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Comment on gmd-2021-303

Baptiste Vandecrux (Referee)

Referee comment on "Improved representation of the contemporary Greenland ice sheet firn layer by IMAU-FDM v1.2G" by Max Brils et al., Geosci. Model Dev. Discuss., <https://doi.org/10.5194/gmd-2021-303-RC1>, 2021

Review of "Improved representation of the contemporary Greenland ice sheet firn layer by IMAU-FDM v1.2G" by Brils et al.

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General comments:

The article presents an updated version of the IMAU-FDM firn model and its output for the Greenland ice sheet. The presented model and its output are widely used for surface mass balance calculation and for the correction of satellite altimetry products. The main updates, compared to the previous model version, are: i) the use of a different surface snow parameterization, ii) the use of a different firn thermal conductivity, iii) the update of empirically fitted coefficients in the firn densification scheme. The model is of great use for the firn modelling community, its updates are well documented, and the manuscript is clearly written. Only few non-critical points are to be improved. Among these, the analysis of the simulated surface height is interesting but needs to be strengthened. A better acknowledgment of previous work is required throughout the manuscript. Lastly, the lack of attention to the citations and to the reference list made the reading irritating on occasions. The manuscript will be suitable for publication after these points, and the detailed comments below, are addressed.

Detailed comments:

I.20: Please acknowledge other work about on meltwater refreezing in the Canadian Arctic and in Greenlandic peripheral glaciers. e.g.

Gascon, G., Sharp, M., Burgess, D., Bezeau, P., & Bush, A. B. (2013). Changes in accumulation-area firn stratigraphy and meltwater flow during a period of climate warming: Devon Ice Cap, Nunavut, Canada. *Journal of Geophysical Research: Earth Surface*, 118(4), 2380-2391.

Bezeau, P., Sharp, M., Burgess, D., & Gascon, G. (2013). Firn profile changes in response to extreme 21st-century melting at Devon Ice Cap, Nunavut, Canada. *Journal of Glaciology*, 59(217), 981-991.

Ashmore, D. W., Mair, D. W., & Burgess, D. O. (2020). Meltwater percolation, impermeable layer formation and runoff buffering on Devon Ice Cap, Canada. *Journal of Glaciology*, 66(255), 61-73 .

I.24: Please acknowledge other work about on meltwater refreezing in Greenland, e.g.:

Pfeffer, W. Tad, Mark F. Meier, and Tissa H. Illangasekare. "Retention of Greenland runoff by refreezing: implications for projected future sea level change." *Journal of Geophysical Research: Oceans* 96.C12 (1991): 22117-22124.

Braithwaite, R. J., Pfeffer, W. T., Blatter, H., & Humphrey, N. F. (1992). Meltwater refreezing in the accumulation area of the Greenland ice sheet: Pâkitsoq, summer 1991. *Rapport Grlands Geologiske Underselse*, 155, 13-17.

I.39: "Zwally..." These two first references are for Antarctica. Please use work done in Greenland.

I.59: Please add a quick sentence for Section 3

I.63: Here you describe how the model output is evaluated before you describe the model and the output. I recommend changing the structure to describe the model first (which should be at the center of the GMD article). Please make the distinction between the observations that are used to improve the model and the ones that are used for evaluation.

I.70: From the SUMup ReadMe: "When using this dataset please cite both the individual researchers who provided the data as listed in the Citation column as well as the SUMup dataset."

I.73: please cite "Steffen et al. 1996 as processed by Vandecrux et al. 2019"

Steffen, C., Box, J., and Abdalati, W.: Greenland Climate Network: GC-Net., CRREL Special Report on Glaciers, Ice Sheets and Volcanoes, trib. to M. Meier, 96, 98–103, 1996.

Table 1: old values for alpha and beta do not match with the values given line 143-144. Do they come from different studies?

I.162: Please add a statement at the end of the paragraph confirming which values are being used: do you still calculate MO_550 with Eq. 4 and the new parameters in Table 1? or Do you drop the beta and only have a constant term?

I.170 "reasonable approximation" Can you give magnitude of penetration in polar snow and reference supporting this assumption?

I.174 "implicit/explicit" use "implicit (respectively explicit) ... in the absence (respectively presence)" instead of "/"

I.196: "as can be seen" add "in Figure 4"

I.202: "Magnusson and others (Magnusson et al. (2015))" Some effort could have been put into the formatting of the citations, especially knowing that the manuscript would go public in the discussion phase.

I.212-213: Here you mention a sensitivity analysis that is not fully described: how do you evaluate whether it is improving or not the model? Maybe that statement would be more suited in the discussion as an interesting side analysis.

Section 2.2.5. Here you describe quantities that are derived from the model and not the structure of the model itself. I recommend separating these two in the structure of the

method section: one section dedicated to the model and another one dedicated to the model evaluation.

I.220 is it normal that v_{ice} is included in Eq. 8 ?

I.233 "After the spin-up is finished..." Is this still part of the initialization process? Can you explain why the latest period needs to be run before starting the real run again in 1960?

I.251 The statistics of these 29 cores need to be presented separately because they are used in the calibration of the densification scheme.

Figure 5. Please define R_{MA} in the caption and in the text. Please sort out the legend items so that "old" comes before "new" (here and elsewhere). Statistics for calibration cores and evaluation cores should be presented separately, either here or in the text.

I.265: I recommend not using "/" unless it means "divided by". Change to "decreased from -0.40 to 0.61 m and from 2.14 to 1.32 m, respectively." It actually shows that the mean bias actually does not decrease in absolute values. Use "change" instead or rephrase.

Figure 6: For all panels, please limit the y-axis to the observations. Please present the old before the new (here and everywhere else in the manuscript).

I.270: Consider naming this "core-specific RMSE in firn density"

I.274 "improved" please provide the ϕ for these two examples. The improvement is not obvious.

I.282 "main reason..." I am not sure how to interpret this sentence. What is the instantaneous surface density? Please provide statistics (ϕ_{old} , ϕ for a constant 315 kg m^{-3} density and ϕ_{new} for both DAS2 and FA-13) to support this type of statement.

I.288: "cold bias..." Please split this sentence in two and please give the mean bias values to justify that the cold bias has been reduced.

I.290 "The main reason..." How do you identify the main reason? Did you make a sensitivity experiment (like old model + conductivity from Calonne et al. compared to old model + updated densification scheme or compared to old model + new fresh snow density parameterization)?

I.294: "cold bias in RACMO2" Can you give more details about this bias? has it been described in other studies? Also considering the next sentence: is there the same structure in the bias of the surface forcing (cold bias for temperate and warm location and warm bias for the very cold location)? I remember that the ablation area reaches rather high in RACMO in western Greenland (Steger et al. 2017) could it be that some of the observation sites where refreezing and latent heat release warm up the firn when in the model it is actually pure ice and does not see refreezing? Then the cause of the bias is not a cold bias at the surface.

Please mention that the model does not include firn ventilation, which can warm or cool the firn depending on the season (Albert and Shultz, 2002).

Steger, C. R., Reijmer, C. H., van den Broeke, M. R., Wever, N., Forster, R. R., Koenig, L. S., Munneke, P. K., Lehning, M., Lhermitte, S., Ligtenberg, S. R. M., Miège, C., and Noël, B. P. Y.: Firn meltwater retention on the Greenland ice sheet: A model comparison, *Front. Earth Sci.*, 5, 3, <https://doi.org/10.3389/feart.2017.00003>, 2017.

Albert, M.R., & Shultz, E.F. (2002). Snow and firn properties and air-snow transport processes at Summit, Greenland. *Atmospheric Environment*, 36, 2789-2797.

I.304: Since you mention earlier that a potential bias of the surface forcing may be the cause of the bias in the subsurface, can you compare the air temperature in RACMO2.3p2 and as measured by the AWS at these two sites. This will illustrate the potential surface bias unambiguously.

I.319: "agrees better" Please justify your statement by numbers.

I.321: Remove "pilot application". If an analysis is presented, it needs to be thorough. However it does not need to be long. Indeed in this section, you dedicate more than 5 pages, 3 plots (15 panels) and one table to an analysis of simulated surface height at three sites. This seems a bit disproportionate. Some easy updates would make it more concise:

- Right now the climate at each site is described both at the beginning of the section and within each site's subsection. This is redundant.

- The surface temperature panel in each of the three plots are not mentioned in the text. Could be simply removed.

-Accumulation and melt panels could be either moved to the supplementary, or simply removed and replaced by meaningful statistics in the text (e.g. when mentioning variability, you could give the standard deviation, when mentioning a low melt or accumulation period, you could give the average for that period, which can be compared to the long term average values in Table 2).

-With the two previous updates, Figure 10, 11, 12 can be merged.

-In the text, a lot of the description is redundant in the three sites: fresh snow has the same impact on all three sites and melt the same impact at KAN_U and FA13. This leads to many redundant sentences (l. 374 "Just like Summit..." l.386 "a similar picture emerges..."). Analyzing the three sites in one section and using a process-oriented structure (rather than site-oriented) would cut down a lot of text.

l.344 "leads to lower surface density" Can you give an average value for the surface snow density used by the old and new model at that site?

l.392: please quantify "very different"

l.394: Why is the magnitude of the melt different in the new model? That should be presented.

l.394-395: Here this 2.5m difference is a very important update for the use of the IMAU-FDM output in altimetry studies. If the new model is closer to reality, the old model missed this 2.5 m lowering due to snow compaction. Altimetry studies using the old model would then attribute this 2.5 m elevation change to a change in ice thickness and to 2.5 m of ice leaving that grid cell. It brings, for the first time an idea of the uncertainty that applies on the firn height change correction product provided by RACMO. It also raises the question: is there other sites where the new model leads to a different trend in 1990-2020 surface elevation? It would be highly valuable to produce a map of difference in 1990-2020 surface elevation trend. This additional analysis would further build trust in the RACMO product for use in altimetry. Making this section more concise would also leave more room for this spatial analysis of surface height evolution.

I also realize that the introduction misses some background about the use of firn models

in altimetry to fully motivate this firn height analysis. Reference to previous work on firn thickness should be acknowledged, e.g.:

Sørensen, L. S., Simonsen, S. B., Nielsen, K., Lucas-Picher, P., Spada, G., Adalgeirsdottir, G., Forsberg, R. and Hvidberg, C. S.: Mass balance of the Greenland ice sheet (2003-2008) from ICESat data -The impact of interpolation, sampling and firn density, *Cryosphere*, 5(1), 173–186, doi:10.5194/ tc-5-173-2011, 2011.

Zwally, H. Jay, and Li Jun. "Seasonal and interannual variations of firn densification and ice-sheet surface elevation at the Greenland summit." *Journal of Glaciology* 48, no. 161 (2002): 199-207. Li, J. and Zwally, H.J., 2011. Modeling of firn compaction for estimating ice-sheet mass change from observed ice-sheet elevation change. *Annals of Glaciology*, 52(59), pp.1-7.

Hawley, R. L., Neumann, T. A., Stevens, C. M., Brunt, K. M., & Sutterley, T. C. (2020). Greenland Ice Sheet Elevation Change: Direct Observation of Process and Attribution at Summit. *Geophysical Research Letters*, 47(22), e2020GL088864.

I.408: "predicts predicts"

I.416: Thanks for sharing the code!

I.418: Please add a data availability section with links to freely available data used in the study.

Give a link to and cite the SUMup dataset:

Lora Koenig and Lynn Montgomery. 2017. Surface Mass Balance and Snow Depth on Sea Ice Working Group (SUMup) snow density, accumulation on land ice, and snow depth on sea ice datasets. Arctic Data Center. doi:10.18739/A2W950P44.

Give a link to and cite the firn temperature data:

Baptiste Vandecrux. 2020. Firn temperatures and measurement depths at nine Greenland Climate Network (GC-Net) weather stations, 1998-2017. Arctic Data Center. doi:10.18739/A2833N00P.

Give a link and cite the upGPR data if it has been made available.

I.426: Please fix link

I.458: Double entry

I.479: A more appropriate description of the SUMup data is:

Montgomery, L., Koenig, L., and Alexander, P.: The SUMup dataset: compiled measurements of surface mass balance components over ice sheets and sea ice with analysis over Greenland, *Earth Syst. Sci. Data*, 10, 1959–1985, <https://doi.org/10.5194/essd-10-1959-2018>, 2018.

I.578: Correct reference:

Vandecrux, B., Fausto, R. S., van As, D., Colgan, W., Langen, P. L., Haubner, K., Ingeman-Nielsen, T., Heilig, A., Stevens, C. M., MacFerrin, M., Niwano, M., Steffen, K., and Box, J. E.: Firn cold content evolution at nine sites on the Greenland ice sheet between 1998 and 2017, *J. Glaciol.*, 66, 591–602, <https://doi.org/10.1017/jog.2020.30>, 2020a.