



Comparison of calibration methods of a PICO basal ice shelf melt module implemented in the GRISLI v2.0 ice sheet model

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Abstract. Future sea level rise uncertainties are mainly due to uncertainties in Antarctic ice sheet projections. Indeed, modelling the future of the Antarctic ice sheet presents many challenges. One of them is being able to model the physical interactions between the ocean and the ice shelves. As a result of limited understanding of these ice-ocean interactions and limited computational resources, these interactions are parametrized rather than explicitly resolved in most ice sheet models. These parameterisations vary in complexity and calibration method, eventually leading to differences in resulting sea level rise contribution of several meters. Here we present the implementation of the PICO basal ice shelf melt module in the GRISLI v2.0 ice sheet model. We compare six different statistical methods to calibrate PICO and assess how robust these methods are if applied at different resolutions and areas of the Antarctic ice sheet. We show that computing the Mean Absolute Error of the bins is the best method as it allows us to match the entire distribution of melt rates retrieved from satellite data at different resolutions as well as for different Antarctic ice shelves. It also results in a smaller parameter space than the other tested methods. This method makes use of melt rate bins and minimizes the differences between the values of the bins of the model and the ones of the observational target. We find that, using this method, region-specific calibration of ice-ocean interactions is not needed and we can avoid using ocean temperature bias corrections. Finally, we assess the impact of the implementation of PICO in GRISLI and of the calibration choice on future projections of the Antarctic ice sheet up to the year 2300.

1 Introduction

The future evolution of the Antarctic ice sheet is the largest uncertainty in sea level rise projections for the end of the century (Edwards et al., 2021). The mass loss of the Antarctic ice sheet is primarily driven by basal melting of ice shelves (Pritchard et al., 2012). The ice shelves have a buttressing effect, slowing the ice flow towards the ocean (Dupont and Alley, 2005). Their thinning observed over the last decades (Rignot et al., 2013; Paolo et al., 2015; Adusumilli et al., 2020) is due to increased warmth provided by circumpolar deep water in the cavities directly beneath the ice shelves (Schmidtke et al., 2014; Stewart and



Thompson, 2015; Jenkins et al., 2018). Sub-surface melt of the ice shelves on the other hand, impacts the oceanic circulation in the ice cavities as well as larger scale oceanic circulation (Bennetts et al., 2024). These feedbacks and the large range of spatio-temporal scales at play, from turbulence to large-scale ocean circulation, make the ice-ocean interaction a complex process challenging to model accurately (Bennetts et al., 2024). Additionally, on a retrograde bathymetry, such as in West Antarctica, the thinning of ice shelves and retreat of the grounding line can trigger marine ice sheet instabilities (Weertman, 1974; Schoof, 2007) leading to irreversible commitment to sea level rise. Hence, understanding and having the ability to model the ocean-ice interaction accurately is crucial to constrain uncertainties of projections of the future rise in sea level.

With our current understanding and computational resources, it is necessary to use parameterisations in ice sheet models to compute the physical interactions between the ocean and the ice. Over the last decade, several basal melt parameterisations have been developed and implemented in ice sheet models with different complexities in the melt physics (Reese et al., 2018; Lazeroms et al., 2019; Pelle et al., 2019; Jourdain et al., 2020; Lambert et al., 2023). Berends et al. (2023) demonstrated that the choice of the sub-shelf melt parameterisation has a strong impact on the Antarctic ice sheet retreat for idealised as well as realistic geometries. However, all the parameterisations are approximations of the physical processes using parameters. The values of these parameters are poorly constrained, and in some cases the parameterisations require ocean temperature corrections up to 2 K to be able to match the basal melt rates observed (Jourdain et al., 2020; Reese et al., 2023).

Here, we present the implementation of the Postdam Ice-shelf Cavity mOdel (PICO) (Reese et al., 2018) in GRISLI v2.0 (Quiquet et al., 2018) but also a comparison of methodologies to calibrate PICO. We aim at calibrating the module to match the whole distribution of values from the observations as best as possible. In this research no ocean temperature corrections are added in the calibration process in order to have a more physical relationship between the forcing and the computed melt rates. The article is structured as follow. The section 2, the methodology, contains (1) a brief presentation of PICO, (2) the choices made in the implementation of PICO in GRISLI, (3) a description of the calibration ensemble, (4) the data we use as forcing and target, (5) a description of the 6 calibration methods tested in the present study, and (6) an application of the calibrated GRISLI-PICO with future projections to 2300. In the section 3, the results, we look at (1) the differences between the calibration methods, (2) whether it matters to calibrate PICO at a smaller scale than Antarctic wide, and (3) how much the calibration method matters for future projections. Finally, in the section 4, the discussion, we assess (1) the robustness of the methods under different conditions (resolution and areas of Antarctica), (2) the sensitivity to the forcings, (3) the sensitivity to different targets (basal melt rates from satellite retrieval) ; we further (4) discuss the PICO sensitivity in the light of the future projections done up to the year 2300. Section 5 concludes this research.

2 Methodology

2.1 PICO basal ice shelf melt module

PICO is a parameterisation that computes the basal melt rates under the ice shelves. It is described in details in Reese et al. (2018). We present here only the key concepts of PICO. It is a box model, based on the work of Olbers and Hellmer (2010). The ice shelves are divided into boxes, and the shape and number of boxes in one ice shelf are dependent on two variables:



55 distance to the ice shelf front and distance to the grounding line. The number of boxes n_D in one ice shelf D is then defined by :

$$n_D = 1 + \text{rd} \left(\sqrt{d_{\text{GL}}(D)/d_{\text{max}}} (n_{\text{max}} - 1) \right) \quad (1)$$

with d_{GL} the distance of each pixel to the grounding line, d_{max} the maximum distance between the grounding line and the ice shelf front among all the ice shelves of the ice sheet, and n_{max} the maximum number of boxes kept here at 5.

60 PICO accounts for one-dimensional overturning circulation in ice-shelf cavities (Lewis and Perkin, 1986). The overturning flux under the ice shelf q is driven by the density difference between the ocean box B0 (ρ_0) and the first box B1 under the ice shelf at the level of the grounding line (ρ_1):

$$q = C (\rho_0 - \rho_1) \quad (2)$$

The value of q must be greater than zero. A single overturning flux value is calculated for all boxes of the same ice shelf.
65 The constant overturning coefficient C ($\text{Sv.m}^3.\text{kg}^{-1}$) captures effects due to friction, rotation and bottom form stress, more details are given in Olbers and Hellmer (2010). C is one of the two PICO parameters that we calibrate in the present study. To compute basal melt rates m_k in the box B_k , PICO requires 2 ocean inputs: ocean temperature T_{k-1} and salinity S_{k-1} ; and one ice sheet input: the ice draft to calculate the under-burden pressure under the ice shelf p_k using $p_k = \rho_{\text{Ice}} * g * z_{\text{IceDraft}}$. For the box B_1 , the ocean inputs are the average temperature (T_0) and salinity (S_0) at the continental shelf depth in front of
70 the corresponding ice shelf. For the next boxes B_k , the forcing temperature and salinity depend on the overturning q and the temperature and salinity computed for the previous box T_{k-1} and S_{k-1} . The details of the analytical derivation are given in Reese et al. (2018) in appendices A and B. The melt rate in the box k is then computed as follows:

$$m_k(x, y) = -\frac{\gamma_T^*}{\nu \lambda} (aS_{k-1} + b - cp_k(x, y) - T_{k-1}) \quad (3)$$

where γ_T^* is the heat exchange coefficient (m.s^{-1}), the second of the two PICO parameters calibrated in this paper, $\nu = \rho_i / \rho_w \sim$
75 0.89 , $\lambda = L/c_p \sim 84$ °C. The coefficient a is the salinity coefficient of the freezing equation and equals -0.0572 °C.PSU $^{-1}$, b is the constant coefficient of the freezing equation and equals 0.0788 °C, c is the pressure coefficient of the freezing equation and equals 7.77×10^{-8} °C.Pa $^{-1}$.

2.2 Choices for the implementation of PICO in GRISLI

To implement PICO in GRISLI and to select the values of the two parameters (C and γ_T^*) we made some choices that differ
80 from Reese et al. (2018). We give an overview of these choices here. All the PICO implementation has been done in Fortran90 to corresponds to GRISLI development language.

First, the heaviest computation part in the module is the computation of the geometry of the ice shelves. To make it faster to run, we decide to make use of the drainage basins defined in (Mouginot and Rignot, 2017) and used in (Rignot et al., 2019), with the difference that we combined the two drainage basins of the two largest ice shelves as done by Jourdain et al. (2020):
85 Ronne with Filchner ice shelves and Ross East with Ross West ice shelves. Each drainage basin defines the external borders of



the geometry of the ice shelves and is used to compute the oceanic forcing inputs. This implies that if two different ice shelves are in a same drainage basin, they are seen as one ice shelf for PICO. Inversely, if one ice shelf has two drainage basins, it is then seen as two separate ice shelves for PICO. In all cases, the ice shelf front and the grounding line are defined in the same way by being neighbors to open ocean or grounded grid cells, respectively. The geometry of the ice shelves is recomputed at every time steps to readjust the boxes to the changing grounding line and ice shelf front position.

Then, Reese et al. (2018) used four selection criteria to calibrate PICO and define the values of the PICO parameters C and γ_T^* . The two first criteria are: (1) to not have freezing dominating the melt rates values in the first ice shelf box and (2) the overall mean basal melt rates must decrease between the first and second box of the ice shelf. The criteria (3) and (4) are constraints on the average values the melt rates that should be in the cold ice cavities of Filchner-Ronne Ice Shelf (FRIS) and in the warm ice cavities of Pine Island glacier respectively. All the four criteria are here not followed, and we apply different criteria. The rational is that while the PICO equations assume that (1) and (2) are true for the one horizontal dimensional case, melt rate patterns are complex in two horizontal dimensions. Indeed, the retrieved basal melt rates from remote sensing (Adusumilli et al., 2020; Paolo et al., 2023) show in some areas refreezing close to the grounding line but also higher melt rates close to the ice-shelf front. Instead of criteria (3) and (4), the calibration methods we tested here (presented in section 2.5) are designed to be able to capture the whole distribution of values, not only the average values, at an Antarctic wide scale as well as at an ice shelf scale.

When identifying the PICO boxes, we consider as grounding line any ice points that is surrounded by grounded ice and not grounded ice, and as ice front any ice point that is floating and adjacent to ocean. In PISM-PICO (Reese et al., 2018) they did not include the grounding line of ice rises and also excluded holes in ice shelves as ice front when identifying PICO boxes. The grounding lines of ice rises are defined as not being directly connected to the main grounded part of the ice sheet which is identified by the size of the connected grounded region. Thus, it is possible to have ice shelves without grounding line connected to the main ice sheet, where PICO cannot define a box geometry. In these places, the parametrisation of Beckmann and Goosse (2002) enables to have a rough estimate of the basal melt rates.

Additionally, outside of the ice shelves in the open ocean we apply the parameterisation of DeConto and Pollard (2016) defined as follow:

$$m = \frac{K_T \rho_w C_w}{\rho_i L_f} |T_o - T_f| (T_o - T_f) \quad (4)$$

The main difference is the inclusion of a quadratic dependence between the melt rate and the difference of the temperature between the ocean T_o and the ocean freezing point at the ice base T_f . This quadratic relation enables to limit the growth of the ice shelves towards the ocean. The combined factor $\frac{K_T \rho_w C_w}{\rho_i L_f}$ equals to $0.224 \text{ m.yr}^{-1} \cdot ^\circ\text{C}^{-2}$. The parameterisation chosen for the open ocean does not impact the calibration results but does impact the transient ice sheet simulations.

Finally, in GRISLI v2.0 the iceberg calving is defined by a simple ice thickness threshold criterion (Quiquet et al., 2018). The threshold value varies in space and time as it is dependent on the depth of the bathymetry at the location of the ice shelf front.



2.3 Calibration ensemble

120 To calibrate the two PICO parameters C and γ_T^* we run an ensemble of 169 members of PICO implemented in GRISLI corresponding to all possible combinations between 13 values for the parameter C (ranging from $0.01 \text{ Sv.m}^3.\text{kg}^{-1}$ to $15.00 \text{ Sv.m}^3.\text{kg}^{-1}$) and 13 values for the parameter γ_T^* (from $0.01 \times 10^{-5} \text{ m.s}^{-1}$ to $15.00 \times 10^{-5} \text{ m.s}^{-1}$). The geometry of the ice sheet and the ice shelves is kept fixed to remove the influence of ice shelves geometry changes on the computed basal melt rate. The fixed geometry corresponds to Bedmap2 (Fretwell et al., 2013) with a 30 years relaxation with GRISLI. With this
125 ensemble of 169 simulations, we apply six different methods, presented in subsection 2.5, to evaluate which members of the ensemble provide the best fit with respect to the observational dataset.

2.4 Data: ocean forcing and basal melt rates target

The oceanic forcing we use for the calibration ensemble presented above in subsection 2.3 is the dataset produced by Jourdain et al. (2020). This is a present-day estimate of three-dimensional fields of temperature and salinity of the ocean surrounding the
130 Antarctic ice sheet. Jourdain et al. (2020) computed this estimate by using the following data sets: a pre-release of NOAA World Ocean Atlas 2018 covering the period 1995-2017 (Locarnini et al., 2018; Zweng et al., 2019), the Met Office EN4 subsurface ocean profiles for the period 1995-2017 (Good et al., 2013), and Marine Mammals Exploring Oceans from Pole to Pole for the period 2004 to 2018 (Treasure et al., 2017). The final dataset created by Jourdain et al. (2020) includes extrapolation of the ocean properties into the ice shelf cavities where observations are not available. The end product is on a polar stereographic
135 grid with a resolution of 8 km horizontally and 60 m vertically.

Our target is the average basal melt rates retrieved by Adusumilli et al. (2020), a dataset that used CryoSat-2 altimetry to create an average value estimate of basal melt rates of the ice shelves of Antarctica for the period 2010-2018 at a resolution of 500 m.

These ocean forcings and basal melt rates target differ from Reese et al. (2018) where they used Schmidtke et al. (2014) for
140 the ocean forcing and Rignot et al. (2013) as the target for the basal melt rates. The selected datasets in the present study are more up to date but also have good overlap with the time period of data retrieval between the forcings and the target. For all the methods and analysis, all the datasets, the forcings and the observational target, are up-scaled to the same resolution as the ice sheet model.

2.5 Six statistical methods of calibration of the two PICO parameters: C and γ_T^*

145 The six statistical methods of calibration compared in this study are explained here. The overview of the methods is given in table 1, including names, equations, and short description. We present first the three ones that do not use binning of melt rates, then how we process the binning, and finally the three methods that use binning. For all the methods, the model data and the observational data are expressed in m.yr^{-1} . The analysis methods that do not use binning are the following:

- Absolute Difference of Averages (ADA): we compute the average value of each ensemble member and of the target, and
150 compute the absolute difference between each ensemble member average with respect to the average of the target.



- two Dimensions Root Mean Square Error (2D RMSE): we compute the RMSE pixel-to-pixel with the same geographical location between each ensemble member and the target.
- two Dimensions Mean Absolute Error (2D MAE): we compute the MAE pixel-to-pixel with the same geographical location between each ensemble member and the target.

155 Despite being similar to the RMSE, the MAE differs by the absence of the square and the square root, and has instead the absolute value applied to the error computation. The absence of the squared on the error computation in the MAE makes the MAE less sensitive to outliers than the RMSE.

Methods name	Statistical formulas	Description of methods to rank the ensemble members
ADA	$\left \frac{1}{n} \sum_{i=1}^n x_{member,i} - \frac{1}{n} \sum_{i=1}^n x_{obs,i} \right $	Lowest ADA (Absolute Difference of Averages) between each ensemble member and the target
2D RMSE	$\sqrt{\frac{1}{n} \sum_{i=1}^n (x_{member,i} - x_{obs,i})^2}$	Lowest value of the RMSE (Root Mean Square Error) between each ensemble member data points and the target data points, with 2D geographical correspondence
2D MAE	$\frac{1}{n} \sum_{i=1}^n x_{member,i} - x_{obs,i} $	Lowest value of MAE (Mean Absolute Error) between each ensemble member data points and the target data points, with 2D geographical correspondence
ADA of bins	$\left \frac{1}{m} \sum_{j=1}^m \bar{B}_{member,j} - \frac{1}{m} \sum_{j=1}^m \bar{B}_{target,j} \right $	Lowest ADA of bins (Absolute Difference of Averages of the bins) between the bins of each ensemble members and the bins of the target
RMSE of bins	$\sqrt{\frac{1}{m} \sum_{j=1}^m (\bar{B}_{member,j} - \bar{B}_{target,j})^2}$	Lowest value of the RMSE (Root Mean Square Error) between the bins of each ensemble member and the bins of the target
MAE of bins	$\frac{1}{m} \sum_{j=1}^m \bar{B}_{member,j} - \bar{B}_{target,j} $	Lowest value of the MAE (Mean Absolute Error) between the bins of each ensemble member and the bins of the target

Table 1. Statistical methods applied to rank the ensemble members compared to the target (observations): names, equations and short descriptions. Where n is the number of data points existing in both data sets, $x_{member,i}$ refers to any single data point in one ensemble member, m is the number of bins (10 in this study), $\bar{B}_{member,j}$ is each bin of a single ensemble member. The same nomenclature is applied for ensemble members and the observations.

160 By applying the three first methods, we do not manage to constrain the method to pick systematically the ensemble members with the best fit to the target. To improve that, we decide to proceed a binning on the datasets, the ensemble members as well as the target, in order to be able to force method to pick ensemble members that fit the target distribution, including the higher and lower tails of the distribution. We proceed with the binning of the melt rates as shown in the schematic figure 1. Each bin ($\bar{B}$) is the average value of 10% of the total number of ordered data points. The data points must be ordered to make each bin



representative of a specific share of the dataset. For instance, if an ensemble member has 200 data points, the 20 points with the lowest values are averaged and become one bin value. We proceed similarly for all the following bins and end up with 10 bins for each of the 169 members of the ensemble $\bar{B}_{\text{member},j}$ and 10 bins for the target too $\bar{B}_{\text{target},j}$. Once the binning is done, we apply the following statistical analysis methods. They are similar to the three presented above, but applied to the 10 bin values rather than 2D data fields.

- Average Difference of Averages of the bins (ADA of bins): we compute the average value of the bins of each ensemble member and of bins of the target, and compute the absolute difference between the two.
- Root Mean Square Error of the bins (RMSE of bins) : we compute the RMSE value between the bins of each ensemble member and the bins of the target.
- Mean Absolute Error of the bins (MAE of bins): we compute the MAE value between the bins of each ensemble member and the bins of the target.

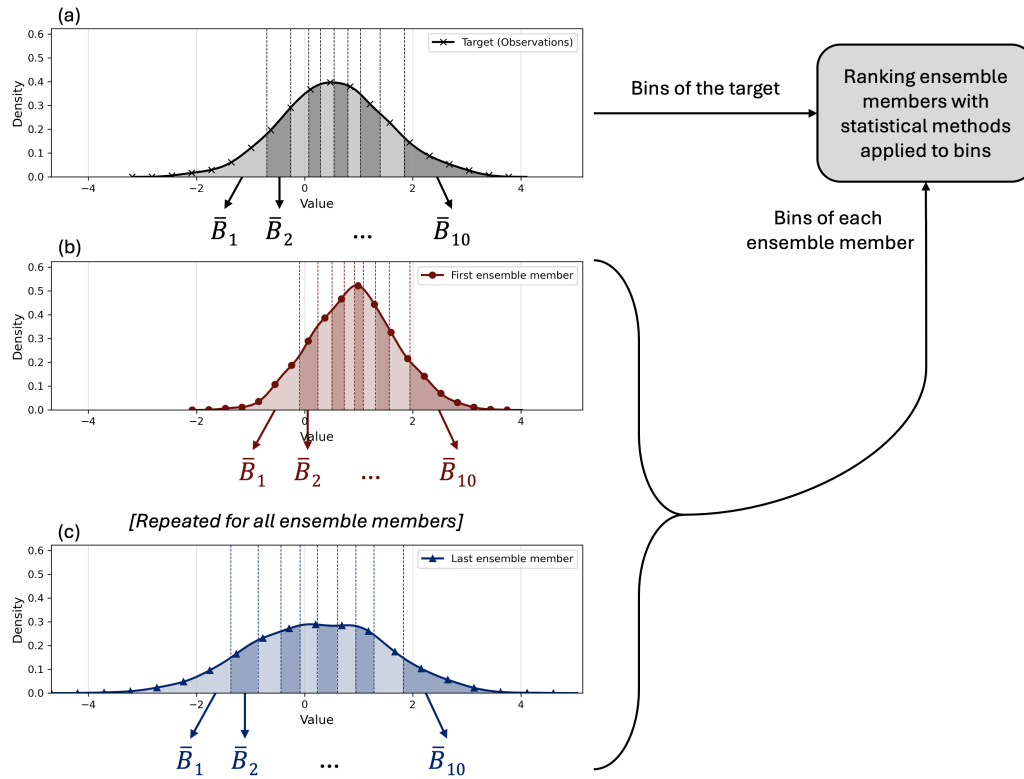


Figure 1. Schematic showing how the binning of melt rates is done. $\bar{B}_x$ stands for the value of each bin which is the average value of 10% of the ordered values. The darker and lighter shadings represent each 10% of the corresponding dataset. The panel (a) is the distribution of the values of the target, the panel (b) is the distribution of the values of the first ensemble member, and the panel (c) is the one of the last ensemble member. Once the bins for the target and all the ensemble members is calculated we apply the statistical methods to rank the ensemble members.

For all of the methods above, the ranking of the best ensemble members is given by the lowest values obtained with the given equations in the table 1. The results of the analysis applied to all ice shelves of the Antarctic ice sheet are given in subsection 3.1.1. We also apply the above methods at a more local scale than Antarctica to test whether a local calibration is needed. For that we apply the above methods to two additional areas of the Antarctic ice sheet: the Filchner-Ronne ice shelf (FRIS), and the sector of the Bellingshausen and Amundsen seas (BA seas). The results are given in subsection 3.1.2. To test the robustness and sensitivity of the methods under more conditions we also test them with different resolutions of the ice sheet model, ocean temperature and salinity forcings, and targets of basal melt rates. We discuss these results in section 4.

2.6 Future applications: ISMIP 2300

To make a preliminary assessment of the relevance of this implementation and of the calibration methods, we run a small ensemble of future scenarios. PICO parameters values are chosen in line with the analysis of the calibration ensemble defined



in sub-section 2.5. We make use of the ISMIP6 2300 protocol in which GRISLI and other ice sheet models using PICO participated (Seroussi et al., 2024). The basal melt parameterisation used in the submitted GRISLI simulations for the ISMIP 2300 was the quadratic non-local melting parameterisation from Jourdain et al. (2020) which, in the following, will be referred to as QuadNL. For these simulations with PICO we do not re-calibrate GRISLI mechanic parameters and use the same initial state as for QuadNL. Here we repeat the experiment "expAE05" from ISMIP 2300 which corresponds to climate forcing computed by the UK Earth System Model (UKESM1-0-LL) for the scenario SSP5-8.5 (Seroussi et al., 2024). With our new simulations we will assess: i- the relative sensitivities of PICO and QuadNL with the same model and same forcings; ii- the importance of calibration choices on model results and; iii- how the response of GRISLI-PICO differs from other ISMIP participating models that also used PICO. The results are presented in subsection 3.2.

3 Results

3.1 Calibration of the PICO parameters

3.1.1 Can we capture the spatial or binned distribution of melt rates using any of the six calibration methods?

Here we present the results for the six calibration methods explained above in section 2 applied to all ice shelves of Antarctica at a 16 km resolution. The main calibration results for each method are presented in the figure 2, more detailed results are shown in the supplementary materials section 1. In the figure 2, we show on panels (a), (b), (c), (g), (h), and (i) the distribution of the values of the five best ensemble members according to each methods that we can compare directly with the distribution of the observations from Adusumilli et al. (2020). In panels (d), (e), (f), (j), (k), and (l) we show on the heatmaps the ranking of all the ensemble members for each corresponding method. We also highlight the five best members with the black dots numbered of their member number.

Panels (a) and (d) show the results using the ADA method. We see that the best members using the ADA method cover a large range of values from $0.1 \times 10^{-5} \text{ m.s}^{-1}$ to $3.0 \times 10^{-5} \text{ m.s}^{-1}$ for γ_T^* and from $0.1 \text{ Sv.m}^3.\text{kg}^{-1}$ to $5.0 \text{ Sv.m}^3.\text{kg}^{-1}$ for C. Also, the matching with the target distribution of the top five members is in some cases good (members 36 and 35) and in other not (members 133, 56 and 44). The large spread of the top five members demonstrate that with this method the best parameters will not be systematically in the same order of magnitude of values and can depend heavily on the sampling ensemble. The results for the 2D RMSE and 2D MAE methods are shown on panels (b), (e) and (c), (f), respectively. Both methods gives quite similar responses, the top five members for both methods are side-by-side. In comparison to the ADA methods, these two methods enable to have a narrower range of PICO parameter values, in particular for the parameter γ_T^* . However, none of the selected top five members, for both methods, matches the distribution of the observations (panels (b) and (c)).

The following panels, from (g) to (l), correspond to the results of the methods using binning. The first of the three, the ADA of bins (panels (g) and (j)), selects almost the same members as the ADA without binning. Therefore, using binning before computing the ADA is not enough to have a small set of best members and fitting the distribution.



215 The next methods, RMSE of bins and MAE of bins, minimise the differences between the bins of the ensemble members and the bins of the target systematically. Because of this we obtain a selection of best ensemble members that systematically fit the distribution of the target (panels (h) and (i)). But also the range of parameters corresponding to the best five members is small, all the top members are side-by-side (panels (k) and (l)). This gives us confidence that these two last methods consistently give the same range of parameter values for different ensemble sampling that would also matches best the distribution of the target.

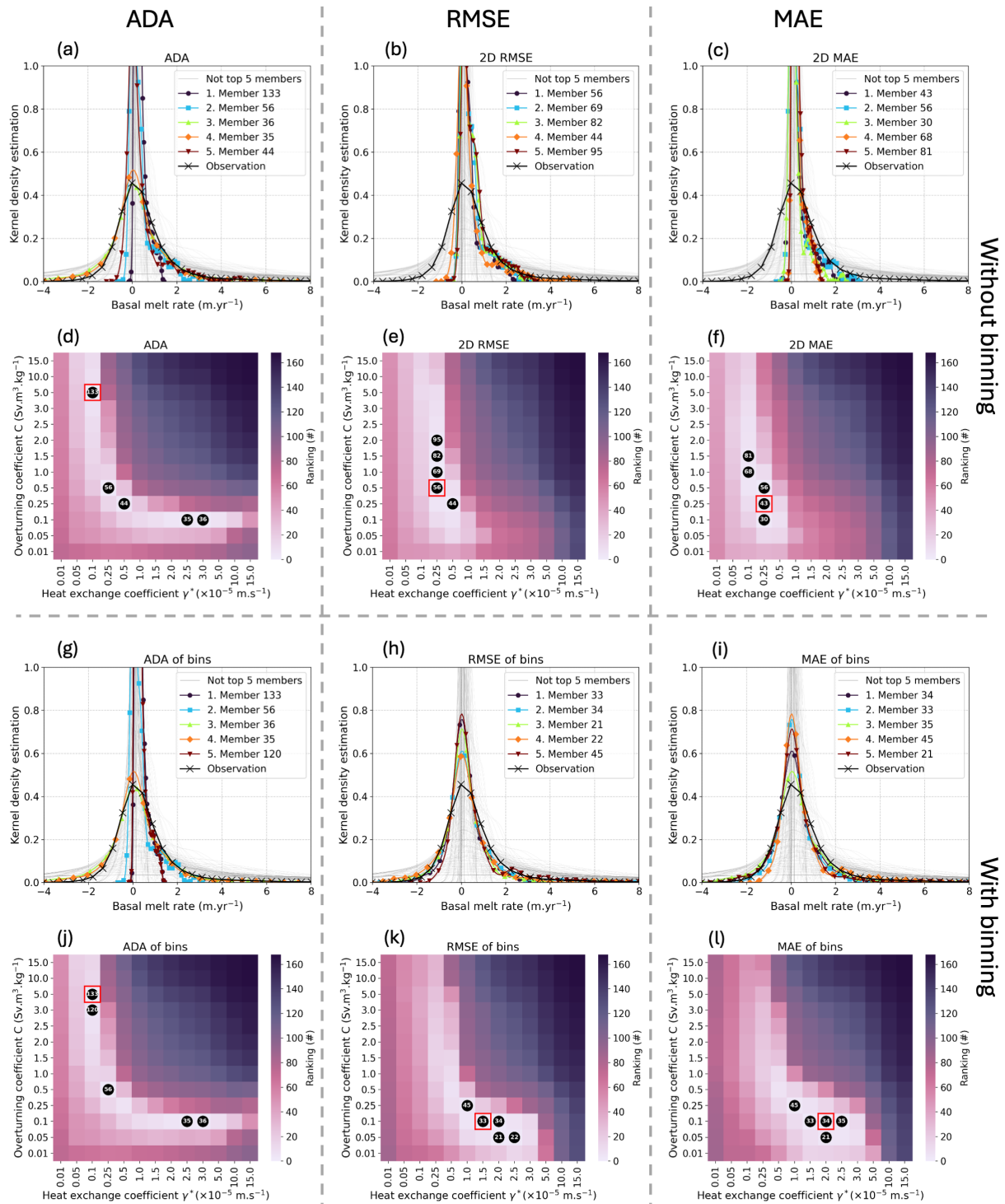


Figure 2. Comparison of the 6 methods. The panels (a), (b), (c), (g), (h) and (i) are the results of the distribution of the best five members according to each methods. The panels (d), (e), (f), (j), (k), and (l) show the ranking of all the ensemble members according to each methods. The red square shows the best member. The black dots with numbers show the best five members for each method, the same members as on the distribution panels.



220 The inability of ADA of bins to give a small range of parameter values can be explain by the fact that it allows compensation
between bins. Figure 3, shows the values of the 10 bins of the five best members according to the three methods using bins. We
see a compensating effect between the lower and higher parts of the values of the bins, in particular for the members 133, 56
and 120. In other words, these members score well with this method because, in this case, the positive differences to the target
in the lower bins is compensated by the negative difference to the target in the higher bins. Whereas, the RMSE of bins and the
225 MAE of bins have systematically smaller differences to the target and do not allow for compensating effect.

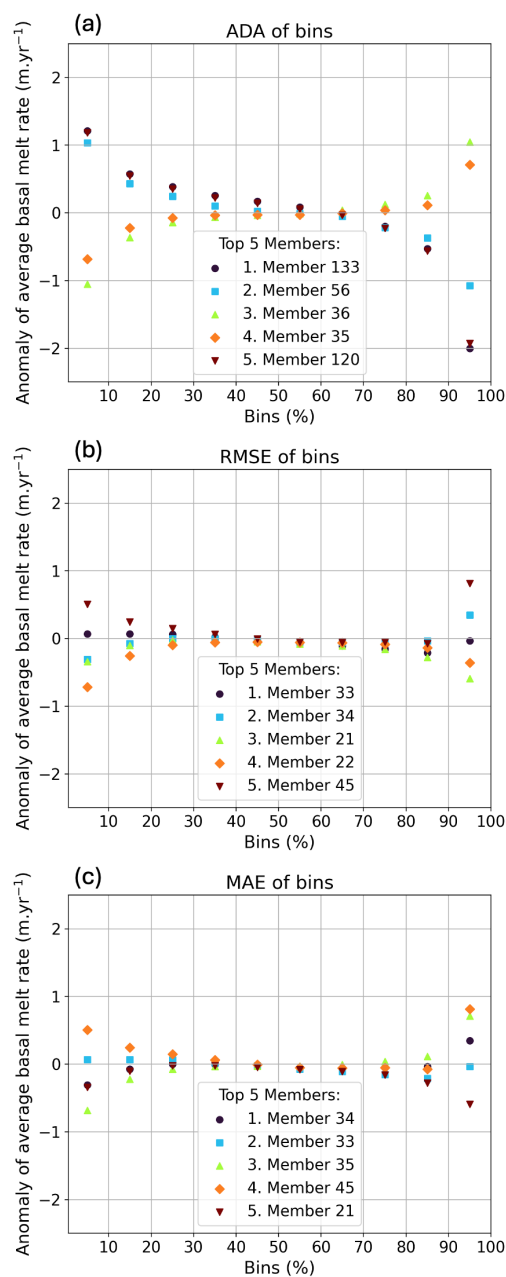


Figure 3. Anomaly of bins values of the five best members according to each methods, ADA of bins (a), RMSE of bins (b) and MAE of bins (c), with regard to the target Adusumilli et al. (2020). The closer the value is to 0, the closer value of the bin of the ensemble member is to the value of the bin of the target.



Nonetheless, being able to match the distribution can also mean spatial compensation between different locations. Therefore we look at the spatial distribution of the values on the figure 4. It shows the single best member of each methods corresponding to the red square on the heatmaps of figure 2. We see that four methods (ADA, 2D RMSE, ADA of bins, and 2D MAE) lead to a spatial distribution with little contrast between higher and lower values, they even do not have values more negative than -1 m.yr⁻¹ in blue (figure 4 panels (a) to (c)). This is because this selection led to low γ_T^* values, $0.1 \times 10^{-5} \text{ m.s}^{-1}$ and $0.25 \times 10^{-5} \text{ m.s}^{-1}$. Whereas, the best single member following the RMSE of bins or the MAE of bins have a lot more contrast (figure 4 panels (d) and (e)), which corresponds better to what is seen in the observations (figure 4 panel (f)). These two methods led to higher γ_T^* values: $1.5 \times 10^{-5} \text{ m.s}^{-1}$ and $2.0 \times 10^{-5} \text{ m.s}^{-1}$.

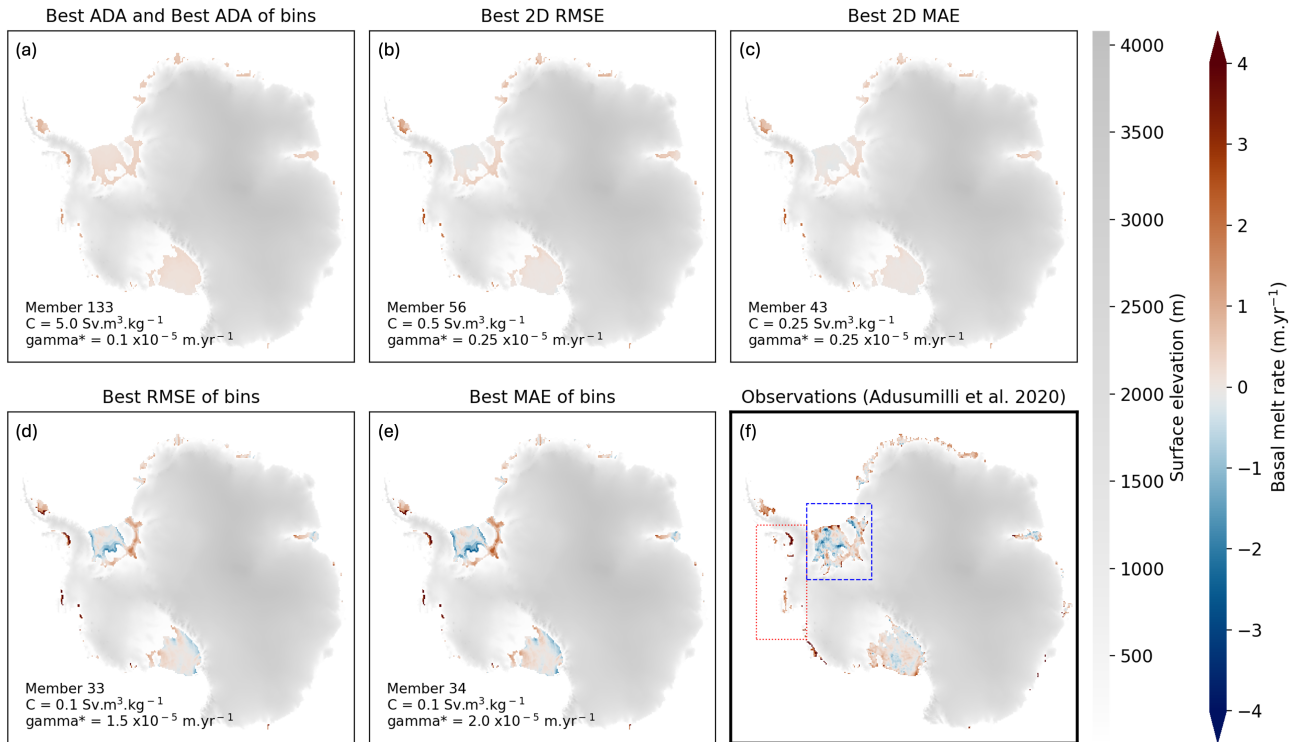


Figure 4. Spatial distribution of the basal melt rate values for the six calibration methods tested ((a) to (e)), N.B. (a) represent two methods (ADA and ADA of bins) as they give the same best ensemble member. (f) is the spatial distribution of the observations from Adusumilli et al. (2020). In panel (f), the rectangles show the two chosen areas to test the calibration at two smaller scale than Antarctic wide and presented in sub-section 3.1.2, the red further to the left is the Bellingshausen and Amundsen seas (BA seas) area and the blue further to the right the Filchner-Ronne ice shelf (FRIS) area.

Overall, we see that calculating the average, with or without binning, can lead to very different optimal PICO parameter values, which is can be explained by the possibility to compensate between negative and positive values. The four other methods shows more systematic results where the best members points are all side-by-side. However, between the without (2D



RMSE and 2D MAE) and with binning (RMSE of bins and MAE of bins) the selected members are in different parameter spaces. By observing the spread of the rankings combined with the distributions, we can consider the methods RMSE of bins and MAE of bins as the best ones among the six tested here. This is justified by the fact that the selected members are: i) better
240 able to match the distribution curve from the target, ii) systematically give best values in the same small range of values, and
iii) the magnitude of the spatial patterns is similar to the target.

3.1.2 Do we need to calibrate the PICO parameters locally?

Here we show how different the results would be if we would calibrate PICO for a specific domain of the Antarctic ice sheet, and we assess whether a Antarctic wide calibration is suited to domain-wide applications. Figure 5 presents a selection of
245 the analysis similar to the previous section, but applied to the two domains: BA seas on the left side, and FRIS on the right side. The results shown here correspond only to the method MAE of bins considered as one of the two best methods, results for the other methods can be seen in the supplementary materials sections 2 and 3. First, with panels (a) and (b) we see that despite the 169 members of the ensemble it is more challenging to match the observation distribution in the Bellinghausen and Amundsen seas sector (BA seas) than for the Flichner-Ronne ice shelf. This can be explained by the difference in the number
250 of data points. But also, on these two panels we also show the best Antarctic-wide calibration following the MAE of bins. In the BA seas, the top member, 34, is the same as for the Antarctic wide selection. For FRIS, the best Antarctic wide selection is also part of the top five members. Second, with panels (c) and (d), we see a strong difference between the two sectors in the sensitivity of the average basal melt to change of the PICO parameter values. A change of the overturning coefficient of $+0.4 \cdot 10^{-5} \text{ m.s}^{-1}$ would lead to an average basal melt value higher than 4 m.yr^{-1} above the average of the target in the case of
255 the BA seas sector, whereas it would barely make any difference for the FRIS sector. Thus, the best Antarctic wide calibration using the MAE of bins is similar to the best possible local calibration, with negligible differences in less sensitive areas.

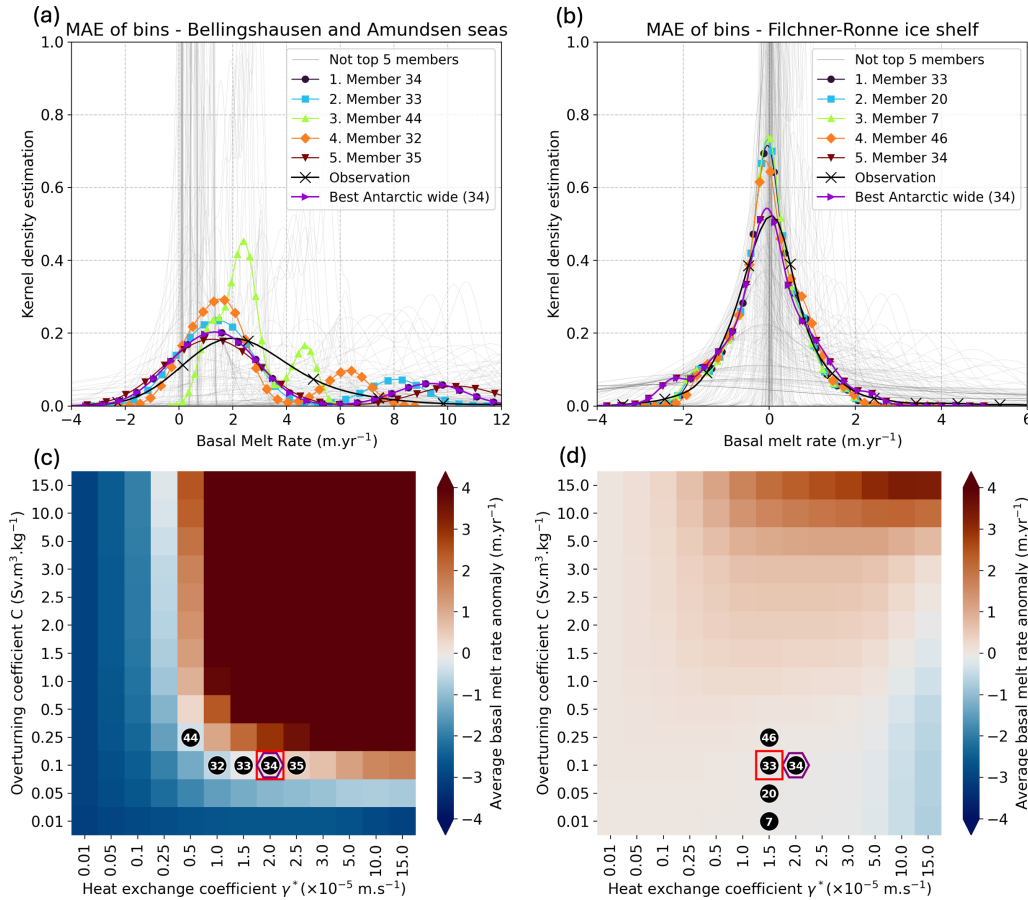


Figure 5. Comparison of the calibration between the Bellinghausen/Amundsen seas sector (on the left side) and Filchner-Ronne ice shelf sector (on the right side). (a) and (b) are the distribution of the five best members for both sectors using the MAE of bins methods, with the distribution of the best calibration applied Antarctic wide (in purple). (c) and (d) show the absolute difference between the average of each of the 169 ensemble members and the average of the observations. However, the five best members shown with the numbered black dots correspond to the best members with the MAE of bins method (as in (a) and (b)). The best member for the local and Antarctic wide calibration using the MAE of bins is given by the red square and the purple hexagon respectively.

3.2 How much does it matter for future projections?

Following the previous analysis, we select seven cases to make a first-order assessment of the impact of the calibration method choice on future projections of the Antarctic ice sheet until 2300 (Figure 6 (a)). The seven cases correspond to the six best members according to the six methods applied Antarctic-wide. It corresponds to five members since the best ADA and best ADA of bins give the same best member. The two additional members correspond to the parameter values chosen by the ice



sheet models PISM/Elmer-ice (101) and Kori (102) that use PICO for the ISMIP 2300 experiment Seroussi et al. (2024). Figure 6 panel (b) shows the distribution of the basal melt rate at the very start of the simulations for the ISMIP 2300 simulation for the year 2015, compared to the observations from Adusumilli et al. (2020). For comparison, we include GRISLI with the QuadNL parameterisation (Jourdain et al., 2020).

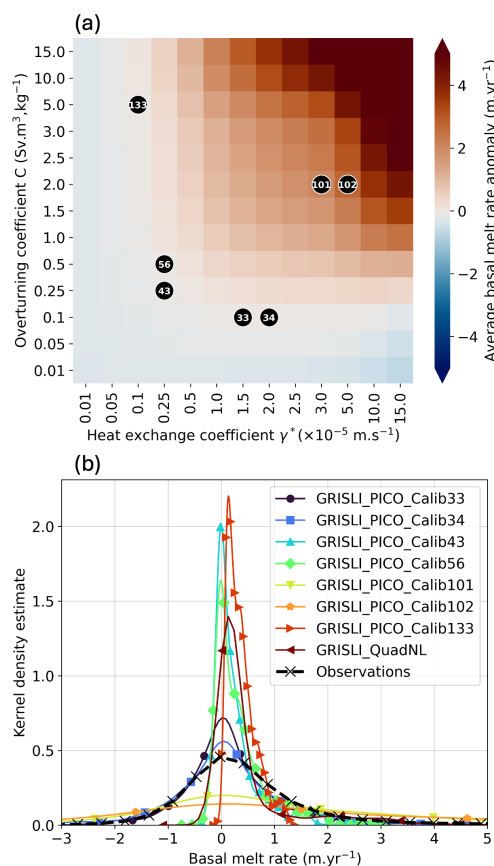


Figure 6. (a) Selection of PICO parameter values for ISMIP2300 applications in this study. (b) comparison with Adusumilli et al. (2020) at the start of the simulation ($t=2015$).

The main results of this small ensemble of ISMIP 2300 members are shown in figure 7. On figure 7 panel (a) we see the total basal mass balance flux (BMB flux) over time. We can see very different behaviours between ice sheet models and parameterisations. Over the whole simulation the highest values are obtained with the QuadNL parameterisation with GRISLI and Kori. Then in the medium range we have the calibrations 101 and 102 of PICO with different ice sheet models (Elmer-ice, PISM, Kori and GRISLI). On the upper part of the plot, the group of simulations with the lowest basal melt rates corresponds to all the GRISLI-PICO simulations with the different calibration methods done above. On the figure 7 panel (b), the floating ice area representing the size of the ice shelves show significant differences between the different simulations, including the



GRISLI-PICO with different calibrations. The growth of the floating ice of the GRISLI-PICO calibrations 101 and 102 is something observed also in the Kori-PICO simulation. The calibration 34, considered as the best one in the calibration process, show very steady ice floating area with a small decreasing trend. Finally, figure 7 panel (c) shows the contribution to sea level rise of all the simulations. We can see that simulations with PICO with the same PICO parameters lead to lower values of sea level contribution by 2300 for both GRISLI and Kori than using the QuadNL parameterisation. Elmer-ice with PICO is the only simulation leading to an ice sheet growth, hence a negative contribution to sea level rise. The simulations of GRISLI-PICO result all in a low value of sea level contribution by 2300.

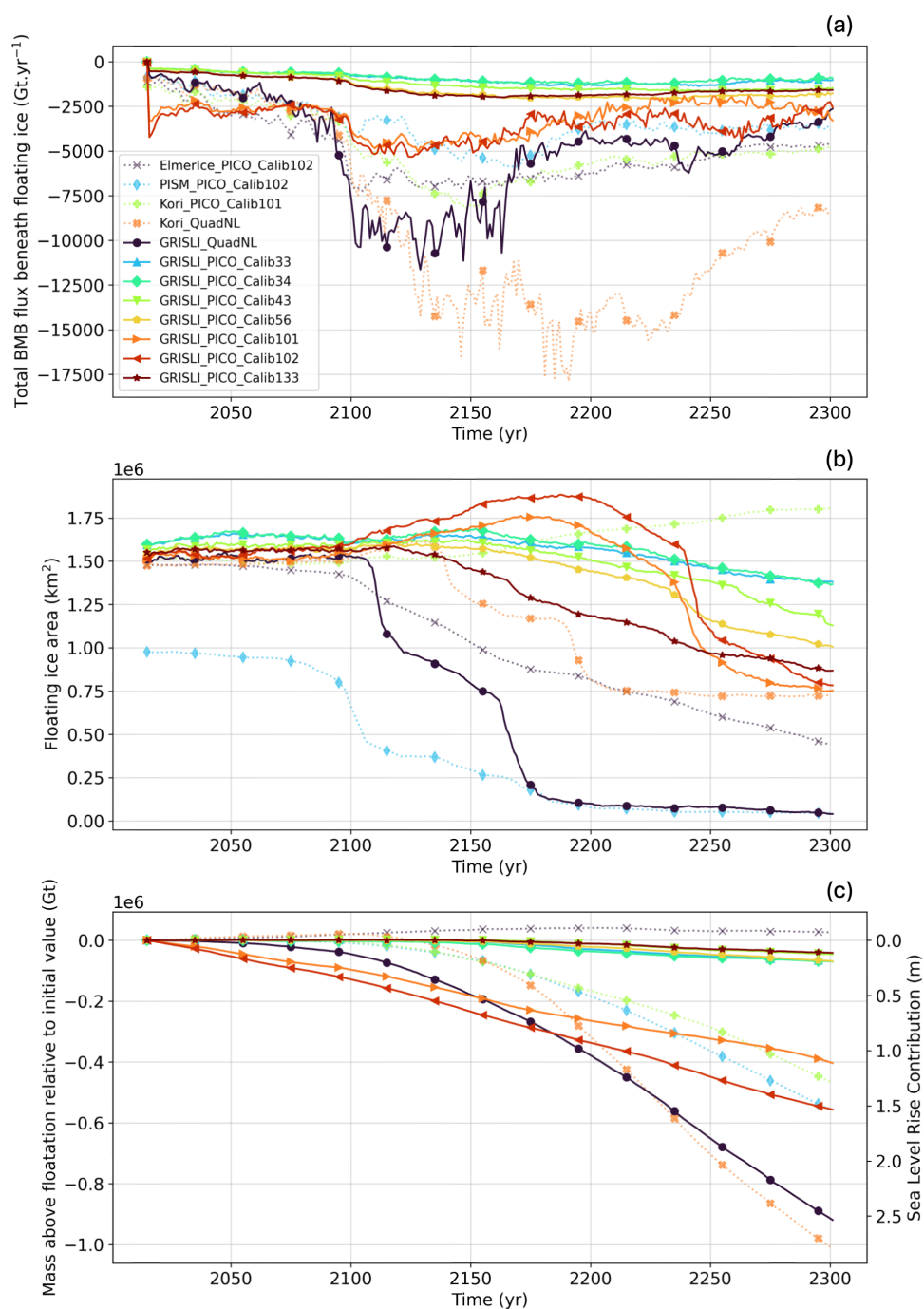


Figure 7. ISMIP 2300 applications with different PICO calibrations. (a) shows the evolution of the total basal melt balance (BMB) beneath floating ice over time. (b) shows the evolution of the floating ice area. (c) shows the contribution to sea level rise.



280 4 Discussion

Here we discuss how robust the results of the different methods are by applying them under different resolution and areas of Antarctica. Then we assess the sensitivity of the result to the choice of the forcings and to the choice of the target. Lastly, we discuss further about the ISMIP 2300 results obtained using PICO.

4.1 How robust are the methods if applied at different resolutions and areas of the ice sheet?

285 To test how robust the results are, we run an additional calibration ensemble of 169 members with a resolution of 40 km. We use the same forcing from Jourdain et al. (2020) and target from Adusumilli et al. (2020) regridded at 40 km. With this new calibration ensemble we renew the analysis for Antarctica wide as well as for BA seas sector and FRIS. We therefore test each statistical methods with six different cases: two resolutions $\times$ three areas of interests. The detailed analysis are shown in supplementary materials for all six methods in all six conditions in supplementary materials sections 1 to 6. We summarise
290 all these conditions by cumulating the top five members in all the six conditions for each statistical methods and plot them on figure 8. It enables us to visualise the spread of the top PICO parameters cumulated over the different cases. We can see that the methods RMSE of bins and MAE of bins are the two ones that gives consistent optimal PICO parameter under all different conditions. But also they give more systematically the same members (see appendix A), suggesting to use the same order of magnitude of the parameters for all the tested conditions. This consistency can matter to: i) inter-compare different
295 parameterisations ; ii) inter-compare when the same parameterisation used in different ice sheet models ; iii) inter-compare results at different resolutions. No clear trend can be seen between the best members at 16 km and 40 km resolution (see appendix A2). It is particularly relevant to have robust methods over different resolutions to make the comparisons more systematic such as in the scope of Ice Sheet Model Inter-comparison Projects (ISMIP) (Seroussi et al., 2024), Marine Ice Sheet-Ocean Model Intercomparison Project (MISOMIP) (Rydt et al., 2024), or comparison between paleo and future ice
300 sheet behaviours (Golledge et al., 2021).

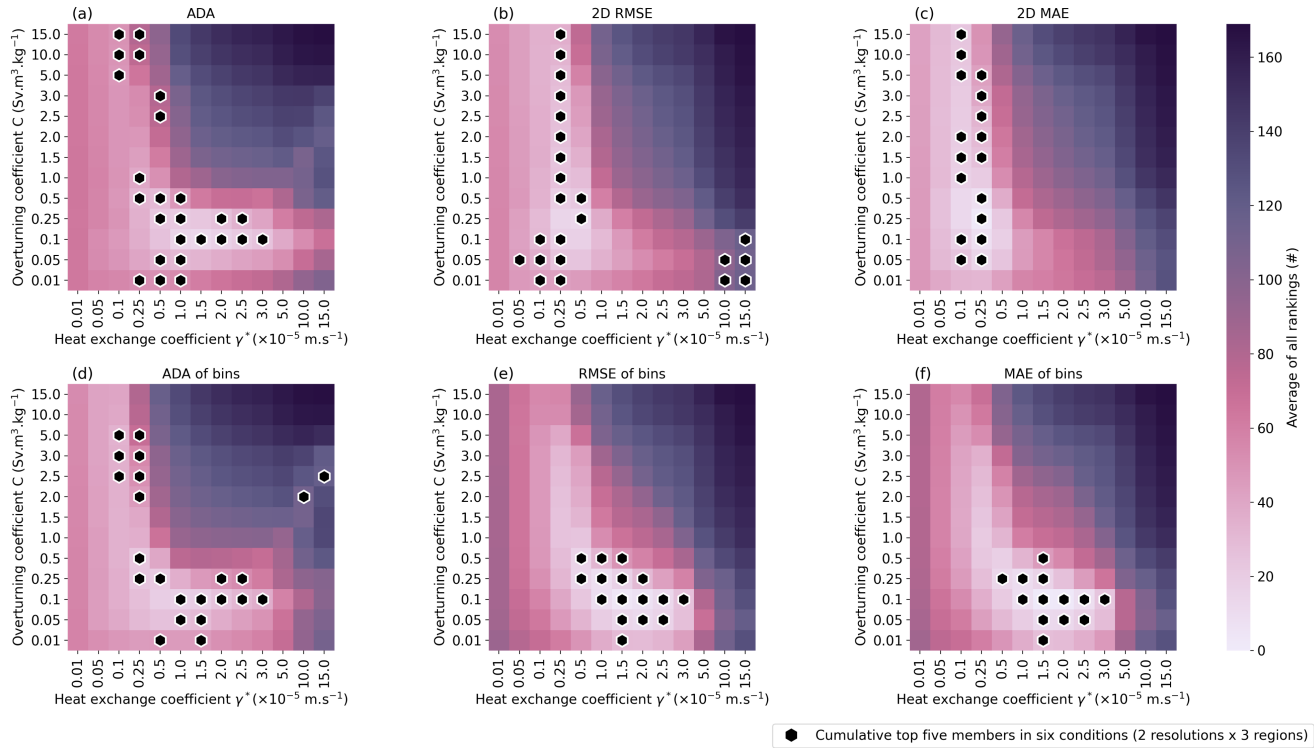


Figure 8. Average ranking of each calibration method tested under two different resolutions (40 km and 16 km) and applied to three different sectors (Antarctic wide, BA seas, and FRIS). The top five members of all six conditions are shown with the black and white hexagons.

4.2 How sensitive are the methods to the forcings?

In all presented results until here we used the forcing from Jourdain et al. (2020). Here, we assess how sensitive the results are to this forcing. We run three additional calibration ensembles of 169 members at 16 km resolution, using the same forcing by Jourdain et al. (2020), but with a different temperature correction on the top of it. The temperature corrections are (1) + 1 K, (2) + dT from Reese et al. (2023) (see their table S1), and (3) + dT from Jourdain et al. (2020) (see their figure 5 panel (a) for the quadratic non local parameterisation. Reese et al. (2023) and Jourdain et al. (2020) apply a temperature correction that differs per drainage regions. To remain concise, we present in figure 9 results only the ranking for the MAE of bins method (for additional analysis see supplementary materials section 7, 8 and 9). We can observe that with a correction of +1 K both PICO parameters shift to slightly lower values. The opposite is happening with the correction from Reese et al. (2023), which is expected since the temperature are almost all negative values, reaching up to -2 K. The correction from Jourdain et al. (2020) makes only minor differences as the values are rather low with a maximum absolute value of +1.07 K. These results suggest that using warmer forcing for the calibration will lead to a calibrated PICO less sensitive to temperature changes, and vice versa with a colder forcing. Finally, we can state that, even after cumulating all the ranges of values suggested by the four different



forcings, forcing uncertainties lead to a smaller range of PICO parameter values than using different statistical calibration
315 methods. In other words, the choice of the calibration method is more important than the choice of the forcing.

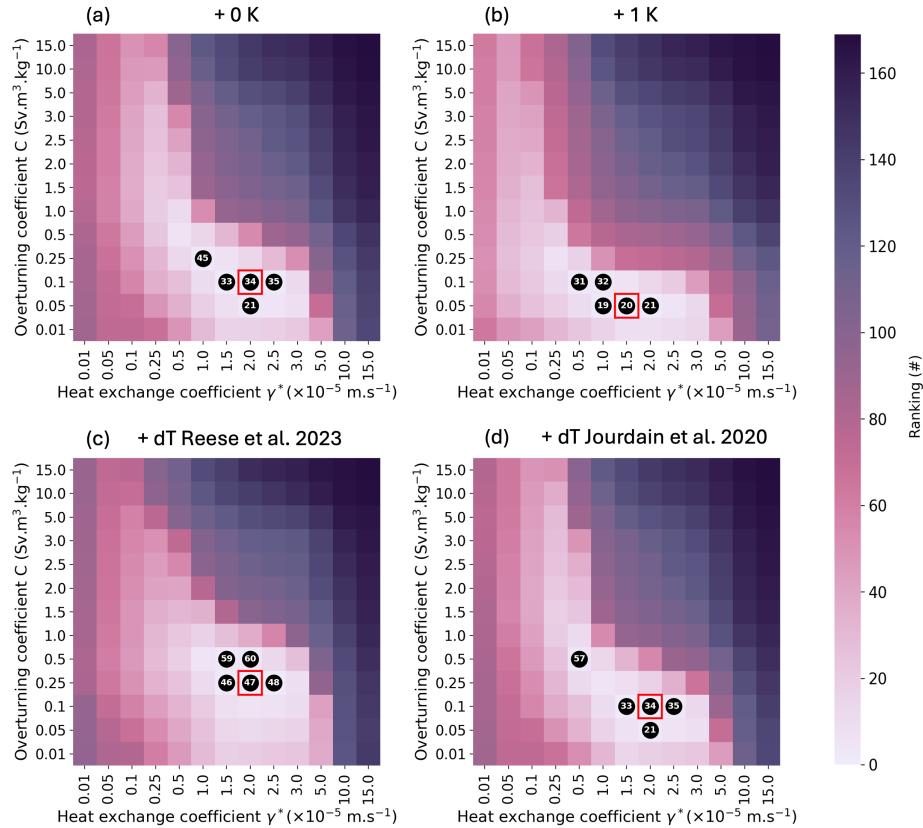


Figure 9. Ranking using the MAE of bins to all Antarctic ice shelves with different forcings. (a) is without additional temperature correction. (b) is with + 1 K, (c) is with dT defined by Reese et al. (2023), and (d) is with dT defined by Jourdain et al. (2020).

4.3 How sensitive are the methods to the target?

As presented in subsection 2.4, we took as target the basal melt rates retrieved from Adusumilli et al. (2020). However, the retrieval of basal melt rates from satellite observations is poorly constrained. Hence, we could argue to choose a different target for the calibration of the basal melt rate parameterisation. Therefore, to assess the uncertainty due to the choice of the melt
320 rate target, we ran the same robustness analysis as in section 4.1, but with as target the basal melt rates retrieved by Paolo et al. (2023) instead of the target of Adusumilli et al. (2020). The detailed results are shown in appendix B. They are overall similar to the ones obtained with Adusumilli et al. (2020) as target, with a slight shift towards higher γ_T^* values. This is expected as the distribution and the main statistics are very similar (see figure 10 panel (a), with a higher standard deviation for the Paolo et al. (2023) dataset). Figure 10 panel (b) shows the spatial differences between the two datasets. The magnitude of these differences
325 is of the same order of magnitude as the values of basal melt rates themselves, reaching values below -4 m.yr^{-1} and above 4



m.yr^{-1} . This observation is made for both resolutions 16 km and 40 km (see supplementary materials section 10). The average difference between the two datasets is about 25% of the average value of Adusumilli et al. (2020) at 16 km. The observation of the disagreement between the two datasets is important to justify the usage of bins suggested in the present study. Indeed, by using the binning methods we give spatial freedom to the datasets and constrain them by their values. This is in agreement with Joughin et al. (2021) who argue that the ocean-induced melt volume, regardless of the spatial distribution, directly paces the ice loss. However, one limitation is that by scaling up the resolution the observational datasets to the ice sheet resolution, 16 km or 40 km here, we are losing most of the data points with melt rates values above 6 m.yr^{-1} (see supplementary materials section 10). This also means that a calibration by using the same method but for higher resolution models or with irregular grids might have different values of the PICO parameters than the ones found here. At a higher resolution we could also consider to compute more than 10 bins, this has not been explored in this study.

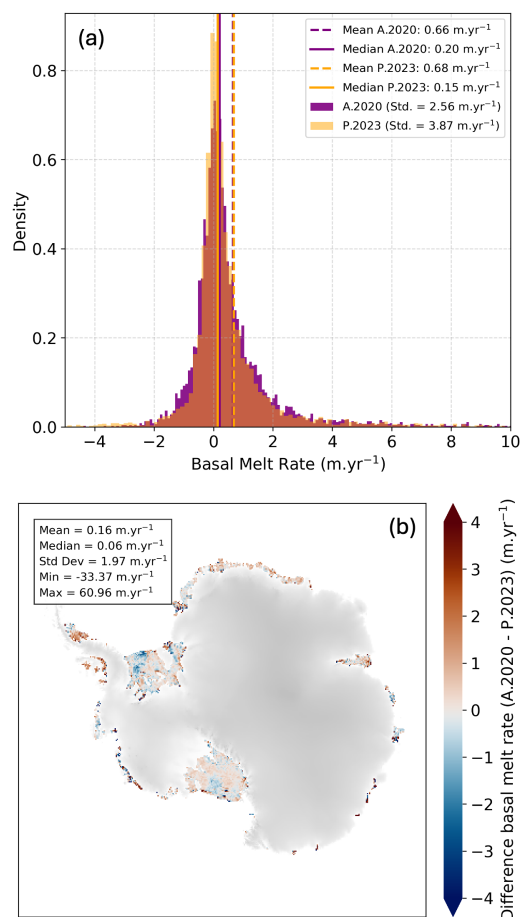


Figure 10. (a) Spatial distribution of the two datasets and main statistics. (b) Difference of basal melt rates between Adusumilli et al. (2020) and Paolo et al. (2023).



Nonetheless, with this analysis using the observational dataset from Paolo et al. (2023) we can justify that the MAE of bins method is more robust than the RMSE of bins in a case where we want to use one set of parameters for the all Antarctic ice shelves. Indeed, as shown on figure 11, the range of values of the parameters suggested by the top five members is smaller for the MAE of bins (C ranging from 0.01 to 0.25 $\text{Sv.m}^3.\text{kg}^{-1}$ and γ_T^* from 1.00×10^{-5} to $5.00 \times 10^{-5} \text{ m.s}^{-1}$) than the RMSE of bins (C ranging from 0.01 to 0.50 $\text{Sv.m}^3.\text{kg}^{-1}$ and γ_T^* from 1.00×10^{-5} to $15.00 \times 10^{-5} \text{ m.s}^{-1}$).

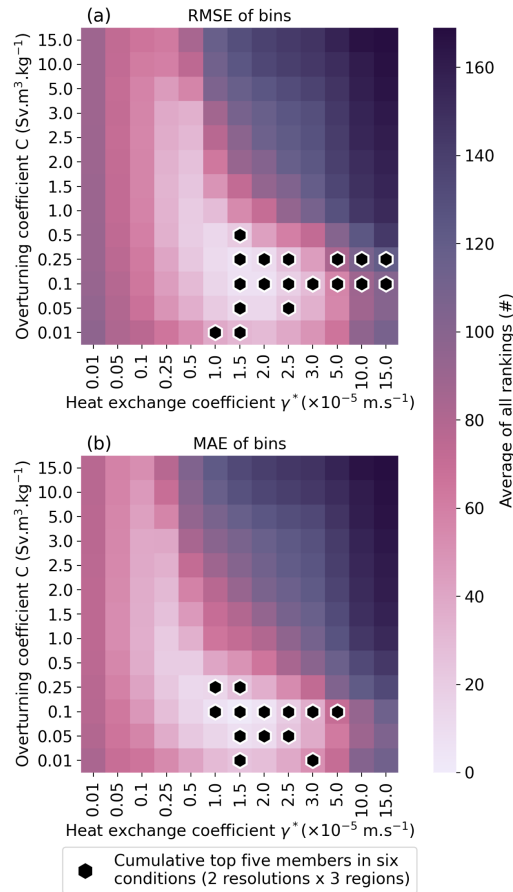


Figure 11. Average ranking of two calibration methods, RMSE of bins (a) and MAE of bins (b), tested under two different resolutions (40 km and 16 km) and applied to three different sectors (Antarctic wide, BA seas, and FRIS) with target the observational dataset from Paolo et al. (2023). The top five members of all six conditions are shown with the black and white hexagons.

4.4 Why does PICO lead to lower sea level contribution estimates than QuadNL in GRISLI?

Overall, including PICO in ice sheet models leads to lower sea level contribution in the simulations up to 2300 shown in figure 7. Indeed, Kori with the PICO parameterisations produces 1.5 m sea level equivalent less than with the QuadNL parameterisation. Similarly, all the PICO calibrations with GRISLI have a lower sea level contribution than with the QuadNL parameterisation.



345 Elmer-ice with PICO suggests even a negative sea level contribution from Antarctica all along the simulation. Of course, there are many other factors influencing future sea level predictions in ice sheet models that are not related to the parameterisation of the ice-ocean interactions; and it is definitely possible to have larger sea level contribution with PICO as shown with the simulation with PISM. But we want here to provide some hypotheses that could explain this overall pattern of lower sea level contribution from simulations with PICO. We outline five possibilities:

- 350
- PICO includes overturning circulation under the ice shelves, which tends to reduce the basal melt rate. This freshwater negative feedback is not included in the QuadNL parameterisation.
 - PICO includes a linear relationship between the ocean temperature and the basal melt rate for high temperatures, whereas QuadNL has a quadratic one. It means that for high projections, if both start off with a similar basal melt rate, the QuadNL will project significantly higher melt rate values with increasing temperatures.
- 355
- The QuadNL parameterisation takes as input 3D fields of oceanic forcings. Whereas PICO takes one value per ice-shelf (T_0 and S_0) which is an average of values over the continental shelf at the depth of the continental shelf, in front of the concerned ice-shelf.
 - PICO tends to have more smoothed out melt rates and does not peak that high at the grounding line. If the basal melt rates at the grounding line is a major factor for ice loss, it could explain a less sensitive response.
- 360
- The QuadNL calibration from Jourdain et al. (2020) implemented in the analysed simulations does not match the re-freezing part of the observations whereas PICO does (see figure 6 panel (b)), therefore this QuadNL calibration could overestimate basal melt rates and its sensitivity to oceanic forcings.

In addition, the results show that a decrease in the total ice shelves area does not mean a positive contribution to sea level rise, and vice versa. We can also obtain a similar sea level contribution with a difference in ice shelves area of up to about 40%.

365 This means that we can have different pathways to the same contribution of sea level rise and the challenge is to understand which pathway is closest to the real physical behaviour of the ice sheet. Here, we advocate for a calibration methodology that fits best the full distribution of the observational datasets, it is a more physical calibration of the process modelled than simply matching the average value for instance. This methodology can potentially be applied to modules in other models that benefit from existing observational datasets. However, regardless to the quality of the calibration, all parameterisations are

370 simplifications of processes. Therefore, one should be aware of the processes represented or not in a model for the interpretation of the outputs.

5 Conclusions and perspectives

The Antarctic ice sheet retreat is driven by ice-ocean interaction and differences in the ice-ocean parameterisations can lead to major differences in future dynamics of the ice sheet. We presented the implementation of the PICO basal ice shelf melt module



375 (Reese et al., 2018) in the GRISLIv.2 ice sheet model (Quiquet et al., 2018). Then we compared six statistical calibration
methods to find the best set of two PICO parameters C and γ_T^* . We demonstrated that the only two methods, the RMSE of bins
and the MAE of bins that forces to fit the target values also at the low and high extremes, provide a robust constraint of both
parameters in a narrower range of values. They give more systematic results, making them more reliable and less dependent
upon the ensemble sampling. The results from these two methods also better reproduce the spatial contrasts observed in the
380 chosen target (Adusumilli et al., 2020). By using these two methods that matches well the entire distribution of the target for
all Antarctic ice shelves combined we also show that we do not need to have a region specific calibration. According to this
research, the best values of the PICO parameters in our specific set up are $\gamma_T^* = 2.0 \times 10^{-5} \text{ m.s}^{-1}$ and $C = 0.1 \text{ Sv.m}^3.\text{kg}^{-1}$.

We did future simulations without re-calibration of the mechanical parameters of GRISLI, such as ice flow and drag, to have
a preliminary assessment of the impact of the choice of the calibration method applied to PICO. On the one hand, we see that
385 the re-calibration of the PICO parameters can lead to major differences in sea level contribution compared to simulations using
parameters values used in previous studies. We showed that only our calibration fits the whole distribution of sub-shelves melt
rates from the observations. On the other hand, the choice of the calibration method does not have a major direct impact on
the sea level contribution, yet it does have a significant impact the ice shelves extent. This remains coherent as the relationship
between ice shelves changes and sea level contribution is still uncertain and ice sheet model dependant (Sun et al., 2020).
390 Thus, our analysis of future simulations is not enough to gain confidence in one specific projection, further work is needed to
constrain the sensitivity of the Antarctic ice sheet using paleo records.

Finally, we thoroughly tested the statistical methods by assessing how robust the results are by applying them to additional
cases such as different resolutions, regions of Antarctica, forcings, and targets. This assessment give us confidence in our
results confirming that the RMSE of bins or the MAE of bins methods are the most robust ones and could avoid modellers to
395 use temperature corrections on top of the parameterisation as well as give more confidence in paleo ice sheet applications at
lower resolutions using present-day data for the calibration (Quiquet and Roche, 2024). The principle of using bins is justified
by observing the magnitude of the spatial disagreement between the observational datasets (Adusumilli et al., 2020; Paolo
et al., 2023). As the MAE of bins gives a smaller parameter space under the six conditions and different targets tested, we
recommend using this method.

400 To progress further, we invite ice-ocean interaction modellers to test the MAE of bins method in their own set up of ice-ocean
parameterisation, ice sheet model and initial state. But also, as the present study has the limitation of targeting a given basal
melt rate for a given ocean temperature rather than the sensitivity of the basal melt rate to changes of ocean temperatures. Reese
et al. (2023) PICO calibration to temperature sensitivity required use of temperature corrections, to combine it with the MAE
of bins calibrations method could enable to calibrate to sensitivity without additional temperature corrections. Alternatively,
405 the low sensitivity of PICO in comparison to QuadNL could also be adjusted by developing a quadratic dependence to thermal
forcing that would give a quadratic parameterisation that also accounts for overturning circulation under the ice shelves.

<https://doi.org/10.5194/egusphere-2025-777>

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Code and data availability. The GRISLI model with the PICO implementation, the outputs of the simulations, as well as the Jupyter Notebook files to do the figures are available on Zenodo (Menthon et al., 2025).



**Appendix A: Standard deviation of the rankings for each methods applied to 6 different conditions (two resolutions *
410 three areas of the Antarctic ice sheet)**

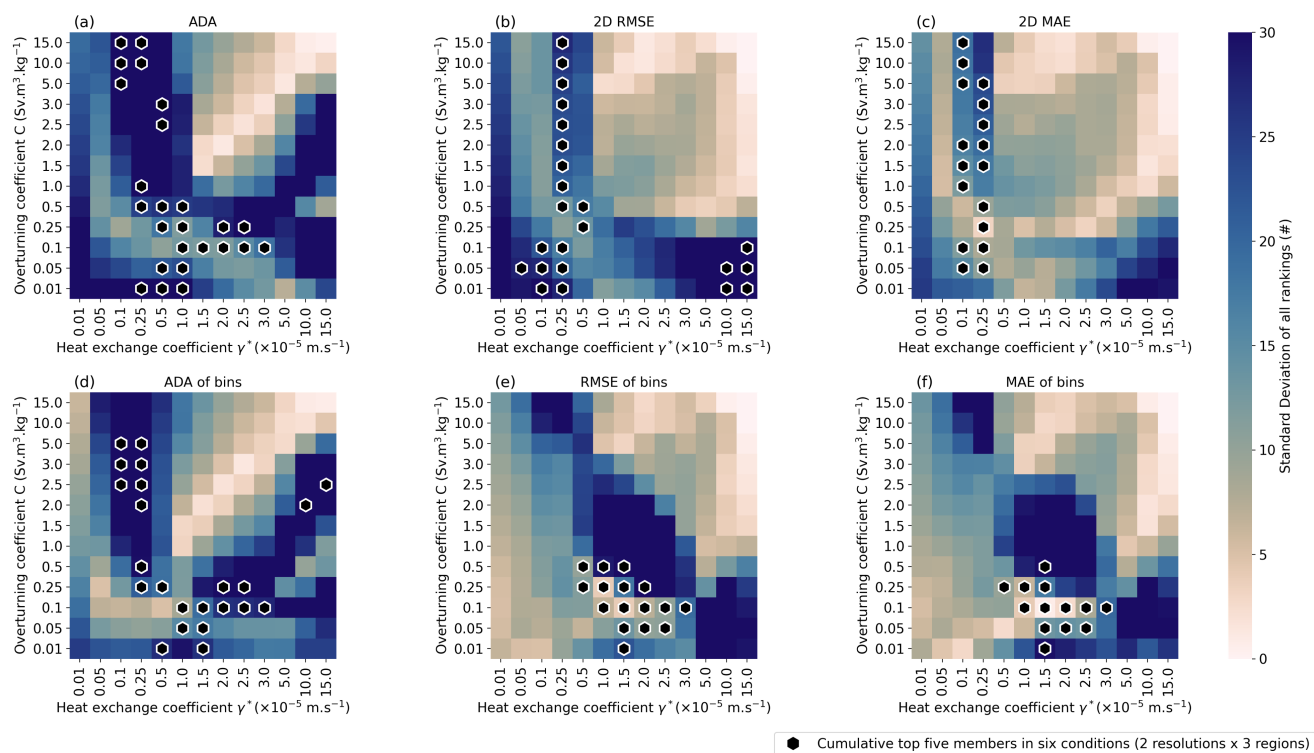


Figure A1. Same as Figure 8 but showing the standard deviation of the rankings under the six different conditions instead of the average. It gives additional information about the degree of confidence and robustness of the methods.

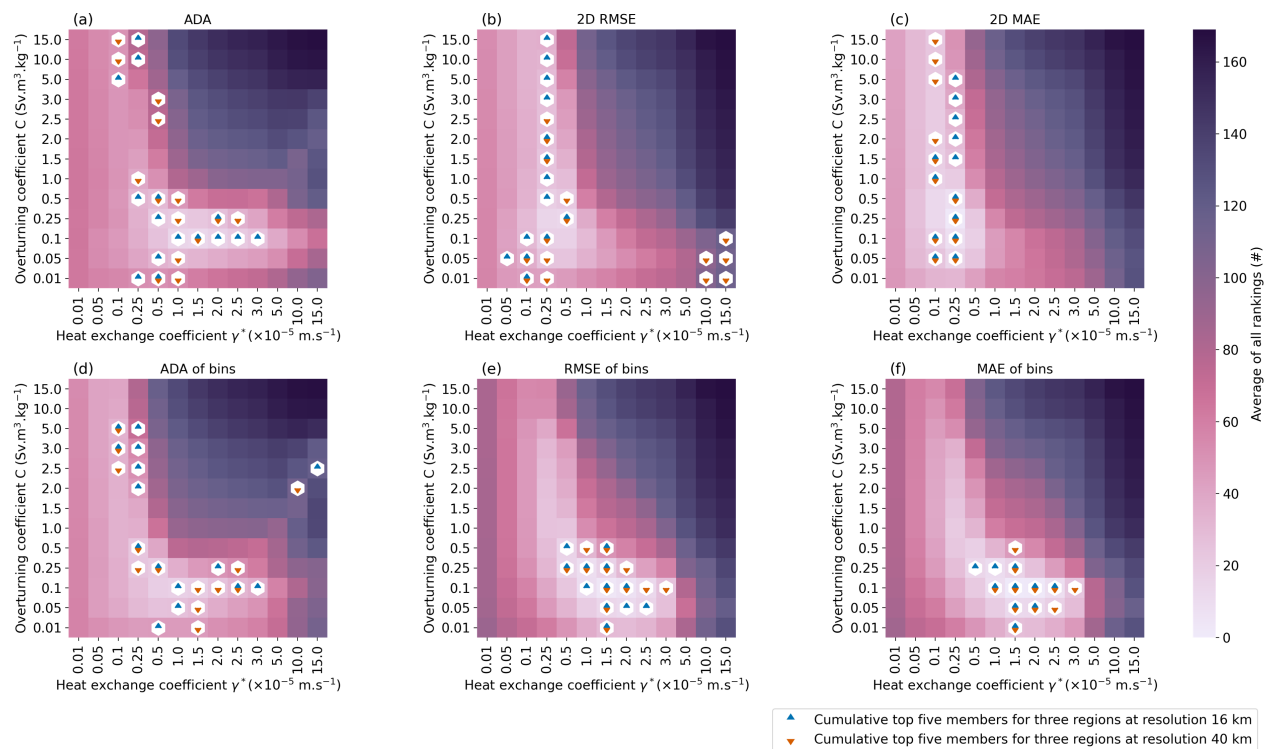


Figure A2. Same as Figure 8 but differentiating the 2 resolutions.



Appendix B: Average and standard deviation of the rankings for each methods applied to six different conditions (two resolutions $\times$ three areas of the Antarctic ice sheet) with as target Paolo et al. (2023) instead of Adusumilli et al. (2020)

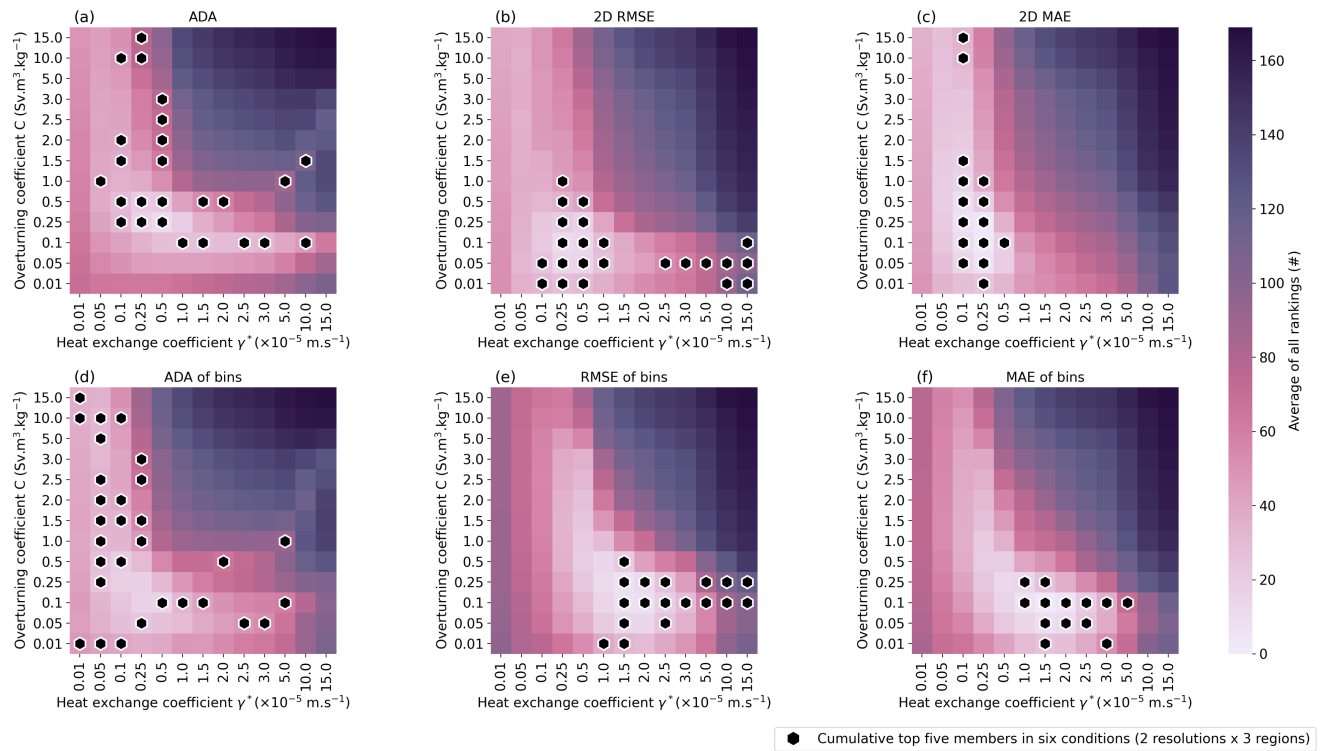


Figure B1. Same as Figure 8 but with target Paolo et al. (2023)

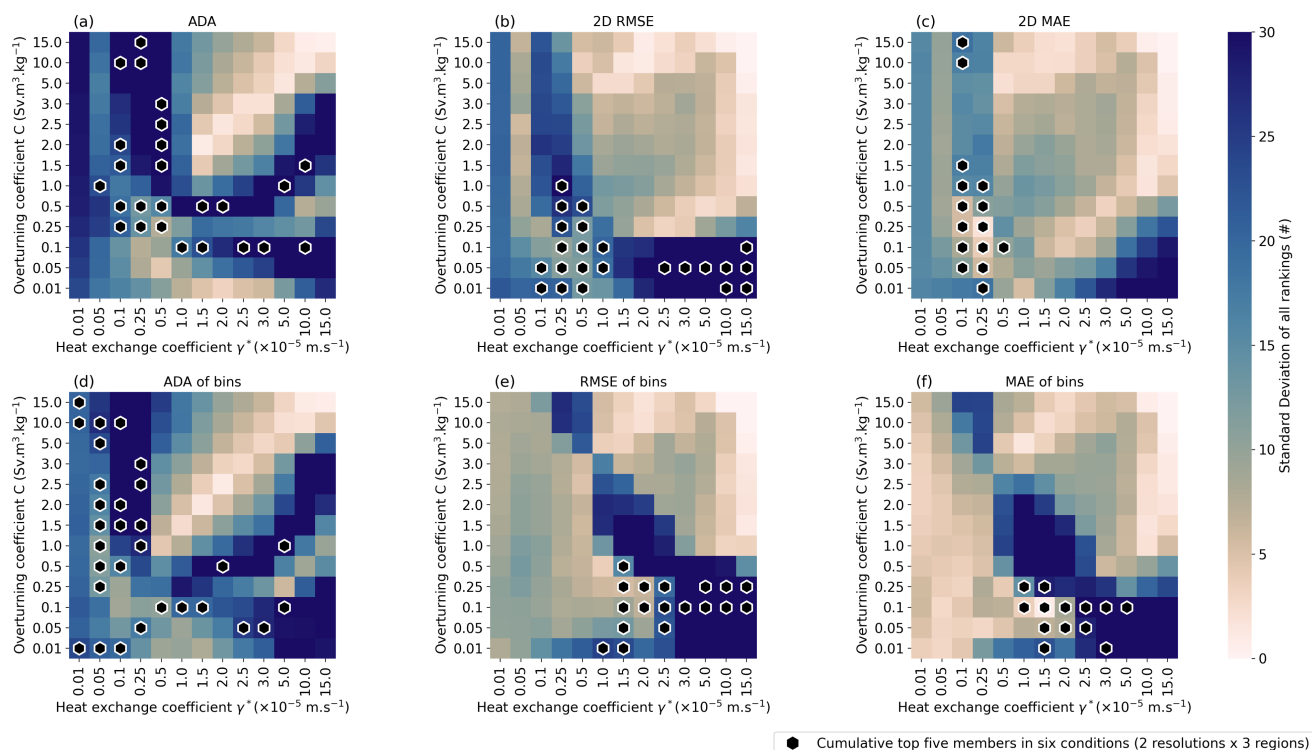


Figure B2. Same as Figure 8 but the standard deviation with target Paolo et al. (2023)

Author contributions. MM led the project and performed the majority of the work. MM made the PICO development and implementation in GRISLI with contributions from PB, AQ and DMR. MM, PB, AQ and RR designed the simulations. MM ran the simulations and analysed the results. MM wrote the manuscript with comments and contributions from all co-authors. PB, AQ and DMR supervised the project. PB acquired the fundings.

Competing interests. The authors declare that they have no conflict of interest.

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ters (see details on the CMIP Panel website at <https://wcrp-cmip.org/cmip-overview/>). Original forcings data sets and simulations results for two-dimensional fields are available on Ghub (<https://theithub.org/dataset-listing>) under “ISMIP6 23rd Century Forcing Data sets”: <https://theithub.org/resources/5161> and <https://zenodo.org/records/13135571> (Nowicki and ISMIP6 Team, 2024a) (Nowicki & ISMIP6 Team, 2024a). Model outputs from the ISMIP-2300 simulations are available on Ghub (<https://theithub.org/dataset-listing>) under “ISMIP6 23rd Century Projections”: <https://theithub.org/re-sources/5163> and <https://zenodo.org/records/13135599> (Nowicki and ISMIP6 Team, 2024b).

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