664.6,3413.0]	1843.5 [282.3,3203.3]	1548.6 [140.0,2864.5]	1408.7 [55.0,3056.5]	1398.0 [0,3230.5]
Surface runoff	23.5 [8.5,67.9]	57.0 [18.2,202.9]	76.0 [24.5,333.1]	77.2 [24.0,664.5]	111.9 [23.5,1081.0]
Scenario SSP5-8.5					
Total	3140.6 [1312.9,5373.3]	4008.0 [1322.9,6876.0]	6273.0 [2296.6,12,630.6]	12,650.7 [5994.2,28,995.2]	14,248.8 [5635.0,29,670.1]
Sub-shelf melt	1250.5 [643.7,1905.2]	2061.9 [1036.1,3400.4]	4048.9 [1924.7,7654.9]	6991.9 [3657.0,15,674.8]	6348.8 [2753.6,10,428.4]
Iceberg calving	1865.3 [660.6,3390.2]	1842.7 [250.3,3155.1]	1532.2 [157.3,3.47.0]	2006.5 [303.3,6030.7]	2175.3 [358.8,5534.5]
Surface runoff	24.8 [8.7,77.9]	103.4 [36.5,320.5]	691.9 [214.6,1928.8]	3652.2 [2033.9,7289.7]	5724.8 [2522.6,13,707.1]

Note. Bayesian calibrated medians of the total Antarctic meltwater discharge and the respective contributions of sub-shelf melting, iceberg calving, and surface meltwater runoff for the 1990–2020, 2090–2100, 2190–2200, and 2290–2300 time periods under SSP1-2.6 and SSP5-8.5. Values in brackets for the scenarios SSP1-2.6 and SSP5-8.5 are the Bayesian calibrated 5th–95th percentiles (likely range). Values in brackets for the observations are shown as the estimates ± 1.64 σ, with σ the observational error.

According to our model results, the majority of the pan-Antarctic freshwater discharge over 1990–2020 occurs in the Weddell and Amundsen/Bellingshausen Seas (Figure 1). Iceberg calving is the dominant contributor to freshwater discharge in all regions except the Amundsen/Bellingshausen Sea, where the Bayesian calibrated median sub-shelf melt contributes to 62% of the total freshwater flux. Runoff hindcasts are negligible in all 5 regions (with the highest median contribution of 2% in the Amundsen/Bellingshausen Sea, originating from the Antarctic Peninsula; see Figure S3 in Supporting Information S1). The partitioning of freshwater flux components for different regions is also consistent with observational estimates (Davison et al., 2023; Figures 1a–1j).

When equal weight is assigned to all simulations, our ensemble displays a large spread in freshwater fluxes over the historical period due to the sampled parametric uncertainty (Figures 1a–1j). However, attributing a lower weight to parameter choices that are not in line with observations through the Bayesian calibration reduces the spread of the posterior distribution compared to the prior, thereby reducing uncertainty in the model hindcasts and increasing confidence in the projections through 2300. In particular, the posterior distributions of parameters related to sub-shelf melting, iceberg calving, and ice-shelf damage are most affected by the calibration process (Figure S1 in Supporting Information S1). Similarly, our modeled spatial pattern of mass loss over the historical period (Figure 1k) shows rapid grounded-ice mass losses around the margins of the ice sheet, particularly in the Amundsen Sea Embayment and the Aurora Basin in East Antarctica, in line with observations over the past decades (Smith et al., 2020; Rignot et al., 2019; Nilsson et al., 2022, see Figure S4 in Supporting Information S1).

3.2. Projections to 2300

By 2100, we project an increase in total pan-Antarctic freshwater fluxes of 12% under SSP1-2.6, and of 100% under SSP5-8.5 (Table 1), mostly in the Amundsen/Bellingshausen and Weddell Seas (Figure 2). Sub-shelf melt (and to a lesser extent surface melt) increases under both scenarios during the first half of this century, leading to a slight decrease in iceberg calving fluxes. Consequently, sub-shelf melting is projected to become the dominant freshwater contributor by 2100, surpassing calving and shifting the balance from predominantly solid to liquid freshwater export. This transition is expected to occur by around 2050 under both scenarios. Meltwater runoff remains negligible under SSP1-2.6 but starts to increase in the second half of the century under SSP5-8.5, reaching about 10% of the total freshwater discharge by the end of the century.

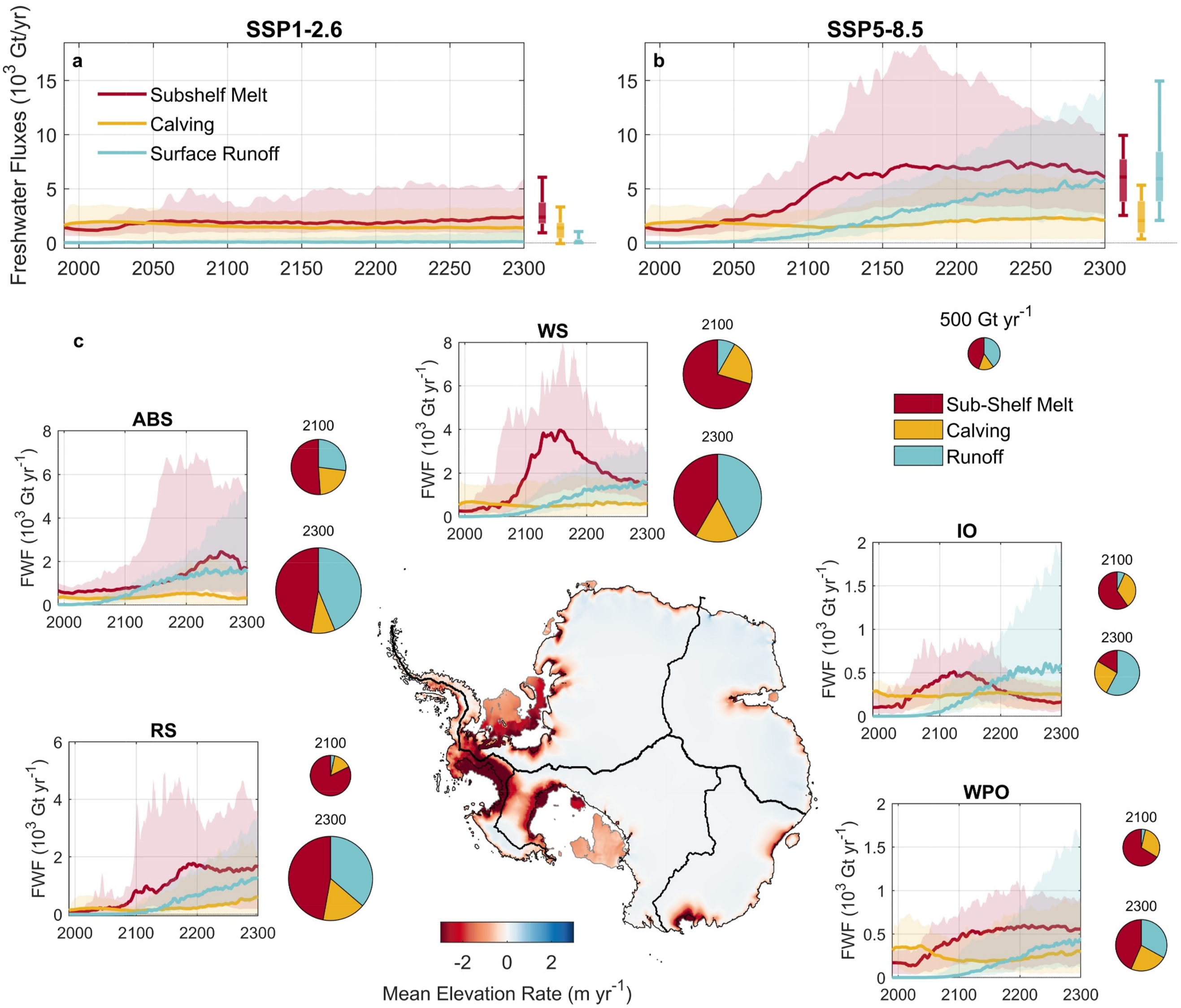

Figure 2. Calibrated probabilistic projections of the Antarctic freshwater fluxes until the year 2300. (a–b) Evolution of the ensemble projected pan-Antarctic freshwater fluxes (sub-shelf melt, calving, and runoff) for the 1990–2300 period under SSP1-2.6 (a) and SSP5-8.5 (b). Solid lines and shaded regions show the medians and 5%–95% probability intervals ($N = 240$ per SSP scenario), with 5-year running average applied. Boxes and whiskers show [5, 25, 50, 75, 95] percentiles at year 2300. (c) Evolution of the ensemble projected regional freshwater fluxes for the 1990–2300 period under an SSP5-8.5 scenario overlain on the 1990–2300 ensemble calibrated mean elevation rate. Note the differing scales on the *y*-axes. Pie charts represent the median regional freshwater fluxes averaged over the 2090–2100 and the 2290–2300 periods.

While sub-shelf melt fluxes are predicted to plateau in the second half of this century under the low-emission scenario, they keep increasing under SSP5-8.5, reaching twice their 2040–2050 magnitude by 2100 (Table 1). This difference in the amplitude of sub-shelf melting between the two emission scenarios is especially pronounced in the Weddell Sea, where fluxes under SSP5-8.5 reach four times those of SSP1-2.6 by 2100 (see Figure S5 in Supporting Information S1). This is likely due to the Ronne-Filchner ice shelf transitioning from a cold to a warm cavity (Hellmer et al., 2017; Naughten et al., 2021). In addition, the unique partitioning of the freshwater sources in the Amundsen/Bellingshausen Sea under SSP5-8.5 is noteworthy (Figure 2). Unlike other regions, by 2100, freshwater sources in this sector are characterized by a substantial increase in surface runoff, representing almost 30% of the total (Bayesian calibrated median), and mainly originating from the Antarctic Peninsula side of the Bellingshausen Sea. In the other sectors, meltwater runoff remains the smallest median contributor to the freshwater discharge, never exceeding 10%.

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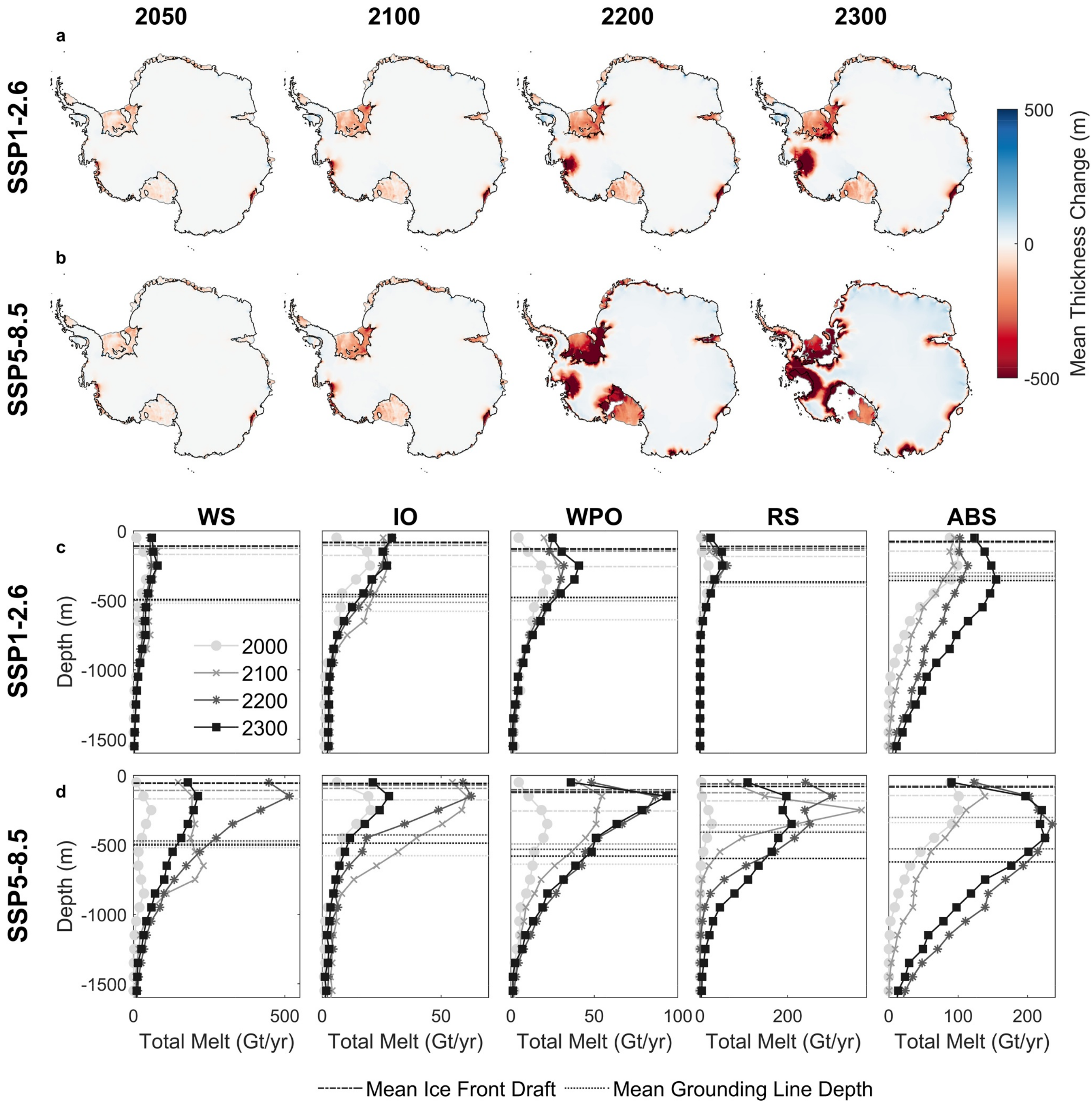

Figure 3. Projected changes in Antarctic geometry until 2300 under low- and very-high emission scenarios. (a–b) Mean ice thickness change in years 2050, 2100, 2200, and 2300 under the shared socio-economic pathways (SSP) 1–2.6 (a) and 5–8.5 (b). The mean thickness change at a given point in time is computed using the Bayesian calibrated mean of the ensemble ($N = 240$ per SSP scenario). Black and gray lines show the ensemble mean grounding line and calving front positions, respectively. (c–d) Bayesian calibrated mean depth profile of freshwater discharge through sub-shelf melting at years 2000, 2100, 2200 and 2300, for the Weddell Sea (WS), Indian Ocean (IO), Western Pacific Ocean (WPO), Ross Sea (RS) and Amundsen and Bellingshausen Sea (ABS) sectors under SSP1-2.6 (c) and 5–8.5 (d). Dashed and dotted lines show the evolution of the Bayesian calibrated mean ice front draft and grounding-line depth for each region, respectively.

After 2100, the pattern of projected Antarctic ice discharge starts to significantly diverge under the two emission scenarios (Figures 3a and 3b). Under SSP1-2.6, mass loss remains largely confined to the Amundsen Sea Embayment. In contrast, under SSP5-8.5, there is an acceleration of mass loss linked to a progressive thinning and collapse of the West Antarctic ice shelves, leading to rapid grounded ice loss. In addition, we note the onset of grounding-line retreat in the marine basins of East Antarctica, despite a thickening of a few tens of meters of the inland ice sheet.

As a consequence, by 2300, the median total pan-Antarctic freshwater flux increases by 23% under SSP1-2.6 and by 354% under SSP5-8.5 compared to the 1990–2020 average (Figure 2 and Table 1). Under the low-emission scenario, the partitioning of the freshwater discharge remains overall unchanged after 2100 (Table 1), both at the continental and regional scales (Figure S5 in Supporting Information S1). In contrast, under SSP5-8.5, the increase in sub-shelf melting triggered in the second half of the 21st century continues beyond 2100. Sub-shelf melt fluxes stabilize in the second half of the 22nd century, reaching nearly 7000 Gt yr^{-1} by 2200, and then eventually decline with the ongoing collapse of the ice shelves (Figures 2b and 3b). Surface runoff increases steadily with warming air temperatures, reaching median fluxes of about 6000 Gt yr^{-1} by 2300 (i.e., of the same order of magnitude as the sub-shelf melt), and potentially becoming the dominant source of freshwater discharge (5%–95% probability interval; Figure 2b and Table 1). Regionally, median surface runoff fluxes dominate the freshwater discharge in the Indian Ocean by 2300, and are of a similar magnitude to sub-shelf melting in the other regions. Unlike the other two freshwater sources, calving fluxes under SSP5-8.5 remain fairly constant after 2100. They may slightly increase after 2150, likely due to the decrease in total sub-shelf melting, which is caused by an overall reduction in ice-shelf area (Figure 2), particularly within the 5%–95% probability interval. Overall, consistent with the 21st century trend, most of the freshwater will be discharged into the Weddell, Amundsen, and Bellingshausen Seas by 2300 (Figures 2 and 3).

4. Discussion

We present spatially integrated timeseries of freshwater fluxes for the main Antarctic drainage basins, here aggregated over 5 oceanic sectors. Therefore, our estimates do not consider details in both horizontal and vertical dimensions, which may influence climate dynamics (Pauling et al., 2016; Thomas et al., 2023). Although our model simulations contain information about the horizontal distribution of individual freshwater sources down to the model grid scale (8-km resolution), we do not include it in this analysis. Given the often coarse resolution of CMIP-class climate models, the spatial distribution of freshwater fluxes at kilometer scales is unlikely to significantly affect their response, as these sources will rapidly merge and diffuse away from the coastline. In addition, while the regional distribution of freshwater fluxes is key to understanding local ice-sheet–climate feedbacks (such as changes in ocean dynamics and melt rates due to changes in upstream freshwater release), our standalone ice-sheet simulations forced by CMIP6 data do not capture such feedbacks. We therefore focus on the basin-scale trends and partitioning of different freshwater sources for a range of uncertain ice-sheet processes.

In the case of sub-shelf melting, changes in the draft of the ice shelves can cause a shift in the vertical distribution of freshwater input. The level at which freshwater is injected into the ocean is a key input for simulating the basal-melt-induced overturning circulation and associated changes in ocean stratification on the continental shelves (Mathiot et al., 2017; Thomas et al., 2023). Although we do not provide a comprehensive analysis here, we show that increasing meltwater is projected to be discharged at greater depths through sub-shelf melting in the Amundsen, Bellinghsausen and Ross Seas as well as in the western Pacific Ocean over time, due to the projected grounding-line retreat in the main Antarctic marine basins (Figure 3).

Our projections also do not simulate abrupt discrete calving events or provide detailed spatial distribution of calving fluxes at the ice front, complicating the estimation of where and when freshwater will be released at the ocean's surface. Nonetheless, the ice-shelf thinning projected by our calibrated ensemble indicates an overall decrease in the ice front draft and hence iceberg thickness in the coming centuries (Figure 3 and Figure S6 in Supporting Information S1). Future work should focus on providing more detailed maps of future freshwater fluxes. Meanwhile, our basin-integrated projections can be added as anomalies to present-day spatial distributions (Thomas et al., 2023) derived from observations (e.g., Rignot et al., 2013), allowing for the consideration of regional climate feedback sensitivities (Gorte et al., 2023; Thomas et al., 2023).

In addition, our projections lack a surface meltwater routing and storage scheme. We hence provide a first-order estimate by assuming that all surface meltwater not refrozen in winter is routed laterally toward the ocean within each drainage basin. In reality, ponding of meltwater has been widely observed in Antarctica, especially on the flat ice shelves (Kingslake et al., 2017; van Wessem et al., 2023). Meltwater storage has also been observed in the form of englacial lakes (Lenaerts et al., 2016) and perennial firn aquifers (van Wessem et al., 2021).

Despite accounting for a comprehensive range of uncertain processes, our projections of future freshwater fluxes from the Antarctic ice sheet rely on a single ice-sheet model, hence lacking structural uncertainty. Our estimates are also influenced by the limited number of climate models providing projections until 2300 and the emission scenarios for which such projections are produced (here, only the low and very high emission scenarios). An assessment of the sensitivity of future Antarctic freshwater fluxes to intermediate pathways is thus lacking. Moreover, the SSP5-8.5 scenario is considered very unlikely to be followed on multi-centennial timescales (Hausfather & Peters, 2020; Schwalm et al., 2020). Our projections under this very-high emission scenario may therefore be seen as high-end estimates. While calibration adds robustness to projections, it is important to recognize that exploring additional sources of uncertainties will likely alter and broaden the distributions of the projections (Edwards et al., 2021). Similarly, alternative choices for the magnitude of the structural error (and therefore discrepancy variance; see Supporting Information S1) would also influence our calibrated projections (Coulon, Klose, et al., 2024). A future comparison with freshwater fluxes from the ISMIP6 extended ensemble (Seroussi et al., 2024) could aid in limiting the structural uncertainty.

5. Conclusion

Large changes in the spatial distribution, magnitude and partitioning (calving vs. ice-shelf melt vs. surface runoff) of future Antarctic freshwater discharge are expected in the coming decades and centuries, particularly under high-emission scenarios. Overall, the freshwater release from the Antarctic ice sheet into the Southern Ocean, currently amounting to about 3140 Gt yr^{-1}, is expected to increase. While this increase remains limited under a low emission scenario, it reaches a factor of 2 (with almost 6300 Gt yr^{-1}) by 2100, and 4.5 (~14,250 Gt yr^{-1}) by 2300 under a very-high emission scenario, significantly increasing the potential to trigger feedbacks within the global climate system. We also project a shift in the form and depth of freshwater discharge from solid to liquid, as the dominant contributor to Antarctic freshwater fluxes is expected to transition from calving to sub-shelf melt, and potentially to surface meltwater runoff, which may become a dominant contributor under a very-high emission scenario. Although almost all Antarctic regions are projected to experience increased freshwater discharge, most of this discharge will occur in the Amundsen and Weddell Seas. Given that some climate model studies have already found significant climate impacts from freshwater forcing changes of only a few percent (e.g., Bintanja et al., 2013), accounting for these large spatiotemporal trends in climate projections will allow for a better assessment and quantification of the climate system's response and feedback to changing ice-sheet-driven freshwater input from Antarctica, as well as the role of uncertain ice-sheet processes such as calving in that response.

Data Availability Statement

The code and reference manual of the Kori-ULB ice-sheet model are publicly available on Github and can be downloaded from Pattyn (2024). The code of the specific Kori-ULB model version used in this study is currently available on Github from Coulon (2024). This version of the code is hosted on Zenodo, along with the simulation outputs and the scripts needed to produce the figures and tables in this paper (https://doi.org/10.5281/zenodo.14163522, Coulon, De Rydt, et al., 2024b). The freshwater flux estimates are also available on Zenodo (https://doi.org/10.5281/zenodo.14162775, Coulon, De Rydt, et al., 2024a). All data sets used in this study are freely accessible through their original references. The CMIP6 forcing data used in this study are accessible through the CEDA ESGF node (CEDA ESGF, 2024). Ice and bedrock geometry data from Bedmachine v3 are available in Morlighem (2022). Outputs from RACMOv2.3p2 are available in van Wessem et al. (2018). Present-day ocean climatology data are available in Jourdain et al. (2020). Ice-sheet mass balance estimates are available in Otosaka et al. (2023) and calving and sub-shelf melt fluxes estimates are available in Davison et al. (2023).

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