Blue color: Editor’s comment
Black color: Authors response

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Initialization procedure:

While both reviewers are to varying extents overall favourable, they have both raised issues that need to be addressed in the revisions. Tijn Berends has raised three major concerns about initialization and basal drag, tipping points under steady state forcing, and climate forcing which have been only partly addressed in the author responses. I urge some additional experiments to better address the concerns raised, where feasible.

We thank the editor for his comments. Concerning initialization, we did not use optimized friction coefficients because we believe this approach is not entirely valid for the period investigated. Given the long time elapsed since the Pliocene, we cannot assume constant basal conditions, as both the ice geometry and the temperature varied considerably with respect to the present day (PD). Nevertheless, we have followed the reviewers’ suggestion and performed a new set of experiments where we have optimized friction coefficients and basal-melting rates following Lipscomb et al., (2019) for the same set of values of enhancement factors and sliding exponents that simulated realistic PD states in our first submission. First we optimize for 30.000 years for PD conditions. The ensemble mean simulated PD state is shown in Figure 1, together with the root-mean square errors. Figure 2a and 2b show the root-mean square error of each simulation and Fig. 2c the ice volume and extent difference with the observations.

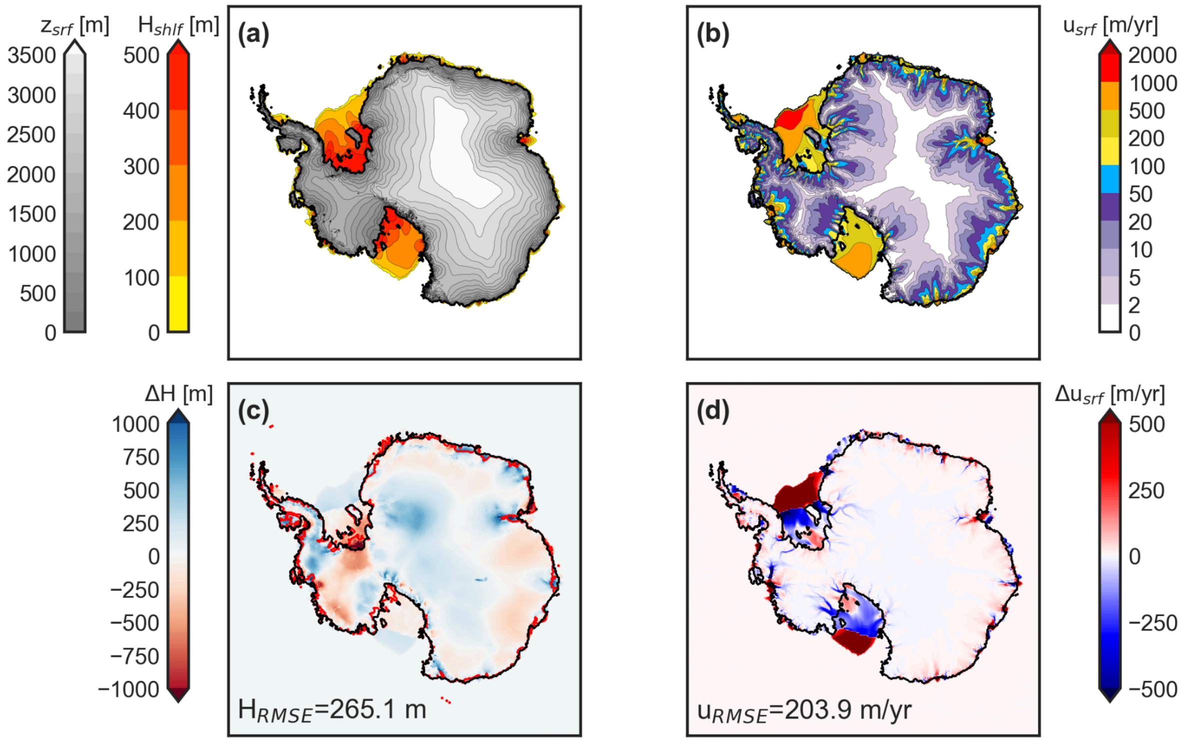


Figure 1: Mean PD state of all the optimized PD simulations. (a) surface elevation (grey colors) and ice shelf thickness (orange); (b) surface velocity; (c) ice thickness (d) surface velocity anomalies with PD observations and its respective RMSE.

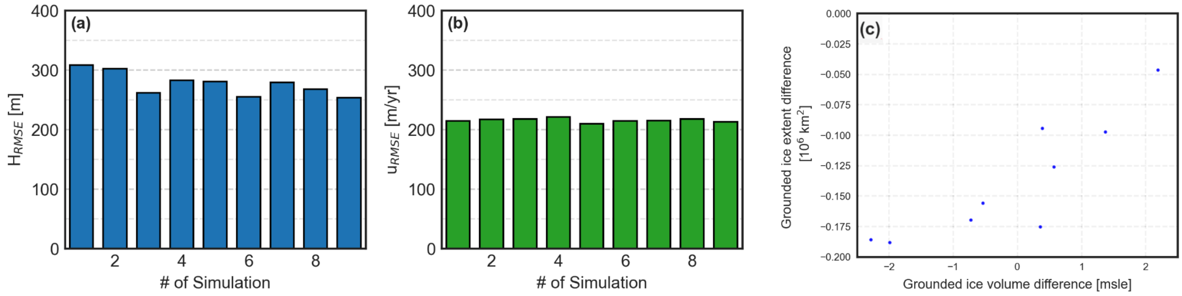


Figure 2: RMSE of ice thickness (a) and surface velocity (b) of the ensemble of simulations performed with the same set of values that simulated realistic PD present-day states in our first submission. (c) Ice volume and extent difference with the observations.

We then force these PD states with the PlioMIP2 climatologies (Figure 3). In terms of sea-level contribution, the optimized results are similar to those of the simulations with non-optimized friction coefficients, but the spread is lower, since we consider less simulations (9 optimized simulations, 31 non-optimized simulations). In terms of ice extension, both cases show similar values except for MIROC4m, which shows a lower ice extent. However, this is not surprising at all, since the optimized simulations have not reached equilibrium. If we let the optimized experiments run for 30.000 years with PD forcing we see that the ice volume decreases for 7 of 9 cases indicating a WAIS collapse (Figure 4). Such a trend in ice volume for optimized friction coefficients has been observed in other ice-sheet models for even shorter timescales (i.e. *Seroussi et al., in prep.; Coulon et al., 2023*). Though our optimized values simulate similar Pliocene contributions as our non-optimized case, we believe that basal-friction coefficient optimization is not the best approach for long timescales since it leads to a trend. Since, in addition, this approach is not totally justified, we prefer to maintain our original methodology.

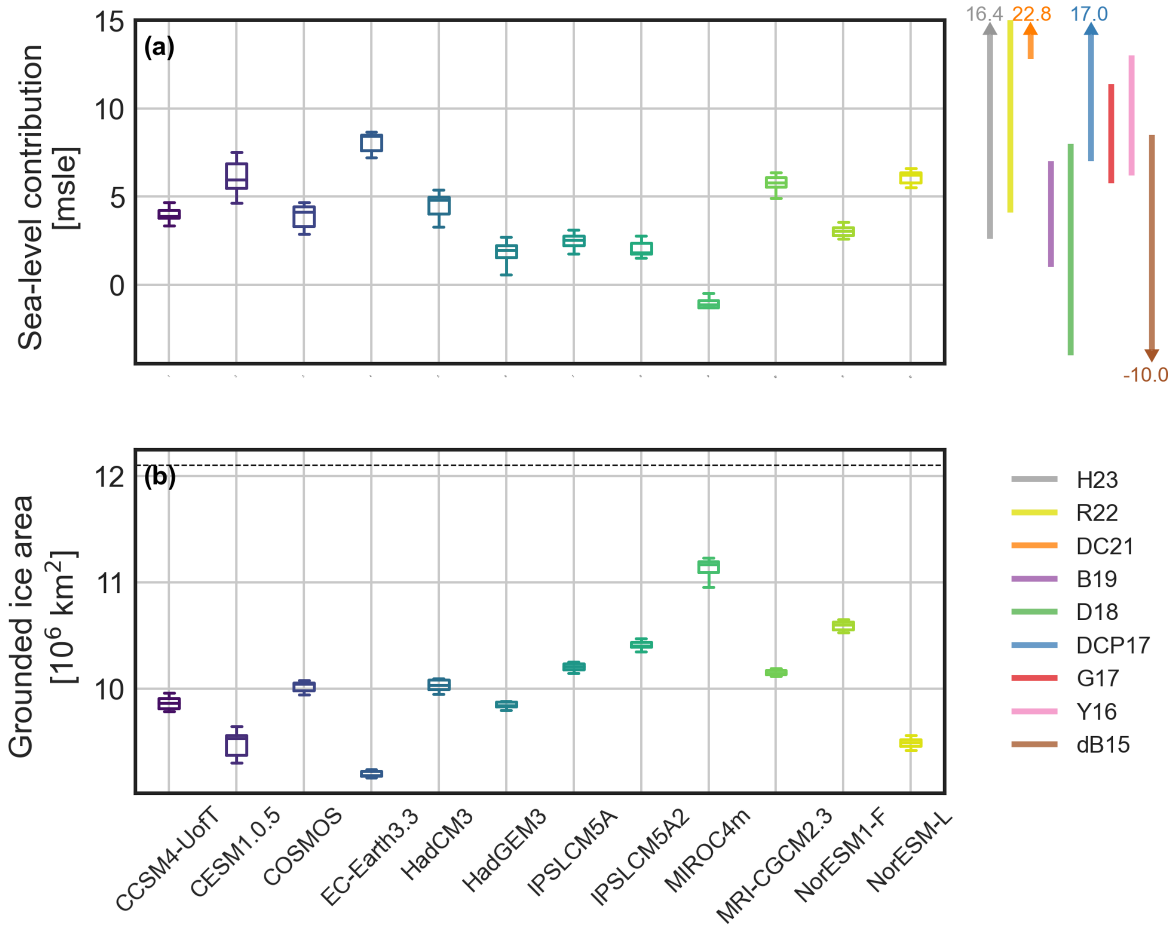


Figure 3: Boxplot of the simulated (a) sea-level contribution (positive/negative numbers indicate a lower/higher ice volume); (b) grounded ice extent for every AOGCM. The scatter-point shows the mean values of the ensemble. The error bars represent the lowest/highest simulated AIS state starting from PD conditions. Light shaded colors at the right show the sea-level uncertainty ranges from the studies of deBoer et al., (2015, brown); Yan et al., (2016, pink); Golledge et al., (2017, red); DeConto and Pollard (2017, blue); Dolan et al., (2018, green); Berends et al., (2019; purple); DeConto et al., (2021, orange); Richards et al., (2022; yellow); Hollyday et al., (2023; grey). The dashed black line in (b) represents the PD grounded ice extent.

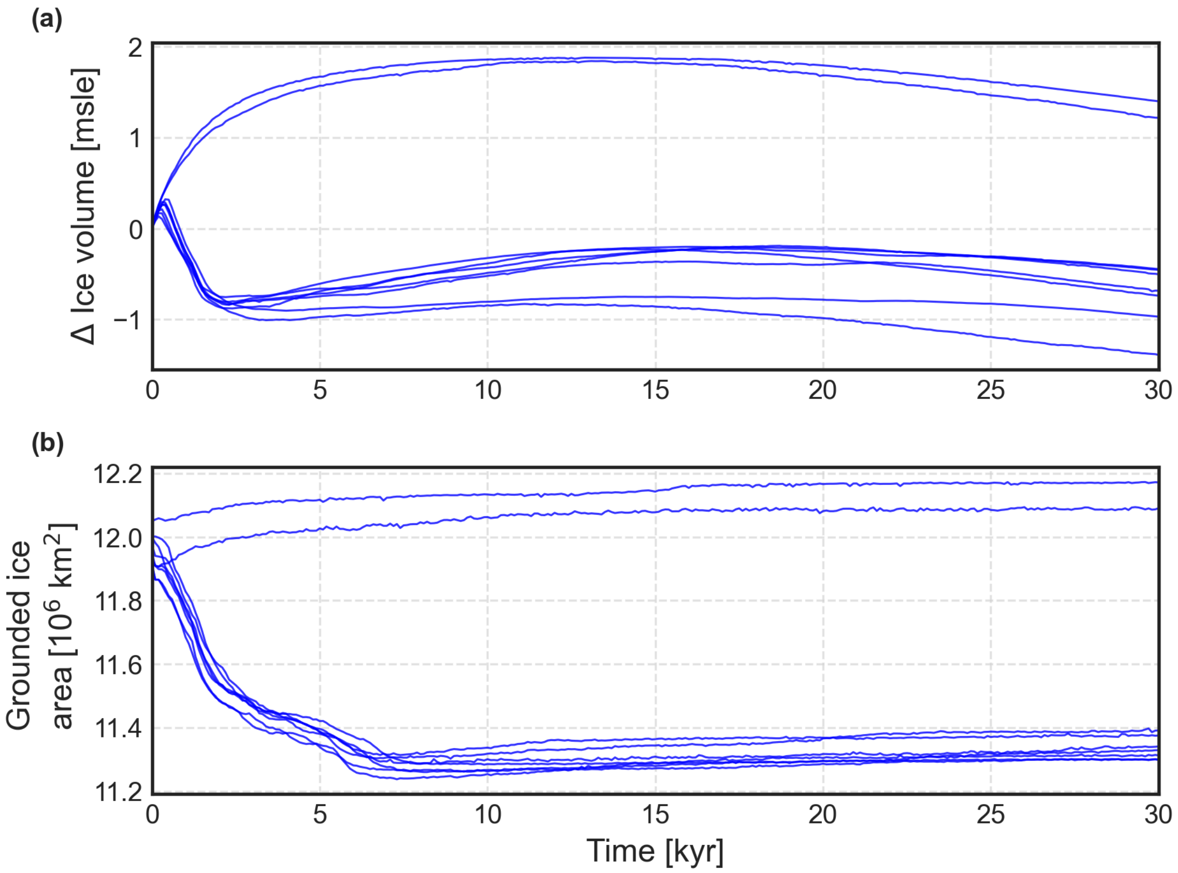


Figure 4: Ice volume evolution and grounded ice extent for PD optimized experiments under PD forcing.

Technical comments:

20 terrain-following vertical layers.
do you mean sigma coordinates?

Yes, we have changed it in the updated manuscript. .

basal friction is scaled at the grounding-line points with its proportional grounded fraction
incomprehensible

Indeed; in the updated manuscript it is now clearer.

eq 4 What exactly to do you mean by Tatm? 2 meter air temperature or ?

Indeed, the 2 m air temperature. It is made clearer in the following submission.

order to account for surface temperature and precipitation changes in elevation, due to the Clausius-Clapeyron relation, a lapse rate correction factor is applied, 0.008 K m−1 for annual

temperatures and 0.0065 K m−1 for summer temperatures (Ritz et al., 1996; De- Conto and Pollard, 2016; Quiquet et al., 2018; Albrecht et al., 2020).
eq 4 What exactly to do you mean by Tatm? 2 meter air temperature or ?
not clear how lapse rate is used for precipitation changes also, make clear as to whether the indicated lapse rates are based on free air vertical gradients, present-day surface elevation gradients, or 2 m air temperature gradients. And justify your choice if not based on the latter.

Equations 4 and 5 refer to sea-surface elevation. PD climatologies obtained from RACMO2.3 as well as from the mPWP are scaled to sea-surface elevation through a lapse-rate factor with the surface elevation provided by RACMO2.3 and PlioMIP2, respectively. The lapse rate factor is taken as a free parameter with the typical value of -0.008 K/m for annual temperatures and to -0.0065 K/m for summer temperatures. Then, these climatologies are scaled to the ice-sheet surface elevation through the same lapse-rate factor. This ensures that changes in elevation are taken into account in our simulations and any potential bias driven by elevation differences are avoided. The lapse rate factor affects precipitation via an exponential temperature scaling - this is now clarified in the new manuscript.

model description far from complete. Missing (need not be extensive) descriptions: GIA, bed thermal model, surface melt refreezing, calving, ..

If the temperature at the ice base reaches the pressure melting point, then it is set to the pressure melting point, and the basal mass balance is diagnosed as in Cuffey and Paterson (2010), where the geothermal heat flow field is obtained from Davies (2013). The glacial isostatic adjustment is computed with the elastic lithosphere-relaxed asthenosphere method (Le Meur and Huybrechts, 1996), where the relaxation time of the asthenosphere is set to 3000 years.The calving rate C is derived as a sum between the principal stresses (τ1 and τ2) as in Lipscomb et al. (2019). From the computed melting through the ITM model we assume that a 60% refreeze as in Robinson et al. (2010). All of these details have now been included in the new manuscript.

Fig S1:
are the values plotted total or grounded fraction?

Only for grounded ice. We changed the y-axis description.

there are a few place where you use ice "extension", when you mean 'area', eg Fig 5 caption, Fig S1

We changed it to “extent”.

Ocean forcing : make clear if you account for subglacial meltwater discharge on ocean salinity, and justify if this is not the case.
what about uncertainties in marine climate/circulation which controls submarine ice melt?

We do not take subglacial meltwater discharge into account since we do not couple any AOGCM to our ice sheet model. The updated manuscript includes a discussion on this.

do you really mean "probability" without doing a proper statistical analysis?
please provide a clear argument why this would be "statistically significant"? I don't see one

Statistically speaking, the more data you have, the more robust the conclusion is. In probability theory the distribution of the mean of a random sample converges to a normal distribution if the sample is large enough (the central limit theorem). Usually 30 and above are considered as valid sample sizes to apply the central limit theorem. We give our simulations which fall inside our threshold range (< 2% difference with PD ice volume and extension) the same weight. Then, we use boxplots to assess the 1st quartile (25%) and 3rd quartile (75%). Our updated uncertainty range in the manuscript is included inside the interquartile range. We believe this can be interpreted as a statistical analysis.

some uncertainties not addressed: earth rheology for GIA, geothermal heat flux, climate downscaling Crow et al, (in this same special edition).

Indeed, we have extended our discussion section by mentioning uncertainties which were not previously considered in our study, such as GIA, geothermal heat flow, a spatial variable lapse-rate factor or coupling with an AOGCM.

“Here, cf is a dimensionless field representing the basal properties of the base, such as soft/hard beds. Here we will use it for calibration of the model”
you need to document somewhere how this is done. And by calibration, do you just mean tuning?
need more details about parameter selection. Eg, is PD ice volume and area only sieve conditions? What about fit to observed grounding lines?

Yes, with calibration we mean tuning towards PD conditions.

The friction law used in this study follows

$$\boldsymbol{\tau}_\mathrm{b} = c_\mathrm{b} \left(\frac{|\mathbf{u}_\mathrm{b}|}{|\mathbf{u}_\mathrm{b}| + u_0} \right)^\mathrm{q} \frac{\mathbf{u}_\mathrm{b}}{|\mathbf{u}_\mathrm{b}|}$$

$$c_\mathrm{b} = c_\mathrm{f} \lambda N$$

$$\lambda = \begin{cases} 1 & \text{if } z_b \geq 0 \\ \max\left[\exp\left(-\frac{|z_b|}{400}\right), 10^{-4}\right] & \text{if } z_b < 0 \end{cases}$$

where c_f is a unitless coefficient, which in our study ranges from 0.1 (soft beds) to 1.0 (hard beds).

The parameters are chosen to simulate a difference between the observed ice volume of less than 1 mSLE and a deviation in the grounded area of less than 2%. This has to be fulfilled for the whole AIS. We found that these conditions matched a good PD state in terms of ice volume and extension.

To assess the grounding-line mismatch we plot the ice-mask difference between the simulated and the observed ice mask (1: grounded ice, 0: floating ice/ocean) for our parameter space that fulfilled the above condition. The lowest and best fit are then chosen as a quadratic sum of the mask difference (Figure 2). Overall we find more advanced EAIS and Ronne grounding lines. On the other hand, the Ross grounding line tends to retreat more than observations. These initial states fit well within the range of ISMIP6-Init (Seroussi et al., 2019), thus we believe that our approach can be considered as valid. This figure will be included also in the supplementary material of the manuscript.

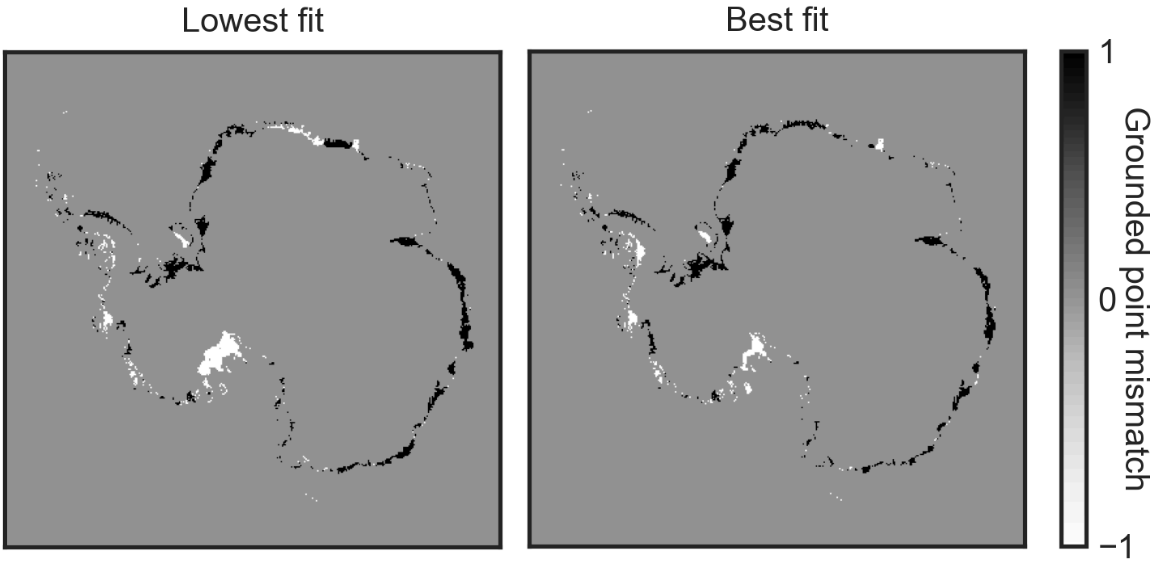


Figure 2: Lowest and best fit of our chosen ensemble parameters. Value zero represents the same mask value between the simulated and the observed ice mask. 1/-1 represent advanced/retreated grounded points with respect to the observations.

need to justify range choice for this parameter. 6 is awefully high
and the statement is misleading when you only have 3 adjustable parameters (going by table 1)

The choice of this parameter was to cover the whole range that simulates realistic ice volumes and extensions, including extreme cases. It was based on Ma et al., (2010), who considered values up to 5 (though with lower enhancement factors for ice shelves). Actually, the value 6 did not simulate a realistic extension or ice volume. We will therefore remove it from the manuscript.

Some additional constraints such as present-day basal temperature at EDC and EDML would offer some independent constraint on this parameter.
“Regarding ice dynamics, our analysis revealed that the enhancement factor has the strongest influence on the extension of ice”

Figure 5 shows the PD mean simulated basal temperature of the AIS, highlighting the Dome C (EDC) and EDML ice-core locations. In the case of EDML all simulations reach the pressure-melting point, which leads to a temperate bed (Table 1). At Dome C we find that with the exception of two simulations, the rest yield a base temperature close to the pressure-melting point (the lowest temperature is -0.8 °C). These results are in agreement with observations and modeling studies (Van Liefferinge et al., 2018).

The simulated base temperature is therefore not only a function of the enhancement factor, but also dependent on other variables subject to uncertainty, such as geothermal heat flow, basal friction or water drainage system. Since the obtained values are similar, we do not believe that it can be used as a metric to constrain values of the enhancement factor.

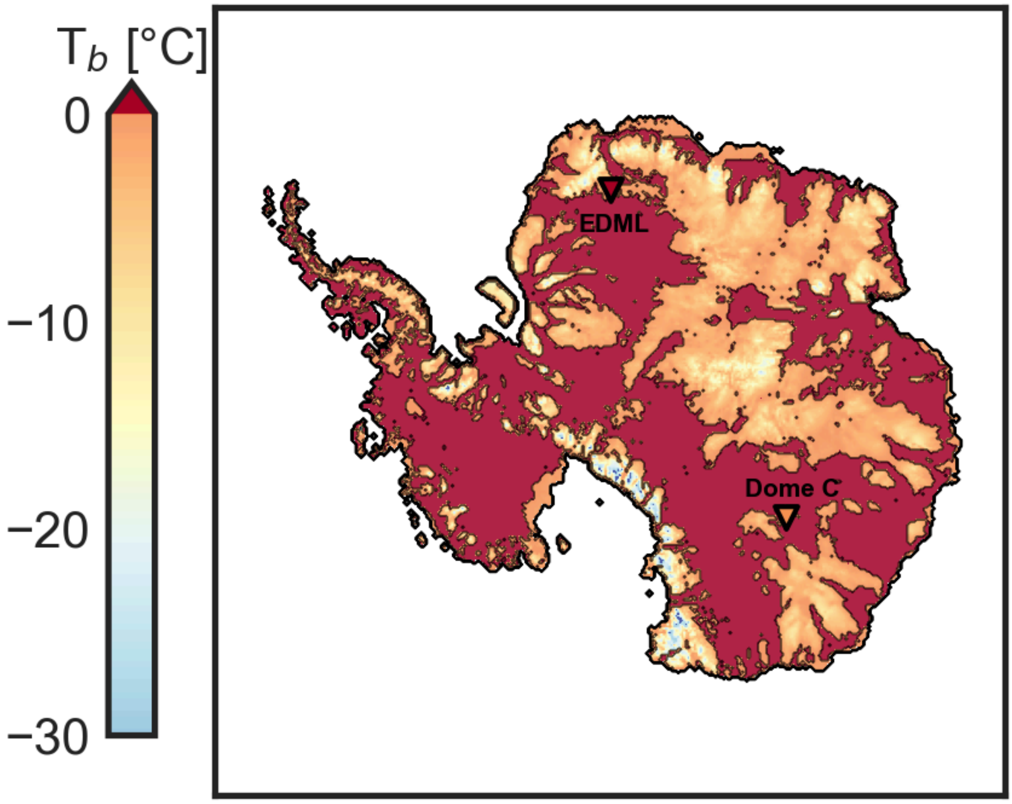
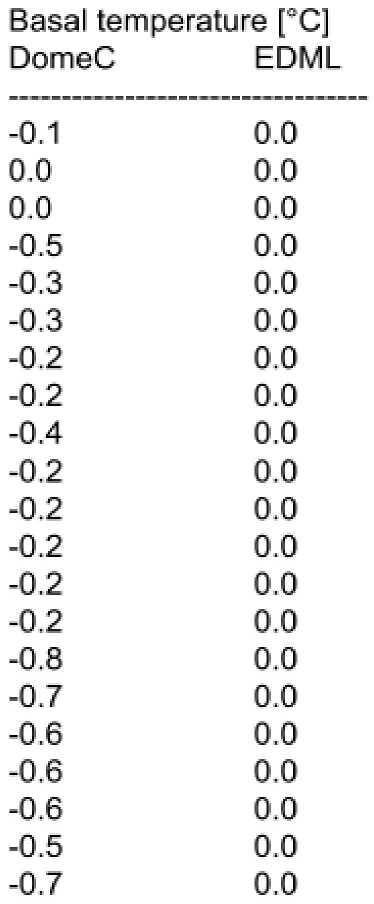


Figure 5: Mean simulated basal temperature highlighting the EDML and DomeC. Red color indicates a temperate base.



Basal temperature [°C]	
DomeC	EDML
-0.1	0.0
0.0	0.0
0.0	0.0
-0.5	0.0
-0.3	0.0
-0.3	0.0
-0.2	0.0
-0.2	0.0
-0.4	0.0
-0.2	0.0
-0.2	0.0
-0.2	0.0
-0.2	0.0
-0.2	0.0
-0.8	0.0
-0.7	0.0
-0.6	0.0
-0.6	0.0
-0.6	0.0
-0.5	0.0
-0.7	0.0

Table 1: Simulated basal temperature for every simulation at DomeC and EDML.

References:

- Ma, Ying, et al. "Enhancement factors for grounded ice and ice shelves inferred from an anisotropic ice-flow model." *Journal of Glaciology* 56.199 (2010): 805-812.
- Van Liefferinge, Brice, et al. "Promising Oldest Ice sites in East Antarctica based on thermodynamical modelling." *The Cryosphere* 12.8 (2018): 2773-2787.
- Seroussi, H., Nowicki, S., Simon, E., Abe-Ouchi, A., Albrecht, T., Brondex, J., Cornford, S., Dumas, C., Gillet-Chaulet, F., Goelzer, H., Golledge, N. R., Gregory, J. M., Greve, R., Hoffman, M. J., Humbert, A., Huybrechts, P., Kleiner, T., Larour, E., Leguy, G., Lipscomb, W. H., Lowry, D., Mengel, M., Morlighem, M., Pattyn, F., Payne, A. J., Pollard, D., Price, S. F., Quiquet, A., Reerink, T. J., Reese, R., Rodehacke, C. B., Schlegel, N.-J., Shepherd, A., Sun, S., Sutter, J., Van Breedam, J., van de Wal, R. S. W., Winkelmann, R., and Zhang, T.: initMIP-Antarctica: an ice sheet model initialization experiment of ISMIP6, *The Cryosphere*, 13, 1441–1471, https://doi.org/10.5194/tc-13-1441-2019, 2019.
- Coulon, V., Klose, A. K., Kittel, C., Edwards, T., Turner, F., Winkelmann, R., and Pattyn, F.: Disentangling the drivers of future Antarctic ice loss with a historically calibrated ice-sheet model, The Cryosphere, 18, 653–681, https://doi.org/10.5194/tc-18-653-2024, 2024.
- Seroussi et al. (*in rev.*): Evolution of the Antarctic Ice Sheet over the next three centuries from an ISMIP6 model ensemble.