Review of the paper “Coupling the regional climate MAR model with the ice sheet model PISM mitigates the melt-elevation positive feedback, by Delhasse et al.

I would like to congratulate the authors for their efforts to make clearer the manuscript and for their detailed responses to my comments. However, I feel that the paper would be improved if further explanations were provided.

PISM description: I acknowledge that the PISM description has been extended. I wonder if the explanations are sufficient for someone not familiar with ice sheet modelling but I understand that the authors ask the readers to refer to the original publications. However, there is a mix between some very specific terms and very general explanations. I give a few examples below:

- Mentioning the value of the exponent(q=0.6) in the sliding law does not make sense if the Mohr-Coulomb criterion is not explained.
- The basis of the von Mises calving law could be explained
- The hypotheses underlying the shallow-ice and shallow-shelf approximations are missing
- Specify that E = 3 is a value often used in most ice-sheet models.

We have adapted our section to address your comment and the editor’s recommendations:

“In PISM, the geometry, temperature, and basal strength of the ice sheet are incorporated into stress balance equations at each time step to determine the ice velocity**. In some models, the full stress field is calculated by using the full Stokes equation. But this is computationally expensive. As an ice sheet can be treated as “shallow” (meaning the area of the ice sheet is far greater than its thickness),** PISM employs two approximations for shallow ice sheets: the Shallow Ice Approximation (SIA) and the Shallow Shelf Approximation (SSA).
The SIA simplifies by neglecting longitudinal stresses, which involve along-flow stretching and compression, as well as transverse stresses, which result from lateral drag against slower ice or valley walls. This approximation is suitable for slowly flowing ice that deforms under its own weight, assuming a strong connection between the ice base and the bedrock. The softness of the ice, affecting its flow velocity, is modulated by an enhancement factor, which we set to E = 3 in our experiments. **A typical SIA velocity profile in a cross-section shows zero velocity at the bed (frozen to the bed) and increasing velocities at the surface.**

Faster-flowing ice, such as ice streams, glaciers, and shelves, **is typically** approximated using the SSA. **In this case, longitudinal stretching dominates and membrane stresses must be taken into account. The ice base is assumed to be slippery, and velocities at the bed equal velocities at the surface, allowing for depth averaging in the SSA equations. While SIA can be numerically solved individually in each ice column, the SSA is nonlocal, meaning the velocity of a certain grid point depends on the whole spatially distributed stress field.**

PISM combines both approximations into a hybrid stress balance mode (Bueler and Brown, 2009; Aschwanden et al., 2012, **Winkelmann et al. 2011)). Throughout the entire domain, PISM calculates velocities for both SIA and SSA. SSA velocities result in very small velocities in the ice interior, where membrane stresses are low and basal resistance is high. They increase in regions with basal slip. Therefore, the overall velocities in PISM for grounded ice are the sum of SSA velocities and SIA velocities, expressed as v = v_SIA + v_SSA (Winkelmann et al., 2011). This superposition method helps avoid discontinuities in the model.**

[...]

We also enforce a minimum thickness of 50 m for floating ice at the calving front von Mises calving law, which is suitable for glaciers in Greenland (Morlighem et al., 2016). **The von Mises yield criterion is a widely adopted yield criterion in the fields of solid mechanics and structural analysis. Calving is predominantly influenced by stretching, and the von Mises stress is a fundamental measure for quantifying deformation and fracture. Therefore, it directly impacts the calving speed and is incorporated in PISM following this law:**

c = ||v|| o/o_max

where ||v|| is the velocity perpendicular to the ice front, o is the von Mises stress for ice (Morlioghem, 2015), and o_max is a threshold. If the von Mises stress is greater than the threshold the ice front retreats (c>||v||) if it is smaller the ice front advances. PISM uses a threshold value of 1e6 Pa.”

PISM initialisation: The explanations do not still sound very clear to me. I suggest to reorganize this section:
1/ Keep the first sentence and continue with “For a realistic thermodynamics representation
2/ Explain why you use anomalies. Note that I do not fully understand the sentence “This is why it is common practice...” Find a clearer explanation or remove this sentence. Also, you should replace “For a glacial spinup, it is assumed that” by “For a glacial spinup, we assume that...”.
3/ Mention at the end of the section that your reference climate is given by the MAR mean fields (ST and SMB) over the 1961-1990 when Greenland was close to balance.

We adapt this entire section following your advise:

“PISM is forced by yearly ST and SMB from MAR forced by CESM2. To achieve a stable spinup state, we forced PISM with the MAR mean fields (ST and SMB) over 1961–1990, when the GrIS was close to balance (Fettweis et al., 2017). However, for a realistic thermodynamics representation of the ice sheet, the temperature evolution of the last glacial cycle has to be considered, because the surface temperature slowly propagates down the ice column and determines the vertical ice profile of the ice sheet. The ice profile determines the ice softness and deformability, thus affecting the flow velocity of the ice.

For a glacial spinup, we assume that the initial state of the ice sheet prior to a glacial cycle is identical to the present-day state, including ice topography and surface temperatures.

Therefore, we start with a contemporary ice sheet and force it with surface temperatures corresponding to the last glacial cycle. To maintain model continuity, historic surface temperatures spanning the last 125,000 years were incorporated as climate anomalies into the present-day climatological mean (ST for 1961-1990). This approach means that temperature anomalies were zero at both 125,000 years ago and at the present day, but they varied during the glacial period. As our coupled spin-up progresses, we obtain different surface topographies that result in varying surface temperatures and, consequently, distinct climatological mean values. By using these anomalies, we ensure that the assumption of equivalent glacial states before and after the glacial cycle remains valid, as the anomalies are consistently zero at those two time points.

The first model initialisation (see Fig. 2) spanned 125,000 years, incorporating a scalar temperature anomaly derived from the 2D-temperature mean field of 1961-1990, a period when Greenland was near a state of balance. This 2D temperature and SMB mean field were calculated by MAR using the present-day PISM topography. The historical time series (Johnson et al., 2019) includes the temperature derived from Oxygen Isotope Records from the Greenland Ice Core Project (GRIP, Johnson et al., 2019). To optimize computational efficiency, we followed the grid refinement defined by Aschwanden et al. (2016). Starting in SIA-only mode, and an 18 km grid at -125,000 years, we refined our grid to 9 km at -25,000 years and to 4.5 km at -5,000 years. For the last 1,000 years, we maintained a fixed resolution but introduced SSA to the SIA stress regime to better represent the behavior of fast-flowing outlet glaciers."

Offline-correction method: The explanations of the method are now much clearer. However, I have to admit that I found it hard to understand what the 16 pairs of grid points corresponded to and how they were obtained. I finally came to the conclusions that the following associations are considered: (1,2,4,5), (2,3,5,6), (4,5,7,8) and (5,7,8,9). Is my understanding correct? If so, this should be explained or mentioned in Fig. 1 (or at least in Fig. 1 caption).

Thanks for your comment, there is a mistake that seems to compromise the correct understanding of this example. There are not 16 pairs of grid-cells compared, but 36! The 9 low-resolution cells selected are compared 2 by 2 in terms of SMB and according to their difference in altitude to obtain a local gradient (the 9 low-resolution pixels closest to the position of the high-resolution pixel) of SMB as a function of differences in surface elevation in the low-resolution grid.

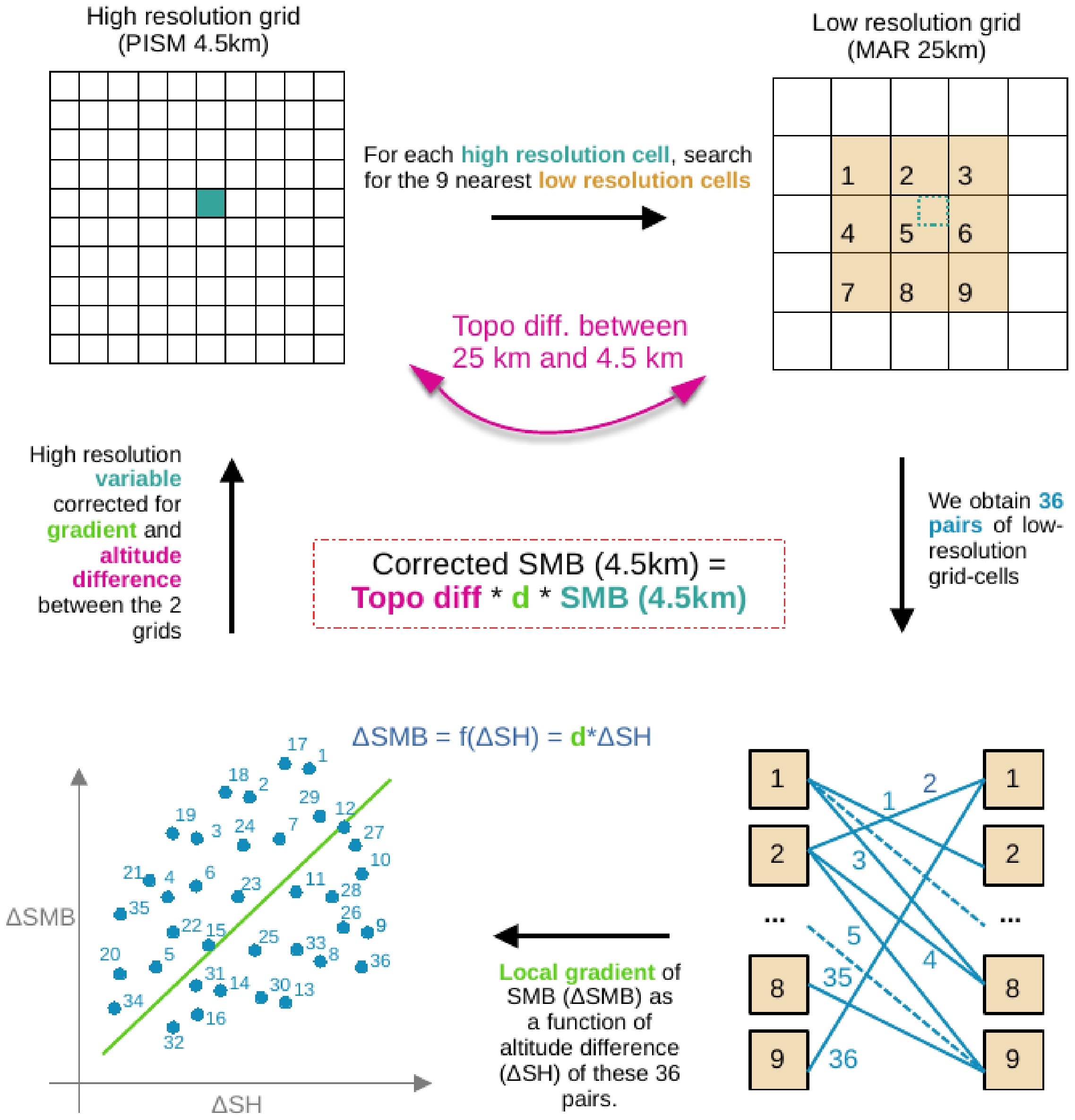

Figure R1. Figure 1 modified.

Figure 1 is corrected in consequences, and we also adapted its caption as follows:

“Figure 1. Steps of the offline correction as described in Franco et al. (2012). After interpolation of a variable (SMB, surface mass balance, in this figure) from a low to higher resolution grid, this variable is corrected to consider the influence of the temperature lapse rate with altitude. The correction is based on a local gradient (d) calculated by considering SMB differences (ΔSMB) between 9 nearest grid cells in the neighbourhood of the current one in the source grid in function of the surface elevation difference (ΔSH). Modified from Wyard (2015).”

Becomes:

“Figure 1. Steps of the offline correction as described in Franco et al. (2012). After interpolation of a variable (SMB, surface mass balance, in this figure) from a low to higher resolution grid, this variable is corrected to consider the influence of the temperature lapse rate with altitude. The correction is based on a local gradient (d) calculated by considering SMB differences (∆SMB) between 9 nearest low-resolution grid cells in the neighbourhood of the high-resolution grid cell position in function of the surface elevation difference (∆SH). Modified from Wyard (2015).”

Also, Page 6 (L23-24), the fields obtained with the offline-correction method are computed using the eight surrounding grid points, but in Fig. 1 you mention the nine nearest grid points. I think it is a typo error. Otherwise, clarifications should be made.

It’s actually the nine nearest pixels of the low-resolution grid to the position in the high-resolution grid which are considered. We have to change in Page 6, the wording “the eight surrounding grid cells of the current one.” which is confusing.

MAR initialisation: It would be interesting to have an idea of how MAR is initialised, particularly with regard to the snowpack model to which the authors refer extensively in the Discussion section.

To address this comment we propose to add this short description of MAR initialisation in Section 2.1.1 :

“The polar version of MAR requires a fairly long spinup period to reach an equilibrium state for both the snowpack and the atmosphere. Concerning the snowpack, the parameters that are important for achieving an equilibrium state and representing coherent configuration (temperature, density and liquid water content, Lefebre et al., 2003) are pre-initialised based on former simulations. These simulations have undergone an extensive spinup process spanning over 50 years to establish a coherent representation of the snowpack (Fettweis et al., 2020).”

Abstract: Line 4: Positive-degree day models cannot be classified as atmospheric models. They just parameterise the amount of runoff.

We adapt this sentence as follows:

“This process is called the melt-elevation feedback and can be considered by using two types of models: atmospheric models, which can represent the surface mass balance (positive degree day, or polar-oriented regional climate models for instance).”

Becomes:

“This process is called the melt-elevation feedback and can be considered by using two types of models: atmospheric models, which can represent the surface mass balance, or SMB estimates resulting from simpler models such as positive degree day models.”

Section 2.3.1: The velocity fields are compared to those provided by Joughin et al. (2018) over the 1995-2015 period. Differences between modelled and observed velocities are on average ± 80 m s-1 and are much larger on the margins. The authors refer to problems of resolution to explain these differences. However, these differences may also be explained by the fact that Greenland was not in balance in 2015 (and even before). This could be mentioned as an additional possible explanation.

Thank you for your comment. We'll add this hypothesis to this section:

“In some fast-flowing glacier regions, differences are well larger. However, the coarse resolution (4.5 km) compared to the proximity of smaller glaciers (500 m), which are solved by the observations, leads to strong deviation in their comparison. **Furthermore, from 1995 to 2015, Greenland was not in balance, and glaciers were already experiencing speed up and retreat (King et al., 2020).**”

Supplement: I guess that the authors did not upload the revised version of the Supplement as there is a mismatch between figure numbering in the main text and in the Supplement.
Thank you for your comment. It seems that the supplements have not been loaded for the revised version. We'll be even more careful with the latest version.

Other comments
I mention below some English mistakes (but the list is not exhaustive). I insist on the need to have the manuscript proof read and corrected by a native speaker. My feeling is that some sections are quite difficult to read with often long sentences which are not always grammatically correct.

We have revised our manuscript to address this comment and transformed some rather difficult sections to make them more readable. We have also included the following brief comments.

P1-L17: Replace “highlighted” by “highlight”
P3-L6: Remove “First”
P3-L21: “input by” → “inputs to”
P3-L25: mention → mentioned
P3-L31: for a doubling of CO2 → for a doubling of atmospheric CO2 concentration.
P6-L3: Add a reference to Section 2.3.1 when you refer to the coupled spinup runs.
P9-L15: of melt-elevation feedback → of the melt-elevation feedback (and in other places in the manuscript).
P9-L22: “are only responsible for 10% of the MB” →How is it evaluated ??
As presented in Figure S6 in the supplement, these 10% are obtained by comparing differences in SMB as computed on the respective grid of both simulations (PISM from MAPI-1w and -2w) and the same differences computed on the same grid (PISM fully coupled grid). These differences of differences (Fig. S6c) represent about 10% of the real SMB differences obtained (Fig S6a or b). For the sake of clarity, we decided to neglect this 10% because it was not the main cause, and certainly not the physical cause, of the differences between the two simulations.
P9-L31: “since 1991 of > “ → Remove “of” (same remark for P10-L3)
P14-L1: What do you mean with “intermediate results”? Please reformulate
“The MB overestimation by MAPI-1w could be contrary to the intermediate results from MAR of both MAPI-1w and -2w simulations.”
Becomes:

“The overestimation of MB by MAPI-1w could be contrary to the intermediate results from MAR **before interpolation and correction onto PISM-grid** of both MAPI-1w and -2w simulations.”

P14-L14: add in MAPI-1w after “from the ME excess”
P14-L15-16: SHF is not plotted in Fig. 9
P15-L7: changes to → changes in
P17-L17: What do you mean with “at depth”?
This sentence has been changed as follows: “In general, as depicted in Fig. 11a, the uncoupled simulation exhibits a greater presence of warm air at the periphery of the ice sheet, where the original topography acts as a barrier preventing deep air intrusion.”
P19-L4 “They used MAR and GRISLI” → “They used MAR and the GRISLI ice sheet model. Add a reference for GRISLI. For example Quiquet et al. (2012).

Reference:

Quiquet, A., Punge, H. J., Ritz, C., Fettweis, X., Gallée, H., Kageyama, M., Krinner, G., Salas y Mélia, D., and Sjolte, J.: Sensitivity of a Greenland ice sheet model to atmospheric forcing fields, The Cryosphere, 6, 999–1018, https://doi.org/10.5194/tc-6-999-2012, 2012.