Downscaled surface mass balance in Antarctica: impacts of subsurface processes and large-scale atmospheric circulation by Hansen et al., 2021

Hansen et al. reconstructed the Antarctic surface mass balance using two versions of an offline subsurface model forced by HIRHAM5. These two versions have a common basis but differ in the way the snow layers are discretized and in the way melt is taken into account. They found SMB estimations similar for both subsurface models and is comparable to estimates from RCMs. Model results are compared to observed firn densities while SMB is evaluated against GRACE using two ice discharge estimations. Finally, the relation between SAM and SMB is investigated.

The differences between the two versions of the subsurface model are clearly presented, especially the vertical discretization of each version, as well as HIRHAM5 inputs, comparison data and the experimental set-up. Each reconstruction using the two versions (and spinup variation) leads to a coherent SMB even if some components are outside of the range suggested by previous estimations. The relation with SAM and SMB not only confirmed other studies but add more details notably in the relation of each basin with this atmospheric index. This is an interesting paper paving the way to SMB estimates relying on (sub)surface models with a higher resolution. However some comments should be addressed before publication.

Major comments

Since the subsurface model is forced by HIRHAM5, how does the use of HIRHAM5 affect the results? The subsurface model is forced by water (evaporation, sublimation) and energy (latent and sensible heat, downwelling longwave) fluxes that are strongly linked to the surface state as computed by HIRHAM5 (and in general for the method, by a model with a less sophisticated surface scheme than the one from the subsurface model). It looks like a vicious circle where results from the subsurface model might be not independent from the surface scheme of the forcing model.

The evaluation of the physical conditions (densities and temperature) of the snowpack is exhaustive however I wonder if the main product of the paper (the SMB) is sufficiently evaluated. Considering all uncertainties in GRACE and discharge estimations, the present evaluation should rather be a supplement comparison than the main part of the evaluation. I recommend the authors to evaluate their SMB against in-situ local observations. It might also help to assess the added value of using the subsurface model instead of the HIRHAM5 SMB by comparing their reconstruction over the observation (see first comment).

Although SAM influences on SMB is still an open question, other studies (ignored in this manuscript) have attempted to contribute to answer this question. I suggest the authors to add some references in their introduction and discussion to better situate their work in the existing literature. Here is a list of some potentially interesting references on the subject (all may not have the same relevant level and probably do not need to be included, and the list is far for being exhaustive):

Dalaiden, Q., Goosse, H., Lenaerts, J. T., Cavitte, M. G., & Henderson, N. (2020). Future Antarctic snow accumulation trend is dominated by atmospheric synoptic-scale events. Communications Earth & Environment, 1(1), 1-9.

Kim, B. H., Seo, K. W., Eom, J., Chen, J., & Wilson, C. R. (2020). Antarctic ice mass variations from 1979 to 2017 driven by anomalous precipitation accumulation. Scientific reports, 10(1), 1-9.

Medley, B., & Thomas, E. R. (2019). Increased snowfall over the Antarctic Ice Sheet mitigated twentieth-century sea-level rise. Nature Climate Change, 9(1), 34-39.

Previdi, M., & Polvani, L. M. (2017). Impact of the Montreal Protocol on Antarctic surface mass balance and implications for global sea level rise. Journal of Climate, 30(18), 7247-7253.

Thomas, E. R., Van Wessem, J. M., Roberts, J., Isaksson, E., Schlosser, E., Fudge, T. J., ... & Ekaykin, A. A. (2017). Regional Antarctic snow accumulation over the past 1000 years. Climate of the Past, 13(11), 1491-1513.

Vannitsem, S., Dalaiden, Q., & Goosse, H. (2019). Testing for dynamical dependence: Application to the surface mass balance over Antarctica. Geophysical Research Letters, 46(21), 12125-12135.

Minor comments

P10 L216-217: This should be verified by comparing the albedos of the different simulations. How is the albedo prescribed in subsurface models? Is it the same parameterisation as in HIRHAM5? There is no information on this subject whereas the albedo is a determining parameter and will be even more so in a warmer climate.

All the experiments reveal particularly high melt values that are significantly different from other estimations based on RCMs (eg., Van Wessem et al., 2018; Agosta et al., 2019; Kittel et al., 2021) or satellites (eg., Trusel et al. 2013). It does not mean that these values are erroneous since there are by definition no observations of melting, but they deserve further discussion even if they have no impact on the SMB in the current climate.These large differences in the present climate might suggest that the model cannot be used in a warmer climate where melting and runoff would have much more impact. The authors could compare their estimates with SEB model estimates forced by AWS (Jakobs et al., 2020) or any other estimates.

Specific comments

Gt per year: to be consistent with kg m^{-3}, consider Gt yr^{-1}
P1 L11-L14: consider to remove the section about the density and temperature biases from the abstract as it does not seem to be a particularly important information.

P2 L32: Add blowing snow erosion/deposition in the SMB definition or specify that is naturally included in the local¨ solid precipitation balance.

P2 L40-43: RCMs also improve the physical representations of specific processes over polar areas (see for instance Lenaerts et al., 2019).

P2 L43-44: “Mottram et al. (2020) evaluated the atmospheric output from five different RCM simulations of Antarctic SMB driven by ERA-Interim (1987-2017).”
Atmospheric output vs SMB (= surface output) is confusing, please rewrite.

P2 L44-47: Indicating the original values of the models does not provide much more information since these are the models that were used in Mottram et al., 2020. It is more of a repetition with perhaps less relevant information because the masks are different (i.e. the SMB is also different, whereas this artifact is corrected in Mottram et al., 2020). I would remove the individual values, and if the authors still want to link this comparison study with original model publications, they could cite the name of the models (+reference) that were used in Mottram after the SMB ranges.

P3 L65-67: Please add some references here.

P3 L66-70: Even is SAM has indeed a strong effect on precipitation patterns, Marshall et al. (2017) rather suggest that precipitation patterns result from a combination of the different modes. Consider add other references to better justify the selection (ie, Kim et al., 2020)

P4 L100-101: "Despite the forcing is based on 6 hourly values the subsurface scheme is used to simulate the subsurface at 1-hour time steps."
Is there an interpolation between two 6-hourly inputs to produce a smooth transition between two forcing time steps?

P4 L105: Please specify if this is vertically or also laterally transferred?

P5 L131: Replace weighed by weigh**t**ed

P5 L137: Could you be more specific? Does this mean that the melting is taking place on several layers in the vertical at the same time, i.e. that the energy is transmitted into the snowpack?

P5 L141-142: What climatological means did you use? Is it based on Hirham5 inputs?

P5 L144: Why did you initialized with a uniform density over the whole ice sheet, that is close to snow values given by Kasper et al. parameterisation? I guess that spinup time remove the dependency to the initialization but it could have been more consistent?

P12 L240-242: Could it also due to overestimated melt/refreezing (see minor comment #2). Overestimated precipitation could also result in more fresh snow with lower/uncompacted densities. It could also result from an overestimation of the "fresh" surface snow density (linked to the parameterisation itself or HIRHAM biases)

P14 L54: Why did you select these specific cores? Are they the only ones with a high vertical resolution or are they representative of the region? It would be interesting to state the objectives of this comparison in order to extrapolate the conclusions that can be drawn from these few examples.

P16 L293: Melt is not a balance, there are either no melt or melt and then positive values.

P17 L306: Do you mean that one layer in the pack can be ice and snow at the same time or that melt occurred at different vertical layers simultaneously? (see also P5L137)

P20 L399-404: Check the SMBa units, shouldn't it be Gt m^{-1} (as monthly SAM values or as Figure 8) instead of Gt yr^{-1} ?

Figures and Tables

P6- Table 1: replace fist by fi**r**st

P8- Figure 1: The colormap is confusing as it is non-continuous. Please select something with a linear transition that will allow the reader to easily identify SMB variations. (See for instance https://matplotlib.org/stable/tutorials/colors/colormaps.html, perceptually uniform colormaps or sequential colormaps). Consider to use the abbreviation you defined for water equivalent (and similar remark than the first specific one).

P13 – Figure 4: similar remark than Figure 1 about the colormap + consider to make it bigger (maybe on a whole page with the elements one below the other?) to improve the reading.

P21 Figure 8: add the time unit relative to the SMB accumulation (m^{-1})

Stylistic <u>suggestions</u> (feel free to refuse them all if you wish without justification)

P1 L3-4 : I suggest '[...] in determining SMB before *influencing* the total mass balance of Antarctica and global sea level *variations.'*

AIS SMB : Maybe the authors could avoid the repetition of a double accronym and could keep the form used at the beginning of their abstract (Antarctic SMB).

P1 L19-20: 'Finally, we compare the modelled SMB to GRACE data by subtracting the solid ice discharge. *We* find a good agreement in East Antarctica, but large disagreements over the Antarctic Peninsula *potentially caused by* large difference between published estimates of discharge that make it challenging to use mass reconciliation in evaluating SMB models on the basin scale'.

P2 L46-57: Please, try to decrease the occurrence of "show".

P2 L53: "full-subsurface"

P2 L54: "over 1979-2017'' … « Antarctic SMB »

P4 L96 : replace Thereby (already used at the previous sentence)

P4 L108 : replace «layer's conductivity » by layer conductivity or conductivity of the layer (similarly for P5L125/6)

P6 L172 : Try to avoid repeating the « To see if » structure (two times in this sentence and already a bit earlier)

References

Agosta, C., Amory, C., Kittel, C., Orsi, A., Favier, V., Gallée, H., van den Broeke, M. R., Lenaerts, J. T. M., van Wessem, J. M., van de Berg, W. J., and Fettweis, X.: Estimation of the Antarctic surface mass balance using the regional climate model MAR (1979–2015) and identification of dominant processes, The Cryosphere, 13, 281–296, https://doi.org/10.5194/tc-13-281-2019, 2019.

Jakobs, C. L., Reijmer, C. H., Smeets, C. P., Trusel, L. D., Van De Berg, W. J., Van Den Broeke, M. R., and Van Wessem, J. M.: A benchmark dataset of in situ Antarctic surface melt rates and energy balance, Journal of Glaciology, 66, 291–302, 2020.

Kim, B.-H., Seo, K.-W., Eom, J., Chen, J., and Wilson, C. R.: Antarctic ice mass variations from 1979 to 2017 driven by anomalous precipitation accumulation, Scientific reports, 10, 1–9, 2020.

Kittel, C., Amory, C., Agosta, C., Jourdain, N. C., Hofer, S., Delhasse, A., Doutreloup, S., Huot, P.-V., Lang, C., Fichefet, T., and Fettweis, X.: Diverging future surface mass balance between the Antarctic ice shelves and grounded ice sheet, The Cryosphere, 15, 1215–1236, https://doi.org/10.5194/tc-15-1215-2021, 2021.

Lenaerts, J. T., Medley, B., van den Broeke, M. R., and Wouters, B.: Observing and modeling ice sheet surface mass balance, Reviews of Geophysics, 57, 376–420, 2019.

Trusel, L. D., Frey, K. E., Das, S. B., Munneke, P. K., & Van Den Broeke, M. R.. Satellite-based estimates of Antarctic surface meltwater fluxes. Geophysical Research Letters, 40(23), 6148-6153, 2013.

van Wessem, J. M., van de Berg, W. J., Noël, B. P. Y., van Meijgaard, E., Amory, C., Birnbaum, G., Jakobs, C. L., Krüger, K., Lenaerts, J. T. M., Lhermitte, S., Ligtenberg, S. R. M., Medley, B., Reijmer, C. H., van Tricht, K., Trusel, L. D., van Ulft, L. H., Wouters, B., Wuite, J., and van den Broeke, M. R.: Modelling the climate and surface mass balance of polar ice sheets using RACMO2 – Part 2: Antarctica (1979–2016), The Cryosphere, 12, 1479–1498, https://doi.org/10.5194/tc-12-1479-2018, 2018.