Responses to Reviewer #2

In this manuscript, the authors present observational and modelling results for the temperature distribution of the Amery Ice Shelf. Observations are from borehole measurements along three different flow lines and encompass sites with and without basal layers of marine ice. Two types of simulations are discussed, namely (i) 3-D simulations with the Elmer/Ice model, and (ii) 1-D simulations of ice columns advected along flow lines. The authors compare the findings from the observations and simulations, revealing a generally reasonable agreement. Systematic deviations occur in the marine ice layers, for which the observations show essentially isothermal conditions due to the presence of liquid saltwater. Reproducing this by the simulations would require a particular treatment of the thermodynamics of marine ice, which is identified as a crucial component for future work.

The study is somewhat preliminary in nature, and I do not think it has the potential to be a game-changer in the field. However, science is largely an evolutionary process, and not every paper can be. It is still a decent piece of work and presents results that are of interest to the community. Therefore, I think it should be considered for publication. However, I would like to raise some issues that should be dealt with before that.

Clearly this is not the last word in simulating the 3-D temperature distribution in the Amery Ice Shelf. We were pleased that the reviewer recognised that our study highlights the need for a more sophisticated treatment of the thermodynamics of marine ice zones. We naturally agree that the results should be of interest to the community. To the best of our knowledge, this is the most comprehensive comparison of modelled and observed ice shelf temperatures presented to date.

Since the paper draws strongly on Gladstone et al. (2021), I think it should not be published before the latter one is available at least as a preprint with a persistent identifier (e.g., DOI). The separation of the two studies does not always become clear. This refers in particular to Section 2.2: I don't fully understand what was already done by Gladstone et al. (2021), and what is new. This should be made crystal clear in all details. Further, as Section 2.2 is a subsection of "Data and methods", any results (such as Fig. 2 and accompanying text - even if already discussed by Gladstone et al. (2021)) should be moved to Section 3.

The paper we cited in our original manuscript as Gladstone et al. (2021, in preparation) has been delayed, and we have taken up the reviewer's suggestion as much as possible by making the detailed methodology of that work available and citable as Gladstone et al, (2022) on Zenodo (https://doi.org/10.5281/zenodo.5862046).

We recognize that the original Sect. 2.2 was not clear enough, and the boundary between this manuscript and Gladstone et al. (2021, in preparation) was a bit vague. We have reconstructed the structure of Sect. 2.2 to make clearer the relationship between Gladstone et al. (2022) and this manuscript.

"The simulations presented here build on a larger study currently in progress (methodology described by Gladstone et al., (2022)), and we take simulations from that work as our starting point…"

We also provide more details of our model set-up in Sect. 2.2 to make it self-contained.

To summarise the methodology document:

Gladstone et al (2022) describes exploration of several approaches to initialising regional Antarctic ice sheet models, with respect to optimisation of parameters controlling basal sliding and ice stiffness, via the basal resistance parameter β, and the viscosity enhancement factor E_η, respectively. It also examines alternative boundary conditions for the solution of the dynamical equations (the Stokes or momentum balance equations).

Our paper uses several of those concepts. In particular, by prescribing the basal mass balance

of the ice shelf as part of the dynamical ice shelf basal boundary conditions, as suggested by Gladstone et al. (2022), we are able to explore how different estimates of the distribution of basal melting and freezing for Amery Ice Shelf affect the 3-D ice velocity field and thereby influence the 3-D temperature distribution throughout ice shelf. The other novel feature used in our paper is that, again based on the experience of studies in Gladstone et al. (2022), we adopted a different dynamical boundary condition at the upper ice surface. We have explained both these non-standard boundary conditions in more detail in our revised Sect. 2.2.2.

Regarding the presentation of the optimized parameter fields for our starting point, in Figure 2 (Figure 3 in the revised version), we disagree with the Reviewer's contention that these belong in Results. They are not results of our work, but inputs. In our revised Sect. 2.2.1, we further clarify this point:

"The current study uses the final model state of their experiment E3 as our starting point, including the optimized basal resistance parameter β, and viscosity enhancement factor E_η. The spatial distributions of the two parameters are shown in Fig. 3, together with the achieved match to observed velocities (Rignot et al., 2017)."

The story with the temperature field of the 3-D simulations confuses me. In line 165, the authors say that the temperature field is computed by Elmer/Ice, whereas in lines 188-190, they explain that they use englacial temperatures computed by SICOPOLIS for ISMIP6-Antarctica. The latter statement is essentially repeated in lines 198/199 ("The original ice temperature field from the SICOPOLIS modelling is retained throughout"). How does this go together?

We apologise for the confusion, and have revised in the new Sect. 2.2 to clarify this:

"In our simulations, we first optimize the ice flow dynamics across the LAGS for each of our choices for ice shelf BMB forcing. We do this by optimizing spatial distributions of basal resistance and ice viscosity using adjoint inverse methods..." And "we use a 3-D ice temperature field from the SICOPOLIS modelling (Greve et al., 2020; Seroussi et al., 2020) throughout the two inversion steps (Fig. 2)."

After these two inversion steps, "we then generate the corresponding 3-D steady-state temperature distributions, using Elmer/Ice to solve the steady-state advection-diffusion equation..."

I noticed quite a few issues with the English writing. Some of them are pointed out below, but the manuscript can certainly do with a very thorough round of proofreading.

Thanks for your suggestions below. We have read the full text repeatedly and conducted a very thorough proofreading. Several authors have also reviewed the entire manuscript as suggested.

Detailed comments:

Line 33/34: Inconsistent capitalization. I'd suggest capitalizing the whole term as "Lambert-Amery Glacial _S_ystem (LAG_S_)". This entails several further changes to "LAG_S_" throughout the manuscript.

Thanks for pointing this out. We agree to use the term LAGS throughout the manuscript.

Line 50: "of _the_ marine ice layer"

Modified.

Line 56: "in_-_situ"

We checked the English guidelines of The Cryosphere. It said that *Latin phrases should not be hyphenated (e.g., "in situ", not "in-situ").*

Line 64: "water_-_filled"

Modified.

Line 84: "in_-_situ"

As we responded regarding Line 56, *Latin phrases should not be hyphenated (e.g. "in situ", not "in-situ") as required by the Cryosphere.*

Line 91: of _the_ basal melt rate

Modified.

Line 94: "lower surfaces_,_ and the transition temperature"

Added.

Line 120: "through _the_ AM03 borehole"

Added.

Line 121: "close by _the_ AM02 borehole"

Added.

Line 124: "ice shelf temperature_,_ and the other"

Added.

Line 163:"The 3-D steady-state temperature simulations"->"3-D steady-state temperature simulations"

Modified.

Line 166: "ice flow dynamics_,_ the current study"

Added.

Equation (1): Add a comma after the equation.

Added.

Line 171: "varies the viscosity, η" -> "varies the viscosity η"

Modified.

Equation (2): Add a comma after the equation.

Added.

Equation (3): Add a full stop after the equation.

Modified.

Equation (4): Why is the enhancement factor squared? Usually (e.g., Greve and Blatter, 2009, "Dynamics of Ice Sheets and Glaciers", Springer, Sect. 4.3.4), it appears as a linear term in the ice viscosity.

In Greve and Blatter (2009), their viscosity expression is actually

$$\eta = \frac{1}{2} E^{-1/n} A(T_h)^{-1/n} \dot{\varepsilon}_e^{\frac{(1-n)}{n}}$$

because they term E a *flow enhancement factor* for the Glen flow relation, connecting strain rates to deviatoric stresses (essentially a prefactor to the *flow rate factor* A). So, the relationship between their factor and our *viscosity enhancement factor* is:

$$E^{-1/n} = E_\eta^2$$

In the inversion process, the parameter we optimise doesn't have to be the flow enhancement factor (E) itself. We use the square of our optimizing parameter to ensure that the factor rescaling the viscosity is never negative which would be non-physical. This is about the separation between the optimization process itself and the actual enhancement factor in the ice flow relation, as used to calculate the effective viscosity. In a similar fashion, the use of the dimensionless parameter β to parameterize the basal drag coefficient ensures that the coefficient is always positive so that basal friction always opposes the sliding velocity.

Equation (4): Add a full stop after the equation.

Added.

Line 188: "In this study_,_ we utilize"

Added.

Line 190:"generated with the SICOPOLIS model (Greve et al., 2020; Seroussi et al., 2020)"

Modified.

Line 210, "Tikhonov regularisation parameters": Give a reference for this.

Thanks for this comment. We added two related references here.

Equation (5): Add a comma after the equation.

Added.

Lines 259/260: "We use _a_ surface resistance coefficient..., and _a_ reference speed..."

Modified.

Line 290: "is assumed _to be_ given by"

Modified.

Equation (6): Add a comma after the equation.

We removed Equation (6) after rewriting the 1-D simulation descriptions.

Lines 293/294: "scale it linearly with depth to zero at the lower surface to approximate the vertical advection": While this should be a reasonable approximation for grounded ice, I don't think it is good for floating ice because of the generally significant basal mass balance (melting/freezing). This requires a comment.

Thanks for drawing attention to a source of confusion. This original remark was meant to apply only to the grounded ice sheet. We have substantially rearranged the description of the 1-D column simulations (Sect. 2.3) and improved the wording.

We clearly present the SMB and BMB used throughout the 1-D simulation process "According to the location of the ice column at each time step, the surface mass balance (SMB) is extracted from the 1979–2016 mean data of RACMO2.3p2 (a regional atmospheric model; Van Wessem et al., 2018). Similarly, the BMB within the floating sector is extracted from Adusumilli et al. (2020) (i.e., BMB_CAL), while zero BMB is imposed for the grounded ice." And we clarified that "The vertical velocity in the ice column, taken as varying linearly with depth, is thus determined by the prescribed SMB, BMB and vertical strain rate."

Line 313: "column simulation_s_"

Modified.

Line 335: "at _the_ pressure melting point "

Modified.

Line 344: "Borehole thermal regime_s_"

Modified.

Fig. 5b: What is the meaning of the dotted parts of the red curve?

We have explained this in the last sentence of the caption of Fig. 5 (Fig. 7 in the revised manuscript).

Line 357: "(a) at AM01, AM04 and AM05, and (b) at AM02, AM03 and AM06" -> "(a) at AM01, AM04 and AM05 (with marine ice), and (b) at AM02, AM03 and AM06 (without marine ice)"

Thanks for this suggestion. Modified.

Line 359: "mark impermeable (solid line) _and_ permeable (dotted line)"

Modified.

Line 360: of _the_ upper and lower surfaces

Added.

Line 370: "500m" -> "500 m"

Modified.

Lines 452/453: "from grounded ice to floating ice shelf" -> "from grounded to floating ice"

We wanted to emphasise the different regimes clearly, so we have replaced with "from grounded ice sheet to floating ice shelf".

Line 510: "at _the_ AM02, AM03 and AM06 sites"

Modified.

Line 536: "at high-elevation" -> "at high elevation"

Thanks for pointing out the stray hyphen. We replaced this with “at high elevations”.

Line 545: "with _the_ ocean below"

Added.

Lines 581/582, "Considering that it takes ~1100 years for ice to reach the ice front from the southern grounding zone": This statement requires a reference.

We modified this to read: “Considering that it takes ~1100 years for ice to reach the ice front from the southern grounding zone under present day velocities (Rignot et al., 2017), this could cause a bias in our simulated temperature distribution.”

Line 583: "20th _c_entury"

Modified.

Line 584: "steady state_,_ then"

Added.

Line 586: "spatially variations" -> "spatial variations"

Modified.

Line 608: "measurements)_,_ which means"

Thank you. Resolved when we rewrote this long sentence (lines 696-610) in response to Reviewer 1.

Line 632: "in_-_situ"

As we responded for Line 56, *Latin phrases should not be hyphenated (e.g. "in situ", not "in-situ") as required by the Cryosphere.*

Lines 694-697: These two sentences are a bit convoluted. Rather something like "The AM01, AM04 and AM05 boreholes have a permeable basal layer of porous marine ice approximately 100 m thick, which appears to conform to the pressure-dependent seawater freezing temperature. The AM02, AM03 and AM05 boreholes experience active melting, and large temperature gradients up to -0.36 degC m-1 are found at the base."

Thanks for this suggestion, modified.

Line 721: "This study presents the first quantitative analysis of the 3-D temperature field of the Amery Ice Shelf":

Is this really true in view of the companion paper by Gladstone et al. (2021, in prep.)?

As mentioned earlier, Gladstone et al (2021, in preparation) has been delayed. That paper demonstrates the sensitivity of ice shelf temperatures to the different choices of different upper surface dynamic boundary conditions, but this is certainly the first quantitative analysis for the Amery Ice Shelf capable of discriminating between different temperature distributions by comparison with experimental observations.

Line 730: "of _the_ depth-averaged"

Modified.

Line 733: Put the divisor "(RT_h)" in brackets.

Modified.

Lines 824/825: This reference is wrong. It should rather be

"Greve, R., Calov, R., Obase, T., Saito, F., Tsutaki, S. and Abe-Ouchi, A.: ISMIP6 future projections for the Antarctic ice sheet with the model SICOPOLIS, ..."

Thanks for pointing this out. Modified. In addition to this, we have thoroughly checked all the references for errors.