

Glacier Energy and Mass Balance (GEMB v1.0): A model of firn processes for cryosphere research

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General Comments

The authors present a new 1 dimensional snow/firn model to be applied to glacier studies. The model is of intermediate complexity relative to state-of-the-art existing models, but retains high computational efficiency suitable for long-spinup periods and sensitivity studies. It is therefore well-suited for these applications as well as inclusion in ice flow models such as ISSM.

The paper is quite well written and generally very clear. I think it can be published with relatively minor corrections discussed below.

Some general comments are:

- (1) The model is evaluated over ice sheets, but temperate glaciers are not discussed. Perhaps the authors can comment on applicability to temperate glaciers.
- (2) The relative advantages and disadvantages of GEMB relative to existing models could be more explicitly stated in the abstract and introduction (e.g. its suitability for running within ISSM or in conjunction with other glacier/ice sheet models).
- (3) The computational efficiency is mentioned briefly but not quantified in the manuscript. It would be interesting if some metrics could be provided regarding this.

Specific Comments

- 1. Line 31:** Are “spatial gradients” referring to vertical gradients? Please clarify.
- 2. Line 47:** Can the authors specify how these changes affect the net energy balance? Are these all positive feedbacks?
- 3. Line 75:** Discussion of perched ice layers could be added here to clarify that it is not necessary to completely fill up pore space to enhance runoff (e.g. Culberg et al., 2021; Miller et al., 2022; Macferrin et al., 2019)

Culberg, R., Schroeder, D. M., and Chu, W.: Extreme melt season ice layers reduce firn permeability across Greenland, *Nature communications*, 12, 1, 1-9, 2021.

Miller, J. Z., Culberg, R., Long, D. G., Shuman, C. A., Schroeder, D. M., and Brodzik, M. J.: An empirical algorithm to map perennial firn aquifers and ice slabs within the Greenland Ice Sheet using satellite L-band microwave radiometry, *The Cryosphere*, 16, 103–125, <https://doi.org/10.5194/tc-16-103-2022>, 2022.

MacFerrin, M., Machguth, H., van As, D., Charalampidis, C., Stevens, C. M., Heilig, A., Vandecrux B., et al.: Rapid expansion of Greenland's low-permeability ice slabs, Nature 573, 7774, 403-407, 2019

4. **Line 95:** Spell out DAKOTA.
5. **Line 105:** Although it is touched on here, it would be helpful to have a description of the benefits and drawbacks of GEMB relative to other similar models, e.g. why it is particularly well-suited for ice sheet model simulations in contrast with other 1D models.
6. **Line 128:** This “near-surface” region and why it is necessary have not been explained yet. Perhaps include a sentence prior to this explaining the near-surface portion of the column.
7. **Line 130:** Can the authors explain in a bit more detail how the scaling by depth works and why it is implemented this way?
8. **Line 173:** Does this include an integrated snow/ice albedo as a function of snow depth for shallow snow?
9. **Line 197:** How is the thermal time step determined?
10. **Line 150:** Assign equation numbers here and throughout.
11. **Line 211:** Should this be “gray body” rather than “black body”?
12. **Lines 227-231:** It would be helpful to reiterate which of these parameters are model inputs here.
13. **Lines 231-232:** This sentence about longwave emissivity seems out of place in the turbulent heat flux section. Should it be mentioned in the previous section instead?
14. **Line 244:** Specify that “initial” refers to fresh snow here.
15. **Lines 248-258:** Does this mean that the rain is assumed to refreeze instantaneously unless the layer reaches the melting point? Please clarify.
16. **Line 269-271:** I don't understand how there could be excess thermal energy that does not contribute to melting. Would this occur if the layer completely melts away? Please clarify.
17. **Lines 293-294:** However, addition or removal of mass from the bottom of the column would not be included in surface mass balance estimates, correct?
18. **Lines 299-300:** Some of these models use the mean accumulation rate as a parameter. Can this be specified by the user or is it determined during the spinup period?
19. **Line 310:** Can the authors briefly explain how the c_0 and c_1 rate parameters are applied, or include the equations where they are used?
20. **Line 316:** Please explain the b and m parameters.
21. **Line 318:** Is there a module within GEMB that allows the user to include the observational data, or was this done independently?
22. **Line 328:** Can the authors explain why this initial smoothing was performed?
23. **Line 330:** How is the bare ice extent initialized at the start of a simulation. I suppose this may not be important given the long spinup period.

- 24.Line 349:** Again I am curious as to how the model was initialized, though I suppose this doesn't have much effect given the long spinup period.
- 25.Lines 359-360:** The reference to Figure 4 is misleading here. The description here seems to indicate that Figure 4 is showing MO_{550} and MO_{830} as a function of C. I think the equation on Line 315 should be referenced here instead. It can also be mentioned, perhaps at the end of this section, that Figure 4 shows modeled vs. observed 550 kg m^{-3} and 830 kg m^{-3} depths.
- 26.Line 369:** It would be helpful to have a brief description of the RACMO model simulations used here to have an idea of the inter-model differences.
- 27.Line 375:** There might also be differences in subsurface components that contribute to differences, e.g. differences in snow density that contribute to differences in refreezing and thermal conductivity.
- 28. Line 380:** Figure 6 is not mentioned until the following section. I suppose combining Figures 5 and 6 to match Figure 7 would make it difficult to see the details for the Greenland ice sheet inter-comparison. Perhaps Figure 6 can be mentioned briefly here, then described in detail later.
- 29.Line 390:** Any idea why fresh snow melt would be underestimated?
- 30.Lines 493-494:** Is this sentence regarding albedo in reference to Antarctica? It would be interesting to see a comparison between GEMB and RACMO albedo for both Antarctica and Greenland either in the main text or as a supplemental figure.
- 31.Line 402:** Is this higher retention of meltwater due to differences in estimated porosity, or due to differences in thermodynamic properties?
- 32.Line 403:** Clarify that this is for GEMB.
- 33.Lines 411-412:** Clarify that this is relative to IMAU-FDM.
- 34.Lines 417-418:** I suggest using parentheses rather than slashes to avoid confusion with division here. Also, what explains why these scaling coefficients end up different between the two models?
- 35.Line 427:** Change "Figure 8" to "Figure 8c" and "Figure 9" to "Figure 9c".
- 36.Lines 432-442:** I'm a bit unclear on how the spinup affects the trends here. Are the authors saying due to the spinup GEMB is in a steady-state condition over the 1979-2005 period, while IMAU FDM is not? Also, could these differences also contribute to the spatial differences shown in Fig. 6?
- 37.Line 452:** Add "change" after "larger rates of FAC".
- 38.Lines 453-454:** Any idea why this difference occurs over Antarctica?
- 39.Line 484:** Figure 11 shows results for dz_{top} but apparently not dz_{min} . Can the authors provide some discussion of those results?
- 40.Lines 524-525:** Add "(GEMB)" after "Glacier Energy and Mass Balance".
- 41.Line 564:** Remove "Glacier Energy and Mass Balance (GEMB) model" and replace with "GEMB" as this is already defined in this section.
- 42.Lines 858-859:** Revise to " dz_{top} is the maximum near-surface layer thickness".
- 43.Figure 5:** In previous studies, red tends to be used for higher melt, while blue is for lower melt. It might be more intuitive to flip the red-blue color bars for the first two rows, if the authors agree.

- 44. Figure 7:** The same could be done as for figure 5 for melt, runoff, and evaporation if the authors agree.
- 45. Figure 11:** Again both color bars could be flipped if the authors agree.
- 46. Figure 12:** Note that units of temperature and temperature differences are in K somewhere on the figure or caption.

Technical Corrections

- 1. Line 46:** Change “modify” to “modified”, “enhance” to “enhanced”, “increase” to “increased” and “feedback” to “feed back”.
- 2. Line 73:** Change “persists” to “persist”
- 3. Line 297:** Change “increases” to “increase”.
- 4. Line 337:** Change “pacing” to “spacing”.
- 5. Line 355:** Remove italics from “Medley et al., 2020”.
- 6. Line 385:** Change “concentrated to” to “concentrated in”
- 7. Line 414:** Replace comma with semicolon after “higher FAC”.
- 8. Line 431:** Add “between” before “1975 and 2005”
- 9. Line 441:** Change “perform” to “performs”. Start a new sentence after “1978”.
- 10. Line 526:** Replace “allows the model” with “allows it”.
- 11. Lines 566-568:** This is a bit of a run-on sentence. Please revise.