



Considering ocean conditions within ice-shelf cavities moderately reduces projected mass loss from the Antarctic Ice Sheet

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Abstract. Ocean-forced melt of ice shelves is a key determinant of the stability of the Antarctic Ice Sheet (AIS). Currently, most Earth-system models (ESMs) do not simulate ocean circulation in the cavities beneath ice shelves, and ice-sheet models must infer ice-shelf melt rates from ocean conditions external to the ice shelf. A recent configuration of the Energy Exascale Earth System Model, E3SMv2.1, resolves ocean conditions within ice-shelf cavities with an eddy-permitting mesh in the Southern Ocean. Using projected ocean temperatures from E3SMv2.1 that follow prescribed historical and SSP3-7.0 emission scenarios, we parameterize ice-shelf melt using 1) simulated thermal forcing (TF) within cavities and 2) extrapolated TF from the ice-shelf calving front, similar to the community-standard approach when ice-shelf cavities are absent. We then force the MPAS-Albany Land Ice (MALI) ice-sheet model with the parameterized melt from both methods and project AIS mass change to 2100. Results show that using simulated TF from ice-shelf cavities yields a smaller sea-level contribution (SLC) from the AIS through 2100, by ~4 mm (~13%), compared to the experiment that uses extrapolated ocean conditions from the calving front. In the context of other ice-sheet model uncertainties, an SLC projection error of this size may be acceptable. If open ocean conditions become warmer than simulated cavity conditions beyond 2100, extrapolation risks overestimating the SLC by a larger margin. Our results demonstrate the value of using cavity-resolving ocean models for multi-century ice-sheet projections.

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1 Introduction

Ocean-induced melting under floating ice shelves is one of the largest drivers of mass loss of the Antarctic Ice Sheet (AIS; Jacobs et al., 2011; Rintoul et al., 2016; Jenkins et al., 2018). Since ice shelves are floating, mass loss from melting has a small, direct effect on sea-level rise. Instead, ice-shelf melting can thin ice shelves, which can reduce the buttressing of inland glaciers and lead to increased ice discharge into the ocean and, ultimately, sea-level rise (Pritchard et al., 2012; Gudmundsson, 2013; Gudmundsson et al., 2019; Seroussi et al., 2014; Reese et al., 2018a). In recent ice-sheet model (ISM)

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projections of the AIS from the Ice Sheet Model Intercomparison Project for CMIP6 (Nowicki et al., 2016; Nowicki et al., 2020), the representation of ice-shelf basal melting dominated the total uncertainty in the projected contribution of AIS to sea-level rise (Seroussi et al., 2020; Seroussi et al., 2024).

35 This uncertainty stemmed from two major factors. The first factor was the lack of resolved ice-shelf cavities in the ocean outputs generated by the Coupled Model Intercomparison Project (CMIP; Eyring et al., 2016) atmosphere-ocean general circulation models (AOGCMs). Ice-shelf cavities in Antarctica are spaces beneath ice shelves that control the exchange of heat between AIS and the Southern Ocean (Bennetts et al., 2024). Without cavities, ocean circulation and, consequently, ice-shelf basal melt, cannot be simulated directly. To compensate for this, ice-sheet modelers often
40 parameterize ice-shelf basal melt using extrapolated ocean conditions from the open ocean available outside these cavities (Jourdain et al., 2020). Subsequent to CMIP6, some Earth-system models (ESMs) have begun to incorporate ice-shelf cavities into their global ocean domains to better simulate ice-shelf basal melt (Smith et al., 2021; Comeau et al., 2022; Song et al., 2025); however, cavity-resolving ESMs are still uncommon and so parameterizations of ice-shelf basal melt remain widely used (Lambert and Burgard, 2025; Burgard et al., 2022; Asay-Davis et al., 2017).

45 The second source of uncertainty was that the ISMIP6 experiments utilized standalone ice-sheet models run independently from ESMs. Ideally, one would use an ESM with a fully coupled ice-sheet component (also referred to as an ESM–ISM) to capture the two-way interactions between an evolving ice sheet and ocean in tandem. However, ESM–ISMs are rare due to the computational and algorithmic complexity of implementing dynamic ice-shelf–ocean boundaries; only one such ESM with a dynamic ice-sheet model is currently in use (Smith et al., 2021). Thus, stand-alone ice-sheet models,
50 especially those forced with parameterized basal melt (e.g. Hill et al., 2024; Seroussi et al., 2020; Seroussi et al., 2024), are currently the most common means for generating century-scale projections of sea-level contribution (SLC) from the AIS and were the only practical route at the time the ISMIP6 experiments were carried out.

The most common type of ISM parameterization for basal melt calculates sub-shelf melt as a function of thermal forcing (TF), which is defined as the difference between the in situ ocean temperature and the pressure- and salinity-
55 dependent freezing temperature (Favier et al., 2019; Burgard et al., 2022). Various parameterizations of this type exist and vary from simple linear (Beckmann and Goosse, 2003) and quadratic (Deconto and Pollard, 2016; Favier et al., 2019; Jourdain et al., 2020; Holland et al., 2008) functions of TF to more complex constructions such as the plume model (Lazeroms et al., 2019; Lazeroms et al., 2018), box model (PICO; Reese et al., 2018b), and the box and plume model (PICOP; Pelle et al., 2019). While the complex parameterizations are more sophisticated in representing ocean circulation
60 and boundary layer processes within cavities, it was found that in an idealized framework (Favier et al., 2019), and later in semi-realistic experiments that used a cavity-resolving ocean model (Burgard et al., 2022), the more simple quadratic basal melt parameterization performed at least as well as the complex parameterizations. Given their performance, comparative computational efficiency, and simplicity to implement within ISMs (Jourdain et al., 2020; Seroussi et al., 2020), simple parameterizations remain a widely used choice, and it is expected that they will continue to be used in future standalone ice-
65 sheet modeling experiments.



Conversely, ocean models that resolve cavities can simulate the oceanic processes within ice-shelf cavities (Dinniman et al., 2016 and references therein; Mathiot et al., 2017; Zhou and Hattermann, 2020; e.g. Comeau et al., 2022). These include the buoyancy-dependent circulation that drives and is impacted by basal melting, the transportation and transformation of water masses into and out of cavities, and the exchange of heat at the boundary layer of the ice-shelf–
70 ocean interface (Dinniman et al., 2016; Asay-Davis et al., 2017). The majority of coupled ice–ocean studies with resolved cavities have been conducted using idealized geometries (De Rydt and Gudmundsson, 2016; Jordan et al., 2018; Goldberg et al., 2018; Favier et al., 2019; Zhao et al., 2022) and realistic geometries in regional settings (Thoma et al., 2015; Seroussi et al., 2017; Timmermann and Goeller, 2017; Pelle et al., 2021; Goldberg and Holland, 2022; Bett et al., 2024; De Rydt and Naughten, 2024). However, ESMs are only just starting to incorporate ice-shelf cavities into their global ocean domains
75 (Smith et al., 2021; Siahann et al., 2022; Comeau et al., 2022; Song et al., 2025; Comeau et al., 2025) and thus, the impact of their inclusion on estimates of SLC has not yet been thoroughly tested.

Here, we evaluate the implications of not having ocean cavity information available when calculating melt rates for ice-sheet model projections. We take advantage of the inclusion of 3-d ice-shelf cavities within the Department of Energy’s Energy Exascale Earth System Model (E3SM; Golaz et al., 2026; Comeau et al., 2022; Comeau et al., 2025; Vaňková et al.,
80 2026) and compare projections of Antarctic SLC that make use of cavity information with those that do not. We run standalone MPAS-Albany Land Ice (MALI; Hoffman et al., 2018) simulations forced with two different experiments of parameterized ice-shelf basal melt using TF generated by E3SM. The first experiment parameterizes basal melt using ocean TF explicitly simulated within ice-shelf cavities, whereas the second experiment mimics the standard ISMIP6 approach and parameterizes basal melt using extrapolated ocean TF from the ice-shelf calving front. We run MALI from 2000 to 2100 and
85 compare the parameterized basal melt rates, resulting ice-sheet thickness changes, and SLC for both experiments at both the continent-wide and regional scale. We end by discussing the impacts of relying on open ocean extrapolation when parameterizing basal melt for standalone ice sheet projections to 2100 and beyond.

2 Methods

2.1 Models

90 2.1.1 E3SMv2.1-SORRM and MPAS-Ocean

We use ocean TF outputs generated using version 2.1 of E3SM (E3SMv2.1; Smith et al., 2025; Golaz et al., 2022) configured using its Southern Ocean Regionally Refined Mesh (SORRM; Comeau et al., 2025; Vaňková et al., 2026). E3SMv2.1 has active atmosphere, land, river, ocean, and sea-ice coupled components and can run century-scale, global simulations. E3SMv2.1-SORRM (hereafter known as E3SM-SORRM) simulates ocean circulation and basal melt fluxes
95 within Antarctic ice-shelf cavities using a regionally refined mesh with 12km resolution in the Southern Ocean and 30–60 km resolution elsewhere. The atmosphere and land components use a nominal 1° horizontal resolution and the river



component at 0.5° resolution. E3SM-SORRM does not include an active ice-sheet component; therefore, the ice-shelf cavity geometry in the ocean component remains static. Further information on E3SM-SORRM can be found in the previous references.

100 The ocean model component within E3SM-SORRM, MPAS-Ocean (Petersen et al., 2019; Ringler et al., 2013), uses an expanded ocean domain with geometrically static but thermodynamically active 3-d ice-shelf cavities. The model uses a finite-volume spatial horizontal discretization (Ringler et al., 2010; Thuburn et al., 2009) and solves the three-dimensional primitive equations under the hydrostatic, incompressible, and Boussinesq approximations on a staggered Arakawa “C-grid” (Petersen et al., 2019; Arakawa and Lamb, 1977). The C-grid computes scalars (such as temperature and
105 salinity) at cell centers and horizontal normal velocities at cell edges. The vertical mesh uses a “z-star” vertical coordinate system across most of the ocean domain, in which ocean layer thicknesses expand or contract based on the sea surface height (Petersen et al., 2019; Adcroft and Campin, 2004). In the cavities and in a buffer zone outside the calving front, a non-standard vertical coordinate is used that implements a terrain-following top coordinate along the ice-shelf base (also known as the ice-shelf draft). Across the entire ocean domain, bottom ocean layers are disabled if they fall below seabed bathymetry
110 (see Appendix A in Comeau et al., 2022). Mixed-layer eddies are parameterized using the “Fox-Kemper 2011” mixed-layer eddy parameterization (Fox-Kemper et al., 2011) and mesoscale eddies are parameterized using the “GM” eddy transport parameterization (Gent and McWilliams, 1990).

2.1.2 MALI ice-sheet model

We use the MPAS-Albany Land Ice model (MALI; Hoffman et al., 2018) to run standalone ISM simulations and to
115 simulate the Antarctic Ice Sheet response to the E3SM-SORRM ocean TF. MALI uses the same Model for Prediction Across Scales (MPAS) framework as MPAS-Ocean combined with the Albany multiphysics library for solving ice velocity (Tezaur et al., 2015). Ice velocity is solved on a finite-element Delaunay triangular mesh, and advection, thermodynamics and other model physics are solved by finite volumes on the dual Voronoi tessellation. MALI solves the three-dimensional, first-order approximation to the nonlinear Stokes equations for ice-sheet flow (Dukowicz et al., 2010; Schoof and Hindmarsh, 2010).
120 The first-order approximation, also referred to as the Blatter–Pattyn model (Blatter, 1995; Pattyn, 2003), uses a small geometric aspect ratio $\epsilon = H/L \ll 1$ where H and L are the vertical and horizontal length scales of an ice sheet, respectively. The approximation simplifies the full Stokes equations by eliminating vertical resistive stresses (Van Der Veen and Whillans, 1989) and reduces the computational complexity while preserving accuracy for large-scale ice-sheet modeling. The system of partial differential equations that are solved are:

$$\begin{cases} -\nabla \cdot (2\mu \dot{\epsilon}_1) + \rho g \frac{\partial s}{\partial x} = 0, \\ -\nabla \cdot (2\mu \dot{\epsilon}_2) + \rho g \frac{\partial s}{\partial y} = 0, \end{cases} \quad (1)$$



where g is the gravitational acceleration, ρ is the ice density, $s \equiv s(x, y)$ is the elevation of the ice-sheet upper surface, $\dot{\epsilon}_1$ and $\dot{\epsilon}_2$ are the horizontal components of the strain rate tensor given by:

$$\dot{\epsilon}_1^T = (2\dot{\epsilon}_{xx} + \dot{\epsilon}_{yy}, \dot{\epsilon}_{xy}, \dot{\epsilon}_{xz}), \quad (2)$$

$$\dot{\epsilon}_2^T = (2\dot{\epsilon}_{xy}, \dot{\epsilon}_{xx} + 2\dot{\epsilon}_{yy}, \dot{\epsilon}_{yz}), \quad (3)$$

130 and μ is the effective viscosity, given by Glen's flow law (Glen, 1955; Nye, 1951):

$$\mu = \frac{1}{2} A^{-\frac{1}{n}} \dot{\epsilon}_e^{\frac{1}{n}-1}. \quad (4)$$

Here, A is the temperature-dependent factor that follows an Arrhenius-type relationship, $\dot{\epsilon}_e$ is the effective strain rate which is given by the second invariant of the strain rate tensor, and n is the Glen's flow law exponent. We set $n = 3$, which represents a shear-thinning, non-Newtonian fluid flow. Additional details about the velocity solver and conservation of mass

135 and energy can be found in Hoffman et al. (2018).

2.1.3 MALI Initialization

We use the initial ice-sheet state described by Hillebrand et al. (2025), which was the standard ice-sheet configuration for MALI in the ISMIP6-Antarctica-2300 model intercomparison study (Seroussi et al., 2024). This configuration uses a 4–20 km variable resolution mesh, with 385,379 cells and 5 vertical layers with constant but
140 nonuniform thickness fraction ("sigma" vertical coordinate system; Hillebrand et al., 2025). Cell spacing is determined both by the observed surface velocities, u_{obs} (m yr⁻¹), and distance to the grounding line. The finest resolution is given to fast-flowing ice (when $\log_{10}(u_{obs}) \geq 2.5$) or ice within 40 km of the grounding line. The cell spacing linearly increases with distance to its coarsest resolution, which is applied at distances greater than 250 km from the grounding line or when ice velocities are low (when $\log_{10}(u_{obs}) \leq 0.5$; (Hillebrand et al., 2025). The ice-sheet model is initialized using an adjoint
145 optimization method (Perego et al., 2014; Hoffman et al., 2018) that solves for basal traction coefficient and ice stiffening factor fields that minimize the difference between the observed and modeled surface velocities, subject to regularization constraints on smoothness. For grounded ice, sliding at the base is governed by the Weertman power law (Weertman, 1957) with an exponent of 1/5. Basal melting beneath ice shelves is calculated by the "non-local" quadratic parameterization of Jourdain et al. (2020) using ocean TF from E3SM-SORRM (see Section 2.3). Subglacial melt at grounded glacier termini is
150 calculated by an undercutting parameterization (Rignot et al., 2016). For marine-terminating margins, calving is applied to prevent the calving front from advancing, but retreat is allowed where local mass balance thins the ice column to zero thickness. Ice thermodynamics are coupled to dynamics and are calculated following a temperature-based formulation (Hoffman et al., 2018; Hillebrand et al., 2025).

Our simulations were nominally initialized to reflect conditions during the year 2000. Modeled velocities for the
155 initial ice-sheet state are optimized using the MEaSUREs 1996–2016 ice velocity dataset (Rignot et al., 2011; Mouginot et al., 2012; Rignot et al., 2017). We use BedMachine Antarctica v2 (Morlighem, 2020; Morlighem et al., 2020) for basal topography and ice thickness for most of Antarctica, but calculate ice thickness from Bedmap2 (Fretwell et al., 2013) surface



elevations in the Amundsen Sea Embayment (ASE), which produces a more stable initial condition reflective of observed dynamics in the late 1990s to early 2000s. Local adjustments were made to bed topography beneath ice shelves to ensure continuity of troughs across the grounding line at some outlet glaciers and ice streams. We use geothermal heat flux from Martos et al. (2017) and surface air temperature from Lenaerts et al. (2012). Additional details describing the necessary modifications to approximate observed mass loss are available in Hillebrand et al. (2025).

2.2 E3SM-SORRM simulations

The E3SM-SORRM simulation campaign focused on simulating and projecting Antarctic ice-shelf basal melting and its impacts within a coupled ESM (see Table 1 in Comeau et al., 2025). These simulations include a 1000-year control run with repeated 1950 greenhouse gas (GHG) conditions, three historical simulations that branch off the control run at years 701, 751, and 801 and prescribe observed GHG conditions from 1950–2014, and three SSP3-7.0 projection simulations that extend the historical simulations from 2015 to 2100 (Comeau et al., 2025; Vaňková et al., 2026). The projections follow the “medium high” or “rocky road” Shared Socioeconomic Pathway 3 (SSP3-7.0) from the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) with 7.0 W/m² of radiative forcing by 2100 (Ipcc, 2023). The set of three historical and projection simulations form a small ensemble with each ensemble member containing its own realization of the climate with unique internal variability.

For our purposes, we split the E3SM-SORRM simulations into two subsets; the first from 1970–1999 and the second from 2000–2100 (Fig. 1). We use the 1970–1999 temporal- and ensemble-averaged TF in the first subset (which we refer to as “1970–1999 Temporal-Ens Mean”) for our temperature calibration (see Section 2.3.3). We use the same 1970–1999 Temporal-Ens Mean TF field as repeated forcing for our MALI control simulations (Section 2.4), and we use the evolving 2000–2100 TF from the three ensemble members and ensemble mean (which we refer to as “Ens Mean”) in the second subset as forcing for our MALI projection simulations (Section 2.4). Note the TF in the second subset includes the last 15 years of the E3SM-SORRM historical simulations as well as the full temporal range of the E3SM-SORRM projections.

We compute annual averages from the monthly-averaged TF for all three ensemble members and the Ens Mean. To supply the ocean TF fields as inputs to MALI, we linearly interpolate the vertical dimension of MPAS-Ocean to 30 equally spaced vertical levels with 60 m thickness, consistent with the ISMIP6 configuration (Jourdain et al., 2020). A few ice shelves have drafts that fall below the domain’s maximum depth of -1800 m, particularly around Amery, Filchner–Ronne, Totten, and Dronning Maud Land. To provide TF inputs under ice shelves with drafts below this maximum depth, we adjust TF in the deepest level by the depth-dependent freezing temperature. We also horizontally re-grid the TF data from the native 12–60 km E3SM-SORRM ocean mesh to the 4–20 km MALI ice-sheet mesh using bilinear interpolation.

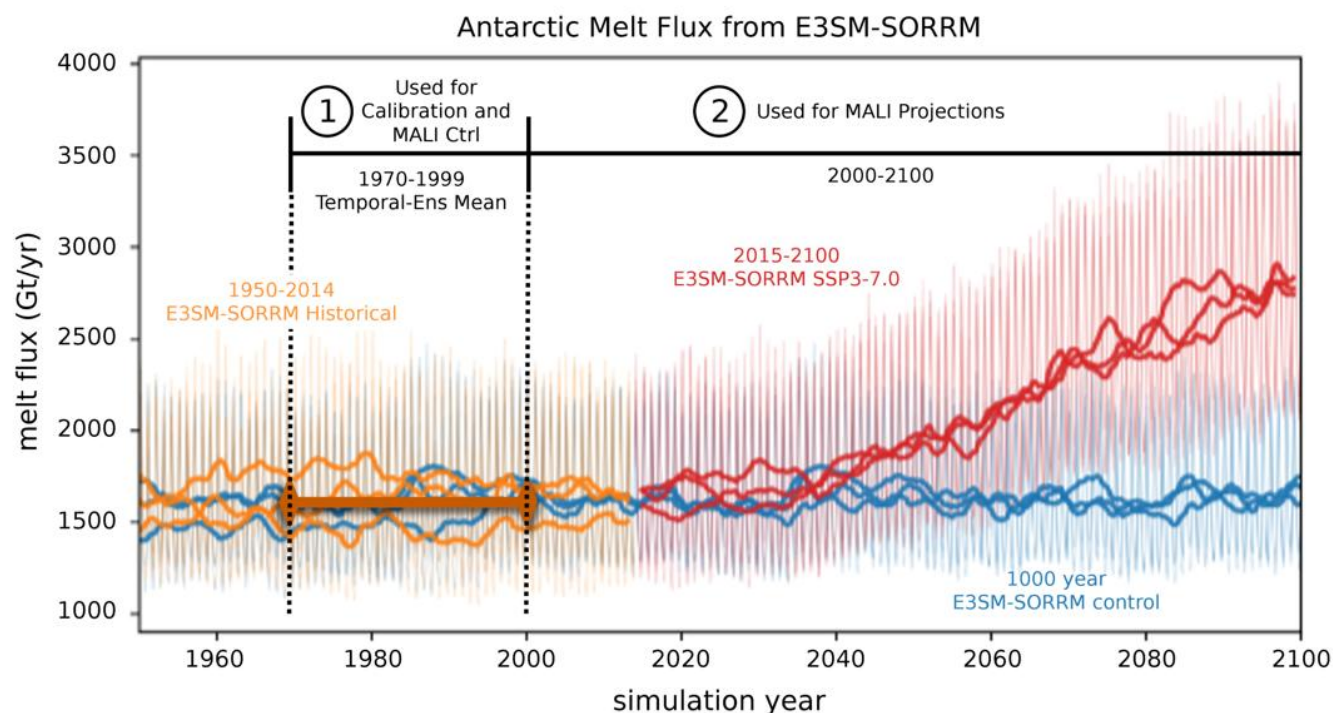


Figure 1: Simulated total Antarctic melt flux (Gt yr^{-1}) from E3SM-SORRM. The E3SM-SORRM simulations include a 1000-year control run using repeat 1950 greenhouse gas (GHG) conditions (blue), three historical simulations from 1950–2014 based on observed GHG conditions (light orange), and three SSP3-7.0 projection simulations from 2015–2100 that extend the historical simulations. From the first subset (1), we use the temporal-ensemble mean TF from 1970–1999 (dark orange bar between vertical black dotted lines) to both calibrate δT and force our MALI control simulations from 2000 to 2100. From the second subset (2), we use the evolving TF from all three ensemble members and the ensemble mean as forcing for our MALI projections, also run from 2000 to 2100. Note that the second subset includes both the last 15 years of the E3SM-SORRM historical runs (2000–2015) and the entire set of E3SM-SORRM SSP3-7.0 runs (2015–2100).

2.3 Parameterizing ice-shelf basal melt

In this section, we outline the steps needed to parameterize ice-shelf basal melt from the E3SM-SORRM TF. Because the purpose of our study is to compare results of applying the ISMIP6 protocol with and without considering ice-shelf cavities when determining TF, we do not use the E3SM-SORRM basal melt rates. As an aside, using E3SM basal melt rates introduces additional challenges that make parameterization based on TF more attractive: First, because E3SM-SORRM cavity geometries were fixed through time while MALI cavities evolved their shape, some extrapolation of ocean properties was necessary whether or not E3SM-SORRM cavities were considered for determining melt rates. TF is a more physically realistic parameter to extrapolate than melt rates, given that TF can be extrapolated in 3-d while melt rates are constrained by ice-shelf geometry. Second, the E3SM-SORRM ocean state (and its melt rates) have substantial biases; for example, melt rates at the Amery Ice Shelf were high compared to observations, but low for Thwaites and Pine Island (Comeau et al., 2025). Thus, we achieve melt rates closer to observation by bias-correcting the TF prior to computing melt rates.



2.3.1 Experiments

210 We consider two different experiments to test the influence of including ice-shelf cavities on the Antarctic contribution to sea-level change. The first experiment, “CAV” for cavity, parameterizes ice-shelf basal melt using the interpolated E3SM-SORRM TF within the 3-d ice-shelf cavities (Fig. 2a). The second experiment, “OO” for open ocean, uses the same interpolated E3SM-SORRM TF fields as used in the CAV experiments, except we mask out TF within cavities, giving us TF in the open ocean only (Fig. 2b). We define the term “open ocean” as the region immediately outside
215 the ice-shelf calving front, not just beyond the continental shelf break. The OO experiment mimics the CMIP5 and CMIP6 ocean outputs used as forcing in the ISMIP6 experiments (Seroussi et al., 2020), with the notable caveat that the CMIP models did not include cavities at all and the E3SM-SORRM conditions at the ice-shelf front in our OO experiment are still influenced by the presence of thermodynamically active cavities. This is an important difference, as heat loss to land ice melt, accounted for in E3SM-SORRM but missing from CMIP models, dominates the Antarctic coastal heat budget
220 (Moorman et al., 2026).

2.3.2 Extrapolation

Both experiments require TF extrapolation to ensure that valid information is input into MALI at its ice-shelf–ocean interface at all timesteps. This is because 1) the initial MALI cavity geometry and grounding-line position are slightly different than the initial static MPAS-Ocean domain, 2) the cavity geometry and grounding-line position in MALI evolve
225 while the MPAS-Ocean domain does not change, which creates an increasingly larger gap to be filled as the grounding line retreats (Fig. 2a), and 3) the cavity is empty after it is masked out in the OO experiments. In the CAV experiment, we extrapolate from the static 3-d MPAS-Ocean ice-shelf draft (green in Fig. 2a) to account for points 1 and 2, whereas in the OO experiment, we extrapolate from the initial MALI 2D ice-shelf calving front (green in Fig. 2b) to account for points 2 and 3. Both experiments extrapolate out to a position beyond the final grounding line extent (yellow bar in Fig. 2a and 2b).
230 Both experiments also follow the same extrapolation scheme, described below.

The extrapolation scheme occurs on the higher-resolution MALI mesh and alternates between horizontal and vertical extrapolation until the required cavity space is filled. The extrapolation scheme begins with horizontal extrapolation using a “creep-fill” approach (Kara et al., 2007) where empty cells are filled with an area-weighted average of neighboring values. The horizontal extrapolation continues until it either reaches a bedrock obstacle or the specified extrapolation extent
235 slightly inland of the grounding line (yellow bar in Fig 2), ignoring the presence of floating ice. Vertical extrapolation is then applied to project the bottom-most valid TF layer downward to fill regions that were missed due to obstacles and deeper regions that were not accessible during the first horizontal iteration. The vertical extrapolation adjusts the TF following the pressure-dependence of the freezing point of seawater. The extrapolation scheme alternates between horizontal and vertical modes until all required cells are filled. TF along the ice-shelf draft is then calculated by interpolating between the
240 extrapolated TF layers.

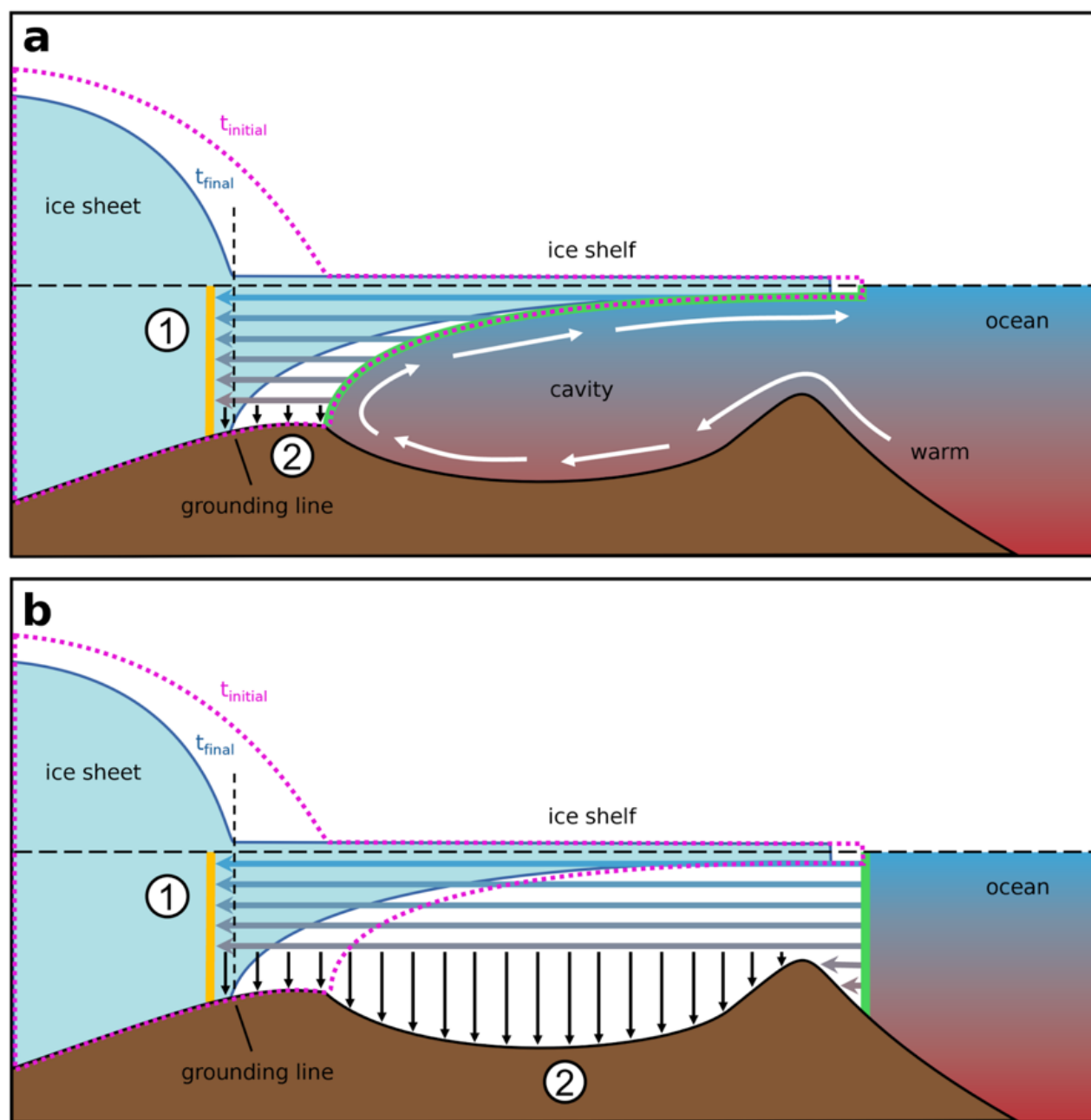


Figure 2: Extrapolation scheme for the (a) CAV and (b) OO experiments. (a) In CAV, ocean TF is simulated within the ice-shelf cavity. TF is extrapolated from the static 3-d MPAS-Ocean ice-shelf draft (green) and the extrapolation extends beyond the evolving MALI ice-shelf draft to a position (yellow) past the final MALI grounding-line position. (b) In OO, ocean TF within cavities is masked out, leaving empty space within the cavity. Ocean information at the initial MALI ice-shelf calving front (green) is extrapolated to fill the empty cavity and to a position (yellow) beyond the final MALI grounding line. The extrapolation scheme is the same for both experiments and alternates between (1) horizontal and (2) vertical extrapolation until all required space is filled with TF information.



Our extrapolation method differs slightly from the approach described in Jourdain et al. (2020). Whereas Jourdain et al. (2020) extrapolated using many neighbors within a ~ 25 km stencil, we instead use only nearest neighbors on the MALI mesh. During horizontal extrapolation, all extrapolated cells are updated at every iteration, including those with already valid values. At each iteration, the value in an extrapolated cell is computed as a weighted average of its value from the previous iteration (if previously assigned) and the mean value of all valid horizontal neighbors, accounting for their respective areas. We use a weighting of 0.7, which puts a higher weight on the local cell than its neighbors. The procedure is repeated until no additional cells require assignment.

2.3.3 Parameterization of ice-shelf basal melt and calibration

We use the modified ‘non-local’ quadratic parameterization described by Jourdain et al. (2020) to calculate the sector-dependent basal melt rate $m(x, y)$:

$$m(x, y) = \gamma_0 \left(\frac{\rho_{sw} c_{pw}}{\rho_i L_f} \right)^2 \times (TF(x, y, z_{draft}) + \delta T_{sector}) \times |\langle TF_{draft \in sector} \rangle + \delta T_{sector}| \quad (5)$$

where a sector is defined as one of 16 regions around Antarctica (Jourdain et al., 2020). Here, γ_0 is a constant coefficient, ρ_{sw} is sea water density, c_{pw} is the specific heat of sea water at constant pressure, ρ_i is ice density, L_f is the latent heat of fusion of ice, $TF(x, y, z_{draft})$ is the TF at the ice-shelf draft, $\langle TF \rangle_{draft \in sector}$ is the average TF across all ice shelves in an entire sector, and δT_{sector} is the temperature bias correction applied to the TF in each sector in order to match observed basal-melt rates in each sector (Rignot et al., 2013).

Jourdain et al. (2020) use a distribution and random sampling approach to calibrate both γ_0 and δT_{sector} . In our study, we adopt the Jourdain et al. (2020) γ_0 value of 14500 m yr^{-1} , which is the median value found for their nonlocal ‘meanAnt’ calibration method, and calibrate δT_{sector} only. We use the 1970–1999 Temporal-Ens Mean TF field as the reference field and generate two sets of 16 δT_{sector} values, one for OO and one for CAV (Table 1). To do that, we use the equation above and sample through a range of δT and find the value that calculates a basal melt rate field that, when averaged, best matches the observed basal melt rate for each sector (Rignot et al., 2013). We keep these calibrated δT_{sector} values fixed in time and apply them to all TF fields used for our MALI simulations within our study (Fig. 3).

Table 1 shows the calibrated δT_{sector} values for all 16 sectors for both experiments. OO generally shows smaller δT_{sector} values (less positive or more negative) compared to CAV. This implies that the conditions in the open ocean are generally warmer compared to the simulated ocean conditions within the cavity. Thus, OO TF values generally require a reduction relative to CAV so that the initial parameterized basal melt values in both experiments match the observed values from Rignot et al. (2013).



Sector	Name	Open Ocean δT ($^{\circ}\text{C}$)	Cavity δT ($^{\circ}\text{C}$)
A–A'	Dronning Maud Land	-0.88933	-0.71885
A'–B	Enderby Land	0.09339	0.11254
B–C	Amery–Lambert	-0.73109	-0.36862
C–C'	Phillipi, Denman	0.23170	0.26481
C'–D	Totten	-0.06102	0.00560
D–D'	Mertz	0.00456	0.00888
D'–E	Victoria Land	0.40337	0.14859
E–F	Ross	-0.11534	0.09059
F–G	Getz	-0.24450	-0.26342
G–H	Thwaites/PIG	0.50740	0.50232
H–H'	Bellingshausen	-0.34651	-0.20238
H'–I	George VI	-0.94303	-0.88812
I–I''	Larsen A–C	-0.10155	0.07063
I''–J	Larsen E	-0.21500	-0.18496
J–K	FRIS	-0.09305	0.22099
K–A	Brunt–Stancomb	-0.47581	-0.29030

280 **Table 1: Regional mean temperature bias corrections (δT_{sector}) for the OO and CAV experiments. Values are calibrated using the 1970–1999 Temporal-Ens Mean TF field. Sector letters in the first column correspond to delineations of the sectors (see Fig. 6).**

2.4 Standalone MALI simulations

We run 10 standalone MALI simulations in total: one control and four projection simulations for both experiments (Fig. 3). The control simulation applies the constant 1970–1999 temporal-ensemble mean TF field (“Temporal-Ens Mean”) for 100 years from 2000–2100, representing the average historical climate frozen in time. The projection simulations apply the yearly-evolving TF for each ensemble member (“701”, “751”, and “801”; see Section 2.2) and the mean of the full ensemble (“Ens Mean”) for 100 years from 2000–2100. The individual ensemble members each contain their own unique

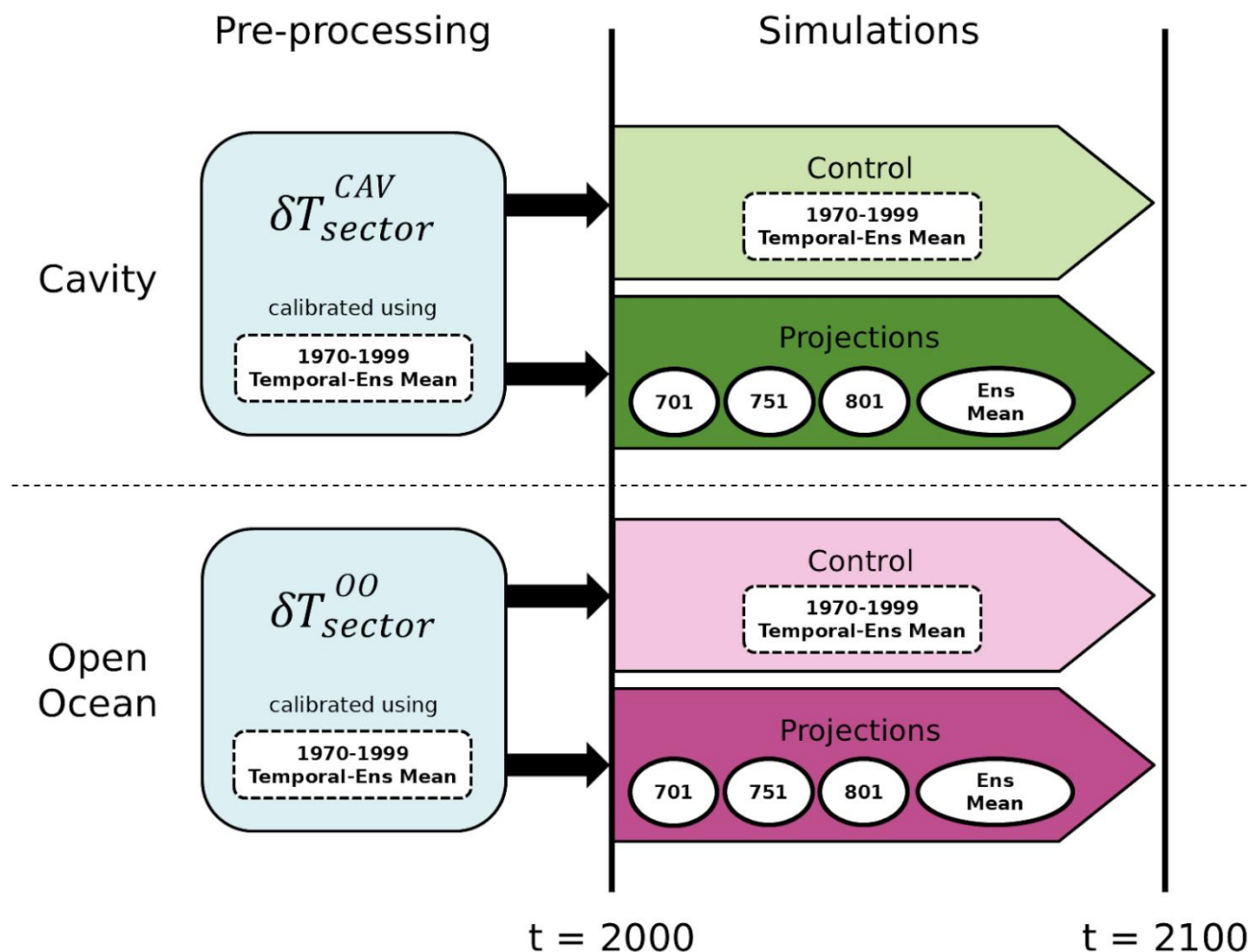


Figure 3: Flowchart illustrating the pre-processing steps and simulation protocols for the CAV (green) and OO (pink) experiments. We calibrate δT_{sector} (light blue boxes) for both experiments using the extrapolated 1970–1999 Temporal-Ens Mean TF fields (dashed boxes). The calibrated δT_{sector} values are then used to correct the constant TF fields used for the control simulations (light pink and light green) and the evolving TF fields for the projection simulations (dark pink and dark green). MALI simulations with the parameterized basal melt are run from 2000 to 2100. In total, 10 total simulations are run from 2000 to 2100, two controls and eight projection simulations.

climate variability, so running the individual ensemble members as well as the Ens Mean provides some representation of the climatic variability, though three members is not sufficient to fully characterize internal variability. These ten simulations were designed to strike a balance between thoroughly exploring the sensitivity to the climatic forcing and running within a reasonable amount of computing time.

We apply a 1995–2017 climatological-averaged surface mass balance (SMB) forcing from the Regional Atmospheric Climate Model version 2.3, polar version 2 (RACMO2.3p2; Van Wessem et al., 2018) to all simulations,



including our control and projection simulations. Our ice-sheet projections use the E3SM-SORRM SSP3-7.0 outputs as an ocean boundary condition but retain constant ice-sheet surface temperatures and SMB boundary conditions. This differs from the ISMIP6 standalone ice-sheet projections, which use an evolving SMB (Nowicki et al., 2020; Seroussi et al., 2024). Keeping SMB forcing constant allows us to isolate changes in Antarctic SLC solely due to the inclusion or exclusion of ocean conditions within cavities.

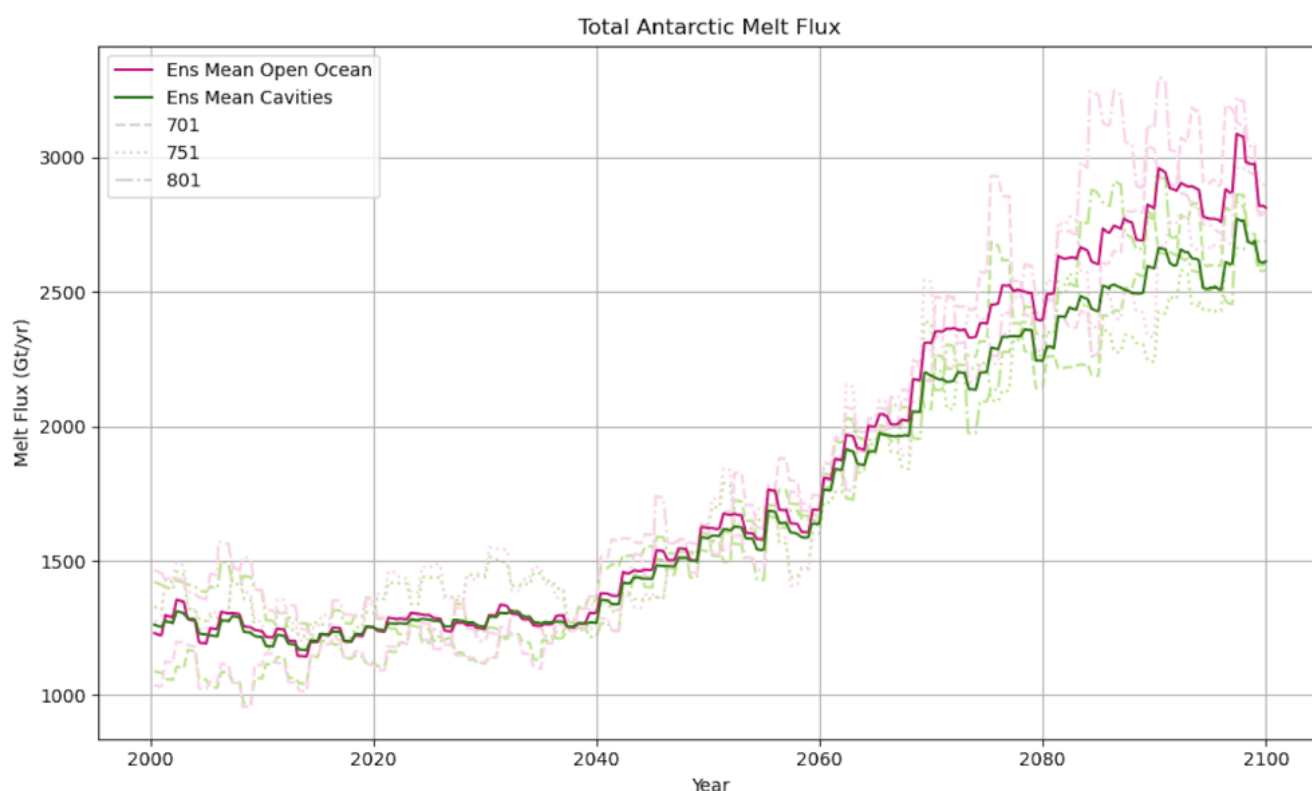


Figure 4: Total, area-integrated Antarctic basal melt flux (Gt yr^{-1}) for the OO (pink) and CAV (green) experiments. Results from the individual ensembles (light pink and light green) and the Ens Mean (dark pink and dark green) are shown. Solid lines are for the Ens Mean, dashed lines are for ensemble “701”, dotted lines are for ensemble “751”, and dashed dotted lines are for ensemble “801”.

3 Results

3.1 Parameterized basal melt rates

The total, area-integrated Antarctic basal melt flux rate for both Ens Mean experiments is largely similar; both start out positive and increase by $\sim 1500 \text{ Gt yr}^{-1}$ (or $\sim 120\%$) from $\sim 1300 \text{ Gt yr}^{-1}$ to $\sim 2800 \text{ Gt yr}^{-1}$ by the end of 2100 (Fig. 4). The similarity in melt flux, especially in the beginning, is by design—we tuned the δT_{sector} values for both experiments such that the resulting parameterized basal melt rates matched the observed rates as closely as possible. For the first ~ 40 years, the melt flux for both sets of experiments stays relatively stable, fluctuating around $\sim 1300 \text{ Gt yr}^{-1}$. The pattern of internal



variability is similar in both sets of experiments, however, by the end of 2100, the OO experiments experience a greater mass loss rate through melting, losing $\sim 200 \text{ Gt yr}^{-1}$ more than in the CAV experiments.

320 Figure 5 shows a matrix of the Ens Mean parameterized ice-shelf basal melt rate maps generated for both experiments at 2000 and 2100. We show snapshots of the basal melt rates at different years, their change over time (2100–2000), and the difference between experiments (OO–CAV). To improve clarity, we mask out cells that compare against zero ice-shelf melt rate. In other words, cells that compare (1) floating ice in one map, but no ice in the other, or (2) grounded ice in one map, but floating ice in the other are masked out. This ensures that we are only comparing cells that have non-zero
325 basal melt in both maps.

Figures 5c & 5f show the change in basal melt rates over time from 2000 to 2100 for the OO and CAV Ens Mean simulations. Ice shelves in the Amundsen Sea show the most dramatic increases in basal melt rate magnitudes in both experiments, with the largest averaged increases located at the Thwaites ($+10.5 \text{ m yr}^{-1}$) and Pine Island Ice Shelves ($+11.9 \text{ m yr}^{-1}$). Ice shelves in East Antarctica also show dramatic increases in basal melt rates. For instance, the Amery and Totten Ice
330 Shelves experience average increases of $+4.8 \text{ m yr}^{-1}$ and $+12.2 \text{ m yr}^{-1}$, respectively, with the greatest melt rate increases near the grounding line. In almost all locations, basal melt rates increase. The only exceptions are beneath the George VI Ice Shelf, which shows a slight negative change in basal melt rate, and beneath the largest “cold-cavity” ice-shelves, the Filchner–Ronne Ice Shelf (FRIS) and Ross Ice Shelf (RIS), which both show negligible increases in melt. Similar ice-shelf basal melt rate differences are seen in the E3SM-SORRM experiments where basal melt rates are directly calculated as
335 opposed to parameterized (see Fig. 8a in Comeau et al., 2025).

We also examine how basal melt rates differ between experiments at the beginning and at the end of the simulations (Fig. 5g & 5h). To do this, we take the difference (OO–CAV) between experiments, such that a positive difference implies greater basal melt rates in the OO experiment and a negative difference implies greater melt rates in the CAV experiment. At 2000, ice-shelf basal melt rates are largely similar between experiments. Exceptions are minor differences near ice-shelf
340 fronts, where CAV tends to have slightly greater melt rates, and near grounding lines, where OO tends to have slightly greater melt rates (Fig. 5g). At 2100, the basal melt pattern where OO has greater melt rates near grounding zones persists; however, larger swaths of the ice shelves now see higher melt rates in OO compared to CAV, particularly at the Amery–Lambert, Totten, Brunt–Stancomb, Dronning Maud Land, and Getz sectors, as well as the cold-cavity RIS (Fig. 5h).

The change in basal melt rates from 2000 to 2100 differs between experiments, as shown in the bottom right panel
345 (Fig. 5i). This panel shows either the difference between panels g and h or panels c and f. The Amery–Lambert, Totten, Brunt–Stancomb, Dronning Maud Land, and Getz sectors have larger increases in basal melt rates in OO than CAV ($\sim 1 \text{ m yr}^{-1}$ or more). RIS also shows greater basal melt rate changes in OO than CAV across a wide swath of the ice shelf, however the difference in magnitude is much smaller ($\sim 0.2 \text{ m yr}^{-1}$).

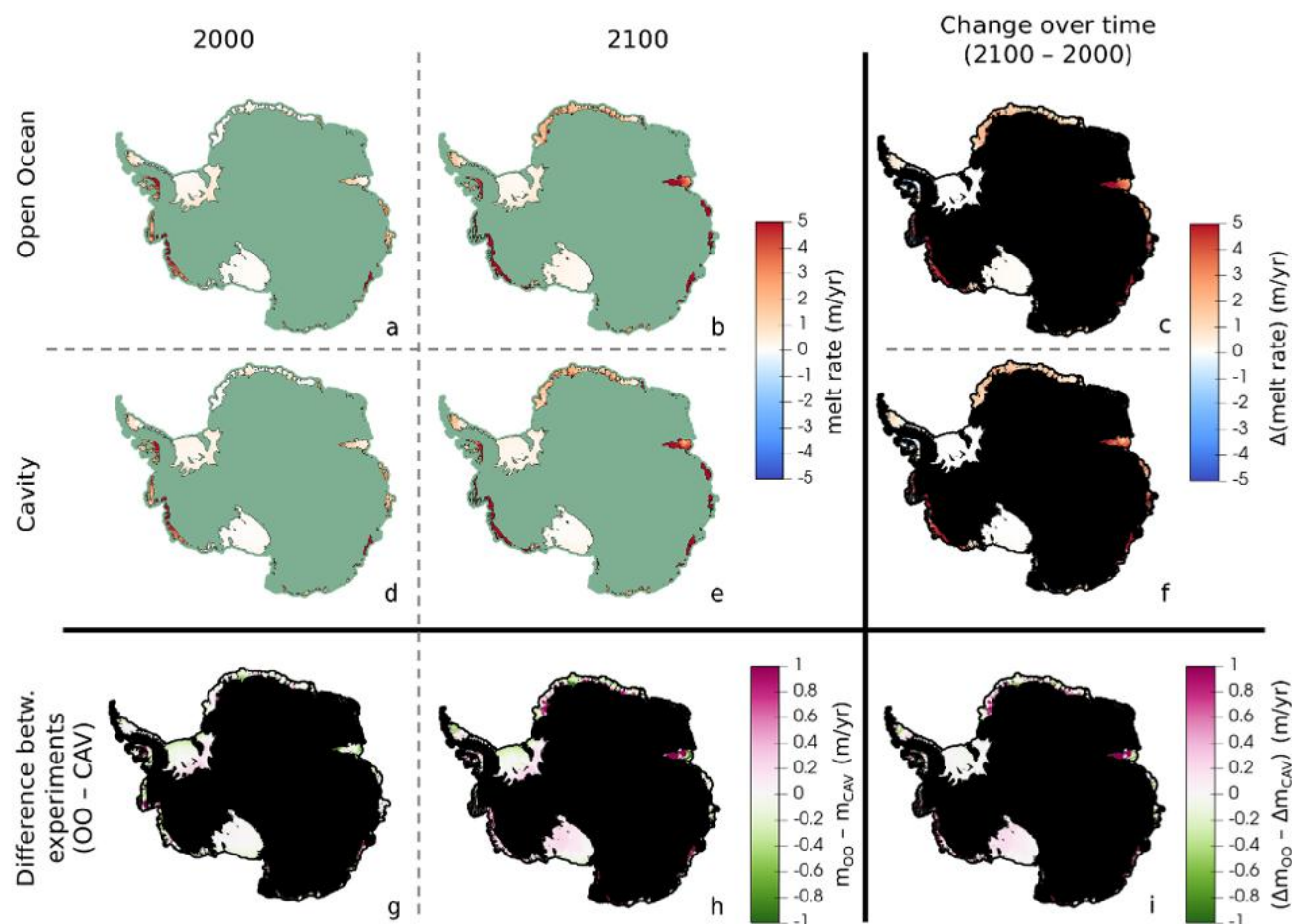


Figure 5: Matrix of Ens Mean parameterized ice-shelf basal melt at years 2000 and 2100 for the OO and CAV experiments (a, b, d, e), the change over time (2100 minus 2000) (c, f), the difference between experiments (OO minus CAV) at 2000 (g) and 2100 (h), and the difference in the change in melt rates between experiments (i). In (a, b, d, e), positive basal melt rate indicates melting (red) whereas negative indicates freeze-on (blue). In (c) and (f), positive indicates an increase in basal melting over time (red) whereas negative indicates a decrease in basal melt over time (blue). In (g) and (h), a positive difference indicates a greater basal melt rate in OO (pink) whereas a negative difference implies a greater basal melt rate in CAV (green). In (i), a positive difference implies a greater change in basal melt rates between 2000 to 2100 in OO (pink) whereas negative implies a greater change in basal melt rates between 2000 to 2100 in CAV (green).

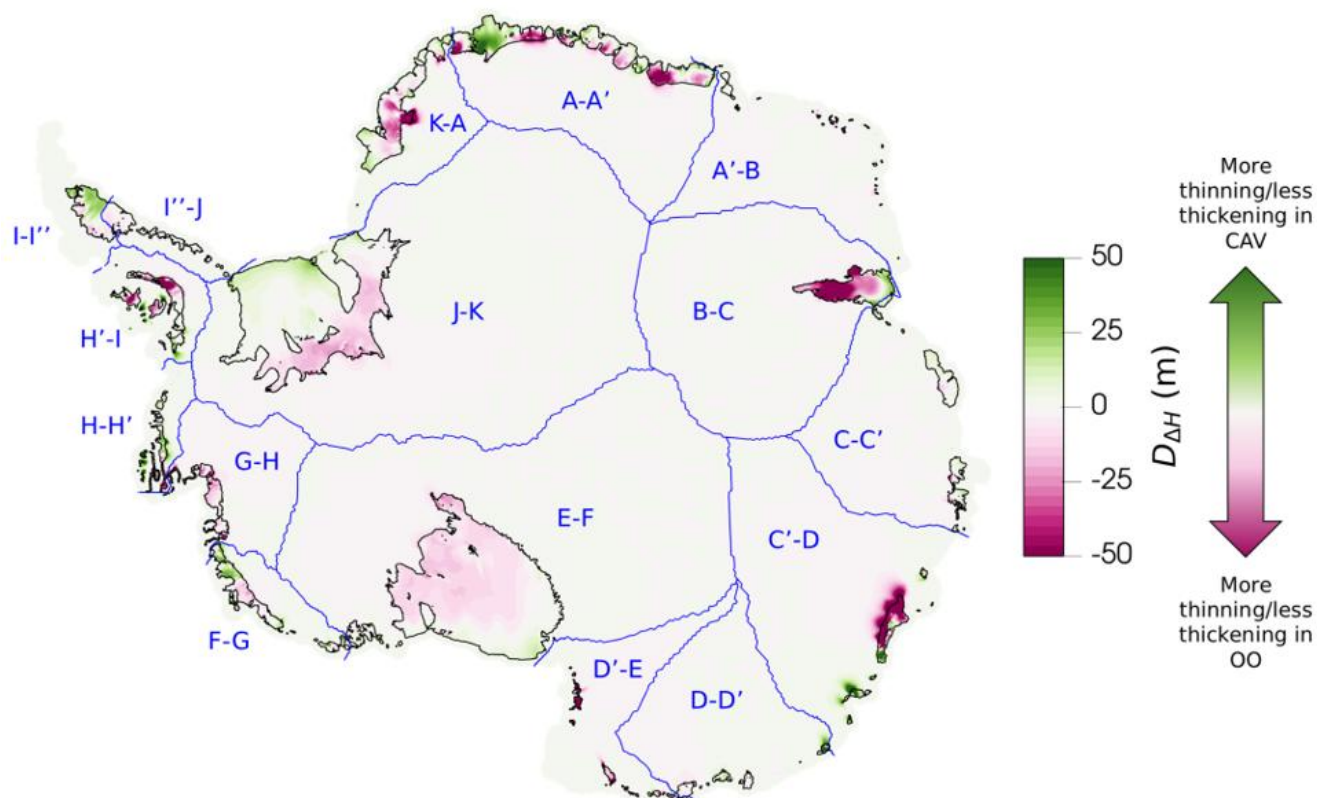
3.2 Ice-sheet thickness change

Figure 6 shows the difference in the thickness change between experiments ($\Delta H_{OO} - \Delta H_{CAV}$) from 2000 to 2100 when forced with the Ens Mean parameterized basal melt rates. Overall, the OO Ens Mean experiment results in more thinning (or less thickening) compared to the CAV Ens Mean experiment during this time period. The largest differences between scenarios are evident at the Amery, Totten and Moscow University ice shelves as well as in the Brunt–Stancomb region. Ice-shelf thinning signals also begin to propagate inland with more thinning of grounded ice occurring in OO in the



365 Totten (C'–D) and Brunt–Stancomb (K–A) sectors. OO shows greater thinning (or less thickening) compared to CAV around the grounding zones of the majority of ice shelves, whereas CAV shows greater thinning (or less thickening) near the ice shelf termini, which is similar in pattern to the basal melt rate differences. This pattern can be seen clearly at the FRIS, Ross, and Amery ice shelves.

Difference in thickness change between experiments, $D_{\Delta H}$



370 **Figure 6: Difference in the Ens Mean thickness change between experiments, $D_{\Delta H} = \Delta H_{OO} - \Delta H_{CAV}$. A positive difference in thickness change (green) shows locations where more thinning (or less thickening) is occurring in CAV compared to OO. A negative difference (pink) shows locations where more thinning (or less thickening) is occurring in OO compared to CAV. Blue contours delineate the 16 sectors used to calibrate δT_{sector} . The black contour is the 2100 grounding line in OO.**

3.3 AIS sea-level contribution

3.3.1 Antarctic Ice Sheet contribution to sea-level

375 Figure 7 shows the time series of AIS volume above flotation (VAF) and associated SLC for both OO and CAV experiments. SLC is calculated following Goelzer et al. (2020) for fixed bedrock. Both Temporal-Ens Mean control runs show positive mass change for the entire 21st century with increased mass gain after the second half of the century. At the close of the century, the control runs reconverge, leading to a total ice-sheet mass gain equivalent of $\sim 12\text{mm}$. The positive



ice-sheet mass change for both control runs is due to insufficient discharge in the ice-sheet initial condition (see Fig. 2c in Hillebrand et al., 2025). The change in mass over time for both control runs is similar, with the CAV control run gaining slightly less mass (~61 Gt or ~1.3%) compared to OO at 2100. This similarity between control runs suggests that the small difference in the spatial pattern of melting is not a significant contributor to mass change.

The projections show an increase in mass of the AIS for the initial decades of the 21st century, followed by accelerating mass loss over the second half of the century under the SSP3-7.0 scenario, leading to a change in SLC of ~28mm for OO Ens Mean projection and ~32mm for the CAV Ens Mean projection at 2100 (Fig. 7). The two experiments yield similar mass change through about 2060, when the mass change in OO begins to outpace that of CAV. By 2100, OO contributes ~4 mm (~13%) more SLC than CAV. The associated SLC for the individual ensemble members 701, 751, and 801 is, respectively, 29.9 mm, 35.0 mm and 33.5 mm for OO and 26.3 mm, 31.5 mm, and 29.6 mm for CAV.

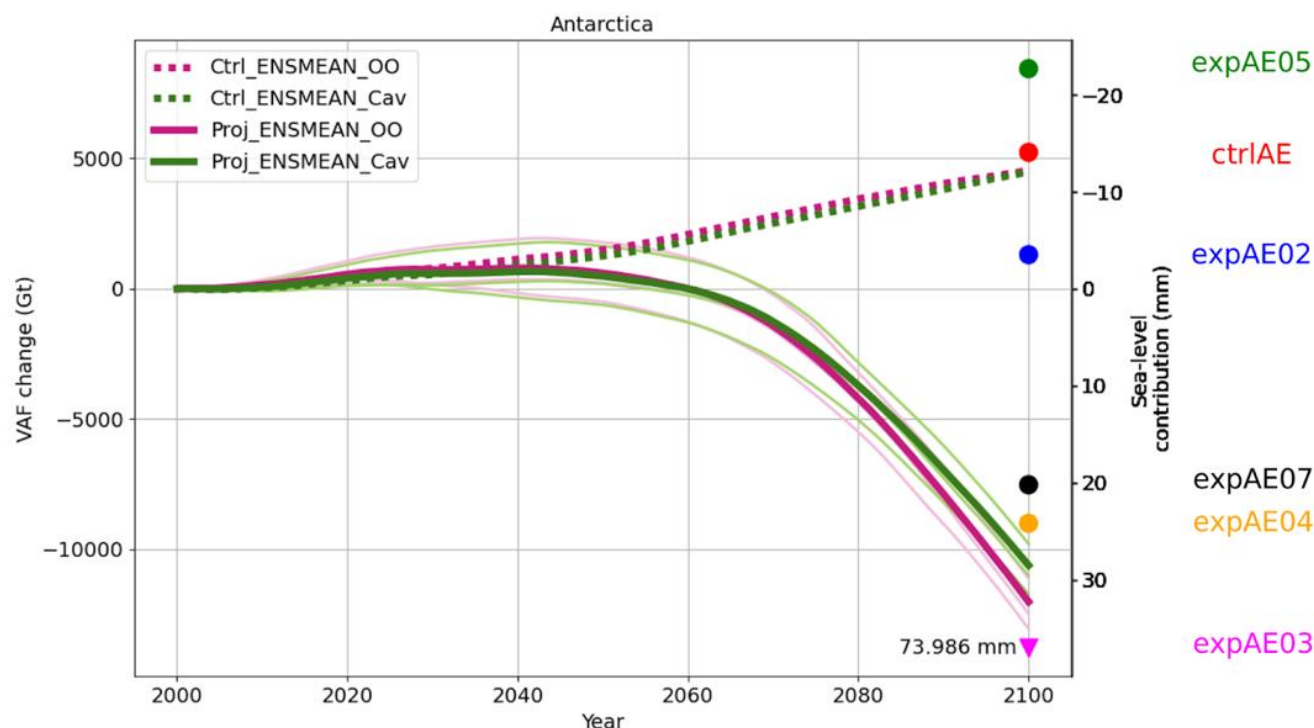


Figure 7: Total projected volume above flotation (VAF) change and associated sea-level contribution (SLC) for Antarctica from 2000 to 2100 for both experimental scenarios “Cavity” (green) and “Open Ocean” (pink). Bold curves correspond to the ensemble mean for both the projected (solid) and control (dotted) simulations. The lighter, solid curves correspond to the three individual ensemble members for the projections. Colored markers (solid circles and downward triangle) are the MALI ISMIP6 2300 results from the high emissions experiments at the year 2100 for reference (Seroussi et al., 2024). The expAE03 value falls outside the plotted range and is noted with the downward-pointing triangle.

3.3.2 Regional melt flux and sea-level contribution

We next examine the Ens Mean Antarctic melt flux and sea-level contribution at the sector scale by partitioning the ice sheet into sixteen geographic sectors. We determine a sector-by-sector change in melt flux and associated SLC for both



experiments before taking the difference between experiments. Figure 8 shows this sector difference (OO–CAV). A positive
400 difference in the change in either melt flux or SLC implies a larger change from 2000 to 2100 in OO compared to CAV.

For the first half century, all sectors show minimal differences between experiments (within ± 15 Gt yr⁻¹) in the
change in ice-shelf melt flux over time. We expect a small difference initially since we forced the melt flux for both
scenarios to match observed values (see total AIS melt flux in Fig. 4). After ~2060, however, the difference in the change in
melt flux between experiments for the Totten, Ross, Amery–Lambert, and Brunt–Stancomb sectors begins to diverge, with
405 OO producing a greater change in melt flux than CAV (Fig. 8a). The Totten sector is the most sensitive to the difference in
the change in melt flux, showing an accelerating divergence in SLC (Fig. 8b). By 2100, the Totten sector contributed
~1.8mm (~36%) more to SLC in OO than in CAV. This difference makes up ~49% of the total net difference. Ross, Brunt–
Stancomb, and Dronning Maud Land also experienced larger mass loss in OO than in CAV, with each accounting for a
difference of ~0.7 mm, ~0.9 mm, and ~0.8 mm, respectively, by 2100. Four sectors experienced less mass loss in OO than in
410 CAV by 2100: Bellingshausen (-0.7 mm), George VI (-0.6 mm), Getz (-0.4 mm), and Mertz (-0.2 mm).

4 Discussion

4.1 Comparison to previous projections

4.1.1 Comparison to ISMIP6 2100 and 2300 AIS projections

Our projected AIS sea-level contribution results fall within the range of previously published studies. The
415 Antarctica ISMIP6 2100 model intercomparison predicted a sea-level contribution between -7.8 cm and 30 cm by 2100
compared to their constant climate (Seroussi et al., 2020). Their result represents a plausible range of SLC projections
generated by various ice-sheet models forced with six different Earth-system models under the RCP8.5 climate scenario
(Barthel et al., 2020). Our experiments use the SSP3-7.0 climate scenario for forcing from the ocean, a more moderate
climate scenario compared to RCP8.5. Our resulting sea-level contribution projections for both experiments fall within the
420 previously projected range, at ~28 mm for CAV and ~32 mm for OO at 2100.

We also compare our results to the ISMIP6 2300 MALI projections from the RCP8.5 and SSP5-8.5 high-emissions
scenarios at 2100 (Hillebrand et al., 2025). The MALI contribution to ISMIP6 2300 used the same initial ice-sheet
configuration as used in our study, but different ocean and SMB forcings. In Fig. 7, we plot six colored points at 2100
representing the SLC from the control and each of the five high-emissions experiments from the MALI contribution to
425 ISMIP6 2300 (expAE02-5 and 7, see Table 1 in Seroussi et al., 2024). Our projections fall within a similar range as the high-
emissions ISMIP6-2300 results.

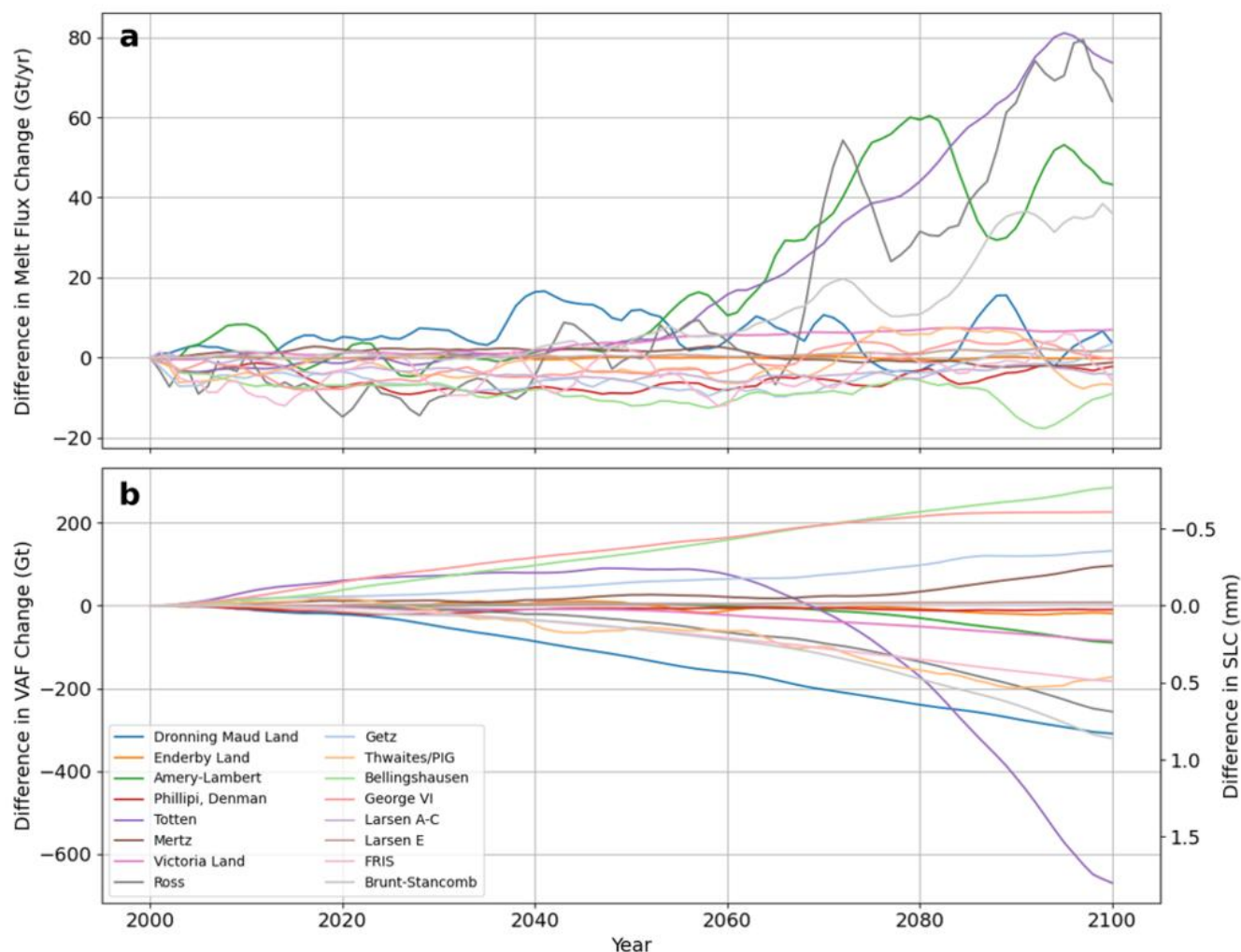


Figure 8. Differences between OO and CAV experiments (OO-CAV) for the (a) change in melt flux (Gt yr^{-1}) and (b) change in VAF (Gt) relative to 2000. Results use the Ens Mean experiment separated into 16 Antarctic sectors shown by color. A five-year moving average was applied for smoothing.

It should also be noted again that our simulations here use the 1995–2017 climatological-averaged SMB from RACMO2.3p2 (Van Wessem et al., 2018) whereas ISMs participating in the ISMIP6 2100 and 2300 experiments applied CMIP-derived atmospheric anomalies to their reference SMB forcing (Nowicki et al., 2020; Seroussi et al., 2020; Seroussi et al., 2024). Generally speaking, the RCP8.5 forcing would lower the SLC by increasing SMB (Seroussi et al., 2024). By using constant SMB, we isolate differences in SLC between scenarios due to basal melt forcing only, at the risk of artificially increasing mass loss.



4.1.2 Comparison to E3SM-SORRM projections

Our total parameterized Antarctic melt flux for both scenarios increases from ~ 1300 to ~ 2800 Gt yr⁻¹, an increase of ~ 1500 Gt yr⁻¹ (Fig. 4) while the melt flux simulated by E3SM-SORRM (Comeau et al., 2025; Vaňková et al., 2026) increases from ~ 1600 to ~ 2800 Gt yr⁻¹, an increase of ~ 1200 Gt yr⁻¹ (Fig. 1). The parameterized melt is sensitive to the choice of γ_0 , which controls how melt rate changes with a change in TF; in previous AIS ISMIP6 simulations, this parameter was responsible for a large portion of the total uncertainty (Seroussi et al., 2023; Seroussi et al., 2024; Seroussi et al., 2020). In our experiments, we used the median calibrated value of $\gamma_0 = 14500$ provided for the ISMIP6 experiments (Jourdain et al., 2020), but our melt flux increase using this parameter value is stronger than what was simulated by E3SM-SORRM. This implies that a smaller value of γ_0 would be required to better match the melt flux increase through 2100 from E3SM-SORRM. Given that γ_0 is a constant of proportionality, we use a simple ratio to calculate an updated γ_0 value of 11600. This new gamma would likely result in a melt rate increase that would better match that predicted by E3SM-SORRM. Jourdain et al. (2020) calibrated a range of γ_0 values using historical temperature and salinity observations but were unable to calibrate γ_0 to changing thermal forcing. The adjusted γ_0 value of 11600 that we calculate is in between the 5th percentile value (9620) and the median value (14500) estimated by Jourdain et al. (2020).

4.2 Differences between OO and CAV experiments

The overall downward trend in the total AIS SLC for both experiments in Fig. 7 is mainly attributed to Thwaites/PIG mass loss, which provides ~ 44 mm to total SLC by 2100, but a difference of only $\sim 1\%$ between experiments. The increasing difference in the total AIS SLC after ~ 2060 , though, can be mostly attributed to the accelerating difference in SLC between OO and CAV at Totten (Fig. 8b). Thus, we focus on the regional results from the Totten sector where we see the largest difference between the OO and CAV experiments in the change in melt flux by the end of 2100 compared to other sectors (Fig. 8a). We also discuss the Ross sector, which showed the second largest difference in the change in melt flux between our experiments. Notably, these sectors show an accelerating difference in SLC by the end of 2100, which is much faster for the Totten sector than for the Ross sector. We note that the Amery–Lambert and Brunt–Stancomb sectors also show a substantial difference in the change in melt flux between the OO and CAV experiments by 2100, however, Amery–Lambert only shows a muted change in the associated SLC. For Brunt–Stancomb, the difference in SLC by 2100 is the second largest in magnitude (~ 0.9 mm more in OO) behind Totten but only shows the fourth largest change in melt flux in magnitude.

4.2.1 Totten sector

The Totten sector showed the greatest difference in the 21st century change in the melt flux between experiments, with the OO experiment contributing ~ 73 Gt yr⁻¹ ($\sim 28\%$) more than the CAV experiment by the end of 2100 (Fig. 8a). It also showed a positive and accelerating difference in SLC, with OO contributing a total of ~ 669 Gt, or ~ 1.8 mm ($\sim 36\%$), more



mass to the ocean compared to CAV by the end of 2100 (Fig. 8b). This difference makes up ~32% of the regional positive differences (sectors where SLC in OO exceeds CAV) and ~49% of the total net difference between experiments.

470 The increasing difference in melt flux between experiments beyond ~2060 (Fig. 8a) is due to the increasing mismatch between the change in open ocean thermal forcing and the change in simulated cavity thermal forcing. The deepest waters outside the mouth of the cavity warm more from 2000 to 2100 than the waters simulated within the cavity (Fig. 9a and 9d). Horizontal and vertical extrapolation in the OO experiment brings the open ocean warming signal along the entirety of the ice-shelf draft (Fig. 9a). The CAV experiment shows a weaker warming signal in the simulated waters within the cavity and at the ice-shelf draft (Fig. 9d). The difference (Fig. 9g) thus shows stronger warming of extrapolated waters in OO compared to simulated waters in CAV from 2000 to 2100, which leads to the enhanced melting in the OO experiment (Fig. 8a and 9j). It is possible that vertical extrapolation does not perform well in this region and exaggerates the intrusion of warm water into the over deepened cavity basin beneath the ice shelf. The subsequent enhanced melting in OO leads to increased thinning (Fig. 6) and reduced buttressing, resulting in dynamic mass loss that contributes to a greater SLC (Fig. 8b).

4.2.2 Ross sector

The Ross Ice Shelf (RIS) has a total area of ~500,000 km² and an ice-shelf front over 600 km long (Rignot et al., 2013), making it one of the largest ice shelves by area in the world. Because of its vast size, ocean conditions and circulation patterns at the ice-shelf front and within the cavity can be spatially heterogeneous, with different water masses of various densities flowing in and out of the cavity opening (Tinto et al., 2019). The EAIS side of the ice shelf features Antarctic Surface Water (AASW) intrusion at the northwestern ice-shelf front, and High Salinity Shelf Water (HSSW) intrusion at depth (Sheehan and Heywood, 2024; Tinto et al., 2019). The WAIS side instead features modified Circumpolar Deep Water (mCDW) intrusion that melts the ice near the frontal zone of the shelf and cooler Ice Shelf Water (ISW) outflow (Tinto et al., 2019).

490 Extrapolation of the open ocean exaggerates the change in warming of thermal forcing within the cavity on the WAIS side of Ross (transect B–B', Fig. 9b). The extrapolation erroneously propagates thermal forcing changes at the calving front all the way to the Siple Coast; in the CAV experiments, the change in thermal forcing on the WAIS side was negligible (Fig. 9e). On the EAIS side (transect C–C'), extrapolation follows the same direction of warm water inflow and thus matches the change in warming signal well, showing minor differences in the change in warming between experiments (Fig. 9i). Because warmer waters (mCDW and HSSW) flow into cavities while cooler ISW flows out, the extrapolation method can bias toward warmer ocean signals and thus overpredict the change in melt rates. Figure 9k shows a map view of the difference in the melt rate change from 2000 to 2100 for RIS.

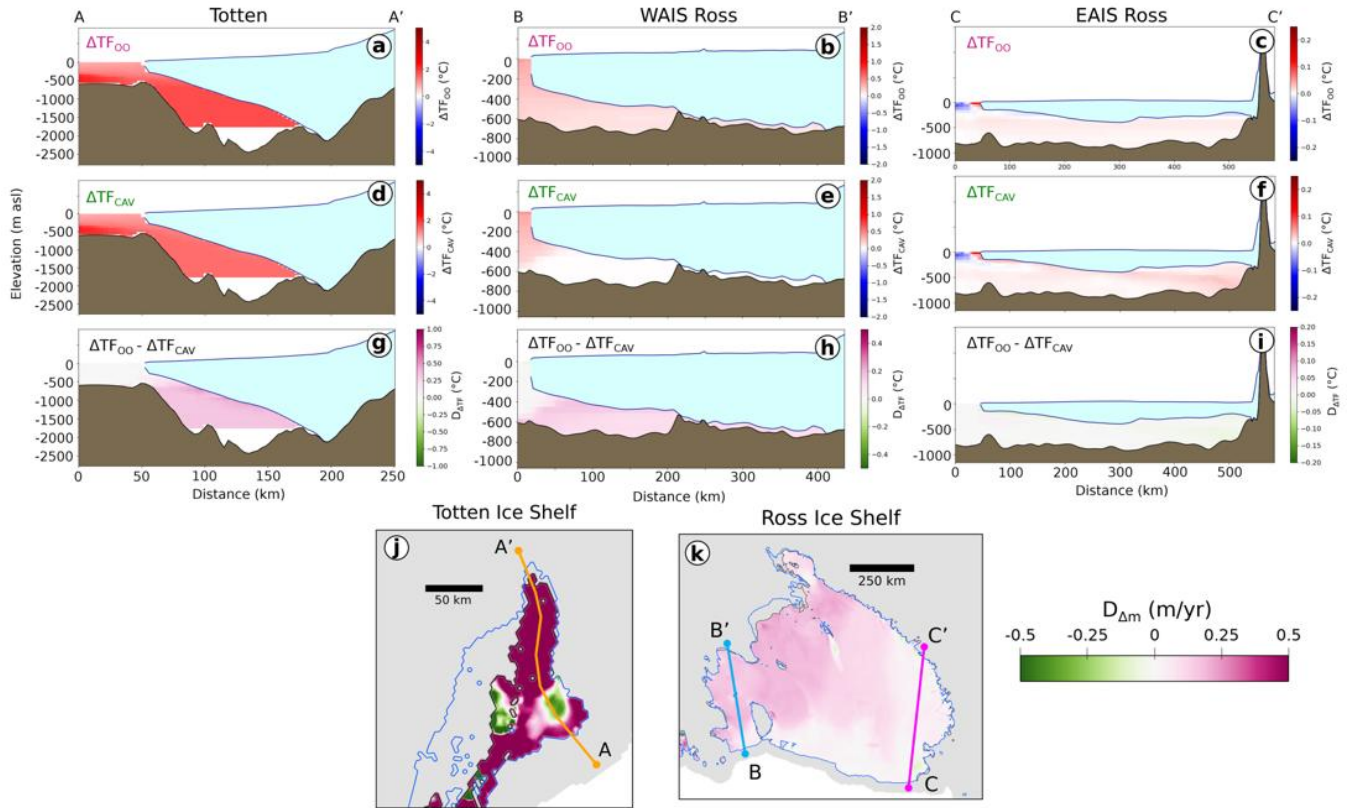


Figure 9. Change in TF (ΔTF) from 2000 to 2100 for OO (a–c) and CAV experiments (d–f), the difference in ΔTF between experiments ($D_{\Delta TF} = \Delta TF_{OO} - \Delta TF_{CAV}$) (g–i) for the Totten and Ross ice shelves, and the difference in the change in melt rates between experiments ($D_{\Delta m}$) for the Totten (j) and Ross (k) ice shelves. The three colored transects in (j) and (k) correspond to the slices where ΔTF and $D_{\Delta TF}$ is plotted in (a–i). Positive (pink) differences are associated with regions that experience either greater changes in TF (g, h, and i) or in basal melt rates (j and k) in OO compared to CAV. Negative (green) differences are associated with greater changes in CAV compared to OO. The black and blue contours are associated with the 2000 and 2100 grounding lines in CAV respectively. Note the different ΔTF and $D_{\Delta TF}$ color bar ranges for each transect.

4.3 The risks of extrapolation and exclusion of cavities

As seen for the Totten and Ross sectors, extrapolation in OO neglects the realistic extent and magnitude of warming within ice-shelf cavities. Warm water masses near the continental shelf seafloor at the calving front (such as mCDW) may warm more than the water masses within the cavity (whereby extrapolation propagates an incorrect signal; Section 4.2.1) or be extrapolated too deeply reaching closer to the grounding line than they do in reality (Section 4.2.2). Artificially enhanced intrusion of warm water leads to inflated basal melt rates in the OO experiments compared to the CAV experiments. The locations that these water masses are being extrapolated to are important because melting at the grounding line has a critical impact on the flow dynamics of the ice sheet behind it, whereas melt near the ice shelf front is less important because buttressing is typically less strong, or non-existent, there (Fürst et al., 2016; Reese et al., 2018a; Zhang et al., 2020). This



515 produces a different dynamic ice sheet response and leads to differences in Antarctic SLC between the OO and CAV experiments (Fig. 7 and 8b).

Another shortcoming of extrapolation is that it occurs instantaneously; in reality, it takes time for water to travel, and therefore to propagate temperature anomalies, from the ice-shelf front to the grounding line. For example, flushing times for FRIS have been estimated to be between 24–30 months (Nicholls and Østerhus, 2004). It is likely that extrapolation
520 artificially expedites basal melting in the OO experiment compared to CAV; the converse “delay” in basal melting when ice-shelf cavities are resolved is similarly reported by Song et al. (2025). However, because the flushing timescales are short and we take 1-year long timesteps, the influence of this time delay in our simulations is likely minimal.

For many applications, an SLC projection error on the order of 10% to 2100, as we find in this study, may be acceptable. Beyond 2100, however, a further warming open ocean combined with more pronounced grounding-line retreat
525 and cavity-shape evolution could compound the errors associated with extrapolation. This error can go in either direction, causing either an overestimate or underestimate of SLC. An overestimation in SLC can be triggered by the extrapolation of warm waters that neglects the depth and extent of their intrusion. Additionally, if the open ocean water masses warm faster than the water masses within the cavity and near the grounding zone, this will introduce a discrepancy in basal melting, which we saw at Totten (Fig. 8b). In a warming world beyond 2100, this discrepancy may continue to increase, however, we
530 do not explore that here.

Extrapolation could also cause an underestimate in SLC. In warm cavities, the overturning circulation induced by the buoyant melt plume draws mCDW into the cavity at a greater flux than it would otherwise intrude on its own in the absence of ice-shelf melting (Jourdain et al., 2017). This overturning circulation is expected to strengthen as basal melting increases, potentially increasing the onshore flux of CDW (Donat-Magnin et al., 2017). Thus, ESMs without resolved ocean
535 cavities are unable to simulate the vertical overturning circulation and will underpredict the extent of mCDW near ice shelves with prominent plumes, and extrapolation would propagate this error into ice-shelf cavities.

Lastly, our OO experiments were based on ocean model simulations that did include cavities but were subsequently masked out. In other words, the ocean at the ice-shelf front in our OO simulations are still influenced by the presence of thermodynamically active ice-shelf cavities. In a true, cavity-less ocean model, heat loss to land ice melting is neglected
540 which would result in a warmer and fresher continental shelf (see Fig. 3 in Moorman et al., 2026). Thus, it is possible that the difference in SLC generated by an ISM that used ocean forcing from a true, cavity-less ocean model versus a cavity-included ocean model could be greater than what we report in our study.

An ESM–ISM is required to capture the feedbacks between an evolving ice sheet and global ocean that are currently neglected in a fixed cavity + extrapolation modeling experiment such as ours. For example, changes in the 3-d
545 cavity geometry can modify ocean dynamics that amplify (as well as suppress) ice-shelf basal melt, and the impact of geometrical feedbacks can dominate melt variability on decadal timescales (De Rydt and Naughten, 2024). Additionally, the meltwater flux itself has a significant impact on ocean conditions, and in turn, ice-shelf basal melt rates (Youngs et al., 2026; Vaňková et al., 2026). In a recent study, when the increase in meltwater flux to the ocean is ignored, the estimated ice-shelf



550 melt flux at 2100 is ~22% too high (Vaňková et al., 2026). Extrapolation cannot capture either of these feedbacks and their omission will become increasingly consequential as ice-sheet and ocean conditions diverge from their present states.

5 Conclusion

555 We explored the impact on standalone ice-sheet projections forced by an ESM projection that includes ice-shelf cavities. Our results show that when we take into account the ocean conditions in cavities, the associated Antarctic SLC at 2100 is moderately reduced by ~4mm, or by ~13%, compared to a scenario that extrapolates ocean conditions from the ice-shelf front into the ice-shelf cavities. This model bias is comparable or smaller to many other ice-sheet model uncertainties, and for many policy and planning applications, an SLC projection error of this size may be acceptable. While the difference is modest through 2100, our simulations suggest that existing SLC projections from standalone ice-sheet models are likely being overestimated beyond 2100. Large changes in ocean conditions and ice-shelf geometries will cause changes to melt rates that the extrapolation approach cannot resolve. ESMs with dynamically evolving ice sheets and two-way coupling
560 between the ocean will be required to capture these feedbacks and improve SLC projections in the future.



Code and data availability

The MALI code used to perform the simulations is available online here <https://doi.org/10.5281/zenodo.19924934> (E3SM Project, 2026). Thermal forcing inputs are available in an archive here <https://doi.org/10.5281/zenodo.20388988> (Shafer et al., 2026). Model outputs and analysis used to recreate the figures are provided here <https://doi.org/10.5281/zenodo.20360030> (Shafer et al., 2026).

Author contributions

MH developed the research study and CS conducted the research. CS performed the MALI-SORRM modelling experiments, updated MALI code for the research experiments, wrote the original draft, and created the table and figures. CS and MH performed the formal analysis and validation of results. TH generated the initialized grids of the Antarctic Ice Sheet. MH, XAD, and HH designed the thermal forcing extrapolation algorithm and HH wrote the initial code for the extrapolation method. MH and AH wrote the code to interpolate MPAS-Ocean information onto MALI grids. DC generated the E3SM-SORRM thermal forcing data used. MH processed the thermal forcing data using the interpolation code. All authors except KP contributed to MALI and E3SM software development. MH and KP supervised the research. All authors contributed to review and editing of the manuscript.

Competing interests

At least one of the (co-)authors is a member of the editorial board of The Cryosphere. The authors also have no other competing interests to declare.

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References

Adcroft, A. and Campin, J.-M.: Rescaled height coordinates for accurate representation of free-surface flows in ocean circulation models, *Ocean Modelling*, 7, 269-284, <https://doi.org/10.1016/j.ocemod.2003.09.003>, 2004.

Arakawa, A. and Lamb, V. R.: Computational Design of the Basic Dynamical Processes of the UCLA General Circulation Model, in: *Methods in Computational Physics: Advances in Research and Applications*, edited by: Chang, J., Elsevier, 173-265, <https://doi.org/10.1016/B978-0-12-460817-7.50009-4>, 1977.

Asay-Davis, X. S., Jourdain, N. C., and Nakayama, Y.: Developments in Simulating and Parameterizing Interactions Between the Southern Ocean and the Antarctic Ice Sheet, *Current Climate Change Reports*, 3, 316-329, 10.1007/s40641-017-0071-0, 2017.

Barthel, A., Agosta, C., Little, C. M., Hattermann, T., Jourdain, N. C., Goelzer, H., Nowicki, S., Seroussi, H., Straneo, F., and Bracegirdle, T. J.: CMIP5 model selection for ISMIP6 ice sheet model forcing: Greenland and Antarctica, *The Cryosphere*, 14, 855-879, 10.5194/tc-14-855-2020, 2020.

Beckmann, A. and Goosse, H.: A parameterization of ice shelf–ocean interaction for climate models, *Ocean Modelling*, 5, 157-170, [https://doi.org/10.1016/S1463-5003\(02\)00019-7](https://doi.org/10.1016/S1463-5003(02)00019-7), 2003.



- Bennetts, L. G., Shakespeare, C. J., Vreugdenhil, C. A., Foppert, A., Gayen, B., Meyer, A., Morrison, A. K., Padman, L., Phillips, H. E., Stevens, C. L., Toffoli, A., Constantinou, N. C., Cusack, J. M., Cyriac, A., Doddridge, E. W., England, M. H., Evans, D. G., Heil, P., Hogg, A. M., Holmes, R. M., Huneke, W. G. C., Jones, N. L., Keating, S. R., Kiss, A. E.,
625 Kraitzman, N., Malyarenko, A., McConnochie, C. D., Meucci, A., Montiel, F., Neme, J., Nikurashin, M., Patel, R. S., Peng, J. P., Rayson, M., Rosevear, M. G., Sohail, T., Spence, P., and Stanley, G. J.: Closing the Loops on Southern Ocean Dynamics: From the Circumpolar Current to Ice Shelves and From Bottom Mixing to Surface Waves, *Reviews of Geophysics*, 62, 10.1029/2022rg000781, 2024.
- 630 Bett, D. T., Bradley, A. T., Williams, C. R., Holland, P. R., Arthern, R. J., and Goldberg, D. N.: Coupled ice–ocean interactions during future retreat of West Antarctic ice streams in the Amundsen Sea sector, *The Cryosphere*, 18, 2653–2675, 10.5194/tc-18-2653-2024, 2024.
- Blatter, H.: Velocity and stress fields in grounded glaciers: a simple algorithm for including deviatoric stress gradients,
635 *Journal of Glaciology*, 41, 333–344, 10.3189/S002214300001621X, 1995.
- Burgard, C., Jourdain, N. C., Reese, R., Jenkins, A., and Mathiot, P.: An assessment of basal melt parameterisations for Antarctic ice shelves, *The Cryosphere*, 16, 4931–4975, 10.5194/tc-16-4931-2022, 2022.
- 640 Comeau, D., Price, S., Asay-Davis, X., Barthel, A., Begeman, C., Hoffman, M., Lin, W., Petersen, M., Vaňková, I., Veneziani, M., Wolfe, J., and Zhang, S.: The DOE E3SM v2.1 Cryosphere configuration: Antarctic ice-shelf basal melt projections through 2100, *ESS Open Archive*, 2025, 10.22541/essoar.176005767.71950078/v1, 2025.
- Comeau, D., Asay-Davis, X. S., Begeman, C. B., Hoffman, M. J., Lin, W., Petersen, M. R., Price, S. F., Roberts, A. F., Van
645 Roekel, L. P., Veneziani, M., Wolfe, J. D., Fyke, J. G., Ringler, T. D., and Turner, A. K.: The DOE E3SM v1.2 Cryosphere Configuration: Description and Simulated Antarctic Ice-Shelf Basal Melting, *Journal of Advances in Modeling Earth Systems*, 14, 10.1029/2021ms002468, 2022.
- De Rydt, J. and Gudmundsson, G. H.: Coupled ice shelf-ocean modeling and complex grounding line retreat from a seabed
650 ridge, *Journal of Geophysical Research: Earth Surface*, 121, 865–880, 10.1002/2015jf003791, 2016.
- De Rydt, J. and Naughten, K.: Geometric amplification and suppression of ice-shelf basal melt in West Antarctica, *The Cryosphere*, 18, 1863–1888, 10.5194/tc-18-1863-2024, 2024.
- 655 Deconto, R. M. and Pollard, D.: Contribution of Antarctica to past and future sea-level rise, *Nature*, 531, 591–597, 10.1038/nature17145, 2016.
- Dinniman, M., Asay-Davis, X., Galton-Fenzi, B., Holland, P., Jenkins, A., and Timmermann, R.: Modeling Ice Shelf/Ocean Interaction in Antarctica: A Review, *Oceanography*, 29, 144–153, 10.5670/oceanog.2016.106, 2016.
- 660 Donat-Magnin, M., Jourdain, N. C., Spence, P., Le Sommer, J., Gallée, H., and Durand, G.: Ice-Shelf Melt Response to Changing Winds and Glacier Dynamics in the Amundsen Sea Sector, Antarctica, *Journal of Geophysical Research: Oceans*, 122, 10206–10224, 10.1002/2017jc013059, 2017.
- 665 Dukowicz, J. K., Price, S. F., and Lipscomb, W. H.: Consistent approximations and boundary conditions for ice-sheet dynamics from a principle of least action, *Journal of Glaciology*, 56, 480–496, 10.3189/002214310792447851, 2010.
- E3SM Project (2026). Energy Exascale Earth System Model
(archive/matthewhoffman/JAMES_2026_MALI_SORRM_Shafer). Zenodo. <https://doi.org/10.5281/zenodo.19924934>



- Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, *Geosci. Model Dev.*, 9, 1937-1958, 10.5194/gmd-9-1937-2016, 2016.
- 675 Favier, L., Jourdain, N. C., Jenkins, A., Merino, N., Durand, G., Gagliardini, O., Gillet-Chaulet, F., and Mathiot, P.: Assessment of sub-shelf melting parameterisations using the ocean–ice-sheet coupled model NEMO(v3.6)–Elmer/Ice(v8.3), *Geoscientific Model Development*, 12, 2255-2283, 10.5194/gmd-12-2255-2019, 2019.
- 680 Fox-Kemper, B., Danabasoglu, G., Ferrari, R., Griffies, S. M., Hallberg, R. W., Holland, M. M., Maltrud, M. E., Peacock, S., and Samuels, B. L.: Parameterization of mixed layer eddies. III: Implementation and impact in global ocean climate simulations, *Ocean Modelling*, 39, 61-78, <https://doi.org/10.1016/j.ocemod.2010.09.002>, 2011.
- 685 Fretwell, P., Pritchard, H. D., Vaughan, D. G., Bamber, J. L., Barrand, N. E., Bell, R., Bianchi, C., Bingham, R. G., Blankenship, D. D., Casassa, G., Catania, G., Callens, D., Conway, H., Cook, A. J., Corr, H. F. J., Damaske, D., Damm, V., Ferraccioli, F., Forsberg, R., Fujita, S., Gim, Y., Gogineni, P., Griggs, J. A., Hindmarsh, R. C. A., Holmlund, P., Holt, J. W., Jacobel, R. W., Jenkins, A., Jokat, W., Jordan, T., King, E. C., Kohler, J., Krabill, W., Riger-Kusk, M., Langley, K. A., Leitchenkov, G., Leuschen, C., Luyendyk, B. P., Matsuoka, K., Mouginot, J., Nitsche, F. O., Nogi, Y., Nost, O. A., Popov, S. V., Rignot, E., Rippin, D. M., Rivera, A., Roberts, J., Ross, N., Siegert, M. J., Smith, A. M., Steinhage, D., Studinger, M., Sun, B., Tinto, B. K., Welch, B. C., Wilson, D., Young, D. A., Xiangbin, C., and Zirizzotti, A.: Bedmap2: improved ice bed, 690 surface and thickness datasets for Antarctica, *The Cryosphere*, 7, 375-393, 10.5194/tc-7-375-2013, 2013.
- Fürst, J. J., Durand, G., Gillet-Chaulet, F., Tavaré, L., Rankl, M., Braun, M., and Gagliardini, O.: The safety band of Antarctic ice shelves, *Nature Climate Change*, 6, 479-482, 10.1038/nclimate2912, 2016.
- 695 Gent, P. R. and McWilliams, J. C.: Isopycnal Mixing in Ocean Circulation Models, *Journal of Physical Oceanography*, 20, 150-155, [https://doi.org/10.1175/1520-0485\(1990\)020<0150:IMIOCM>2.0.CO;2](https://doi.org/10.1175/1520-0485(1990)020<0150:IMIOCM>2.0.CO;2), 1990.
- Glen, J. W.: The creep of polycrystalline ice, *Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences*, 228, 519-538, 10.1098/rspa.1955.0066, 1955.
- 700 Goelzer, H., Coulon, V., Pattyn, F., De Boer, B., and Van De Wal, R.: Brief communication: On calculating the sea-level contribution in marine ice-sheet models, *The Cryosphere*, 14, 833-840, 10.5194/tc-14-833-2020, 2020.
- 705 Golaz, J. C., Van Roekel, L. P., Zheng, X., Roberts, A. F., Wolfe, J. D., Lin, W., Bradley, A. M., Tang, Q., Maltrud, M. E., Forsyth, R. M., Zhang, C., Zhou, T., Zhang, K., Zender, C. S., Wu, M., Wang, H., Turner, A. K., Singh, B., Richter, J. H., Qin, Y., Petersen, M. R., Mametjanov, A., Ma, P. L., Larson, V. E., Krishna, J., Keen, N. D., Jeffery, N., Hunke, E. C., Hannah, W. M., Guba, O., Griffin, B. M., Feng, Y., Engwirda, D., Di Vittorio, A. V., Dang, C., Conlon, L. M., Chen, C. C. J., Brunke, M. A., Bisht, G., Benedict, J. J., Asay-Davis, X. S., Zhang, Y., Zhang, M., Zeng, X., Xie, S., Wolfram, P. J., Vo, T., Veneziani, M., Tesfa, T. K., Sreepathi, S., Salinger, A. G., Reeves Eyre, J. E. J., Prather, M. J., Mahajan, S., Li, Q., 710 Jones, P. W., Jacob, R. L., Huebler, G. W., Huang, X., Hillman, B. R., Harrop, B. E., Foucar, J. G., Fang, Y., Comeau, D. S., Caldwell, P. M., Bartoletti, T., Balaguru, K., Taylor, M. A., McCoy, R. B., Leung, L. R., and Bader, D. C.: The DOE E3SM Model Version 2: Overview of the Physical Model and Initial Model Evaluation, *Journal of Advances in Modeling Earth Systems*, 14, 10.1029/2022ms003156, 2022.
- 715 Golaz, J. C., Lin, W., Zheng, X., Xie, S., Roberts, A. F., Van Roekel, L. P., Thornton, P. E., Barthel, A. M., Bradley, A. M., Wolfe, J. D., Zhang, C., Zhang, K., Zhang, S., Asay-Davis, X. S., Begeman, C. B., Bisht, G., Burrows, S. M., Chen, C. C. J., Feng, Y., Hunke, E. C., Jacob, R. L., Ke, Z., Mahajan, S., Mahfouz, N. G., Maltrud, M. E., Shi, X., Tang, Q., Terai, C. R., Thomas, E. E., Wang, H., Xie, J., Zhou, T., Bartoletti, T., Benedict, J. J., Brunke, M. A., Comeau, D. S., Fan, J., Forsyth, R. M., Foucar, J. G., Guba, O., Hannah, W. M., Hao, D., Huang, X., Jeffery, N., Kang, H. G., Keen, N. D., Lee, H. H., Lee, J., 720 Liu, X., Mametjanov, A., Mülmenstädt, J., Petersen, M. R., Prather, M. J., Price, S. F., Qian, Y., Salinger, A. G., Santos, S.



- P., Shan, Y., Singh, B., Smith, K. M., Song, X., Sreepathi, S., Turner, A. K., Vo, T., Wan, H., Wu, M., Yu, W., Zender, C. S., Zeng, X., Zhang, G. J., Zhang, M., Zhang, T., Zhang, Y., McCoy, R. B., Taylor, M. A., Leung, L. R., Caldwell, P. M., and Bader, D. C.: The Energy Exascale Earth System Model Version 3: 2. Overview of the Coupled System, *Journal of Advances in Modeling Earth Systems*, 18, 10.1029/2025ms005302, 2026.
- 725 Goldberg, D. N. and Holland, P. R.: The Relative Impacts of Initialization and Climate Forcing in Coupled Ice Sheet-Ocean Modeling: Application to Pope, Smith, and Kohler Glaciers, *Journal of Geophysical Research: Earth Surface*, 127, 10.1029/2021jfr006570, 2022.
- 730 Goldberg, D. N., Snow, K., Holland, P., Jordan, J. R., Campin, J. M., Heimbach, P., Arthern, R., and Jenkins, A.: Representing grounding line migration in synchronous coupling between a marine ice sheet model and a z-coordinate ocean model, *Ocean Modelling*, 125, 45-60, <https://doi.org/10.1016/j.ocemod.2018.03.005>, 2018.
- Gudmundsson, G. H.: Ice-shelf buttressing and the stability of marine ice sheets, *The Cryosphere*, 7, 647-655, 10.5194/tc-7-647-2013, 2013.
- 735 Gudmundsson, G. H., Paolo, F. S., Adusumilli, S., and Fricker, H. A.: Instantaneous Antarctic ice sheet mass loss driven by thinning ice shelves, *Geophysical Research Letters*, 46, 13903-13909, 10.1029/2019gl085027, 2019.
- 740 Hill, E. A., Gudmundsson, G. H., and Chandler, D. M.: Ocean warming as a trigger for irreversible retreat of the Antarctic ice sheet, *Nature Climate Change*, 10.1038/s41558-024-02134-8, 2024.
- Hillebrand, T. R., Hoffman, M. J., Han, H. K., Perego, M., Hager, A. O., Nolan, A., Asay-Davis, X., Price, S. F., Watkins, J., and Carlson, M.: Evolution of the Antarctic Ice Sheet from 2000–2300 and beyond: model sensitivity and uncertainty analysis using MPAS-Albany Land Ice, *EGUsphere*, 2025, 1-51, 10.5194/egusphere-2025-3942, 2025.
- 745 Hoffman, M. J., Perego, M., Price, S. F., Lipscomb, W. H., Zhang, T., Jacobsen, D., Tezaur, I., Salinger, A. G., Tuminaro, R., and Bertagna, L.: MPAS-Albany Land Ice (MALI): a variable-resolution ice sheet model for Earth system modeling using Voronoi grids, *Geoscientific Model Development*, 11, 3747-3780, 10.5194/gmd-11-3747-2018, 2018.
- 750 Holland, P. R., Jenkins, A., and Holland, D. M.: The Response of Ice Shelf Basal Melting to Variations in Ocean Temperature, *Journal of Climate*, 21, 2558-2572, 10.1175/2007jcli1909.1, 2008.
- 755 IPCC: Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, DOI: 10.1017/9781009157896, 2023.
- Jacobs, S. S., Jenkins, A., Giulivi, C. F., and Dutrieux, P.: Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf, *Nature Geoscience*, 4, 519-523, 10.1038/ngeo1188, 2011.
- 760 Jenkins, A., Shoosmith, D., Dutrieux, P., Jacobs, S., Kim, T. W., Lee, S. H., Ha, H. K., and Stammerjohn, S.: West Antarctic Ice Sheet retreat in the Amundsen Sea driven by decadal oceanic variability, *Nature Geoscience*, 11, 733-738, 10.1038/s41561-018-0207-4, 2018.
- 765 Jordan, J. R., Holland, P. R., Goldberg, D., Snow, K., Arthern, R., Campin, J. M., Heimbach, P., and Jenkins, A.: Ocean-Forced Ice-Shelf Thinning in a Synchronously Coupled Ice-Ocean Model, *Journal of Geophysical Research: Oceans*, 123, 864-882, 10.1002/2017jc013251, 2018.



- 770 Jourdain, N. C., Asay-Davis, X., Hattermann, T., Straneo, F., Seroussi, H., Little, C. M., and Nowicki, S.: A protocol for
calculating basal melt rates in the ISMIP6 Antarctic ice sheet projections, *The Cryosphere*, 14, 3111-3134, 10.5194/tc-14-
3111-2020, 2020.
- 775 Jourdain, N. C., Mathiot, P., Merino, N., Durand, G., Le Sommer, J., Spence, P., Dutrieux, P., and Madec, G.: Ocean
circulation and sea-ice thinning induced by melting ice shelves in the Amundsen Sea, *Journal of Geophysical Research: Oceans*, 122, 2550-2573, 10.1002/2016jc012509, 2017.
- Kara, A. B., Wallcraft, A. J., and Hurlburt, H. E.: A Correction for Land Contamination of Atmospheric Variables near
Land–Sea Boundaries*, *Journal of Physical Oceanography*, 37, 803-818, 10.1175/jpo2984.1, 2007.
- 780 Lambert, E. and Burgard, C.: Brief communication: Sensitivity of Antarctic ice shelf melting to ocean warming across basal
melt models, *The Cryosphere*, 19, 2495-2505, 10.5194/tc-19-2495-2025, 2025.
- Lazeroms, W. M. J., Jenkins, A., Gudmundsson, G. H., and van de Wal, R. S. W.: Modelling present-day basal melt rates for
Antarctic ice shelves using a parametrization of buoyant meltwater plumes, *The Cryosphere*, 12, 49-70, 10.5194/tc-12-49-
785 2018, 2018.
- Lazeroms, W. M. J., Jenkins, A., Rienstra, S. W., and van de Wal, R. S. W.: An Analytical Derivation of Ice-Shelf Basal
Melt Based on the Dynamics of Meltwater Plumes, *Journal of Physical Oceanography*, 49, 917-939,
790 <https://doi.org/10.1175/JPO-D-18-0131.1>, 2019.
- Lenaerts, J. T. M., Van Den Broeke, M. R., Van De Berg, W. J., Van Meijgaard, E., and Kuipers Munneke, P.: A new, high-
resolution surface mass balance map of Antarctica (1979–2010) based on regional atmospheric climate modeling,
Geophysical Research Letters, 39, n/a-n/a, 10.1029/2011gl050713, 2012.
- 795 Martos, Y. M., Catalán, M., Jordan, T. A., Golynsky, A., Golynsky, D., Eagles, G., and Vaughan, D. G.: Heat Flux
Distribution of Antarctica Unveiled, *Geophysical Research Letters*, 44, 11,417-411,426, 10.1002/2017gl075609, 2017.
- Mathiot, P., Jenkins, A., Harris, C., and Madec, G.: Explicit representation and parametrised impacts of under ice shelf seas
in the z* coordinate ocean model NEMO 3.6, *Geoscientific Model Development*, 10, 2849-2874, 10.5194/gmd-10-2849-
800 2017, 2017.
- Moorman, R., Thompson, A. F., Youngs, M. K., and Stewart, A. L.: The Antarctic coastal ocean heat budget is dominated by
heat loss to land ice melt, *Science Advances*, 12, 10.1126/sciadv.aec7443, 2026.
- 805 Morlighem, M.: MEaSUREs BedMachine Antarctica, Version 2, NASA National Snow and Ice Data Center Distributed
Active Archive Center [dataset], 10.5067/E1QL9HFQ7A8M, 2020.
- Morlighem, M., Rignot, E., Binder, T., Blankenship, D., Drews, R., Eagles, G., Eisen, O., Ferraccioli, F., Forsberg, R.,
Fretwell, P., Goel, V., Greenbaum, J. S., Gudmundsson, H., Guo, J., Helm, V., Hofstede, C., Howat, I., Humbert, A., Jokat,
W., Karlsson, N. B., Lee, W. S., Matsuoka, K., Millan, R., Mouginot, J., Paden, J., Pattyn, F., Roberts, J., Rosier, S., Ruppel,
810 A., Seroussi, H., Smith, E. C., Steinhage, D., Sun, B., Broeke, M. R. V. D., Ommen, T. D. V., Wessem, M. V., and Young,
D. A.: Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet, *Nature
Geoscience*, 13, 132-137, 10.1038/s41561-019-0510-8, 2020.
- Mouginot, J., Scheuchl, B., and Rignot, E.: Mapping of Ice Motion in Antarctica Using Synthetic-Aperture Radar Data,
815 10.3390/rs4092753, 2012.
- Nicholls, K. W. and Østerhus, S.: Interannual variability and ventilation timescales in the ocean cavity beneath Filchner-
Ronne Ice Shelf, Antarctica, *Journal of Geophysical Research: Oceans*, 109, 10.1029/2003jc002149, 2004.



- 820 Nowicki, S., Payne, A., Larour, E., Seroussi, H., Goelzer, H., Lipscomb, W., Gregory, J., Abe-Ouchi, A., and Shepherd, A.: Ice Sheet Model Intercomparison Project (ISMIP6) contribution to CMIP6, Geoscientific Model Development, 9, 4521-4545, 10.5194/gmd-9-4521-2016, 2016.
- 825 Nowicki, S., Goelzer, H., Seroussi, H., Payne, A. J., Lipscomb, W. H., Abe-Ouchi, A., Agosta, C., Alexander, P., Asay-Davis, X. S., Barthel, A., Bracegirdle, T. J., Cullather, R., Felikson, D., Fettweis, X., Gregory, J. M., Hattermann, T., Jourdain, N. C., Kuipers Munneke, P., Larour, E., Little, C. M., Morlighem, M., Nias, I., Shepherd, A., Simon, E., Slater, D., Smith, R. S., Straneo, F., Trusel, L. D., Van Den Broeke, M. R., and Van De Wal, R.: Experimental protocol for sea level projections from ISMIP6 stand-alone ice sheet models, The Cryosphere, 14, 2331-2368, 10.5194/tc-14-2331-2020, 2020.
- 830 Nye, J. F.: The flow of glaciers and ice-sheets as a problem in plasticity, Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences, 207, 554-572, 10.1098/rspa.1951.0140, 1951.
- Pattyn, F.: A new three-dimensional higher-order thermomechanical ice sheet model: Basic sensitivity, ice stream development, and ice flow across subglacial lakes, Journal of Geophysical Research: Solid Earth, 108, 10.1029/2002jb002329, 2003.
- 835 10.1029/2002jb002329, 2003.
- Pelle, T., Morlighem, M., and Bondzio, J. H.: Brief communication: PICOP, a new ocean melt parameterization under ice shelves combining PICO and a plume model, The Cryosphere, 13, 1043-1049, 10.5194/tc-13-1043-2019, 2019.
- 840 Pelle, T., Morlighem, M., Nakayama, Y., and Seroussi, H.: Widespread Grounding Line Retreat of Totten Glacier, East Antarctica, Over the 21st Century, Geophysical Research Letters, 48, 10.1029/2021gl093213, 2021.
- Perego, M., Price, S., and Stadler, G.: Optimal initial conditions for coupling ice sheet models to Earth system models, Journal of Geophysical Research: Earth Surface, 119, 1894-1917, 10.1002/2014jf003181, 2014.
- 845 Petersen, M. R., Asay-Davis, X. S., Berres, A. S., Chen, Q., Feige, N., Hoffman, M. J., Jacobsen, D. W., Jones, P. W., Maltrud, M. E., Price, S. F., Ringler, T. D., Streletz, G. J., Turner, A. K., Van Roekel, L. P., Veneziani, M., Wolfe, J. D., Wolfram, P. J., and Woodring, J. L.: An Evaluation of the Ocean and Sea Ice Climate of E3SM Using MPAS and Interannual CORE-II Forcing, Journal of Advances in Modeling Earth Systems, 11, 1438-1458, 10.1029/2018ms001373, 2019.
- 850 2019.
- Pritchard, H. D., Ligtenberg, S. R. M., Fricker, H. A., Vaughan, D. G., Van Den Broeke, M. R., and Padman, L.: Antarctic ice-sheet loss driven by basal melting of ice shelves, Nature, 484, 502-505, 10.1038/nature10968, 2012.
- 855 Reese, R., Gudmundsson, G. H., Levermann, A., and Winkelmann, R.: The far reach of ice-shelf thinning in Antarctica, Nature Climate Change, 8, 53-57, 10.1038/s41558-017-0020-x, 2018a.
- Reese, R., Albrecht, T., Mengel, M., Asay-Davis, X., and Winkelmann, R.: Antarctic sub-shelf melt rates via PICO, The Cryosphere, 12, 1969-1985, 10.5194/tc-12-1969-2018, 2018b.
- 860 Rignot, E., Mouginot, J., and Scheuchl, B.: Antarctic grounding line mapping from differential satellite radar interferometry, Geophysical Research Letters, 38, n/a-n/a, 10.1029/2011gl047109, 2011.
- Rignot, E., Mouginot, J., and Scheuchl, B.: MEaSUREs InSAR-Based Antarctica Ice Velocity Map, Version 2, NASA National Snow and Ice Data Center Distributed Active Archive Center [dataset], 10.5067/D7GK8F5J8M8R, 2017.
- 865 Rignot, E., Jacobs, S., Mouginot, J., and Scheuchl, B.: Ice-Shelf Melting Around Antarctica, Science, 341, 266-270, doi:10.1126/science.1235798, 2013.



- 870 Rignot, E., Xu, Y., Menemenlis, D., Mouginot, J., Scheuchl, B., Li, X., Morlighem, M., Seroussi, H., Den Broeke, M. V.,
Fenty, I., Cai, C., An, L., and Fleurian, B. D.: Modeling of ocean-induced ice melt rates of five west Greenland glaciers over
the past two decades, *Geophysical Research Letters*, 43, 6374-6382, 10.1002/2016gl068784, 2016.
- Ringler, T., Thuburn, J., Klemp, J. B., and Skamarock, W. C.: A unified approach to energy conservation and potential
875 vorticity dynamics for arbitrarily-structured C-grids, *Journal of Computational Physics*, 229, 3065-3090,
<https://doi.org/10.1016/j.jcp.2009.12.007>, 2010.
- Ringler, T., Petersen, M., Higdon, R. L., Jacobsen, D., Jones, P. W., and Maltrud, M.: A multi-resolution approach to global
ocean modeling, *Ocean modelling.*, 69, 211-232, 10.1016/j.ocemod.2013.04.010, 2013.
- 880 Rintoul, S. R., Silvano, A., Pena-Molino, B., Van Wijk, E., Rosenberg, M., Greenbaum, J. S., and Blankenship, D. D.: Ocean
heat drives rapid basal melt of the Totten Ice Shelf, *Science Advances*, 2, e1601610, 10.1126/sciadv.1601610, 2016.
- Schoof, C. and Hindmarsh, R. C. A.: Thin-Film Flows with Wall Slip: An Asymptotic Analysis of Higher Order Glacier
885 Flow Models, *The Quarterly Journal of Mechanics and Applied Mathematics*, 63, 73-114, 10.1093/qjmam/hbp025, 2010.
- Seroussi, H., Morlighem, M., Larour, E., Rignot, E., and Khazendar, A.: Hydrostatic grounding line parameterization in ice
sheet models, *The Cryosphere*, 8, 2075-2087, 10.5194/tc-8-2075-2014, 2014.
- 890 Seroussi, H., Nakayama, Y., Larour, E., Menemenlis, D., Morlighem, M., Rignot, E., and Khazendar, A.: Continued retreat
of Thwaites Glacier, West Antarctica, controlled by bed topography and ocean circulation, *Geophysical Research Letters*,
44, 6191-6199, 10.1002/2017gl072910, 2017.
- Seroussi, H., Nowicki, S., Payne, A. J., Goelzer, H., Lipscomb, W. H., Abe-Ouchi, A., Agosta, C., Albrecht, T., Asay-Davis,
895 X., Barthel, A., Calov, R., Cullather, R., Dumas, C., Galton-Fenzi, B. K., Gladstone, R., Golledge, N. R., Gregory, J. M.,
Greve, R., Hattermann, T., Hoffman, M. J., Humbert, A., Huybrechts, P., Jourdain, N. C., Kleiner, T., Larour, E., Leguy, G.
R., Lowry, D. P., Little, C. M., Morlighem, M., Pattyn, F., Pelle, T., Price, S. F., Quiquet, A., Reese, R., Schlegel, N.-J.,
Shepherd, A., Simon, E., Smith, R. S., Straneo, F., Sun, S., Trusel, L. D., Van Breedam, J., Van De Wal, R. S. W.,
Winkelmann, R., Zhao, C., Zhang, T., and Zwinger, T.: ISMIP6 Antarctica: a multi-model ensemble of the Antarctic ice
900 sheet evolution over the 21st century, *The Cryosphere*, 14, 3033-3070, 10.5194/tc-14-3033-2020, 2020.
- Seroussi, H., Verjans, V., Nowicki, S., Payne, A. J., Goelzer, H., Lipscomb, W. H., Abe-Ouchi, A., Agosta, C., Albrecht, T.,
Asay-Davis, X., Barthel, A., Calov, R., Cullather, R., Dumas, C., Galton-Fenzi, B. K., Gladstone, R., Golledge, N. R.,
905 Gregory, J. M., Greve, R., Hattermann, T., Hoffman, M. J., Humbert, A., Huybrechts, P., Jourdain, N. C., Kleiner, T.,
Larour, E., Leguy, G. R., Lowry, D. P., Little, C. M., Morlighem, M., Pattyn, F., Pelle, T., Price, S. F., Quiquet, A., Reese,
R., Schlegel, N.-J., Shepherd, A., Simon, E., Smith, R. S., Straneo, F., Sun, S., Trusel, L. D., Van Breedam, J., Van Katwyk,
P., Van De Wal, R. S. W., Winkelmann, R., Zhao, C., Zhang, T., and Zwinger, T.: Insights into the vulnerability of Antarctic
glaciers from the ISMIP6 ice sheet model ensemble and associated uncertainty, *The Cryosphere*, 17, 5197-5217, 10.5194/tc-
17-5197-2023, 2023.
- 910 Seroussi, H., Pelle, T., Lipscomb, W. H., Abe-Ouchi, A., Albrecht, T., Alvarez-Solas, J., Asay-Davis, X., Barre, J. B.,
Berends, C. J., Bernaldes, J., Blasco, J., Caillet, J., Chandler, D. M., Coulon, V., Cullather, R., Dumas, C., Galton-Fenzi, B.
K., Garbe, J., Gillet-Chaulet, F., Gladstone, R., Goelzer, H., Golledge, N., Greve, R., Gudmundsson, G. H., Han, H. K.,
Hillebrand, T. R., Hoffman, M. J., Huybrechts, P., Jourdain, N. C., Klose, A. K., Langebroek, P. M., Leguy, G. R., Lowry,
915 D. P., Mathiot, P., Montoya, M., Morlighem, M., Nowicki, S., Pattyn, F., Payne, A. J., Quiquet, A., Reese, R., Robinson, A.,
Saraste, L., Simon, E. G., Sun, S., Twarog, J. P., Trusel, L. D., Urruty, B., Van Breedam, J., Van De Wal, R. S. W., Wang,
Y., Zhao, C., and Zwinger, T.: Evolution of the Antarctic Ice Sheet Over the Next Three Centuries From an ISMIP6 Model
Ensemble, *Earth's Future*, 12, 10.1029/2024ef004561, 2024.



- 920 Shafer, C., Hoffman, M., Poinar, K., Asay-Davis, X., Begeman, C., Comeau, D., Hager, A., Han, H. K., Hillebrand, T., & Vankova, I. (2026). Model output for the MALI-SORRM simulations [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.20360030>
- 925 Shafer, C., Hoffman, M., Poinar, K., Asay-Davis, X., Begeman, C., Comeau, D., Hager, A., Han, H. K., Hillebrand, T., & Vankova, I. (2026). Thermal forcing inputs for the MALI-SORRM simulations [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.20388988>
- Sheehan, P. M. F. and Heywood, K. J.: Ross Ice Shelf frontal zone subjected to increasing melting by ocean surface waters, *Science Advances*, 10, 10.1126/sciadv.ado6429, 2024.
- 930 Siahayan, A., Smith, R. S., Holland, P. R., Jenkins, A., Gregory, J. M., Lee, V., Mathiot, P., Payne, A. J., Ridley, J. K., and Jones, C. G.: The Antarctic contribution to 21st-century sea-level rise predicted by the UK Earth System Model with an interactive ice sheet, *The Cryosphere*, 16, 4053-4086, 10.5194/tc-16-4053-2022, 2022.
- 935 Smith, K. M., Barthel, A. M., Conlon, L. M., Van Roekel, L. P., Bartoletti, A., Golaz, J. C., Zhang, C., Begeman, C. B., Benedict, J. J., Bisht, G., Feng, Y., Hannah, W., Harrop, B. E., Jeffery, N., Lin, W., Ma, P. L., Maltrud, M. E., Petersen, M. R., Singh, B., Tang, Q., Tesfa, T., Wolfe, J. D., Xie, S., Zheng, X., Balaguru, K., Garuba, O., Gleckler, P., Hu, A., Lee, J., Moore-Maley, B., and Ordoñez, A. C.: The DOE E3SM version 2.1: overview and assessment of the impacts of parameterized ocean submesoscales, *Geosci. Model Dev.*, 18, 1613-1633, 10.5194/gmd-18-1613-2025, 2025.
- 940 Smith, R. S., Mathiot, P., Siahayan, A., Lee, V., Cornford, S. L., Gregory, J. M., Payne, A. J., Jenkins, A., Holland, P. R., Ridley, J. K., and Jones, C. G.: Coupling the U.K. Earth System Model to Dynamic Models of the Greenland and Antarctic Ice Sheets, *Journal of Advances in Modeling Earth Systems*, 13, 10.1029/2021ms002520, 2021.
- 945 Song, P., Scholz, P., Knorr, G., Sidorenko, D., Timmermann, R., and Lohmann, G.: Regional conditions determine thresholds of accelerated Antarctic basal melt in climate projection, *Nature Climate Change*, 10.1038/s41558-025-02306-0, 2025.
- 950 Tezaur, I. K., Perego, M., Salinger, A. G., Tuminaro, R. S., and Price, S. F.: Albany/FELIX: a parallel, scalable and robust, finite element, first-order Stokes approximation ice sheet solver built for advanced analysis, *Geoscientific Model Development*, 8, 1197-1220, 10.5194/gmd-8-1197-2015, 2015.
- Thoma, M., Determann, J., Grosfeld, K., Goeller, S., and Hellmer, H. H.: Future sea-level rise due to projected ocean warming beneath the Filchner Ronne Ice Shelf: A coupled model study, *Earth and Planetary Science Letters*, 431, 217-224, 10.1016/j.epsl.2015.09.013, 2015.
- 955 Thuburn, J., Ringler, T. D., Skamarock, W. C., and Klemp, J. B.: Numerical representation of geostrophic modes on arbitrarily structured C-grids, *Journal of Computational Physics*, 228, 8321-8335, <https://doi.org/10.1016/j.jcp.2009.08.006>, 2009.
- 960 Timmermann, R. and Goeller, S.: Response to Filchner–Ronne Ice Shelf cavity warming in a coupled ocean–ice sheet model – Part 1: The ocean perspective, *Ocean Science*, 13, 765-776, 10.5194/os-13-765-2017, 2017.
- 965 Tinto, K. J., Padman, L., Siddoway, C. S., Springer, S. R., Fricker, H. A., Das, I., Caratori Tontini, F., Porter, D. F., Frearson, N. P., Howard, S. L., Siegfried, M. R., Mosbeux, C., Becker, M. K., Bertinato, C., Boghosian, A., Brady, N., Burton, B. L., Chu, W., Cordero, S. I., Dhakal, T., Dong, L., Gustafson, C. D., Keeshin, S., Locke, C., Lockett, A., O'Brien, G., Spergel, J. J., Starke, S. E., Tankersley, M., Wearing, M. G., and Bell, R. E.: Ross Ice Shelf response to climate driven by the tectonic imprint on seafloor bathymetry, *Nature Geoscience*, 12, 441-449, 10.1038/s41561-019-0370-2, 2019.



- 970 van der Veen, C. J. and Whillans, I. M.: Force Budget: I. Theory and Numerical Methods, *Journal of Glaciology*, 35, 53-60,
10.3189/002214389793701581, 1989.
- Van Wessem, J. M., Van De Berg, W. J., Noël, B. P. Y., Van Meijgaard, E., Amory, C., Birnbaum, G., Jakobs, C. L.,
Krüger, K., Lenaerts, J. T. M., Lhermitte, S., Ligtenberg, S. R. M., Medley, B., Reijmer, C. H., Van Tricht, K., Trusel, L. D.,
975 Van Ulf, L. H., Wouters, B., Wuite, J., and Van Den Broeke, M. R.: Modelling the climate and surface mass balance of
polar ice sheets using RACMO2 – Part 2: Antarctica (1979–2016), *The Cryosphere*, 12, 1479-1498, 10.5194/tc-12-1479-
2018, 2018.
- Vaňková, I., Hoffman, M., Asay-Davis, X., Branecky Begeman, C., Comeau, D., Price, S. F., and Wolfe, J.: Antarctic
980 Meltwater Accelerates Southern Ocean Evolution Under Projected Atmospheric Warming, *Geophysical Research Letters*,
53, 10.1029/2025gl119952, 2026.
- Weertman, J.: On the Sliding of Glaciers, *Journal of Glaciology*, 3, 33-38, 10.3189/s0022143000024709, 1957.
- 985 Youngs, M. K., Stewart, A. L., Si, Y., Thompson, A. F., and Schodlok, M. P.: Antarctic ice-shelf basal melt shaped by
competing feedbacks, *Nature Geoscience*, 10.1038/s41561-026-01975-6, 2026.
- Zhang, T., Price, S. F., Hoffman, M. J., Perego, M., and Asay-Davis, X.: Diagnosing the sensitivity of grounding-line flux to
changes in sub-ice-shelf melting, *The Cryosphere*, 14, 3407-3424, 10.5194/tc-14-3407-2020, 2020.
- 990 Zhao, C., Gladstone, R., Galton-Fenzi, B. K., Gwyther, D., and Hattermann, T.: Evaluation of an emergent feature of sub-
shelf melt oscillations from an idealized coupled ice sheet–ocean model using FISOC (v1.1) – ROMSIceShelf (v1.0) –
Elmer/Ice (v9.0), *Geosci. Model Dev.*, 15, 5421-5439, 10.5194/gmd-15-5421-2022, 2022.
- 995 Zhou, Q. and Hattermann, T.: Modeling ice shelf cavities in the unstructured-grid, Finite Volume Community Ocean Model:
Implementation and effects of resolving small-scale topography, *Ocean Modelling*, 146, 101536,
<https://doi.org/10.1016/j.ocemod.2019.101536>, 2020.