

Review of revised: “Glacier Energy and Mass Balance (GEMB): A model of firn processes for cryosphere research”

By Alex S. Gardner, Nicole-Jeanne Schlegel, Eric Larour

**General comments:**

I thank the authors for their thoughtful and thorough responses to my prior comments. After reviewing the updated draft, I am satisfied with the revisions. The new draft is much clearer, both in the description of the model and discussion of their model experiments. I am happy to recommend the paper for publication. I do have several minor comments, listed below, that the authors may consider addressing.

Thank you greatly for your considerate and helpful review.

**Line by line comments:**

100: ice sheet wide should have hyphens in both instances: ice-sheet-wide changes and ice-sheet-wide estimation

Fixed throughout

114: do you mean stand-alone rather than stand-along?

Fixed

114: “It is a column model...” consider breaking into two sentences.

Good suggestion. We’ve now split the sentence into two.

155: energy fluxes **are** small

Fixed

168: consider changing word ‘master’ to something like ‘main’, ‘core’, ‘primary’, or similar (here and elsewhere)

Good catch, thanks

Section 2.4: consider mentioning how GEMB handles the advective component of heat transfer (i.e., you are using a Lagrangian framework so advective heat transport is handled implicitly).

We’ve added the following short paragraph to Section 2.4:

“GEMB uses a Lagrangian framework. As such the advective heat transport by firn and ice is

handled implicitly. Redistribution of mass and energy by vertical movement of meltwater within the firn matrix is handled using a bucket scheme and is described in Section 2.7.”

Equation 11: consider using  $\rho_i$  rather than  $\delta_i$  for consistency with density notation.

Done

Equation 16: Consider using  $\dot{b}$  rather than  $C$  to be consistent with Ligtenberg et al. (2011).

Done, for all equations to be consistent

553: You changed the text regarding ‘State of the art’; consider changing the Section title to “7. Comparison to RACMO2.3 and IMAU-FDM” or similar.

Changed to “Comparison to other models”

609: Consider: “IMAU-FDM is a widely used firn model product” or similar.

Done

641: change to “... calibration, as IMAU-FDM had ...”

Done

Table 1: Sturm is misspelled as Strum

Good catch, thanks. Now fixed.

Figures 6 and 7: change panel titles to be consistent –

Fig. 6 uses IMAU-FDM in the caption but FDM on the figure; Fi

g. 7 uses IMAU-FDM in caption but RACMO/FDM on the figure.

Likewise Figure 10.

Thank you for catching this... figures/captions not fixed.

## Review: Glacier Energy and Mass Balance (GEMB): A model of firn processes for cryosphere research

Alex S. Gardner, Nicole-Jeanne Schlegel, Eric Larour

The authors have added substantial details regarding methodology and provided clarifications in the manuscript. I feel the manuscript is ready to be published, subject to minor technical corrections, detailed below.

We kindly thank the reviewer for their very helpful feedback and thorough review.

Line 39: Change “km m<sup>-3</sup>” to “kg m<sup>-3</sup>”

fixed

Line 114: Change “stand-along” to “stand-alone”

fixed

Line 145: I think this should read “horizontal advection or” rather than “horizontal advection of”

Changed to “The model does not yet account for changes in firn due to horizontal advection or ice divergence”

Line 159: Change “User” to “Users”

Fixed

Lines 159-166: I’m still a bit confused about the layering here. Do the minimum and maximum layer thicknesses not apply to the column below the near-surface? Or are the layer thicknesses fixed there? Does the beta parameter apply to maximum thickness below the near-surface, or does it determine a fixed layer depth. What happens if compaction or melt happens in the layers below the near-surface? Please clarify.

Good question. We’ve added the following to the text:

“GEMB will combine cells if they are thinner than  $dz_{min}$  when located within  $z_{top}$  and  $dz_{min}\beta^{(n-n_{top})}$  when located below  $z_{top}$ . GEMB will split cells if they are thicker than  $dz_{max}$  when located within  $z_{top}$  and  $dz_{max}\beta^{(n-n_{top})}$  when located below  $z_{top}$ .”

Line 236: Add "(T)" after "Temperature".

Added

Line 243: Change "layer widths" to "layer thickness" to be consistent with previous sections.

Changed

Line 258: Suggest changing "is calculated" to "can be calculated" as this is one particular option.

Changed

Line 271: I think this should be the "maximum acceptable thermal timestep"? Also, could the authors clarify if this timestep changes by layer and with each GEMB timestep?

Good catch, thanks. This now reads:

The maximum acceptable thermal timestep is calculated, dependent upon the thermal conductivity, and then divided by a scaling-factor to achieve numerical stability. The a single maximum acceptable thermal timestep is calculated for each GEMB timestep.

Line 297: Change "was measures" to "was measured".

Fixed

Line 421: Change to read "compaction rate factors  $c_0$  and  $c_1$ :" for clarity.

Changed

Line 444: I believe  $\sigma$  should be defined here.

We've added " and  $\sigma$  is the overburden pressure"

Line 493: Change "IAMU" to "IMAU". Also, I don't think IMAU has been defined in the text yet.

Fixed and defined.

Line 538: Perhaps define shallow as reaching "beyond the 550 kg/m<sup>3</sup> horizon up to the 830 kg/m<sup>3</sup> horizon" for clarity.

Changed

Figure 4 caption, last sentence: Change “are show in the top” to “are shown in the top”

Changed

Line 557: Change “bilinear” to “bilinearly”.

Fixed.

Line 577: Change “Firn Air Content” to lowercase, remove “the” before “Greenland”.

Changed

Figure 8 and 9 caption: Does E/C refer to evaporation/condensation. Suggest defining it in the caption.

We’ve added “E/C is the mass change due to evaporation, condensation, sublimation and deposition.” To the captions.

Line 641: Place “IMAU-FDM...calibration” in parentheses and change “less cores” to “fewer cores”.

Changed

Lines 786-788: I think this is stated incorrectly. Decreasing, not increasing, the size of layers should increase thermal gradients between the atmosphere and surface. Later this is stated correctly at lines 879-881.

Thanks for pointing out this inconstancy. We actually have it right in Lines 786-788 and incorrect in lines 879-881. Coarser model vertical resolution leads to a larger imbalance with the atmosphere, while muting the thermal gradients within the ice. We have changed lines 879-881 to “We show that coarsening the model’s vertical resolution decreases melt and increases”

831: Are the authors referring to improving near-surface temperatures in models, observations, or both? Also change “glacier surface” to “glacier surfaces”.

This now reads: “Therefore, future work should prioritize improving near-surface atmospheric temperatures over glacier surfaces, from both models and observations, and thermal diffusion within snow and ice. “

841: I noticed “version 1.0” was removed earlier. Should that be done here?

Removed

884: This contradicts line 819 where Sturm was indicated to be slightly better.

That is true for the mean temperature but not the gradient in temperature. Line 658 (827 of the previous draft states) “From this single location comparison, the Calonne parameterization outperforms the Sturm parametrization.”