



A protocol for calibrating basal melt rates in the ISMIP7 Antarctic ice sheet projections

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Abstract. Ocean-driven melting at the base of the floating ice shelves of the Antarctic Ice Sheet is an important driver of current and future ice losses. Ocean models that resolve sub-shelf melt rates at sufficient resolution are too expensive to run in large ensembles or for multi-centennial projections. Instead, ice-sheet models use simple modules to infer sub-shelf melt rates based on far-field ocean properties. However, there is no consensus on the optimal set of parameters for these modules.

- 5 Here, we present a protocol for ice-ocean interactions in ISMIP7 Antarctic Ice Sheet projections. We describe (1) how CMIP model datasets are processed to be used in melt modules, (2) how parameters in melt modules can be selected to be physically constrained by oceanographic knowledge, (3) the rationales for a range of datasets that span possible evolution of the Southern Ocean between 1950 and 2025, (4) design for a melt Module Intercomparison Project (meltMIP) that will allow us to better assess uncertainty in sea level projections related to melt modules. Finally, we summarise lessons from ISMIP7 and potential
- 10 research directions towards the next generation of ice-ocean interaction modelling.

1 Introduction

- Ocean-induced sub-shelf melt, or basal melt, is a central driver of Antarctic mass loss and thus modulates the Antarctic contribution to sea-level rise (Seroussi et al., 2020, 2024). Still, the representation of sub-shelf melt in ice-sheet models is one of the largest sources of uncertainty in ice-sheet projections conducted as part of the Ice-Sheet Model Intercomparison Project
- 15 for CMIP6 (ISMIP6, Nowicki et al., 2020; Jourdain et al., 2020; Seroussi et al., 2023). The uncertainties arising from the representation of sub-shelf melt are mainly the consequences of biases and structural uncertainties: On the one hand, estimated



melt rates can be biased due to biases in the present-day ocean state produced by the CMIP models, or to due to biases in the melt rate calculation itself. On the other hand, there is a structural uncertainty on the projected melt rates due to the fact that not all physical processes are represented in our modelling framework, and an observational uncertainty that impacts the models' calibration. In this study, we design a new protocol for estimating melt rates in ISMIP7 (ISMIP for CMIP7, Nowicki et al., 2026), in which we aim to reduce biases as much as possible and to estimate uncertainty for Antarctic sub-shelf melt rates.

Sub-shelf melt in standalone ice-sheet models is computed via a basal melt module, based on ocean properties drawn from climate model output from the Coupled Model Intercomparison Project (CMIP, Eyring et al., 2016). However, CMIP models can have large biases in the Southern Ocean (Beadling et al., 2020). Also, these models usually have a coarse representation of the Antarctic continental shelf seas and most do not include Antarctic ice-shelf cavities (Jourdain et al., 2020) so that the ocean properties used by the melt module have to be extrapolated beforehand towards any ice-shelf draft possibly simulated by an ice-sheet model. In the first round of ISMIP, ISMIP6, CMIP ocean output was remapped to a south polar stereographic grid, extrapolated onto the continental shelf and into ice-shelf cavities, and bias-corrected assuming spatially varying (3d), temporally-constant biases that were obtained by comparison with a climatology of the Southern Ocean generated from most recent datasets. In ISMIP7, we revise the approach of ISMIP6 by updating to the new observational estimate by Zhou et al. (2024a) and improving the extrapolation based on developments for the European H2020 project PROTECT (PROjecting sEa-level rise: from iCe sheets to local implicaTions, e.g., Caillet et al., 2025). As in ISMIP6, standalone ice-sheet models in ISMIP7 can then employ a melt module to model the sub-shelf melt rates using these extrapolated fields of bias-corrected ocean properties.

In contrast to ISMIP6, where the core experiments required the use of one specific type of melt parameterisation (namely a 'quadratic', see Jourdain et al., 2020), in ISMIP7 the choice of melt module is left to the modellers. Depending on the choice of module and its calibration, projected melt rates can differ substantially (e.g. Jourdain et al., 2020, 2022; Seroussi et al., 2020; Burgard et al., 2023). In the ISMIP6 extension to 2300, where the choice of melt module and parameters was left to the ice-sheet modellers, the projected melt rates under any given climate forcing vary largely between models (Seroussi et al., 2024). One outcome of ISMIP6 and studies thereafter is that there is no consensus on a "best-performing" melt module (e.g., Burgard et al., 2022; Lambert and Burgard, 2025) but also that parameter selection of the free parameter(s) in the melt module, e.g., related to the heat exchange at the ice-ocean interface, is important, maybe even more important than the choice of module. However, the way to best calibrate parameters of the melt module remains an open question (e.g., Jourdain et al., 2020; Burgard et al., 2022; Reese et al., 2023). Calibration is a complex issue because the ice sheet is sensitive to melting in various specific areas such as grounding lines, shear margins, and around pinning points. The simulated pattern of melt rates could therefore be as important as the integrated melt of an ice shelf (Reese et al., 2018b; Goldberg et al., 2019).

In ISMIP6, two possible parameter calibrations were suggested for the use of quadratic parameterisations (Jourdain et al., 2020). The 'MeanAnt' calibration was based on matching the total ice-shelf basal mass loss in Antarctica, and the 'PIGL' calibration was based on matching the 10 highest estimated melt rates near Pine Island Glacier grounding line. The 'PIGL' calibration was introduced after criticism of the low melt rates obtained from the 'MeanAnt' calibration near the grounding line of Pine Island Glacier. The likely parameter ranges did not overlap, and yielded an order of magnitude difference in projected



melt rate evolution. This led to a bi-modal melt sensitivity to ocean warming that had to be empirically smoothed to a uni-modal distribution for practical use in sea level projections (Edwards et al., 2021). Later, Jourdain et al. (2022) showed that the large sensitivity of the ‘PIGL’ calibration to ocean warming was not supported by high-resolution regional ocean modelling in the Amundsen Sea. As a consequence, new parameter selection methods were developed (e.g., Burgard et al., 2022; Reese et al., 2023). These are not based only on present-day melt rates, but also aim to be constrained by melt rate sensitivity to ocean temperature changes. For all main melt modules currently used in ice-sheet models, Lambert and Burgard (2025) demonstrated that present-day calibration alone cannot constrain future melt sensitivity to ocean temperature changes and that multiple modules need to be used to avoid underestimating uncertainties in sea-level rise projections. Some ice-sheet modellers have also started adjusting the melt rate parameters to obtain the observed rates of ice thickness changes (e.g., Bernales et al., 2017). However, ideally, melt module parameters are chosen based on the existing knowledge about the underlying physics, and correct ice-shelf thinning rates are obtained for the correct corresponding melt rates to avoid error compensations. This also avoids falsely matching a response for example to damage or calving evolution through melt rate forcing (Greene et al., 2022; Sun and Gudmundsson, 2023).

For physical consistency and robustness across ocean and melt states, it is preferable to base the calibration on the largest and most diverse amount of data possible. In ISMIP6, melt rate estimates from the Amundsen Sea, a region which undergoes substantial decadal variability (Dutrieux et al., 2014; Jenkins et al., 2018; Joughin et al., 2021), as well as melt rates from a number of dynamic, high-resolution ocean model simulations of Antarctic ice-shelf cavities (Seroussi et al., 2017; Naughten et al., 2018) were used for validation of the parameterised melt rates. For ISMIP7, we propose to use such datasets for parameter calibration instead of validation. Moreover, we propose a method that can be expanded in the future to include further observation and simulation data. Instead of prescribing the use of one particular melt module with a given set of parameters, we suggest that the ice-sheet modellers conduct the calibration themselves, following a calibration protocol that is generally applicable to the various melt modules contained in the different ice-sheet models.

In addition, we introduce the protocol for a melt Module Intercomparison Project (meltMIP) to assess the effect of the melt modules and associated parameters in the case of cavity warming, thermocline changes, and geometry changes.

ISMIP6 has been criticized because the ice-sheet simulations generally did not represent the observed mass loss (Aschwan-den et al., 2021). A part of the ice-sheet model biases over the recent decades may be attributed to either oceanic and atmospheric biases in the CMIP models or to the ice sheet models themselves. The ISMIP7 steering committee has therefore decided to propose a forcing set for the recent decades (1950–2025) that is not affected by the CMIP model biases (‘OCX experiments’ Nowicki et al., 2026). This is particularly challenging for Antarctic ocean forcing because observations are sparse over the continental shelves, where the properties of waters entering ice-shelf cavities are established. Many of these regions were not monitored before the 1990s or even the 2000s, and most remain poorly observed today with observations usually available from summer months only. Although ocean reanalyses generally perform well in the open ocean, they often struggle to represent Antarctic continental shelf processes, which require sufficiently high spatial resolution to capture complex, energetic circulation as well as polar-specific processes, such as dense-water formation driven by sea-ice production and ice-shelf melting, that



generate strong vertical exchange. Based on the scientific literature, we nevertheless propose plausible historical temperature and salinity trajectories for some key regions that can be used to constrain the ice sheet response to potential historic trends.

In this manuscript, we first introduce the general approach for the representation of Antarctic ice-ocean interactions in ISMIP7 (Sect. 2). We then introduce the processing of ocean forcing data (Sect. 3), discuss sub-shelf melt modules and their latest updates, explain the calibration protocol for sub-shelf melt rates (Sect. 4), and introduce the meltMIP protocol (Sect. 5). Finally, we discuss open questions and potential research directions towards ISMIP8 (Sect. 6).

2 Approach

The overall strategy that we suggest for handling sub-shelf melt in ISMIP7 ice-sheet simulations is summarised in Figure 1. We refer the reader to the main ISMIP protocol paper for understanding how the ocean protocol links with other components (Nowicki et al., 2026). Note that the parameter calibration using the toolbox is not compulsory for the participation to the core ISMIP7 ice-sheet projections, but we highly recommend following the proposed approach.

Sub-shelf melt rates can be inferred from far-field ocean properties using a range of melt modules. Since ISMIP6, the existing parameterisations have been further evaluated (Burgard et al., 2022) and inter-compared (Lambert and Burgard, 2025), and new options have been proposed, either based on machine learning (Rosier et al., 2023; Burgard et al., 2023) or on 1-layer ocean modelling (Lambert et al., 2023). So far, none of them is unanimously accepted as the best option, and only the simple linear approach of Beckmann and Goosse (2003) does not seem supported by observations and models (Jenkins et al., 2018; Burgard et al., 2022). For ISMIP7, ice-sheet modelling groups are free to make their own choice on which sub-shelf melt module they want to use as long as it can be driven by ocean properties from the CMIP climate model output. We also leave it to the modelling groups to make their own choice on the representation of melting in the grounding zone or at vertical ice faces, i.e. the terminus after ice shelf collapse or the calving front if an ice shelf is present.

To force the melt module, we provide input ocean conditions around Antarctica, bias-corrected with an updated present-day ocean climatology (Zhou et al., 2024a) and extrapolated from CMIP6 and, when available, CMIP7 models. For consistency within ISMIP and with CMIP, e.g., to make it possible to quantify uncertainties comprehensively in ISMIP, CMIP model forcing rather than regional ocean model projections are used. The methodology is explained in Section 3, and all datasets are described in detail in Appendix A.

A novelty compared to ISMIP6 is that we do not directly provide parameters for the melt modules but rather provide datasets and a method and toolbox to calibrate the parameters of the melt modules to achieve good agreement with observations and ocean model projections from consistent data coming from both. This is explained in Section 4. Following the main ISMIP7 protocol (Nowicki et al., 2026), modellers are free to use parameters of their choice and do not need to employ the toolbox. However, we want to highlight that using the melt module parameters as simple tuning parameters for the ice sheet mass loss can yield melt rates in the projections that are not physically well-constrained. Furthermore, we propose an independent meltMIP with the aim to evaluate and inter-compare the melt rates produced by the ISMIP7 ice sheet models and modules. Contributions to meltMIP will be independent from ISMIP7.

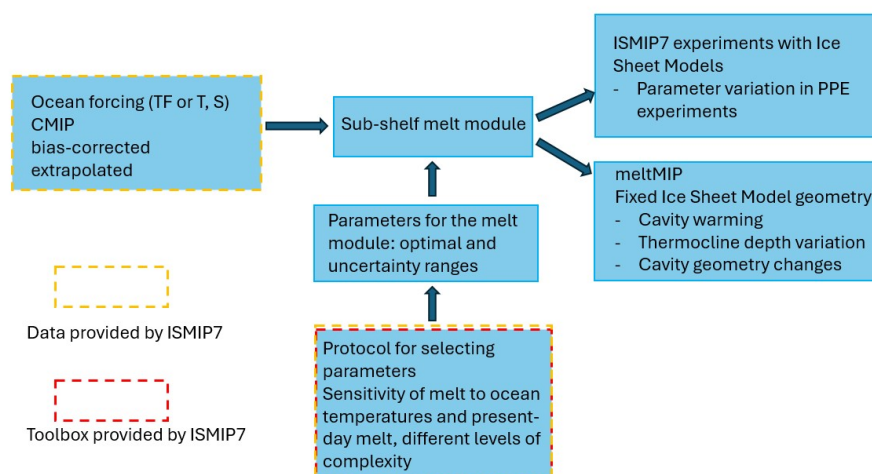


Figure 1. ISMIP7 Antarctic ice-ocean interactions flow chart. Extrapolated and bias-corrected ocean forcing fields of thermal forcing (TF) or temperature (T) and salinity (S) are provided to the ice-sheet modellers. A protocol for selecting parameters in the melt-rate module of modeller’s choice is provided in this manuscript and implemented as a python toolbox. Each ice-sheet modelling group calibrates their melt module parameters following this protocol to calculate sub-shelf melt for the projections. PPE refers to the ‘perturbed parameter ensemble’ planned in ISMIP7 (Nowicki et al., 2026). The module’s reaction to thermal forcing and geometry changes will be tested in a meltMIP.

3 Ocean forcing

120 We here introduce the new climatology of the Southern Ocean hydrography used in ISMIP7, see Sect. 3.1. Then, we discuss
 the extrapolation and bias correction method used to process datasets for ISMIP7, including the CMIP model output and
 datasets for the parameter calibration, see Sections 3.2 and 3.3. In Section 3.4, we present the rationale for different plausible
 representations of the Southern Ocean state between 1950 and 2025. The resulting Southern Ocean climatology, contemporary
 ocean pathways, and CMIP projections as provided for ISMIP7 are shown in Section 3.5. All datasets used are summarised in
 125 Appendix A.

3.1 Present-day climatology for the Southern Ocean

The observational climatology used in ISMIP7 is derived from Zhou et al. (2024a). The climatology is constructed based on
 an updated Southern Ocean profile compilation Zhou et al. (2024b) that incorporates ship-based CTD profiles, Argo floats
 and marine-mammal dataset. Assuming anisotropy in water mass properties along the ocean currents that are topographically-
 130 steered on the continental shelf and governed by large scale ocean circulation in the deep ocean basin, the climatology adopts
 a mixed weighting strategy between the along-isobath distance derived from bathymetry and the anisotropically scaled Eu-
 clidean distance based on a locally defined flow-aligned ellipse to capture the combined effect on ocean dynamics. The final



climatological field is therefore a weighted mean estimate of the in-situ observations. For detailed information of climatology development, the reader is referred to Zhou et al. (2026). For ISMIP7, it is assumed to be an annual-mean product. The climatology has been remapped to the ISMIP ocean grid, see Section A1, and after, extrapolated into ice shelf cavities and ice covered regions using the methods described below, see Sect. 3.2.

The climatology is used as the reference state in bias correction, see Sect. 3.2, and as the ocean state to calibrate present-day melt rates in melt modules, see Sect. 4.2. An important point is that the observational climatology itself spans a wider period (1972–2024 in the default annual product), while the 1995–2024 window is the default period used to compute the CMIP model climatology removed during bias correction. This separation is intentional, however, and reflects the very sparse amount of data entering the observational climatology prior to the mid 1990s.

3.2 Processing of the climatology and CMIP ocean data for Antarctic ice sheet models

In a similar way as in ISMIP6, we directly provide bias-corrected ocean data extrapolated to any possible location of a simulated ice shelf draft on a polar stereographic grid (Sect. A1). Our workflow to process the CMIP ocean outputs (Sect. A6) in ISMIP7 differs from ISMIP6 in the details, based on the updates developed in PROTECT (e.g., Caillet et al., 2025). The procedure is as follows for individual CMIP ensemble members:

1. Convert the CMIP monthly potential temperature and practical salinity to conservative temperature (CT) and absolute salinity (SA) that better conserve energy in the mixing of water masses during the interpolation/extrapolation/averaging process (McDougall, 2025). This is done using the Gibbs SeaWater (GSW) Oceanographic Toolbox of TEOS-10 available from <https://www.teos-10.org/>.
2. Remap both, the observational climatology and the CMIP data, to the $8 \text{ km} \times 8 \text{ km} \times 60 \text{ m}$ standard stereographic grid used in ISMIP7 using bilinear interpolation in the horizontal and linear interpolation in the vertical.
3. Mask out ice-shelf cavities from the observational climatology, as the observations in the cavities were found not to be reliable.
4. Extrapolate oceanic variables to all the grid points that were not covered by ocean points in the observational climatology or CMIP model following four steps:
 - (a) Horizontal extrapolation in a given IMBIE basin, iteratively, and only towards adjacent ocean points, applied only in the open ocean and present-day ice-shelf cavities from Bedmap3 (Sect. A3). To smooth the extrapolated values and to get an isotropic extrapolation, we use a Gaussian function of $\sigma = 24 \text{ km}$ to weight all the contiguous grid points within a circle of 24 km. IMBIE basins are defined following the Ice Sheet Mass Balance Inter-comparison Exercise drainage basin delineation, see Sect. A2.
 - (b) Horizontal extrapolation in a given IMBIE basin, beyond present-day ice shelves, iteratively, towards adjacent grid points going across the ice but not across bathymetric ridges (using the same Gaussian weighting as above).



(c) Horizontal extrapolation everywhere at the second depth level ($k = 2$), not accounting for IMBIE basins or bedrock constraints (even if the bedrock is above sea level), in order to have values that can be extrapolated downward everywhere in the next step. We use level $k = 2$ as $k = 1$ corresponds to the surface layer and therefore has properties that are not representative of the rest of the water column.

(d) Vertical extrapolation from above for all the remaining points (and from below for $k = 1$), which fills isolated pools and the bedrock.

5. Bias correction following the ISMIP6 method (Jourdain et al., 2020), i.e., adjustment of the mean state in the geographical space, by removing the 1995–2024 model climatology and adding the new climatology of Zhou et al. (2025, see Sect. 3.1), itself extrapolated following the previous steps. Other bias correction methods were investigated but found not to be appropriate for our purposes; see Sect. 6.2.

6. Compute the thermal forcing (TF), i.e., temperature above the local freezing point, using the linearisation of the freezing temperature of Jourdain et al. (2017) for CT and SA.

7. Compute annual means (CT, SA and TF).

8. Convert to potential temperature (thetao) and practical salinity (so) for modules based on these variables, using GSW Toolbox for TEOS-10.

The extrapolation steps are similar to the ones that were used in the PROTECT project (e.g., Caillet et al., 2025). The main differences with the previous ISMIP6 extrapolation method (Jourdain et al., 2020) are (i) the extrapolation and annual averages are computed using CT and SA rather than potential temperature and practical salinity, and (ii) the first step horizontal extrapolation is also done into the present-day ice-shelf cavities while it was only done for the open ocean in ISMIP6 (this is expected to give more meaningful results when the grounding line retreats, avoiding too early extrapolation from close unconnected basins, e.g. Weddell Sea properties extrapolated into the Amundsen Sea).

Bias correction is applied consistently to historical and scenario periods, producing a continuous forcing record suitable for scenario experiments. This is the same bias correction as in ISMIP6 (Jourdain et al., 2020), supported by the stationary large-scale biases in CMIP model projections (Krinner and Flanner, 2018). The only difference from ISMIP6 is that we correct a 30-year instead of 20-year average, which decreases the random impact of natural climate variability on the bias correction (Caillet et al., 2025).

3.2.1 The ismip7-antarctic-ocean-forcing (i7aof) software package

The workflow for CMIP model output processing is implemented in the open-source Python package `ismip7-antarctic-ocean-forcing (i7aof)`, which provides a reproducible processing chain from raw CMIP input to final ISMIP7 forcing fields. While intermediate files are produced for transparency and reproducibility, the protocol is designed around the standardised outputs distributed in the final product directory. The package supports consistent forcing generation across CMIP models,



195 scenarios and reference climatologies, and is intended both for central production of protocol datasets and for reproducible re-runs by modelling groups that wish to regenerate or extend the forcing.

3.3 Southern Ocean forcing and melt rates for melt module calibration

To calibrate the melt modules, we provide a range of ocean forcing datasets together with melt rate estimates, as listed below:

1. Present-day Southern Ocean climatology, see Sect. 3.1, together with a compilation of satellite-derived melt rate of Antarctic ice shelves estimates created from Adusumilli et al. (2020), Paolo et al. (2023), and Davison et al. (2023). We provide melt rates integrated over the IMBIE2 basins, as well as over regions of similar buttressing relevance, see Sect. A8.
2. Southern Ocean states as modelled with dynamic, cavity resolving ocean models, together with the corresponding modelled melt rate fields. We employ ocean model simulations that show large-scale changes in cavities, e.g., a flip from ‘cold’ to a ‘warm’ state in the Weddell Sea, or are forced with high emission pathways, in order to be able to constrain the melt modules in case such large-scale changes occur. From the modelling data, a ‘cold’ and a ‘warm’ ocean state are extracted, and corresponding melt rate fields with uncertainties are generated. Ocean modelling data has been remapped onto the ISMIP ocean grid, and extrapolated using the methodology described in Sect. 3.2. Note that we do not bias correct this data, as it is consistent with the corresponding melt rate fields. Only melt rate changes are used for calibration. See Section. A9 for a detailed description.
3. Observational data from the Amundsen Sea for Pine Island Glacier Ice Shelf and Dotson Ice Shelf that covers a range of years with variability in ocean conditions and melt rates. Data is also provided on the ISMIP ocean grid. See Sect. A10 for more details.

The calibration is explained in Section 4.

215 3.4 Ocean forcing for the contemporary experiments

Given the lack of observations before the 1990s, we are not confident that we can propose a unique pathway of the Southern Ocean for the contemporary experiments. We therefore propose a ‘main plausible pathway’, a ‘cold plausible pathway’ and a ‘warm plausible pathway’. We also propose a ‘varying plausible pathway’ that is mostly designed for scientific exploration and sensitivity analyses. Two regions around Antarctica have been characterised as experiencing both important mass loss from the grounded ice sheet and the presence of circumpolar deep water (CDW) in the ice shelf cavities: the Amundsen Sea and the ocean facing the Aurora basin (e.g. Jacobs et al., 1996; Rintoul et al., 2016). These two regions are therefore treated differently from the other regions. The resulting pathways are shown in Sect. 3.5.2.



3.4.1 Plausible pathways for most of the Antarctic coastal seas

For all regions except the Amundsen Sea and the Aurora basin, our approach for the main plausible pathway consists of
 225 applying the present-day climatology to the entire period. The reason for this is that most other regions are either shallow or
 known dense shelf water production regions, and it means that ocean temperature remains near freezing despite the fact that
 there might be some trend in salinity (e.g., Jacobs et al., 2002). Following the estimate of Jourdain et al. (2020), we consider
 that the uncertainty on the ocean temperature climatology is typically $\pm 0.17^\circ\text{C}$, so that the cold plausible pathway is defined
 as the present-day climatology minus 0.17°C (capped by the local freezing temperature), while the warm plausible pathway is
 230 defined as the present-day climatology plus 0.17°C . It is indeed very likely that all the ice-shelf cavities that are currently cold
 have also been cold since 1950. Ocean observations since the late 1970s in front of Filchner and Ronne ice shelves support the
 absence of strong temperature changes (e.g. Foldvik et al., 1985). In the Ross Sea, the ocean temperature has been warming
 by only 0.002°C per decade since the late 1950s (Jacobs et al., 2022). A more significant freshening of -0.024 PSU per decade
 has also been observed in the Ross Sea, but the watermass structure is relatively uniform on the vertical (Jacobs et al., 2022)
 235 and we do not expect a significant impact of this freshening on ice shelf melt rates.

CDW is currently present at several locations on both sides of the Antarctic Peninsula, and there are some indications of
 water warmer than the surface freezing point as early as 1898 (De Deckker, 2018), so extending the present-day climatology
 back to 1950 also seems reasonable there. We also claim that the Peninsula region is not an important contributor to changes
 in sea level (e.g., Seroussi et al., 2020), so that reconstructing the ocean forcing in detail along the Peninsula coastline is not a
 240 priority for ISMIP7.

3.4.2 Plausible pathways for the Amundsen Sea and Getz

In the Eastern Amundsen Sea, hydrographic measurements indicate a mean thermal forcing beneath Pine Island ice shelf
 varying between 1.2 and 2.4°C since 1994, and a mean thermal forcing beneath Dotson ice shelf varying between 1.0 and
 2.0°C since 2000, which is related to variations of the thermocline depth and not to the varying property of CDWs (Dutrieux
 245 et al., 2014; Jenkins et al., 2018; Joughin et al., 2021). A regional ocean model forced by an ensemble of runs from the
 CESM1 model (Naughten et al., 2023) simulates that temperature averaged over the Amundsen continental shelf and the
 depth range 200 – 700 m undergoes a trend between -0.19 and $+0.62^\circ\text{C}/\text{century}$ over the historical period (median trend:
 $+0.14^\circ\text{C}/\text{century}$; mean trend: $+0.24^\circ\text{C}/\text{century}$). However, 24% of this trend can be explained by a decrease in cold convective
 events (supplementary material, Naughten et al., 2023), which occur occasionally in this model but have not been observed
 250 (supplementary material, Naughten et al., 2022). Last but not least, there is multiple evidence that the Amundsen Sea in front
 of Pine Island and Thwaites could have been anomalously warm in the 1940s (Steig et al., 2012; Hillenbrand et al., 2017;
 O'Connor et al., 2023, and references therein), with a resulting grounding line retreat (Smith et al., 2017; Clark et al., 2024).
 The ice flux at the grounding line has been increasing since the late 1970s for several glaciers in the Amundsen Sea (Mouginot
 et al., 2014), but given the possibility of a self-sustained grounding line retreat, it is difficult to conclude that the entire period
 255 since the 1940s has remained warm (e.g. Reed et al., 2024). In view of all this, for the Amundsen Sea (Cosgrove to Dotson,



i.e. “G-H” IMBIE basin), we propose that the main plausible pathway is a trend of $0.0014^{\circ}\text{C}/\text{yr}$ (following the median trend in historical ocean temperatures from Fig. 2, Naughten et al., 2023) that meets the climatology value in the year 1995 and remains constant afterwards. The year 1995 is chosen because the climatology is expected to be broadly representative of 1995–2025, and because no significant trend has been identified over the observed period. The cold plausible pathway that represents a plausible lower bound on the temperatures in the Amundsen Sea is constructed similarly but with a trend of $0.0062^{\circ}\text{C}/\text{yr}$ (following the maximum trend in historical ocean temperatures from Fig. 2, Naughten et al., 2023) that meets the climatology minus 0.17°C in 1995. The warm plausible pathway that is a plausible upper bound on the temperatures in the Amundsen Sea is constructed similarly but with a trend of $-0.0019^{\circ}\text{C}/\text{yr}$ (following the minimum trend in historical ocean temperatures from Fig. 2, Naughten et al., 2023) that meets the climatology plus 0.17°C in 1995. Given the negative trend, the warm plausible pathway gives a slightly warmer state in 1950 than presently, which corresponds to the indications from sediment analyses. For the sake of simplicity, we apply the perturbation uniformly on the vertical. This rough approximation is supported by the historical simulations of Naughten et al. (2023, Fig 4c, grey line) and Naughten et al. (2021, Fig. S10a) in the range of depth where most ice shelf drafts are located. We also keep the salinity at the value of the present-day climatology for all experiments, as we expect the salinity changes to have relatively minor effects on the melt rate calculations with the parameterisations. For the part of the Amundsen Sea facing the Getz ice shelf (“F-G” IMBIE basin), we apply changes half way between the Amundsen Sea and the Ross Sea, i.e. use the same method as in the rest of the Amundsen Sea, but with halved trends.

3.4.3 Plausible pathways for the Aurora basin

There is much less scientific background on the past oceanic conditions in front of the Aurora basin (“Cp-D” IMBIE basin). The central Totten trough, facing the Aurora basin, has been experiencing the presence of CDW since the first CTD measurements in 2015, and even more since 2018 (Hirano et al., 2023). The analysis of ice undulations at the surface of Totten ice shelf in satellite images suggest that the ocean was relatively warm from approximately 1920 to 1965 and from approximately 1980 to present-day, with a colder period from approximately 1965 to 1980 (Miles et al., 2025). However, it remains difficult to translate this into ocean temperature variations. We therefore prescribe a relatively broad range: the main plausible pathway consists of applying the present-day climatology all the way from 1950 to 2025. The cold plausible pathway has a constant temperature at the present-day climatology minus 0.17°C after 1995, and temperature decreases backward in time from 1995, to reach the surface freezing temperature in 1950. In this case, salinity also evolves from a uniform profile in 1950 (average of present-day salinity profile) to the climatology after 1995. The warm plausible pathway consists of the climatology plus 0.17°C .

3.4.4 Varying plausible pathway: (multi-)decadal variability

In the proposed plausible pathways, we do not attempt to capture the decadal or multi-decadal variability due to a lack of observations, and because the effect of ocean decadal variability on the overall ice sheet mass loss is thought to be relatively



small. While ice stream velocities seem to respond to ocean variability (Jenkins et al., 2018), the variability in ice sheet thinning propagates upstream (Konrad et al., 2017) and so is muted when averaged over the catchment (Shepherd et al., 2019).

290 There are nonetheless a few aspects that may be sensitive to decadal variability: (i) most melt modules depend non linearly on the thermal forcing, so for a given mean temperature, a pathway with more variability will generate higher melt rates overall; (ii) variability may provide high melt rates for short periods that can be required to trigger a self-sustained grounding line retreat that possibly keeps going during the following cold period, so the warm extrema may matter more than the mean; (iii) depending on the initialisation method, ice sheet models may be more or less sensitive to temperature variability.

295 For this reason, we additionally propose a ‘varying plausible pathway’ for the Amundsen Sea and Aurora basin. In this pathway, the depth of the thermocline evolves as a cosine waveform that broadly matches the recent observations (Jacobs et al., 2013; Dutrieux et al., 2014; Jenkins et al., 2018; Hirano et al., 2023). The thermocline depth is varied by uplifting and lowering the entire climatological T,S profiles, by $\pm 150\text{m}$ in the Eastern Amundsen Seam and by $\pm 100\text{m}$ in the Getz and Aurora basins. For the three basins, the cosine has a 16-year period, and the thermocline is highest in 1960, 1976, 1992, 2008, and 2024.

300 3.5 Ocean forcing: Results

We show the Southern Ocean climatology, Sect. 3.5.1, plausible pathways of the Southern Ocean continental shelf for the contemporary period, Sect. 3.5.2 and an example of processed CMIP forcing, Sect. 3.5.3.

3.5.1 Southern Ocean climatology

Figure 2 shows ocean potential temperatures around the Antarctic ice sheet at intermediate depth for the new climatology in comparison to the dataset produced for ISMIP6, the latest version of the World Ocean Atlas and the dataset by Yamazaki et al. (2025) that included under-ice profiling floats and marine mammal biologging techniques to generate a seasonal, under sea-ice climatology. In contrast to ISMIP6, in the ISMIP7 climatology, a number of ice shelves are situated in warmer waters: Crosson/Dotson, Getz ice shelf, Shackleton, Mertz ice tongue, Totten and Denman.

3.5.2 Plausible pathways of contemporary Southern Ocean evolution

310 The different plausible pathways for constraining the historical ice sheet contribution due to ocean forcing are shown in Figure 3. While most Antarctic ice shelves are estimated to experience little change, exemplified by Ronne ice shelf, for ice shelves in the Amundsen Sea, we estimate different plausible pathways, ranging from a cooling trend in the warm pathway to a warming trend in the cold pathway indicating potential upper and lower bounds of temperatures in the region. Sinusoidally imposed variability matches well with observations. We note that the years 2000, 2016 and 2017 were also relatively cold beneath Pine Island (Naughten et al., 2022), see Fig. A4. The plausible trends show the largest difference for Totten ice shelf, with the most extreme case being a shift from a cold to a warm cavity in the cold plausible pathway. This does not mean that Totten has experienced the strongest trends, just that data availability for Totten is so low before the 1990s, that such a shift cannot be excluded.

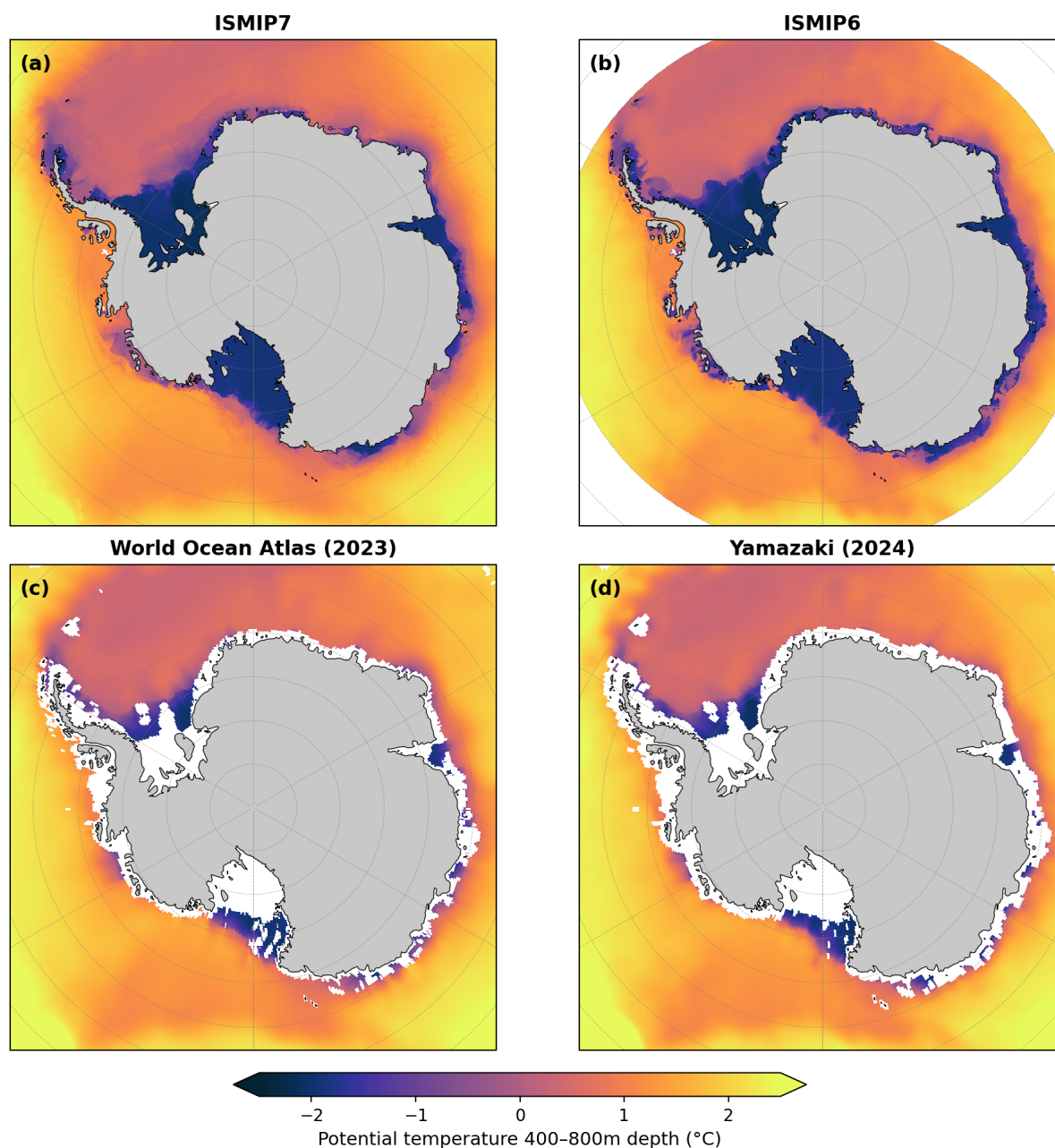


Figure 2. Potential temperatures between 400 and 800 m depth around the Antarctic continent for the climatologies (a) used in ISMIP7 based on Zhou et al. (2024a), (b) used in ISMIP6 (Jourdain et al., 2020), (c) the World Ocean Atlas 2023 version (Locarnini et al., 2024), (d) based on Yamazaki (2024).

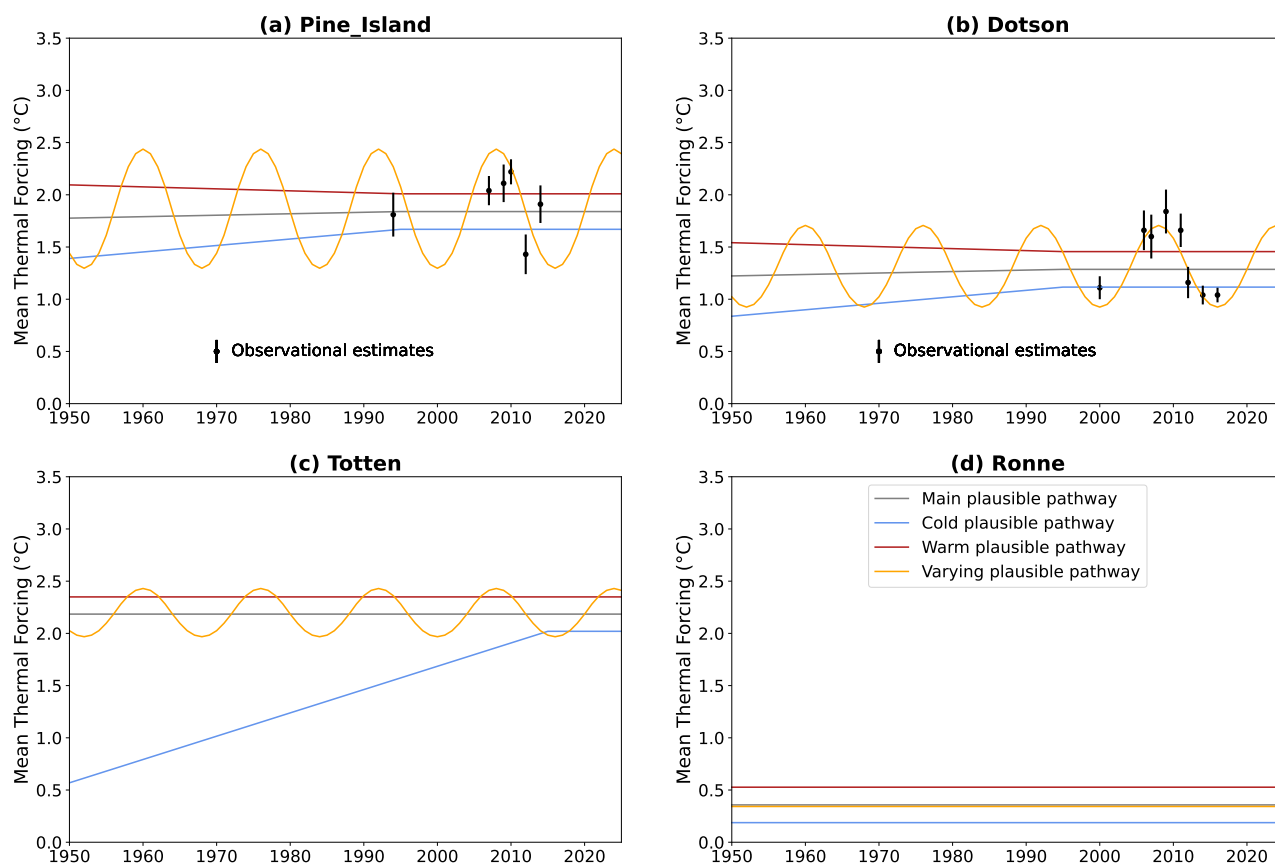


Figure 3. Mean thermal forcing at the base of (a) Pine Island, (b) Dotson, (c) Totten, and (d) Ronne ice shelves, in the four contemporary ocean forcing pathways proposed in ISMIP7. Ronne is an example of constant cold conditions, representative of all ice shelves outside of the Amundsen Sea and Aurora Basin. The observational estimates indicated for Pine Island and Dotson are from Joughin et al. (2021).

3.5.3 CMIP forcing for ISMIP7

Figure 4 shows thermal forcing evolution of the CESM-WACCM derived ocean forcing for ISMIP7. CESM-WACCM was selected for ISMIP7 based on criteria explained in Nowicki et al. (2026). The datasets have been processed as described in Section 3.2 and interpolated onto ice shelf drafts in different regions. Note that Filchner-Ronne Ice Shelf thermal forcing had to be capped at 0 in the historical period. Generally, thermal forcing shows variability of around 0.5 deg C and small trends historically, with a slight increase in Totten Glacier Ice Shelf and the Amundsen Sea ice shelves towards 2015 (the end of the historical CMIP simulation). Filchner-Ronne Ice Shelf shows a rapid increase in thermal forcing starting just after 2000, which has not been seen in observations (e.g., Janout et al., 2021), indicating that the model may be too sensitive here. Until 2050, different SSP scenarios are hard to differentiate on the Antarctic scale and in the cavities shown. Towards the end of the 21st century, scenarios start to diverge with the stronger emission scenarios showing higher changes in thermal forcing. After 2100,

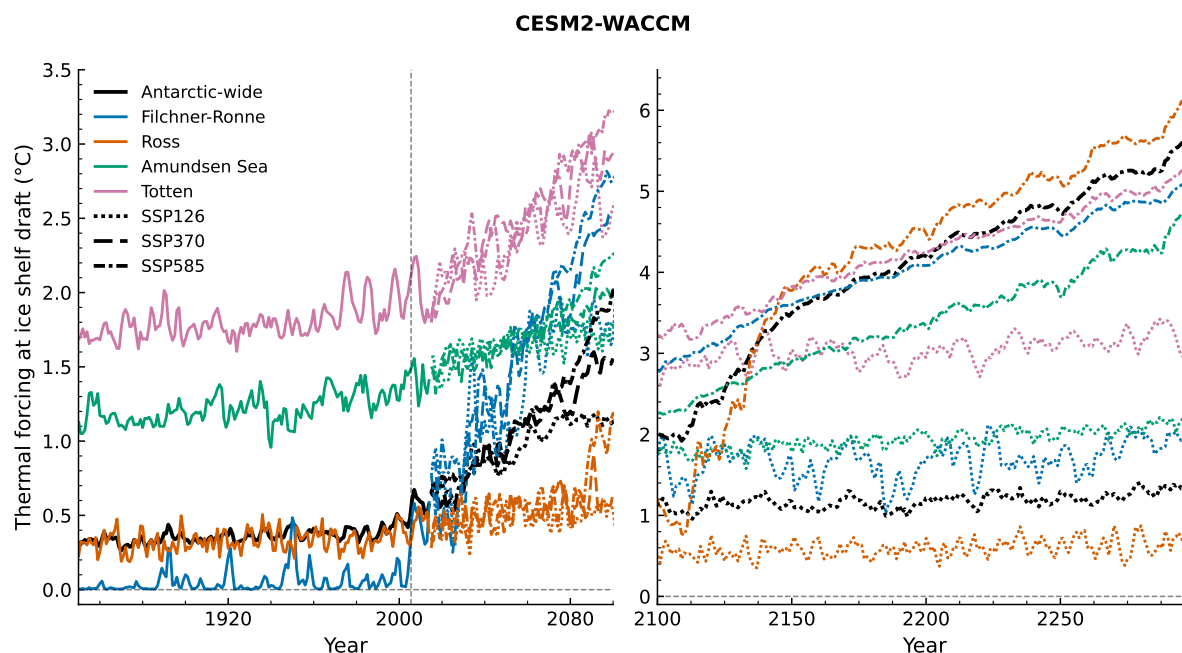


Figure 4. Thermal forcing averaged over the ice shelf draft of the extrapolated, bias corrected CESM-WACCM CMIP data. Shown for the entire continent, and the imbie2 basins containing the Filchner Ronne, Ross, Amundsen Sea and Totten ice shelves.

in SSP585, Ross Ice Shelf experiences the strongest warming trend with thermal forcing climbing up to 6K in 2300, above all other examples with around 3.5K in the Amundsen Sea and Totten. In contrast, towards 2100 and after, the SSP126 scenario shows a flattening of the thermal forcing around 1.1K.

4 Melt rate calculation

Here, we introduce melt modules and suggested improvements (Sec. 4.1), the calibration approach for parameter optimisation (Sec. 4.2), and then show examples of applying the calibration to the quadratic parameterisation, PICO and LADDIE (Sec. 4.3).

4.1 Requirements on melt modules

Ice-sheet modellers are welcome to use their preferred melt module(s). Any module that can be forced using CMIP ocean conditions, i.e., ocean temperature, salinity, or thermal forcing (temperature above the local freezing point), is welcome. A list of existing modules is given in Table 1. If modellers would like to use the quadratic-dependency melt parameterisation that was proposed in ISMIP6 (Jourdain et al., 2020), we suggest to incorporate the recommended updates in Sec. 4.1.1.

We suggest that modellers follow the protocol provided in Section 4.2 to calibrate their melt module and provide examples for the quadratic parameterisation, PICO, and LADDIE in Section 4.3.



Table 1. List of currently available melt modules.

Module	Publication(s)	Relevant parameters
quadratic local	Burgard et al. (2022)	K
quadratic local with slope dependency	Burgard et al. (2022)	K
quadratic semi-local	Burgard et al. (2022)	K
quadratic semi-local with slope dependency	Burgard et al. (2022)	K
Plume	Lazeroms et al. (2018, 2019)	$C_d^{1/2}\Gamma_{TS}, E_0$
PICO	Reese et al. (2018a)	C, γ_T^*
PICOP	Pelle et al. (2019)	$C, \gamma_T^*, C_d^{1/2}\Gamma_{TS}, E_0$
LADDIE	Lambert et al. (2023, 2026)	$C_{d,top}$
Neural networks	Rosier et al. (2023); Burgard et al. (2023)	parameters inherent to the neural networks

4.1.1 Recommended updates to the quadratic melt parameterisations

The updated version of the “quadratic, local” melt parameterisation that was originally developed for ISMIP6 (Nowicki et al., 2020; Jourdain et al., 2020; Favier et al., 2019) now reads as follows, in the revised formulation from Burgard et al. (2022)

345 based on Jenkins et al. (2018):

$$m = K \sin \theta \frac{\rho_o}{\rho_i} \left(\frac{c_o}{L_i} \right)^2 \beta_S S_{loc} \frac{g}{2|f|} |TF_{loc}| TF_{loc}, \quad (1)$$

where $TF_{loc} = T_{loc} - T_{f,loc}$ is the thermal forcing at the ice shelf draft calculated as the difference between local temperature T_{loc} and the in situ freezing point $T_{f,loc}$, S_{loc} is the corresponding salinity, K is the calibration parameter, $\sin \theta$ is the slope of the ice draft, which can be either assumed constant or locally dependent on the ice-shelf topography. The local slope is
 350 estimated as the local slope between the neighbouring grid cells in x and y directions at each ice-shelf point (for the versions of the parameterisation ‘with slope dependency’ in Table 1). Under transient geometry changes, the slopes should be updated at every timestep for physical consistency. The constant slope is an average slope over all Antarctic ice shelves for the quadratic parameterisations without slope dependency from Table 1. In line with Jourdain et al. (2020) the average slope should be kept constant throughout the simulation. Furthermore, ρ_i and ρ_o are, respectively, the density of ice and seawater, c_o is the specific
 355 heat capacity of seawater, L_i is the latent heat of fusion, β_S is the salt contraction coefficient, g is gravity, and f is the Coriolis parameter.

The “semi-local” parameterisation (referred to as “non-local” in Jourdain et al., 2020), equally, can be written as:

$$m = K \sin \theta \frac{\rho_o}{\rho_i} \left(\frac{c_o}{L_i} \right)^2 \beta_S < S_{loc} > \frac{g}{2|f|} |< TF_{loc} >| TF_{loc}, \quad (2)$$



where $\langle \rangle$ denotes the shelf-wide average. If shelf-based averaging is not possible, basin-wide averages can be used too but the meaning of this non-locality might be less physical. Compared to the ISMIP6 formulation, the parameters in Eqs. (1) and (2) have a stronger physical grounding (Jenkins et al., 2018).

Since Favier et al. (2019), there has not been any further evidence that the “semi-local” version of the quadratic module gives better results than the “local” version (Burgard et al., 2022), so any of these versions is welcome in ISMIP7.

4.2 Melt module parameter calibration

The calibration approach for ISMIP7 is designed to help ice sheet modellers identifying parameters for their chosen melt module that are consistent with oceanographic and melt data from simulations and observational estimates. The parameters are calibrated according to present-day melt rates from remote sensing, projected melt rates from ocean circulation models, and melt rate interannual variability from oceanic in-situ measurements. This way, we aim to constrain parameters to provide reasonable present-day melt rates as well as reasonable melt rate projections. To support the parameter optimisation, we developed a python toolbox explained in Section 4.2.4. We provide examples of applying the protocol for the quadratic, LADDIE and PICO modules, respectively (Sects. 4.3.1 to 4.3.4).

The following steps are required for the calibration:

1. Modellers run an ensemble of simulations with their melt module, where they vary (1) the relevant parameters of their module and (2) the ocean forcing (the different datasets are summarised in Table 2). In these experiments, the aim is to simulate melt rates and not to capture the ice-sheet response, so a single ice-sheet model time step or iteration should be sufficient. The simulations should be done with a fixed, present-day ice-sheet geometry.
2. Using the ensemble of resulting melt rates, parameter(s) of the melt module are optimised for the objective function detailed in Sect. 4.2.2. By sampling uncertainty in the objective functions’ targets, a distribution of optimal parameter values is identified, from which a central and upper/lower range parameter values can be selected, see Sect. 4.2.3.

Things to consider:

- In step 1, to ensure consistency with the datasets, modellers are asked to use a recent present-day geometry, e.g., BedMap3 (Pritchard et al., 2025) or BedMachine3 (Morlighem, 2022), for the calibration rather than an ice-sheet model initial state with substantially different grounding line position, ice thickness, or ice shelf extent. A BedMachine and BedMap geometry regridded to 8km is provided through ISMIP, see Sect. A3.
- Ideally, the melt module is calibrated and evaluated in the same setting as it is used in the core ISMIP7 ice-sheet simulations, i.e. with the same code and on the same grid as we anticipate that code differences or resolution affect the results.
- A starting point for parameter ranges that are sampled in the ensemble can be found in previous literature, e.g., Burgard et al. (2022).



- 390 – If modellers are using a deep learning approach as their melt module (Rosier et al., 2023; Burgard et al., 2023), this calibration protocol cannot be applied directly as such. We recommend to adapt the loss function during training to account for the different terms of the objective function and/or to use as many datasets as possible from the provided ensemble to train the deep learning algorithm.
- Basin-wide temperature input corrections, as done in ISMIP6, may be used. Please see the next section.

395 4.2.1 Basin-wide temperature input corrections

In ISMIP6, basin-wide, ad-hoc ocean temperature input corrections ΔT_b for each IMBIE2 basin b were suggested. These corrections may capture biases in the ocean climatology and observational melt rates which can induce significant mismatch between modelled melt based on the ocean climatology in comparison to the observational melt. Further, temperature corrections may account for the transformation of water masses inside the cavities which is not captured in a number of melt modules.

400 We recommend to avoid them if possible as they are only an ad-hoc correction and do not account for example for changes of such processes in the projections. Otherwise, as using temperature corrections for each ocean basin introduces new degrees of freedom, we recommend to keep these corrections as small as possible (definitively no more than $\pm 2^\circ\text{C}$ as the difference between warmest and coldest ice shelves in Antarctica is only about 3 to 4°C).

These corrections are usually calculated such that present-day melt rates in each IMBIE2 basin are matched. Term J_1 introduced in the following Sect. 4.2.2 could be used for this aim. All melt rates, including in the projections, are then calculated using the temperature correction. For example, in the local and semi-local quadratic parameterisations, see Eqns. 1 and 2, melt rates are calculated using $TF_{loc} + \Delta T_b$, with ΔT_b depending on basin b instead of TF_{loc} .

These corrections may be calculate at different stages of the parameter optimisation: (1) prior to the parameter optimisation which requires a larger ensemble for the present-day melt rates as the new parameter ΔT_b , for basins b , needs to be included

410 (see PICO example in Sect. 4.3.3). This can lead to the problem that the parameter bounds are not constrained when present-day melt rates are compared to observations (namely, terms J_1 and J_2). Alternatively, (2), the corrections can be calculated after the parameter optimisation, as in ISMIP6, which means that melt rate sensitivities to ocean temperature changes - if those are non-linear - may change after the calibration (see quadratic example in Sect. 4.3.1).

4.2.2 Melt module calibration target

415 An optimal parameter (set) is obtained by minimising the objective function I with

$$I = a_1 \frac{J_1}{\text{median}(J_1)} + a_2 \frac{J_2}{\text{median}(J_2)} + a_3 \frac{J_3}{\text{median}(J_3)} + a_4 \frac{J_4}{\text{median}(J_4)}, \quad (3)$$

where the terms J_i are functions assessing the fit of modelled melt with present-day basin-aggregated melt (J_1), melt in buttressing relevant regions (J_2), sensitivity of melt to ocean temperature changes simulated by ocean models (J_3), and sensitivity of melt to interannual ocean temperature changes from observational estimates (J_4). To give each term equal importance, they

420 are normalised by the median of the corresponding J_i calculated over the ensemble of parameter values. The coefficients a_i



Table 2. Table of experiments for the melt module calibration. Experiments with X are suggested as the minimal calibration ensemble, and with + as second priority, but exploring the sensitivity to using more calibration data is encouraged. The J term in which each forcing dataset can be used is indicated, as well as the basins involved in the J term calculation, with optional basins in square brackets. Sections 3.1, A9 and A10 describe datasets in detail.

	Experiment	Forcing dataset	Term	Basin(s)
X	present-day	ocean climatology	$J_{1,2}$	all
X	AIS1 cold	Mathiot_NEMO_cold	J_3	all
X	AIS1 warm	Mathiot_NEMO_warm	J_3	all
X	AIS2 cold	Naughten_FESOM_ACCESS_cold	J_3	all
X	AIS2 warm	Naughten_FESOM_ACCESS_warm	J_3	all
	AIS3 cold	Naughten_FESOM_MMM_cold	J_3	all
	AIS3 warm	Naughten_FESOM_MMM_warm	J_3	all
	AIS4 cold	Timmermann_FESOM_cold	J_3	14
	AIS4 warm	Timmermann_FESOM_warm	J_3	14
+	AIS5 cold	Jourdain-Naughten_NEMO-MITgcm_cold	J_3	9,14 [8,10,12,13,15]
+	AIS5 warm	Jourdain-Naughten_NEMO-MITgcm_warm	J_3	9,14 [8,10,12,13,15]
+	AIS6 cold	Naughten_MITamu-MITwed_cold	J_3	9,14 [8,10,12,13,15]
+	AIS6 warm	Naughten_MITamu-MITwed_warm	J_3	9,14 [8,10,12,13,15]
	AIS7 cold	Haid_FESOM_cold	J_3	14
	AIS7 warm	Haid_FESOM_warm	J_3	14
	PIG 1994	Obs_1994	J_4	9
	DIS 2000	Obs_2000	J_4	9
	DIS 2006	Obs_2006	J_4	9
	PIG,DIS 2007	Obs_2007	J_4	9
X	PIG 2009	Obs_2009	J_4	9
	DIS 2009	Obs_2009	J_4	9
	PIG 2010	Obs_2010	J_4	9
	DIS 2011	Obs_2011	J_4	9
X	PIG 2012	Obs_2012	J_4	9
	DIS 2012	Obs_2012	J_4	9
	PIG,DIS 2014	Obs_2014	J_4	9
	PIG,DIS 2016	Obs_2016	J_4	9
	DIS 2018	Obs_2018	J_4	9
	PIG 2019	Obs_2019	J_4	9
	PIG 2020	Obs_2020	J_4	9



set the importance of each term J_i . In order to obtain a distribution of plausible parameters, the a_i 's are later randomly and uniformly sampled between 0 and 1, see Sect. 4.2.3.

The first term J_1 of the objective function assesses the fit with present-day, basin-aggregated melt using the mean absolute error:

$$J_1 = \sum_{b=1}^{16} w_b |\text{BMB}_{\text{mod}}(b) - \text{BMB}_{\text{obs}}(b)|, \quad (4)$$

where $\text{BMB}_{\text{mod}}(b)$ is the basal mass balance in Gt/yr integrated over the IMBIE2 basin b (see Section A2) and modelled with a given melt module using the present-day ocean climatology (see Sect. 3.1), and $\text{BMB}_{\text{obs}}(b)$ is the observed basal mass balance in Gt/yr integrated over the IMBIE2 basin b (see Sec. A8). This term broadly aligns with the approach taken in ISMIP6 (Jourdain et al., 2020). Note however that we use mean absolute error instead of root mean square error following an analysis of the error terms based on Hodson (2022). The weights w_b allow modellers to emphasise or minimise terms. To account for uncertainties in the observed melt rates, $\text{BMB}_{\text{obs}}(b)$ is later on sampled from a normal distribution with mean value and standard deviation from basal melt observational estimates, see Sect. 4.2.3.

The second term J_2 of the objective function assesses the fit with melting integrated over buttressing relevant regions using the mean absolute error:

$$J_2 = \sum_{i=1}^{10} \frac{w_i \text{BFRN}(i)}{\text{median}(\text{BFRN})} |\text{BMB}_{\text{mod}}(i) - \text{BMB}_{\text{obs}}(i)|, \quad (5)$$

where $\text{BMB}_{\text{mod}}(i)$ and $\text{BMB}_{\text{obs}}(i)$ are the modelled and observed sub-shelf melt rates integrated over the i th buttressing bin, respectively. The buttressing bins cluster regions of Antarctic ice shelves of similar buttressing importance as identified in Reese et al. (2018b), with details given in Sect. A7. While buttressing bin 0 contains all Antarctic ice shelf regions that provide no or negligible buttressing, buttressing bin 9 contains the regions with highest buttressing values as measured by the Buttressing Flux Response Numbers (BFRNs). To reflect the importance of each region for buttressing, each bin is weighted with the median BFRN over that bin, $\text{BFRN}(i)$, relative to the median over all values $> 0.02\%$ median(BFRN). This binning approach is inspired by Menthon et al. (2025), but using buttressing bins instead of melt rate bins to make sure that melting in buttressing-relevant regions is well represented. In general, this term will constrain melt in the regions most relevant for buttressing: ice shelf regions near grounding lines of fast flowing ice streams, shear margins, or ice rises and ice rumples. The weights w_i allow modellers to emphasise or minimise terms. To account for uncertainties in the observed melt rates, $\text{BMB}_{\text{obs}}(i)$ is later on sampled from a normal distribution with mean value and standard deviation from basal melt observational estimates, see Sect. 4.2.3.

The term J_3 of the objective function compares the sensitivity of melt to ocean temperature changes with simulations from cavity-resolving ocean circulation models:

$$J_3 = \sum_{j=1}^n \sum_{b=1}^{16} w_{j,b} |(\text{BMB}_{\text{mod,warm}}(j,b) - \text{BMB}_{\text{mod,cold}}(j,b)) - (\text{BMB}_{\text{ref,warm}}(j,b) - \text{BMB}_{\text{ref,cold}}(j,b))| \quad (6)$$

where j is one of the ocean modelling datasets, b a basin, and $\text{BMB}_{\text{mod,cold}}(j,b)$, $\text{BMB}_{\text{mod,warm}}(j,b)$, $\text{BMB}_{\text{ref,cold}}(j,b)$, and $\text{BMB}_{\text{ref,warm}}(j,b)$ are the modelled (with the module) and reference (from the ocean model) melt rates for a “warm” and a



“cold” ocean state averaged over basin b in units of $\text{kg}/\text{m}^2/\text{yr}$. Ocean modelling data processing, including the selection of ‘warm’ and ‘cold’ states, is described in Section 3.3 and Appendix A9. The integer n stands for the number of included datasets from Table 2. As a first approach, for the sake of simplicity, we suggest using only two pairs of cold/warm datasets ($n = 2$, datasets indicated by “X” in Table 2) coming from global ocean simulations that can be used for all basins ($w_{j,b} = 1$ for all b values in J_3 , $j \leq n$). To further improve the calibration robustness, we also strongly suggest including the two datasets from regional ocean simulations ($n = 4$, additional datasets indicated by “+” in Table 2) for two basins ($w_{j,b} = 1$ for Eastern Amundsen, $b = 9$, and for Ronne-Filchner, $b = 14$, and $w_{j,b} = 0$ for the other basins b in J_3). Other basins in the regional model datasets and other circum-Antarctic datasets are provided to the ISMIP7 community and are described in Table 2 and Appendix A9. We encourage exploring the sensitivity of the calibrated parameters to the choice of datasets. It is also possible to emphasise or minimise the importance of individual datasets or basins through the use of different weights $w_{j,b}$. To account for uncertainties in the ocean model melt rates, $\text{BMB}_{\text{ref}}(b)$ is later on sampled from a normal distribution with mean value and standard deviation based on modelled melt estimates and we sample randomly for each summand $j \leq n, b \leq 16$ if it is included, see Sect. 4.2.3.

We note that none of the temperature and salinity fields used in the J_3 calculations are bias corrected. Regional ocean models have biases, but we assume that melt rates are consistent with the ocean properties, i.e. underestimated if the ocean is cold biased as in the Amundsen Sea of Naughten et al. (2018). We are also aware that the ice shelf topography has varied in time and differs from Bedmap3/BedMachine-v3 in the various data used to constrain the ice-shelf topography in the ocean simulations, but we assume that these are relatively small changes that are of second order compared to other uncertainties.

The term J_4 of the objective function further assesses the sensitivity of the melt in the module to ocean temperature changes from observational estimates in the Amundsen Sea:

$$J_4 = \sum_{k=1}^n w_k |\text{BMB}_{\text{mod}}(k) - \text{BMB}_{\text{obs}}(k)| \quad (7)$$

where k is a year of ocean observational data, and $\text{BMB}_{\text{mod}}(k)$, $\text{BMB}_{\text{obs}}(k)$ are the modelled (with the module) and reference (from observations) integrated melt rates in Gt/yr for Pine Island Glacier Ice Shelf or Dotson Ice Shelf. We suggest using at least two years ($n = 2$), 2009 and 2012, of Pine Island data as these yield a good representation of a ‘colder’ and ‘warmer’ state of the cavity. Further data may be added, see Table 2, with all data described in Section A10. The weights w_k allow modellers to emphasise or minimise terms. To account for uncertainties in the observed melt rates, $\text{BMB}_{\text{ref}}(j)$ is later on sampled from a normal distribution with mean value and standard deviation of the observed estimates, and we sample randomly for each summand if it is included, see Sect. 4.2.3.

As mentioned above, the weights, $w_b, w_j, w_{j,b}, w_k$, allow modellers to adjust the importance of individual terms. To represent all components equally as a standard weights in all terms are set to 1 except for basins that are not represented in datasets in terms J_3, J_4 . Modellers are welcome to adjust the objective function to their modules, e.g., adding more datasets or putting the emphasis on specific terms by adjusting the weights.



485 4.2.3 Estimating parameter uncertainty

We suggest to sample uncertainties in the target datasets of the objective function to obtain a distribution of optimal parameter values from which a standard, and lower/higher value can be selected. In the individual terms J_i in Sect. 4.2.2, we point to places where uncertainty is introduced:

- the coefficients a_i of the terms J_i are randomly and uniformly sampled from $[0, 1]$,
- 490 – in J_1 the observed melt rate $\text{BMB}_{\text{obs}}(b)$ in each IMBIE2 basin b is sampled from a normal distribution with mean and standard deviation specified from the observational data (Sect. A8),
- in J_2 the observed melt rate $\text{BMB}_{\text{obs}}(i)$ in each buttressing bin i is sampled from a normal distribution with mean and standard deviation specified from observational data (Sect. A8),
- in J_3 the target melt rates $\text{BMB}_{\text{ref,warm}}(b), \text{BMB}_{\text{ref,cold}}(b)$ in each basin b for each model data representation j are sampled
 495 from a normal distribution with mean and standard deviation specified from the modelling data (Sect. A9) and for each summand of J_3 we randomly sample a pre-factor from $\{0, 1\}$ that decides whether it is included,
- in J_4 the observed melt rates $\text{BMB}_{\text{obs}}(k)$ are sampled from a normal distribution with mean and standard deviation specified from the observational data (Sect. A10) and for each summand of J_4 we randomly sample a pre-factor from $\{0, 1\}$ that decides whether it is included.

500 We suggest sampling at least 100,000 times each of those independently, which yields a distribution of 100,000 optimal parameter values. From those, the median or mode can be chosen as the main parameter value. If the melt module has one parameter, as for the quadratic parameterisations, we suggest to use the 5th, 50th and 95th percentile values from the distribution of optimal parameter values, with the median being the standard parameter and the 5th and 95th percentile values used to explore the parametric uncertainty in the ISMIP projections. If the melt module has two parameters, parameter value selection
 505 is less straightforward. We suggest that modellers investigate the distribution they obtain, and select from this. For PICO, we exemplify this in Sect. 4.3.3. In this case, we found using the mode as standard parameter most plausible. To sample the uncertainty ranges, we analysed 5th and 95th percentile values of individual parameters and the corresponding 5th or 95th parameter of the marginal distribution, which will yield two lower and two higher end parameter values. All four parameter sets can be used to explore parameteric uncertainty, or only those two that yield lowest and highest melt rate sensitivities to
 510 ocean temperature changes may be selected. If modellers aim to run more projections to assess parametric uncertainty, we suggest to explore further modes and the 1st and 99th percentiles of their parameter distribution.

4.2.4 The parameter selection toolbox

The toolbox is written in Python and part of the open source Python package `ismip7-antarctic-ocean-forcing` (`i7aof`). It contains code to optimise melt module parameters (one or two parameters are possible) using a choice of melt rate
 515 targets. The package supports parameter selection across melt modules and datasets.

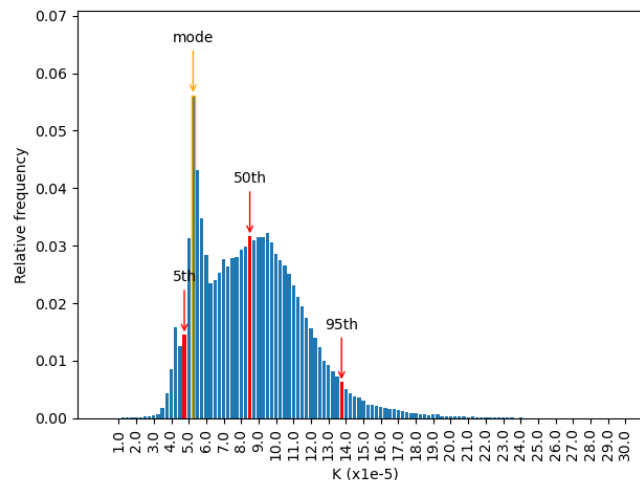


Figure 5. Distribution of optimal parameter values, K , for the quadratic local parameterisation sampling 100,000 times. Red colors and annotations highlight the 5th, 50th, 95th percentile of the parameter distribution, and yellow color the main mode.

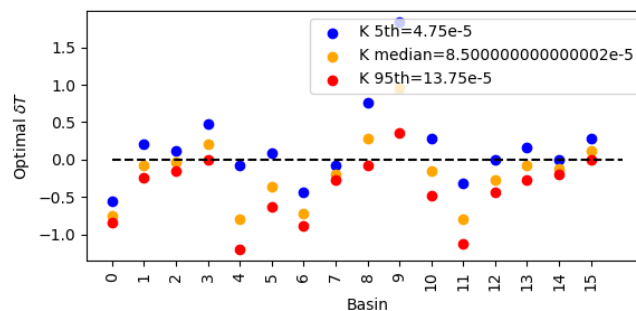


Figure 6. Basin-wide temperature corrections, δT_b , for the local quadratic melt parameterisation with standard and 5th, 95th percentile parameter values.

4.3 Melt rate calculation: Results

In this section, we show examples of parameter calibration for the quadratic local parameterisation (Sects. 4.3.1 and 4.3.2), PICO (Sect. 4.3.3), and LADDIE (Sect. 4.3.4).

4.3.1 Calibration example: quadratic local parameterisation

520 We calibrate the quadratic local parameterisation using the standard procedure outlined in Sect. 4.2. This example assumes an average constant slope around Antarctica ($\sin \theta \approx 0.005$). Here, we calibrate on 8km structured grid resolution and use the formulation from the multimelt python package (Burgard, 2022). We select the parameter K over a range of values between

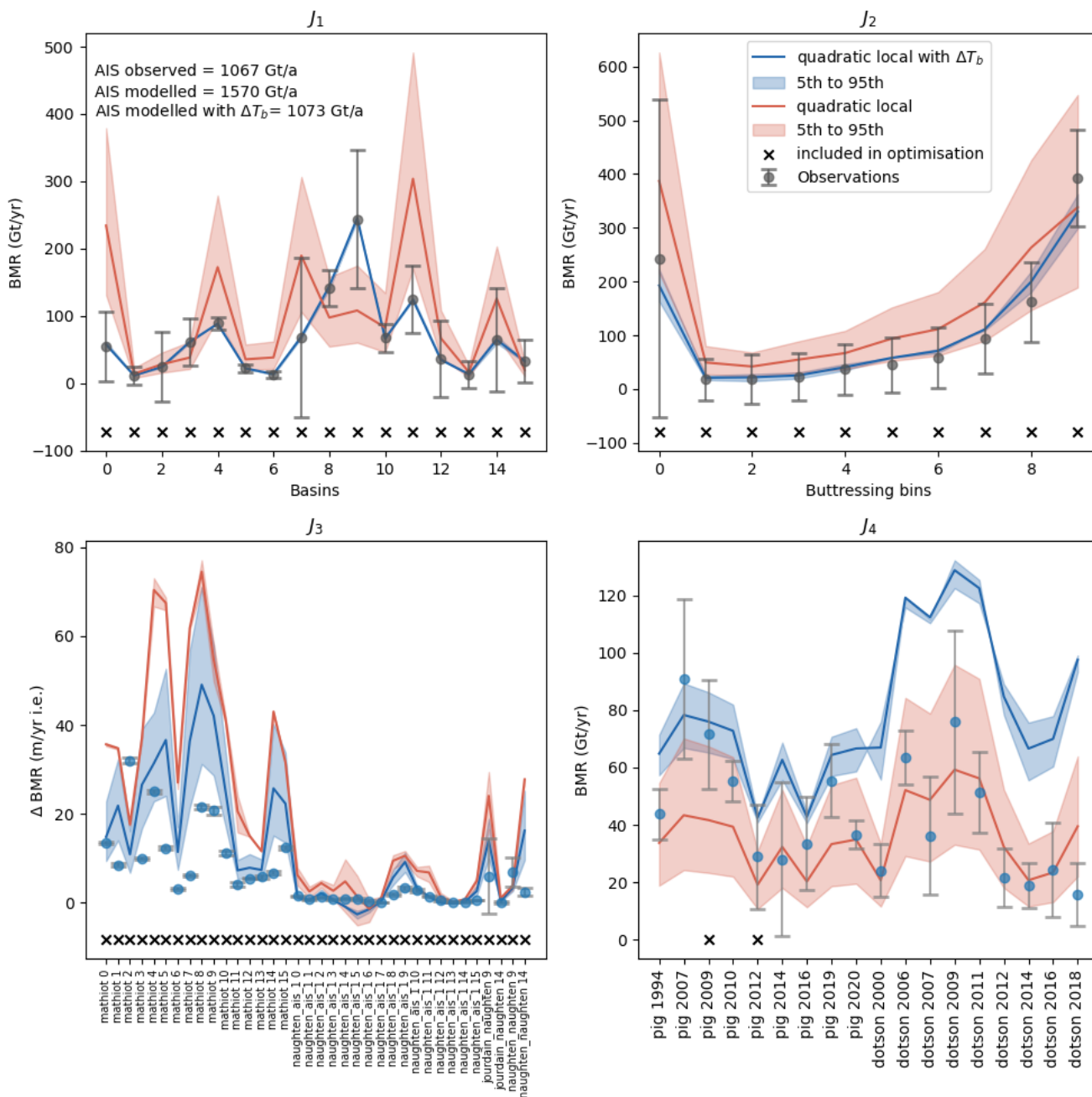


Figure 7. Calibration results for the optimised parameter K of the local quadratic parameterisation. Panels show results and targets in the individual terms J_1, J_2, J_3, J_4 for the respective basin, bin, numerical modelling study, region or year. Note that in term 4 we used only the years 2009 and 2012 of PIG for optimisation, but included all terms in the figure for comparison (indicated by black x).



0.25×10^{-5} and 30×10^{-5} , and sample in steps of 0.25×10^{-5} a total of 120 values. We use the recommended minimal and second priority datasets in term J_3 .

525 Figure 5 shows the distribution of 100,000 optimal parameter values, with a median value of 8.5×10^{-5} , a 5th percentile value of 4.75×10^{-5} , and a 95th percentile value of 13.75×10^{-5} . The mode of the distribution is lower than the median at 5.25×10^{-5} . Note that the 5th, 50th and 95th percentile values roughly correspond to 6,494, 11,620, 18,797 m/yr for the quadratic local parameterisation presented in Jourdain et al. (2020). They are slightly wider than the range of the 'MeanAnt' calibration, with the 5th percentile value being lower (7710), the median matching the MeanAnt median (11,100), and the
 530 95th percentile value being higher than AntMean 95th percentile value (15,300), but lower than the PIGL 5th percentile value (30,200).

In addition, we explore the effect of temperature corrections on the calibration metrics of the objective function. Temperature corrections, see Sect. 4.2.1 are calculated after the optimisation, see Fig. 6. In general, the Amundsen Sea (basin 9) has the highest δT corrections required to match high melt rates. While increasing K requires smaller δT_9 in the Amundsen Sea, δT_4
 535 and δT_{11} in the Aurora basins and the Bellingshausen Sea become more negative showing an overestimation of melt rates. Basin locations are plotted in Fig. A1. Using the corrections, basin-wide melt rates match observed targets as expected, see Fig. 7. However, melt rates cannot fully represent the differences between the buttressing relevant regions, with melt rates being skewed towards the upper end of target melt in bins 6,7,8, and on the lower end on bin 9 where increasing bin numbers indicate higher buttressing relevance. While moderate temperature changes from Naughten et al. (2018) can be matched (J_3), in
 540 many regions the melt parameterisation gives a too high sensitivity for the extreme warming scenario of Mathiot and Jourdain (2023). Melt rate changes compared to Jourdain et al. (2022) in the Amundsen Sea and compared to Naughten et al. (2021) in the Weddell Sea, especially for the stronger greenhouse gas emission scenario, are overestimated. But changes compared to Naughten et al. (2022) can be matched. Sensitivities are reduced when temperature corrections are introduced (compare red and blue curves). Furthermore, the parameterisation with the optimised parameter struggles to represent the full range of
 545 variability in the Amundsen Sea (J_4), independently of the temperature corrections.

The results presented above correspond to a calibration over all Antarctic basins. In the following section (Sec. 4.3.2), we present a calibration confined to a given region, here the Amundsen Sea. In general, we do not recommend calibration on each basin separately, as this would reduce our trust in the physical meaning of the parameter due to possible overfitting. Nevertheless, experiments in previous work have shown that calibrating two different parameters on Filchner-Ronne and Ross ice
 550 shelves on the one hand and all other ice shelves on the other hand leads to a better performance of the quadratic parameterisation in projections (Burgard et al., 2025).

4.3.2 Calibration example: quadratic local parameterisation constrained for the Amundsen Sea

The 'PIGL' calibration in Jourdain et al. (2020) was motivated by sampling high melt rates at the grounding line of Pine Island. We here try a similar approach by focusing on the Amundsen Sea: we only use Amundsen Sea melt as constraint for present-
 555 day melt rates in term J_1 , remove term J_2 , and constrain the melt sensitivity to ocean temperature changes from ocean models in term J_3 to the Amundsen Sea. Term J_4 remains as it is, focusing on the Amundsen Sea. This approach increases K values

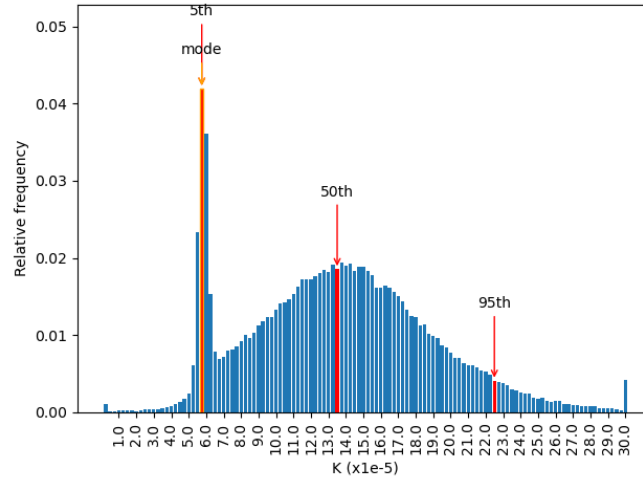


Figure 8. Distribution of optimal parameter values, K , for the quadratic local parameterisation sampling 100,000 times with a focus on the Amundsen Sea. Red colors and annotations highlight the 5th, 50th, 95th percentile of the parameter distribution, and yellow color the main mode.

in comparison to the standard calibration approach, (see Fig. 8), with 5th percentile being now 5.75×10^{-5} , median being 13.5×10^{-5} , the 95th percentile being 22.5×10^{-5} , and the mode being 5.750×10^{-5} . The 5th, 50th and 95th percentile values roughly correspond to $\gamma_T = 7, 861, 18, 455, 30, 759$ m/yr in Jourdain et al. (2020), with the values being higher than using the Antarctic-wide constraints, and the 95th percentile value reaching the 5th percentile of the PIGL parameter tuning (30200, 49500, 514000). This confirms previous results that PIGL is inconsistent with ocean model simulations (Jourdain et al., 2022).

As Figure 9 shows, variability in the Amundsen Sea (J_4) is captured better than in the standard approach (Fig. 7), but not fully yet.

4.3.3 Calibration example: PICO

We calibrate PICO using the minimal procedure outlined in Sect. 4.2.2 using 8km regular grid resolution and the implementation in PISM. PICO has two parameters, the overturning velocity, C , and the heat exchange coefficient γ_T^* . We vary the parameters between $C = 1 \times 10^4$ Sv m^3kg^{-1} to $C = 2 \times 10^7$ Sv m^3kg^{-1} and $\gamma_T^* = 1 \times 10^{-6}$ m s^{-1} to $\gamma_T^* = 1.25 \times 10^{-4}$ m s^{-1} . In this case, we calculate basin-wide temperature correction δT_b before the optimisation, allowing variations up to $\pm 1.5^\circ\text{C}$.

We test sampling all terms as presented in Eqn. 3, which yields a distribution as shown in Fig. 10. The mode of the distribution is $C = 2.5 \times 10^6$, $\gamma_T^* = 2.0 \times 10^{-5}$ that we suggest to use as standard value since sampling a median on the individual distributions might not yield a parameter value that has been found optimal at all. To identify the ranges, it does not make too much sense to use individual 5th and 95th percentiles together, yielding $C = 0.25 \times 10^6$, $\gamma_T^* = 5 \times 10^{-6}$ and $C = 17.5 \times 10^6$, $\gamma_T^* = 7.5 \times 10^{-5}$ as these values do not appear as a plausible parameter set in the 2-dimensional histogram. To explore the upper range of uncertainty, we hence suggest using marginal distributions of the 5th and 95th percentile C and γ_T^* .

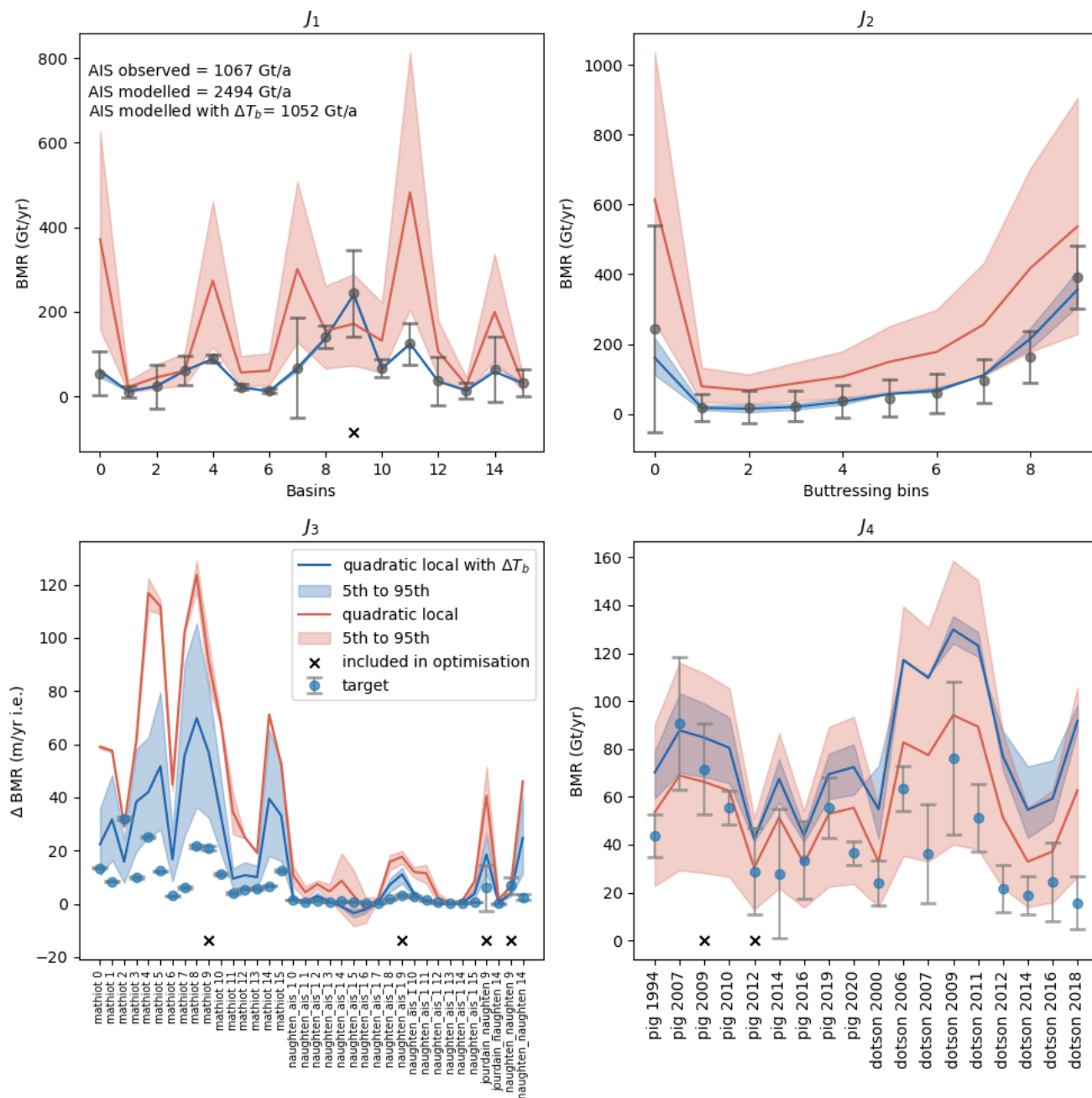


Figure 9. Calibration results for the optimised parameter K of the quadratic local parameterisation with a focus on the Amundsen Sea. Panels show results and targets in the individual terms J_1 , J_2 , J_3 , J_4 for the respective basin, bin, numerical modelling study, region or year. Black “x” indicates terms that are used in the optimisation.

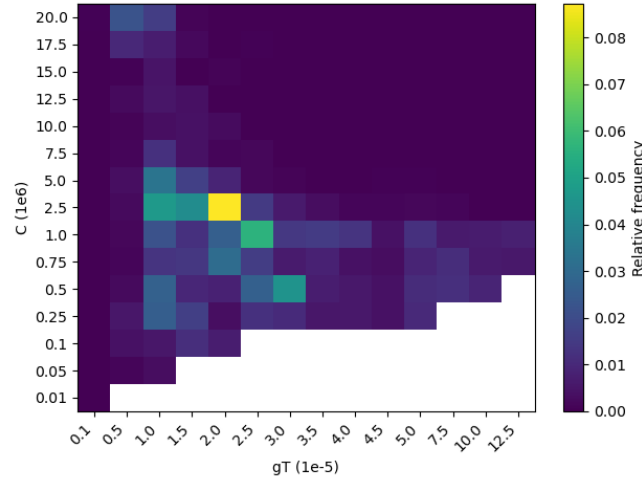


Figure 10. Distribution of optimal parameter values, C and γ_T , for PICO sampling 100,000 times. Masked regions are where PICO physical constraints are not met, see Reese et al. (2018a).

values, and selecting the 5th/95th percentile values from these. For example, for the 5th percentile parameter of $C = 0.25 \times 10^6$, we identify the 5th percentile parameter of γ_T^* from the marginal distribution of optimal parameters corresponding to that C , $\gamma_T^* = 4.5 \times 10^{-5}$. Applying the same procedure starting with the 5th percentile parameter of $\gamma_T^* = 1 \times 10^{-5}$, we identify the 5th percentile parameter of C from the marginal distribution, $C = 0.25 \times 10^6$. Similarly, for the 95th percentile parameter of $C = 17.5 \times 10^6$, we identify the 95th percentile parameter of γ_T^* from the marginal distribution of optimal parameters corresponding to that C , $\gamma_T^* = 1.5 \times 10^{-5}$. For the 95th percentile parameter of $\gamma_T^* = 7.5 \times 10^{-5}$, we identify $C = 1.0 \times 10^6$.

Figure 11 shows that PICO struggles to represent the increase in melt rates into higher buttressing relevant regions (J_2), similar to the quadratic parameterisation. This is in line with PICO smoothing out melt rates within boxes. However, the melt rate changes are closer to the modelled changes in ocean models in J_3 . Interestingly, the upper estimate when selecting first γ_T^* yields a much higher increase in melting than the upper estimate when selecting first C in all basins but 7 (Ross) and 14 (Filchner-Ronne). This is consistent with previous studies that found that melt sensitivity in large ice shelves is controlled by C whereas sensitivity in smaller ice shelves is controlled by γ_T^* . Only the upper range value selecting first γ_T^* allows PICO to capture the variability in Pine Island between 2009 and 2012 (J_4).

Moreover, we test sampling the sensitivity of melt rates to ocean temperature changes in the Amundsen and Weddell Seas, analogously to Reese et al. (2023). We remove term J_1 (as this should be true due to the temperature corrections estimated beforehand), remove J_2 , focus on the Weddell Seas in term J_3 , and on the Amundsen Sea in term J_4 . The result is shown in Fig. 12. We now obtain a higher optimal parameter value of $\gamma_T^* = 5 \times 10^{-5}$ and $C = 5 \times 10^6$ which is close to the best parameters from Reese et al. (2023) for γ_T^* and higher for C . Differences might arise due to the fact that we used a different ocean modelling dataset for the Weddell Sea, and allowed for larger δT corrections. With this sampling, the standard parameters for PICO match the variability in the Amundsen Sea (not shown).

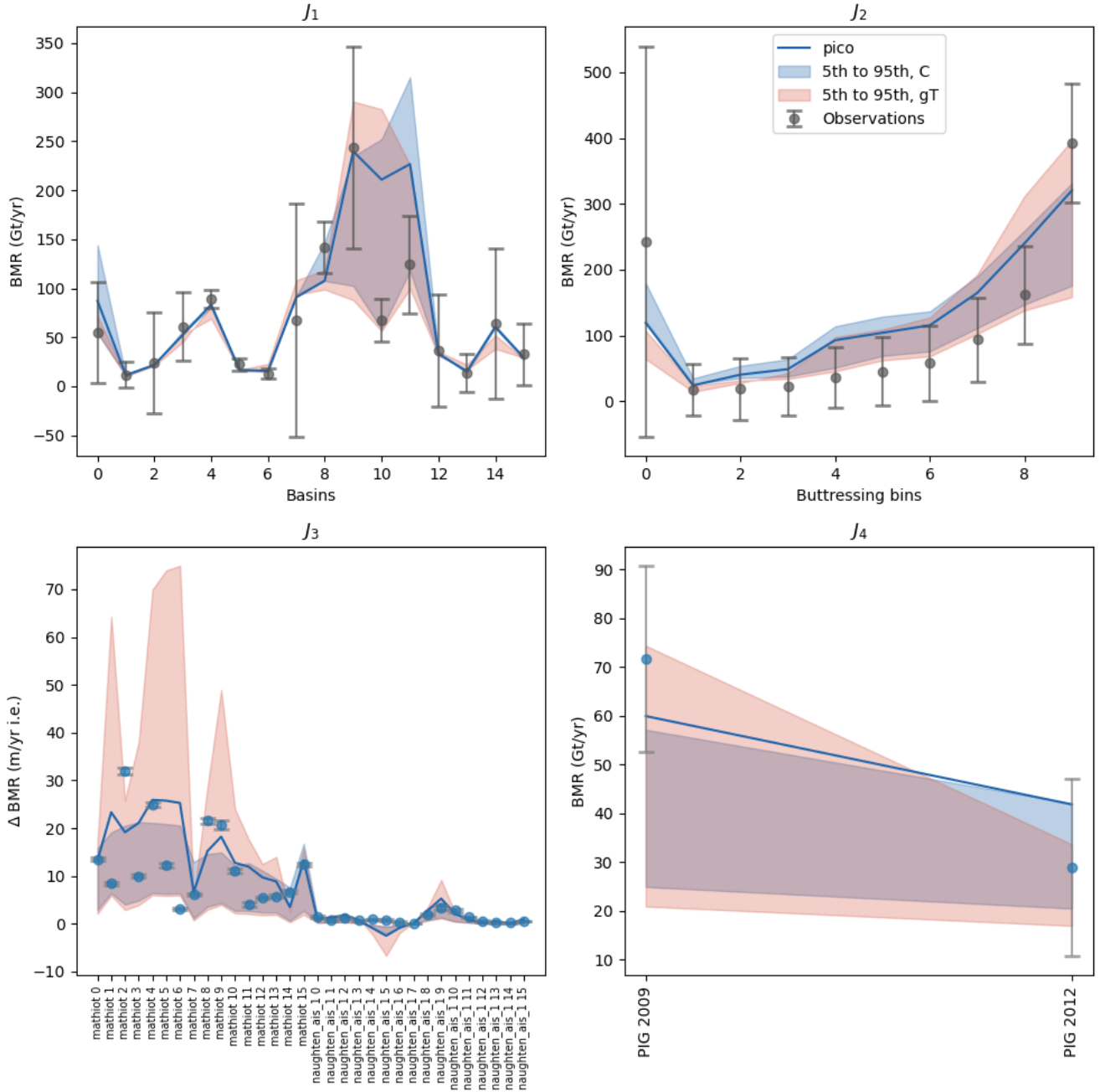


Figure 11. Calibration results for the optimised parameter C , γ_T of PICO. Panels show results and targets in the individual terms J_1 , J_2 , J_3 , J_4 for the respective basin, bin, numerical modelling study, region or year. Blue (red) shading shows the uncertainty range resulting from the parameter selection starting with the 5th and 95th parameter values of C (γ_T^*) and selecting γ_T^* (C) from the marginal distribution.

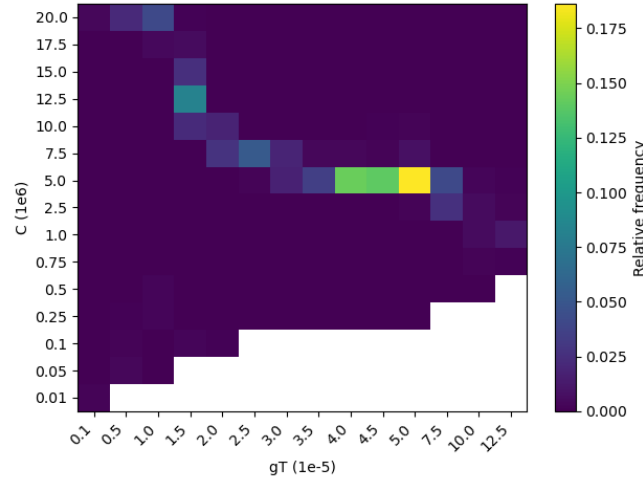


Figure 12. Distribution of optimal parameter values, C and γ_T^* , for PICO sampling 100,000 times with a focus on the Amundsen Sea and Filchner Ronne analogously to Reese et al. (2023). Masked regions are where PICO physical constraints are not met, see Reese et al. (2018a).

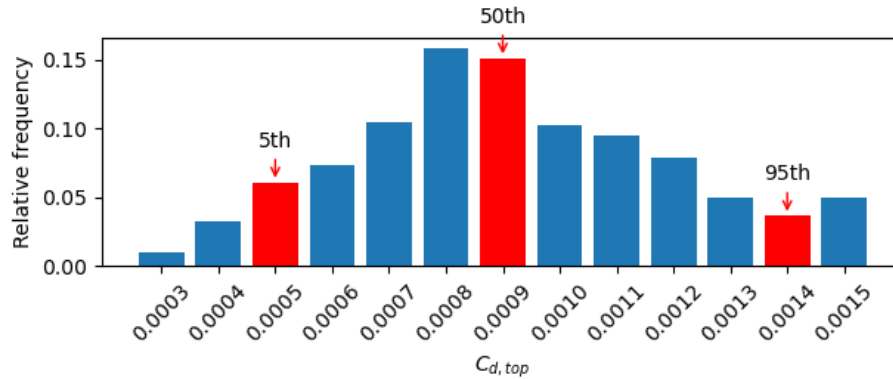


Figure 13. Distribution of optimal parameter values, $C_{d,top}$, for LADDIE sampling 100,000 times. Red colors and annotations highlight the 5th, 50th, 95th percentile of the parameter distribution.

595 4.3.4 Calibration example: LADDIE

As an example of a relatively computationally expensive melt module, we provide the calibration of the two-dimensional numerical melt model LADDIE (Lambert et al., 2023). LADDIE 2.0 (Lambert et al., 2026) is horizontally discretised on an unstructured mesh. For this example, it is configured with an effective resolution of 3 km along the grounding lines of the Amundsen Sea, 4 km over the Amundsen Sea ice shelves, and 6 km over all other ice shelves. Melt rates are computed using the 3 equations parameterisation, commonly used in 3D ocean models (Asay-Davis et al., 2016). Following common practice in ocean models, the drag coefficient in the 3 equations formulation, $C_{d,top}$ is used as a tuning parameter. Simulations are

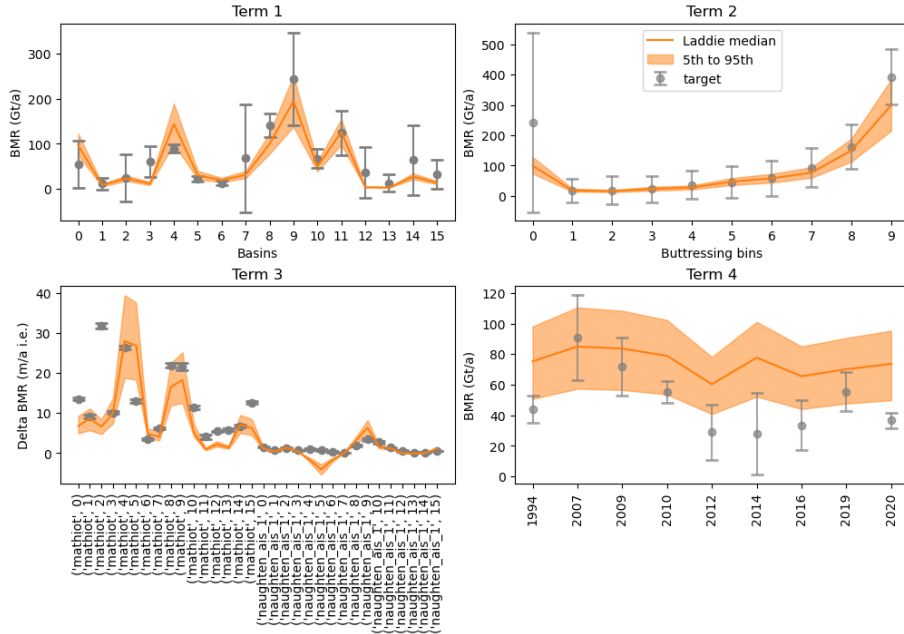


Figure 14. Calibration results for the optimised parameter $C_{d,top}$ of LADDIE. Panels show results and targets in the individual terms J_1, J_2, J_3, J_4 for the respective basin, bin, numerical modelling study, region or year.

integrated for a period of 120 days with a timestep of 240 seconds to achieve a quasi-steady state in most regions of significant melting.

Due to the significant computational cost of this melt module, a limited amount of parameter values could be tested. However, as shown in Fig. 13, a consistent distribution can be achieved with a clear median and 5th and 95th percentiles. To quantify the tail at the higher end of the distribution, additional values above 1.5×10^{-3} need to be tested. Without corrections in ocean temperatures, this calibration allows LADDIE to produce a close match in J_1 and J_2 in all basins and buttressing bins (Fig. 14). Its melt sensitivity is somewhat lower than that of NEMO (J_3 , Mathiot and Jourdain, 2023), and melt rates at Pine Island are slightly overestimated during cold years (J_4). We note that the median calibration value of 0.9×10^{-3} is slightly lower than the value of 1.1×10^{-3} presented in the model description paper (Lambert et al., 2026). This difference is primarily caused by the different calibration targets and observational datasets.

5 Melt Module Intercomparison Project (meltMIP)

5.1 Motivation and aims

Open questions relevant for ISMIP7 that are related to the handling of melt modules for ocean-driven forcing are:



- 615 – How do melt rates modelled with the chosen melt modules and optimised parameters respond to changes in ocean forcing (temperature changes, thermocline shoaling)?
- How do melt rates respond to changes in ice shelf cavity geometry: what influence does the ice sheet initial state have, but also how do melt rates respond to grounding line retreat and cavity changes?
- What influence do ice sheet model resolution and grid have on modelled melt rates?

620 To address these questions, we propose a melt Module Intercomparison Project (meltMIP) with the following aims:

1. Provide a standard protocol for assessing the impact of a choice of sub-shelf melt module and parameters on melt rates and melt rate sensitivity to ocean forcing and geometry changes.
2. Improved understanding of the diversity of ISMIP7 ice sheet projections, i.e., by attributing a part of the diversity to the diversity of melt rates (either due to module choices, resolution or calibration).

625 5.2 Experimental design

The proposed experiments are summarised in Table 3. Experiments tackle changes in cavity temperatures, thermocline depth, cavity geometry and model resolution. Modellers are invited to follow our suggested parameter selection protocol for the melt module of their choice (see calibration design in Sect. 4), but can participate in meltMIP if they opted for another calibration method. If modelling groups have tested several calibration methods, they are welcome to submit several sets of experiments with different selected parameters. For at least one parameter (set), we require modellers to submit all experiments listed in Table 3. If more parameters are tested, e.g., the 5th and 95th percentiles from the calibration in Sect. 4, only the priority experiments may be submitted (5 additional experiments), but all experiments are welcome. For the analysis, it is important that participants use the the melt module through the ice-sheet model (no independent package), and the same model grid as in the main ISMIP7 experiments. Ocean forcing datasets for all experiments are provided on the ISMIP 8km grid as in ISMIP7 (available on globus) and the same preprocessing routines as for ISMIP7 should be applied to obtain the forcing on the required model grid. In general, we anticipate that no transient calculations are required, and for each experiment, the diagnostic solution of the melt module is calculated. If the melt module has a time dependency, a steady state should be used.

5.3 Output format

Following the ISMIP7 standards, we ask for NetCDF files on a regular square ISMIP grid that contain the 2 spatial dimensional variables listed in Table 4. Results should be gridded to the ISMIP grid, on 32km, 16km, 8km, 4km, 2km, 1km resolution depending on the model resolution (the higher resolution the better for analyses).

We also ask modellers to fill in a standard sheet, with information about: model resolution, choice of module and implementation, calibration method and resulting parameters, basin-wide temperature corrections (per basins), information on grounding zone melt. Participants are also encouraged to put such information in the global attributes of their netcdf outputs.



Table 3. List of experiments for meltMIP. Note that the parameters should be kept the same in all experiments. * indicates priority experiments.

Experiment	Description	Values	Purpose	Experiments
BedMap_deltaT*	Calculate melt rates with BedMap v3 ice and seabed geometry and the ocean climatology, adding a uniform temperature perturbation ΔT	$\Delta T = 0, 0.5, 1, 2, 4^{\circ}\text{C}$	Testing the calibration: 1) For $\Delta T = 0$ we have “present-day melt rates” that can be compared to observations, 2) With the $\Delta T > 0$ experiments, we can calculate melt sensitivity	5
BedMap_deltaT_resoX	Same as BedMap_deltaT, but with changing the ice sheet model grid resolution by a factor X	$\Delta T = 0, 1^{\circ}\text{C}$ and $X = 0.5, 2$	Understand the robustness of melt rates and melt rate sensitivity in the melt module under changing ice sheet model resolution	4
Init_deltaT	Same as BedMap_deltaT, but with the modellers choice of initial geometry	$\Delta T = 0, 1^{\circ}\text{C}$	Test the influence of ice geometry used in the ice sheet model initialisation on melt rates and melt sensitivity	2
MISOMIP_deltaT	Same as BedMap_deltaT, but with retreated MISOMIP2 geometry (De Rydt et al., 2024)	$\Delta T = 0, 1^{\circ}\text{C}$	Investigate how melt modules handle large-scale grounding line retreat and geometry changes	2
BedMap_shoalX	Same as BedMap_deltaT but with thermocline shoaling by X metres instead of uniform temperature perturbations	$X = \pm 100\text{m}$	Investigate how melt modules handle shifts in the thermocline	4
BedMap_CMIPX	Same as BedMap_deltaT but with bias-corrected CMIP forcing averaged over years X	$X = 2079 - 2099, 2179 - 2199, 2279 - 2299$ for CESM2-WACCM-SSP5-8.5	Analyse how modules respond to more complex CMIP forcing without ice dynamics	3

645 **6 Discussion**

Here, we discuss the extrapolation and bias correction methods (Sec. 6.1 and 6.2), as well as the melt parameter calibration (Sec. 6.3). We then show an example of projected melt rates using the forcing and melt parameters developed for the protocol



Table 4. Requested outputs for meltMIP experiments.

variable (dimensions)	attribute name	attribute value
x (x)	long_name	“X-coordinate”
	units	“m”
	axis	“X”
	comment	common ISMIP grid
y (y)	long_name	“Y-coordinate”
	units	“m”
	axis	“Y”
	comment	common ISMIP grid
sftff (x,y)	long_name	“Floating Ice Shelf Area Fraction”
	units	“1”
	standard_name	“floating_ice_shelf_area_fraction”
	cell_methods	“area: mean over grid cell”
	comment	Fraction of grid cell covered by ice sheet flowing over seawater.
base (x,y)	long_name	“Ice base elevation”
	units	“m”
	standard_name	–
	cell_methods	“area: mean where land ice”
	comment	Differs from the mean ice shelf depth “depff” used in MISOMIP2 in the sense that “base” also averages the depth of the grounded ice base interpolated to the common grid
thdrff (x,y)	long_name	“Thermal forcing at the ice base under floating ice shelves”
	units	“K”
	standard_name	–
	cell_methods	“area: mean where ice shelf”
	comment	Thermal forcing extrapolated or calculated at the ice draft under floating ice shelves (_FillValue for purely grounded ice or not ice).
libmassbfl (x,y)	long_name	“Basal Specific Mass Balance Flux of Floating Ice Shelf”
	units	“kg m-2 s-1”
	standard_name	“land_ice_basal_specific_mass_balance_flux”
	cell_methods	“area: mean where ice shelf”
	comment	This is the net rate at which ice is added per unit area at the base of ice shelves; positive for ice mass gain (refreezing), negative for ice mass loss (melting).



(Sec. 6.4). Finally, we provide thoughts from the Southern Ocean perspective for ice sheet model initialisation (Sec. 6.5), and lessons learned and research that would benefit towards future ISMIP (Sec. 6.6).

650 6.1 Notes on ocean data extrapolation

The extrapolation described in Sect. 3.2 is a geometric procedure that diffuses ocean properties outward from existing valid points and therefore cannot represent the dynamical processes that control the three-dimensional structure of ocean conditions within ice-shelf cavities. The method does not differentiate between inflowing and outflowing water masses. In reality, Coriolis-driven boundary currents preferentially route warm water toward the grounding line on the western flank of an ice shelf (e.g., Nakayama et al., 2019). Furthermore, buoyancy-driven overturning couples the melt rate and cavity circulation in a geometry-dependent way (e.g., Holland and Jenkins, 1999), and tidal mixing significantly enhances turbulent heat exchange at the ice-ocean interface in many locations (e.g., Padman et al., 2018). Water masses also undergo substantial modification—through mixing and ice-ocean exchange—as they circulate from the ice-shelf front to the grounding line, so that properties valid at the ice-shelf front may not be representative of conditions near the grounding line. In addition, the Gaussian-weighted iterative scheme inherently smoothes sharp lateral gradients, which may misrepresent the steep temperature contrasts near the shelf break or ice-shelf front that control heat delivery into some cavities. We found that the extrapolation together with bias correction can produce vast regions of temperatures below the local freezing point in the historical forcing in presently cold cavities. To avoid this, the resulting negative thermal forcing values are capped at zero in the distributed products, which suppresses the representation of refreezing.

A more fundamental limitation concerns regions where ocean conditions may undergo a large-scale regime shift. The Filchner–Ronne Ice Shelf is the most prominent example: regional and global ocean model simulations suggest that future warming of the Weddell Sea could redirect coastal currents to deliver warm Circumpolar Deep Water beneath the ice shelf, replacing the cold and dense High Salinity Shelf Water currently present on the continental shelf and dominating the melting of the cavity (e.g., Hellmer et al., 2012; Timmermann and Goeller, 2017; Naughten et al., 2021; Haid et al., 2023). Similarly, Ross ice shelf cavity could shift from a currently cold into a warm state (Siahaan et al., 2022). In these simulations the switch can be self-reinforcing: enhanced basal melting exports fresh, buoyant water that alters shelf water-mass structure in a way that draws further warm-water intrusions into the cavity. These interactions cannot arise in most CMIP models, which lack ice-shelf cavities, with so far only one exception (UKESM, Siahaan et al., 2022).

6.2 Which bias-correction method to use?

Two non-default alternatives are currently supported for future exploration of bias correction of CMIP data: (i) a 2000–2024 option, motivated by denser observation coverage in the more recent period, and (ii) a summer climatology option, motivated by concerns that the climatology is mostly based on summer observations, and that an alternative bias-correction method could be based on the model-observation difference in summer. Both are implemented in the software package (Sect. 3.2.1). The default protocol choice is nonetheless annual and 1995–2024, and a correction based on the summer climatology will require further testing.



The bias correction method applied in this protocol follows the ISMIP6 approach (Jourdain et al., 2020): the correction is a function of the (x, y, z) position, which ensures that all corrected CMIP models have the observed mean temperature and salinity over 1995–2024 at every grid point. At an early stage of the preparation of this protocol, we had the ambition to improve this method in a way to better respect the model’s initial water masses and stratification. However, we did not manage to provide evidence for a better method in the time frame of ISMIP7. We nonetheless initiated some investigations that we report here.

We considered four correction methods: (1) no correction, (2) correction in the (x, y, z) space (ISMIP6 protocol Jourdain et al., 2020), (3) correction in the (T, S) space (Naughten et al., 2023), and (4) a correction method based on cumulative distribution functions of temperature and salinity (Verjans et al., 2023). Methods 2 to 4 generally do what they are designed for, i.e., correcting the present-day CMIP simulations to a state close to observations, although methods 3 and 4 are sensitive to the sectors used to calculate the corrections (applying them at the scale of Antarctica is not optimal).

Then, we used a perfect-model approach, in which we assume that CMIP model A is a virtual reality from 1850 to 2300, and we bias correct CMIP model B towards the 1995–2024 mean of model A. This allows evaluating corrected model B until 2300 in comparison to model A. The interpretation of this comparison was a matter of debate among the co-authors: on the one hand, model A has a future that is consistent with the primitive equations of physics and is therefore an informative virtual reality and a good comparison target in a much warmer world (2300 under SSP5-8.5 in our case); on the other hand, every model has its own parameterisations and numerical methods, leading to a broad range of climate sensitivity and making the comparison of little use. We therefore did not attempt to rank the correction methods, but found that the three corrections gave similar amplitude in future thermal forcing bias near the ice sheet margins. Interestingly, using no correction often gave better results in a much warmer world than using any correction. This kind of model convergence suggests that uncorrected CMIP models can be trusted for their representation of the physical equations, but starting the ISMIP7 ice sheet simulations with significantly biased ice shelf melt rates was not an acceptable option.

6.3 Lessons from the melt module parameter calibration

In order to improve the selection of parameters in melt parameterisations, we suggest using as many available datasets from observations and numerical ocean circulation models as possible. Importantly, uncertainties and biases in these datasets will influence the parameter optimisation. Using this wide range of datasets and constraints, we were not only able to estimate parameter values, but also to better understand the strength and weaknesses of the selected parameters. The approach is formulated in a general way that allows new datasets to be included in the future. Furthermore, focus on specific regions or datasets can be set.

We tested the quadratic local melt parameterisation in Sect. 4.3.1 and found that optimised parameters compare with the ‘MeanAnt’ values from ISMIP6. We further tried focusing on the Amundsen Sea, Sect. 4.3.2, which yields higher parameter values, however still lower compared to the ‘PIGL’ values from ISMIP6, consistent with ocean modelling results (Jourdain et al., 2022). The median value for the heat exchange parameter K (8.5×10^{-5}) is lower than the one obtained by Burgard et al. (2022) (11.6×10^{-5}) but higher than the ones obtained by Burgard et al. (2025) ($K_{\text{small}} = 4.7 \times 10^{-5}$ and $K_{\text{large}} = 1.1 \times 10^{-5}$),



715 showing that calibration is difficult and strongly depends on the calibration target and datasets. Since we obtain different
 parameter values for both, the whole of the Antarctic continent and the Amundsen Sea, this indicates that melt parameterisations
 such as the quadratic are too simple to capture all circumstances and conditions we tested for with one set of parameters. This
 is further supported by investigating the individual target terms: while melt rate projections compared to Mathiot and Jourdain
 (2023) were overestimated, variability in Pine Island Glacier ice shelf was underestimated in comparison to observations
 720 (Joughin et al., 2021). Hence, we suggest that modellers consider the specific application of their melt module, e.g., ISMIP7
 projections, and then use the provided datasets and the toolbox in a way that best allows them to constrain the parameter values
 for that specific application.

We further tested the PICO model, and found, similarly, that parameters depend on the chosen application / constraints.
 Focusing on Filchner-Ronne and the Amundsen Sea melt sensitivities, we can reproduce previous tuning for PICO from
 725 Reese et al. (2023), while overall Antarctic-wide optimal parameters are more in line with the previous estimate by Reese
 et al. (2018a). Different estimates from Burgard et al. (2022, $C = 17.8 \times 10^6$, $\gamma_T^* = 0.4 \times 10^{-5}$), Burgard et al. (2025, $C =$
 2.9×10^6 , $\gamma_T^* = 0.88 \times 10^{-5}$), or Menthon et al. (2025, $C = 0.1 \times 10^6$, $\gamma_T^* = 2.0 \times 10^{-5}$) are also within the range of possible
 values.

In the calibration of LADDIE, total melting in all 16 regions could be well reproduced. A slight underestimation is found in
 730 the lowest buttressing class, which is likely related to the lack of mode 3 melting near the calving front. For practical reasons,
 we chose to only tune the top drag coefficient $C_{d,top}$. Including the tuning of the minimum layer thickness H_{min} , following
 Lambert et al. (2023) could lead to a slightly better match in the highest buttressing class. Finally, we found that the median
 $C_{d,top}$ 0.9×10^{-3} is slightly lower than the value 1.1×10^{-3} as found by Lambert et al. (2026). This may be the result
 of the more elaborate calibration protocol presented in this study. Additionally, the discrepancy may stem from the different
 735 resolutions, where Lambert et al. (2026) configured LADDIE at considerably higher resolution for a single simulation. Taking
 these calibration approaches together, a relatively robust value of $C_{d,top}$ of approximately 1×10^{-3} appears to be widely
 applicable. Specifically for Filchner–Ronne, we know that a better reproduction of observed melt rates requires enhanced tidal
 velocities. Modelling groups using a melt module which explicitly includes the 3 equations parameterisation would benefit
 from the inclusion of tidal velocities in the forcing (Jourdain et al., 2019).

740 Note that to keep simulation time minimal, we generated two states from ocean modelling data - one ‘cold’ and one ‘warm’.
 Substantially more data is available, and could be used in future calibrations, e.g., also exploring transient responses, inter-
 mediate warming, and time lag between changes of continental shelf conditions and cavity conditions. Also, the ocean model
 simulations selected employ no or very minimal changes to the ice sheet geometry. Geometry changes and feedbacks between
 ice and ocean have been shown to influence the melt rates (De Rydt and Naughten, 2024; Reese et al., 2026), and future cali-
 745 bration could account for that. With the meltMIP, see Sect. 5, we aim to deepen the understanding of melt modules and their
 parameter influence on ISMIP projections also under cavity geometry changes.

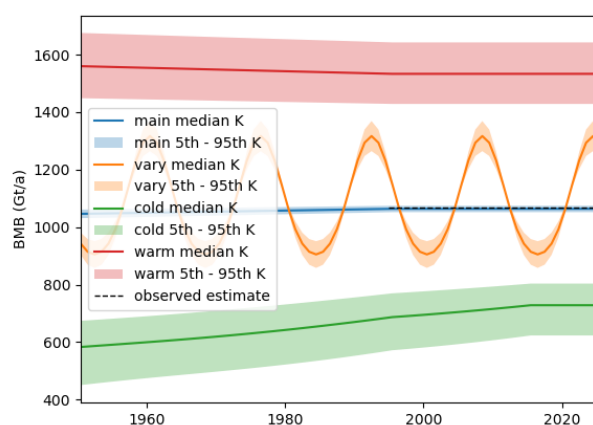


Figure 15. Melt rates for the contemporary forcing calculated with the local quadratic melt parameterisation with parameter values K identified in Sect. 4.3.1.

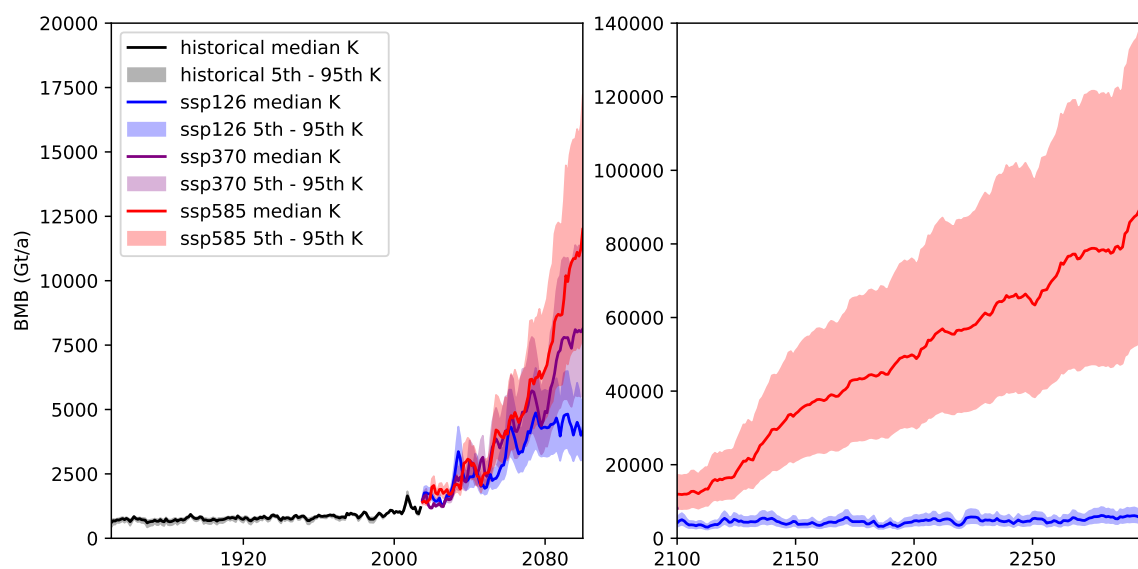


Figure 16. Melt rates calculated using the SSP5.85 CESM WACCM forcing with the local quadratic melt parameterisation and parameter values K identified in Sect. 4.3.1.



6.4 Examples of contemporary and projected melt rates with static ice sheet

We test the parameter values optimised for the quadratic local parameterisation for the datasets created in Sect. 3 assuming a constant ice sheet geometry. Figure 15 shows contemporary melt rate evolution for the four scenarios discussed in Sect. 3.4. These are obtained using the median K for the quadratic local parameterisation, applying the delta T corrections. By construction, values are broadly in agreement with present-day melt rate estimates for the main pathway, are overestimated for the ‘warm’ pathway and underestimated for the ‘cold’ pathways (Paolo et al., 2023; Davison et al., 2023). The ‘varying’ pathway shows melt rates - integrated for the entire Antarctic ice sheet - in the range of observations. Figure 16 shows melt rate projections for CESM-WACCM scenarios. Historically, melt rates do not change much, they start to increase around 2000, with further increases in the future scenarios. Melt rates start to diverge for the different SSP scenarios by the mid of the century, until they reach in 2100 between 3000Gt/yr for the lower range of SSP126 to 17,000Gt/yr for the upper range of SSP585. Note that in dynamical projections with ice sheet models, ice shelf thinning, calving front retreat and ice shelf collapse will mean that projected melt rates might not reach such high values (Seroussi et al., 2024).

6.5 Comments on the ocean conditions for ice sheet initialisations before 1950

There are multiple lines of evidence that warm ocean anomalies triggered ice sheet changes one or two decades before 1950 in the Amundsen Sea (Steig et al., 2012; Hillenbrand et al., 2017; Smith et al., 2017; O’Connor et al., 2023; Clark et al., 2024, and references therein) and in front of the Totten ice shelf (Miles et al., 2025). What happened between the pre-industrial era and the mid-20th century remains unknown and a matter of debate. On the one hand, Caillet et al. (2023) produced simulations suggesting that a pre-industrial climate would give buoyancy fluxes at the surface of the Amundsen Sea that could lead to cold ice-shelf cavities. This was somehow supported by O’Connor et al. (2025) who demonstrated that lower surface buoyancy forcing would lead to cold ice-shelf cavities in the Amundsen Sea. However, there are not enough observations to robustly constrain realistic simulations back to the 19th or early 20th century. There is no consensus on the state of the Amundsen Sea prior to 1940s, and it is unclear whether the current glacial landscape of the Amundsen Sea embayment, which has not varied much in the last centuries according to paleo proxies, is compatible with cold ocean conditions throughout the Amundsen Sea.

In any case, if an ice-sheet modelling approach requires starting from a steady state, we do not recommend reaching such a steady state with constant 1950 forcing. Instead, we recommend either (i) extending the temperature trends discussed for the Amundsen Sea and Aurora basin back to 1900 or 1850, ideally with a warm mid-20th century anomaly to trigger the 1940s retreat, or (ii) using a bias-corrected CMIP simulation in pre-industrial conditions. Finding the exact way to do so is considered as a matter of research for individual modelling groups.

6.6 Lessons learned and outlook towards ISMIP8

We here discuss lessons learned during development of the ISMIP7 Antarctic ice-ocean protocol and then provide an outlook towards ISMIP8, in the hope to inspire new research directions and developments by the wider community.



Continued monitoring and reconstruction of the Antarctic continental shelf seas and ice shelf cavity conditions is essential to reduce uncertainties in the calibration of melt modules and ocean dynamical simulations. One specific problem we face is that there is no reliable re-analysis or reconstruction of Antarctic continental shelf conditions since the 1950s that could be proposed for the OCX ‘contemporary’ experiments, largely due to a historical lack of observations in the region. The pathways we propose represent an envelope of possible conditions based on existing knowledge that can be used to constrain ice sheet model responses to forcing over that period, but by no means represents the real evolution.

Furthermore, a continued and improved dataset from observations of sub-shelf melt rates obtained by remote sensing methods (e.g., Adusumilli et al., 2020; Paolo et al., 2023; Davison et al., 2023), and validated by in-situ observations (e.g., Vaňková et al., 2021) is essential for improved calibration of melt modules/ocean models. At present, observational estimates of melt rates show a wide spread, see Sect. A8, and better uncertainty estimates are required. Time-dependent melt rate estimates from satellite observations need to be corrected for variability in surface mass balance, which poses challenges as surface mass balance in Antarctic undergoes high spatial and temporal variability. Estimating melt rates close to and within the grounding zone - where ice thickness changes are highly relevant for ice dynamics - is particularly problematic due to the flotation assumption being invalid (Elgart et al., 2026). Around the grounding line ocean models particularly struggle to represent melt rates due to the vertical water column thickness reducing (Gwyther et al., 2020; Galton-Fenzi et al., 2025). At the same time, melting in grounding zones can have substantial impact on ice sheet projections (e.g., Wang et al., 2024).

Testing our new calibration protocol for melt parameterisations, we found that simple parameterisations cannot satisfy all requirements. This means that there is no "perfect" set of parameters and that, at present, we suggest that parameters are selected with a given application in mind - e.g., future projections, specific regions etc. Using meltMIP, we aim to better understand the impact of model resolution, implementation, initial state, geometric changes on the melt rates and melt rate sensitivity to ocean temperature changes. Together with the meltMIP results, ocean dynamical modelling studies can also inform future development and testing of computationally affordable melt modules (e.g., Holland et al., 2026). This knowledge could fuel new development of the melt parameterisations to include relevant physical processes. At the same time, it could allow for the benchmarking of melt emulators that are generated using machine learning (e.g., Rosier et al., 2023; Burgard et al., 2023).

Forcing in ISMIP7 is provided as potential temperature and practical salinity, and derived thermal forcing. Future melt parameterisations would ideally update to using the new standards of conservative temperature and absolute salinity (McDougall, 2025). Additionally, recent research (e.g., Jesse et al., 2026) illustrates the importance of subglacial discharge on basal melt patterns, and shows the possibility to incorporate this into LADDIE. Pelle et al. (2023) incorporated subglacial discharge in PICOP and assessed the impact on glacier retreat. Further advancing this capability to other melt modules, and including subglacial discharge as a forcing field may lead to more accurate melting near grounding lines.

A key lesson learned from ISMIP7 is that reducing biases in the simulated Southern Ocean state should be a high priority for future CMIP efforts. In ISMIP7, we found that bias correction of CMIP data was still necessary, similar to ISMIP6. While temperature biases of a few degrees Celsius may be considered acceptable in many global climate modeling applications, they represent a substantial error for the polar ocean, where relatively small temperature changes can lead to large differences in ice-shelf basal melt rates and, consequently, ice-sheet evolution. From an ice-sheet perspective, accurately representing the present-



day ocean state is therefore essential for producing reliable projections. Future model development would ideally place greater emphasis on improving the representation of the Southern Ocean, particularly on the Antarctic continental shelves, through systematic evaluation against available ocean observations and targeted efforts to achieve realistic present-day hydrography and circulation by increasing the resolution on the continental shelf and including more processes linked to the ice sheet (e.g. ice-shelf melt, icebergs, ...). Until this is achieved, bias correction is required. Different bias correction methods have been proposed (Jourdain et al., 2020; Naughten et al., 2022; Verjans et al., 2023), and an initial assessment did not identify any of those as superior. Future work could advise on the optimal bias correction method(s), especially including the transient evolution of biases.

Due to the size of the datasets processed, we decided to keep forcing data annual, similar as in ISMIP7. However, short-term variability in the ocean can drive higher melt due to the non-linear dependency of melt on ocean temperatures. Future approaches could explore monthly forcing data or adding a compensating term to the melt module.

Another challenge in application of CMIP data to force the Antarctic Ice Sheet is the lack of representation of ice-shelf cavities in most CMIP models. In ISMIP7, we rely on extrapolating open-ocean properties beneath ice shelves, which cannot - for example - represent the regime shift in cavity conditions found in regional studies (Hellmer et al., 2012; Timmermann and Hellmer, 2013; Naughten et al., 2021; Caillet et al., 2023). Towards ISMIP8, more CMIP models will include static cavities, or even coupled ice sheets, and represent such regime shifts. Indeed, a coupled ice sheet has recently been developed in the UKESM model (Siahaan et al., 2022), while at least two other CMIP-class models have static cavities (Song et al., 2025; Comeau et al., 2022). Potentially, different approaches can be developed for those models and models that do not include cavities. For those models where developing open cavities is not realistic to achieve, it would be beneficial to build on the understanding of the conditions driving a regime shift (e.g., Haid et al., 2023), and apply this knowledge in the melt modules using, for example, approaches similar to a recent one developed for a simple box model (Saddier et al., 2026).

Moreover, CMIP models with static cavities would not represent two-way feedbacks between an evolving cavity geometry and ocean circulation: as ice shelves thin and grounding lines retreat, the changing cavity shape reshapes the circulation that sets melt, which in turn drives further geometry change (e.g., De Rydt and Naughten, 2024). Analyses of a regime shift in Filchner-Ronne in coupled and static-cavity simulations show that while inflow ocean conditions are similar in both cases, melt rates diverge due to the change in cavity geometry: while Timmermann and Goeller (2017) report an increase in melt rates, Reese et al. (2026) find that melt rates halve due to the geometric changes. If melt modules can represent those changes correctly - to be tested with meltMIP - projections with melt modules might be able to capture such geometric effects sufficiently well.

Looking ahead to ISMIP8, we expect coupled ice-sheet–ocean modelling to become increasingly important, since it represents the two-way feedbacks between melting, cavity circulation, and shelf-sea conditions. Projects such as MISOMIP2 (De Rydt et al., 2024) will greatly advance understanding of coupled and standalone modelling. At the same time, fully coupled simulations that resolve sub-shelf melt at adequate resolution are likely to remain too expensive for the large ensembles and multi-century projections done in the ISMIP framework. A central development we see for ISMIP8 is therefore not to replace parameterised forcing with coupling completely, but to use coupled and high-resolution ocean modelling strategically —



for key projections, to build process understanding, to generate training and benchmarking data, and to test the computationally cheaper melt modules and CMIP forcing processing.

None of these directions can be carried by ISMIP alone. While the focus group assembles a protocol that is robust and applicable across the range of ISMIP ice-sheet models based on the state of knowledge at the time, the work required to answer the questions and challenges above — coupling-informed ocean forcing, improved melt modules, continued observations, development of physical understanding — can only be achieved by engagement of the whole community.

7 Conclusions

We here describe the Antarctic CMIP ocean data processing and a protocol for application of melt modules in standalone ice sheet simulations in ISMIP7. We introduce an expert-based envelope of the potential evolution of Antarctic ocean conditions between 1950 and 2025. Importantly, this is not a representation of the actual oceanic changes, but a guidance that is helpful for modellers to investigate ice sheet model response to a range of plausible changes in the Southern Ocean. We introduce a new way to constrain melt module parameters by oceanographic knowledge - in situ observations, satellite-derived products, ocean circulation simulations, and exemplify its use for the quadratic, PICO and LADDIE modules. Due to the simplicity of the melt modules, we suggest using the toolbox to identify optimal parameters depending on the choice of application. Finally, we introduce the protocol for the melt Module Intercomparison Project that aims to investigate systematically the influence of choices in the melt module on simulated melt rates. We summarise relevant developments that would be beneficial towards ISMIP8 and that hopefully inspire research in the entire community.

Code availability. Code is available through <https://github.com/ismip/ismip7-antarctic-ocean-forcing.git>

Data availability. All data is available via the globus endpoint of ISMIP7.

Appendix A: Datasets

A1 ISMIP7 Antarctic polar stereographic ocean grid

As in ISMIP6, all forcing fields are distributed on a common Antarctic polar stereographic grid (EPSG:3031) to ensure direct interoperability across ice-sheet models. The reference domain spans 6080 km by 6080 km, with x and y coordinates from -3040 km to +3040 km. For the standard ISMIP7 ocean-forcing fields, the horizontal resolution is 8 km and the standard vertical spacing is 60 m over 30 vertical levels. This common grid definition is used for all final distributed forcing fields.



A2 Ice drainage basins and their ocean extension

The basin masks used in ISMIP7, for example for guiding the extrapolation of ocean data into ice shelf cavities and also for defining the optimisation targets to select the melt parameters for the model modules, are based on the IMBIE2 Antarctic drainage basins (Mouginot et al., 2017; Shepherd et al., 2018), with the same 16-basin partition used in ISMIP6-compatible analyses (the two Ross basins are merged as well as Ronne and Filchner). Basin polygons are rasterized to the ISMIP grid and then extended beyond the coastline into the ocean domain to cope with any possible ice sheet extent in the ice-sheet simulations. The ocean extension is performed with a shelf-constrained method. The continental shelf break is defined by the longest contiguous contour following the 1,500 m isobath (avoiding islands and deep wells that also produce contours at this depth). Basin boundaries are propagated from the coastline to the closest point on the continental shelf break, and basin labels are filled between these boundaries. Then, the basin labels are extended into deeper ocean areas based on the nearest distance to the basin labels in the interior and on the continental shelf. This provides complete basin coverage for extrapolation and basin-aggregated diagnostics while minimizing artificial cross-shelf basin leakage. The basins are plotted as outlines in Fig. A1.

A3 Antarctic topography products

Topography and masks are provided on the ISMIP grid and include bed elevation, ice draft, surface elevation, thickness, and fractional masks for ocean, grounded ice, floating ice and rock, remapped from Bedmap3 (Pritchard et al., 2025). These fields are used both to define extrapolation pathways and to support diagnostics needed by melt modules. The *i7aof* software package currently supports Bedmap3 (Pritchard et al., 2025) as the default Antarctic topography source, with support for BedMachine Antarctica v3 (Morlighem, 2022) also available.

A4 Present-day climatology of the Southern Ocean

Please see Section 3.1.

A5 Contemporary forcing of the Southern Ocean

Please see Section 3.4.

A6 CMIP forcing of the Southern Ocean

See Nowicki et al. (2026) for details on each supported CMIP model, variant and scenario used in the ISMIP7 protocol. The CMIP forcing input consists of monthly ocean potential temperature and salinity from selected CMIP models and scenarios (historical and future). Each model is processed through a common pipeline (Sect. 3.2) to produce Antarctic forcing fields. The distributed forcing fields include annual potential temperature (t_{etao}), practical salinity (s_o) and thermal forcing (t_f) fields for each model-scenario combination. Note that the processed CMIP dataset can be used directly by models without computing

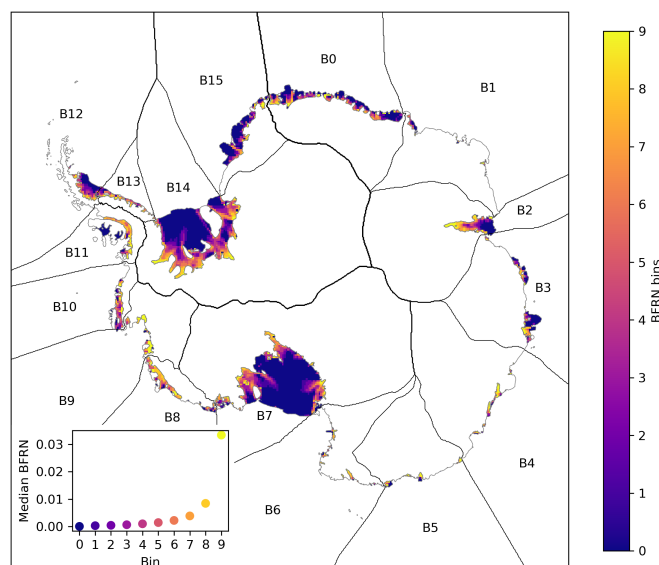


Figure A1. Antarctic ice-shelf grid points are classified into 10 categories of increasing buttressing strength. The potential impact of melting on buttressing is determined using the Buttressing Flux Response Number (BFRN) from Reese et al. (2018b). Inset shows median BFRN value per bin. Contours and B numbers show the IMBIE2 basins.

anomalies or selecting reference observations. If modeling groups need to compute anomalies, they should be computed with respect to the same 1995-2024 period used for the bias correction.

A7 Buttressing-relevant regions of Antarctic ice shelves

We aim to give more importance to melt rates in regions that affect the ice sheet dynamics by employing the Buttressing Flux Response Number (BFRN) from Reese et al. (2018b), which indicates how much local ice shelf melting affects the grounded ice-sheet dynamics through modifying buttressing. Since spatial melt rate patterns have a lot of uncertainty, we follow the approach of Menthon et al. (2025) and bin ice shelves into different regions and compare aggregated melt rates in each bin. In contrast to Menthon et al. (2025), we do not create equally-sized bins of grid-cell melt rates, but create equally-sized bins depending on the grid cell's buttressing values (Fig. A1). Note that we generate 9 bins (1-9), and add afterwards a bin 0 containing all grid cells which are 'passive', i.e., they have negligible buttressing values as defined in Reese et al. (2018b). For each region, we calculate the median BFRN that we will use as a weight for the importance of the bin later on. BFRN from Reese et al. (2018b) are remapped to the ISMIP8km grid for the processing.

A8 Melt rate observations of Antarctic ice shelves

We use the melt rate product from Paolo et al. (2023), Davison et al. (2023), and Adusumilli et al. (2020), corresponding to averages over the periods 1992–2017, 1997–2020, and 2010–2018. Following a similar reasoning to the ocean climatology, we

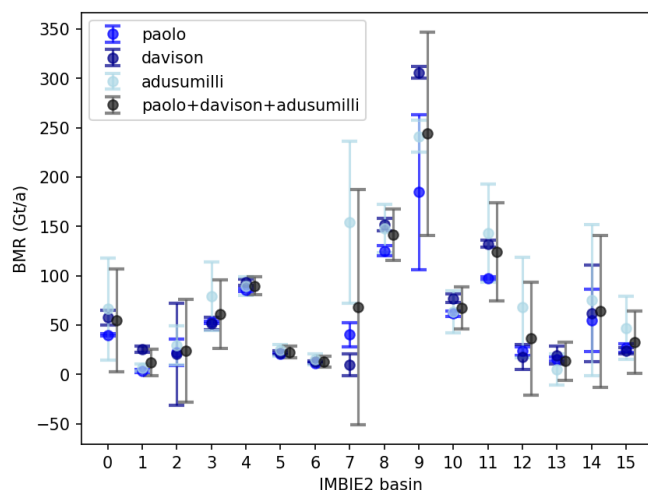


Figure A2. Integrated melt rate targets with uncertainties for the IMBIE2 basins.

decide it is best to use all available data rather than adjusting for the same time period, and reference the observations to the time period of the climatology. From the datasets, we calculate integrated melt rates over the IMBIE2 basins, see Sect. A2, and over buttressing bins, see Sect. A7.

For integrated melt rates over the IMBIE2 basins, we make use of the corresponding shelf wide melt rates provided in each publication, matching ice shelves using lat/lon coordinates to the IMBIE2 basins. Note that for the dataset by Paolo et al. (2023), we remove the melt rates attributed to the part of Thwaites that recently calved and account for this in the uncertainty of Thwaites. No specific estimate for the ice shelf region is given in Davison et al. (2023) or Adusumilli et al. (2020). As target melt rates in each basin, we use the basin-integrated melt rate averaged over the three products. Since uncertainty estimates in the datasets are smaller than differences between the datasets, we expand the uncertainty ranges to span from the highest basin-integrated melt with added uncertainty range to the lowest basin-integrated melt with subtracted corresponding uncertainty and center this around the estimated average melt rate, see Fig. A2.

For estimating melt rates aggregated over regions of equal buttressing importance, see Sect. A7, we use spatial melt rate products from all three sources, regridded to the 8km ISMIP grid. We extrapolate melt rates bilinearly into regions where data is missing, and then integrate over each buttressing bin. We combine uncertainties assuming them to be uncorrelated (which yields larger uncertainty than assuming correlated errors, but still smaller than the difference between datasets). We calculate the mean and uncertainty in the same way as the basin estimate, see Fig. A3.

A9 Ocean modelling data

For the melt module calibration, and in particular the J_3 term, we have processed a number of published ocean simulations that simulates the ocean circulation under ice shelves and include both a cold and a warm state. Note that with ‘cold’ and ‘warm’

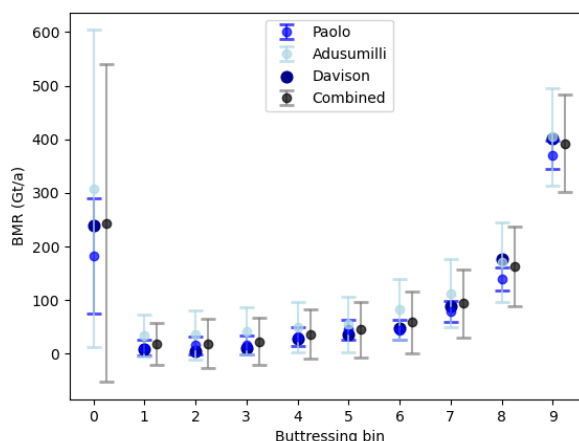


Figure A3. Integrated melt rate targets with uncertainties for the regions of equal buttressing importance.

we refer to relative conditions: the ‘cold’ Amundsen Sea may correspond to current conditions which are not ‘cold’ in the sense of the cavity being dominated by Ice Shelf water close to the surface freezing point, but these conditions are comparably colder than in the corresponding ‘warm’ state, which is usually modelled under strong greenhouse gas emissions. For the warm state, we select the warmest, which is usually the latest period, of the simulations. The gridded products provided for ISMIP7 are listed in Table 2, and here we provide more details on the original simulations and on how these cold and warm states were obtained.

The general approach is that the ocean model outputs (temperature, salinity, ice-shelf melt rate) were remapped onto the 8-km ISMIP grid, without considering temperature and salinity within cavities, in a way to mimic the CMIP model data that generally do not resolve ice shelf cavities. The cold and warm states were usually obtained by averaging 20 years, either over a 20-year period or over multiple ensemble members. Then, we proceed to the extrapolation to the entire space using the methods described in Sect. 3.2.

The regridded outputs include the standard deviation of all processed fields, which is calculated over the ensemble used for the mean, with the idea that the uncertainty will be calculated from the standard deviation σ of the modelled melt in the corresponding period normalised by the square root of the length of the period, i.e., $\sigma/\sqrt{a}$ with a being the number of years (usually, $a = 20$).

The various processed files are as follows:

- **Mathiot_NEMO** contains circum-Antarctic data from simulations carried out with the NEMO-4.0 model at 0.25° resolution (Mathiot and Jourdain, 2023). The cold state is averaged over 1999–2018, forced by an atmospheric reanalysis. The warm state is averaged from year 81 to 100 after the applied perturbation, which corresponds to an atmospheric



forcing anomaly corresponding to the end of the 23rd century simulated by the IPSL-CM6A-LR climate model under the SSP5-8.5 scenario used in CMIP6. In the warm state, Circumpolar Deep Water penetrates in all ice shelf cavities.

– **Naughten_FESOM_ACCESS** contains circum-Antarctic data from a simulation carried out with the FESOM model using an unstructured grid of 3 to 6 km resolution on the Antarctic continental shelf (Naughten et al., 2018). The ocean simulation is forced by the ACCESS-1.0 climate model under the RCP8.5 scenario used in CMIP5. The cold state is calculated over 2006–2025 and the warm state over 2081–2100.

– **Naughten_FESOM_MMM** is similar to Naughten_FESOM_ACCESS, except that the simulation is forced by the multi-model mean (MMM) of 19 CMIP5 models, all under the RCP8.5 scenario. In this simulation and in the one forced by ACCESS-1.0, temperatures in the deep Amundsen Sea are near the surface freezing point in the cold state and they increase by no more than 2°C in the warm state.

– **Timmermann_FESOM** contains circum-Antarctic data from simulations carried out with the coupled FESOM-RIMBAY model using an unstructured grid of down to 1 km resolution in the Filchner-Ronne cavity (Timmermann and Goeller, 2017). The ocean simulation is forced by the HadCM3 climate model under the 20C and A1B scenarios used in CMIP3. The cold state corresponds to the 1979–1999 average while the warm state corresponds to 2179–2199. In these simulations, the melt rates beneath Filchner-Ronne Ice Shelf strongly increase after 2050. The simulations also cover the effect of a thinning ice shelf and FRIS grounding line retreat.

– **Haid_FESOM** contains circum-Antarctic data from a simulation carried out with the FESOM-v1.4 model using an unstructured grid ~4 km resolution near the ice sheet margins and analysed for regime shifts in the Weddell Sea (Haid et al., 2023). The cold state corresponds to 1998–2017 forced by an atmospheric reanalysis (using cycle 4). The warm state results from an atmospheric forcing anomaly corresponding to 2070–2089 simulated by the HadCM3 climate model under the A1B scenario used in CMIP3 (SA_G exp., using cycle 4 Haid et al., 2023).

– **Jourdain-Naughten_NEMO-MITgcm** is a mix of two sets of regional ocean simulations. The first set represents an ensemble of three simulations of the Bellingshausen and Amundsen seas, all from the NEMO-3.6 model at 1/12° resolution, but with different model parameters and bathymetry (Jourdain et al., 2022). The cold state corresponds to 1989–1999 in simulations forced by an atmospheric reanalysis through a regional atmospheric model and, laterally, by a global ocean hindcast. In the warm state, representative of 2080–2100, an climatic anomaly is added to the forcing of the regional atmospheric model and to the lateral boundaries, corresponding the multi-model mean of 33 CMIP5 models under the RCP8.5 scenario. The second set is a single regional simulation of the Weddell Sea from the MITgcm model at 0.25° resolution (Naughten et al., 2021). It is forced by the atmosphere and global ocean of the UKESM1-0-LL model under the 1pctCO2 scenario (+1% in CO2 concentration every year since 1850). The cold state corresponds to 1850–1869 and the warm state to 2030–2049. The NEMO and MITgcm regional domains cover almost entirely 3 and 4 basins, respectively (Table 2), and the remaining basins are filled with the ISMIP7 ocean climatology and zero melt rates for both the warm and the cold states.

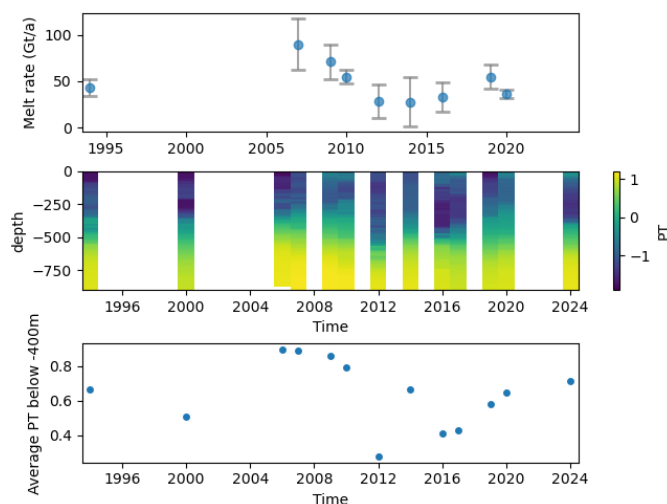


Figure A4. Observational data used to constrain Pine Island Glacier Ice Shelf melt rates.

- **Naughten_MITamu-MITwed** is again a mix of two sets of regional ocean simulations. The first set represents an ensemble of ten simulations of the Bellingshausen and Amundsen seas, all from the MITgcm model at $1/10^\circ$ resolution (Naughten et al., 2023). It is forced by the atmosphere and global ocean of the CESM1 climate model under the RCP8.5 scenario. The cold state corresponds to the average of ten occurrences of 2006 and 2007, and we proceed similarly for the warm state with 2099 and 2100. The second set is a single regional simulation of the Weddell Sea from the MITgcm model at 0.25° resolution (Naughten et al., 2021). It is forced by the atmosphere and global ocean of the UKESM1-0-LL model under the abrupt-4xCO₂ scenario (abrupt transition to 4 times pre-industrial CO₂ concentrations from 1850). The cold state corresponds to 1850–1869 and the warm state to 2030–2049. The two regional domains cover almost entirely a total of 7 basins (Table 2), and the remaining ones are filled with the ISMIP7 ocean climatology and zero melt rates for both the warm and the cold states.

A10 Near-ice-shelf ocean observational data

Temperature, salinity and dissolved oxygen profiles were measured for several years along the front of Pine Island (Dutrieux et al., 2014), Dotson (Jenkins et al., 2018) and some parts of Getz (Jacobs et al., 2013) ice shelves. Ocean density profiles can be estimated from these measurements, from which the main ocean circulation in and out of the cavities can be deduced assuming geostrophy and some estimate of the absolute flow. Combined with the estimation of the meltwater fraction from the three measured quantities, this can be used to estimate the mean melt rate of a cavity, see Figs. A4 and A5. Such interannual melt rate estimates are independent from the remote-sensing estimates and are therefore highly valuable for constraining the melt sensitivity in ISMIP7.

In ISMIP7, we mainly include the estimates for Pine Island Ice Shelf. Getz is a complex cavity with multiple ice fronts and less observations than for the two other ice shelves. Dotson has been monitored for several years, but recent seismic data have

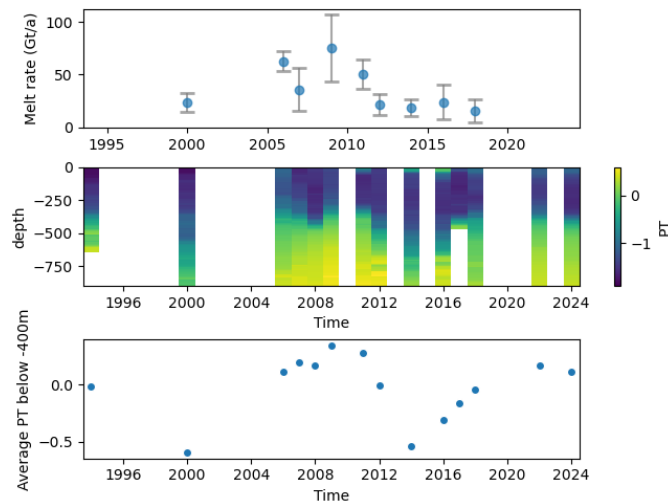


Figure A5. Observational data used to constrain Dotson Ice Shelf melt rates.

confirmed the presence of a sub-ice ocean connection between Dotson and Crosson ice shelves (Jordan et al., 2026), which raises questions about the validity of the observational meltwater budgets, and means it is unclear what ice-shelf region would be used in the observation-model comparison.

1010 For every year with observations, we take the average temperature and salinity profile and apply it uniformly to the entire Amundsen basin. Several years are available (Joughin et al., 2021). To reduce the computational requirements on modellers, we suggest minimally using the data for Pine Island Glacier in 2009 as a representation of a warm year and in 2012 as a representation of a cold year.

1015 *Author contributions.* RR and NCJ led the Antarctic ice ocean focus of ISMIP7 with the aim to develop the protocol. XAD acts as active member and steering committee link of the focus group. CB and EL contributed through active development within the focus group, YN and PH through feedback, discussions and bouncing off ideas. XAD developed the python package, based on an extrapolation routine by NCJ. RR developed the toolbox, with support by CB and EL. All members of the focus group supported writing of the manuscript led by RR. KN,RT,PD,SZ provided datasets essential for the protocol. GT and YT processed data for the manuscript.

Competing interests. NCJ is editor of TC. The authors declare no other competing interests.

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