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The Cryosphere Discussions

Interactive comment on "An improved semi-empirical model for the densification of Antarctic firn" *by* S. R. M. Ligtenberg et al.

Anonymous Referee #1

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An improved semi-empirical model for the densification of Antarctic firn S.R.M. Ligtenberg, M.M. Helsen and M.R. van den Broeke

Summary The authors present an improved model that simulates snow and firn densification over the Antarctic continent. The model uses a densification scheme that accounts for variations in densification with depth, making use of different expressions above and below a critical density value of 550 kg m-3. The densification scheme is unique in that the same expression can be used to simulate both the evolution of firn density over time, and steady-state firn densities, and it accounts for the contribution of melting and refreezing of meltwater to firn densification. The model is forced with output from a regional climate model from 1989-2009. A comparison is conducted between simulated and observed depths of critical density values (= 550 kg m-3 and =

830 kg m-3) revealing that the densification model tends to overestimate densification at the surface, and underestimates densification for deep firn layers. The comparison also reveals that the model overestimates the contribution of accumulation to changes in density; a correction is applied based on observed data that improves model results. The improved densification scheme is applied over the entire Antarctic ice sheet, showing large-scale spatial variations in firn density and firn column depth. Temporal trends are analyzed at three locations, revealing the relative contribution of accumulation and melting to changes in the ice sheet surface elevation over seasonal and decadal timescales.

General Comments This is a well-written and organized manuscript that deserves to be published after relatively minor corrections. The authors present an improved model that is able to replicate the previous success of a steady state model, but can also be used for an analysis of time dependent processes. Promising applications are presented for the model, and the discussion of spatial variability and temporal trends is particularly interesting

General comments are: (1) The major drawback to the approach used here is that all data used to tune the model are again used to validate it. Moreover, the time-dependent solution is not validated with any observational data (which is perhaps hard to find). There should be some discussion in the "summary and conclusions"– an additional paragraph – about the need to test the model against other datasets and suggestions for potential opportunities.

(2) Here, a semi-empirical correction is made. Another option would be to improve the physically based model, i.e. by changing the exponent of the annual accumulation rate, as mentioned on p. 1929 (line 5). Perhaps the authors could also comment on the benefits and drawbacks to this approach vs. the one used here in the "Summary and conclusions".

Additional relatively minor changes are suggested to improve the clarity of the

manuscript below.

Specific Comments

1. P.1922 Lines 6-8: It is not clear what the “two applications” are. Possibly add “First, the steady-state. . .” and “Second, the time-dependent model. . .” or something to this effect to clarify.

2. P. 1923 Lines 1-4: This sentence is a bit awkward. Change “state” to “states” and “provides” to “provide”. Possibly, split the sentence in two, and add the word “needed” after “crucial parameters”.

3. Figure 1: The introduction indicates that firn is the intermediate product of the transition between snow and ice, but no snow layer is included in the figure. If the firn layer is assumed to include both firn and surface snow (if present), note in the caption that the “firn layer” includes snow at the surface.

4. P. 1923 Lines 27-28: for clarity, revise to read: “van den Broeke (2008) showed that the steady-state solution of Barnola et al. (1991), forced with regional atmospheric climate model output from van de Berg et al. (2003), is in good agreement with observations from firn cores.”

5. P.1925 Lines 10-11: Following on comment #3, it would be good to note here that the model simulates both snow at the surface and higher density firn below it, and that the “vertical firn column” includes snow at the surface.

4. P. 1925 Lines 12-13: Kaspers et al. (2004) used annual averages. Is the same true here? If annual averages are not used, it would be best to change to Ts for consistency. If they are, change “average” to “annual average” on line 12. It seems that using the annual averages could have an impact on the performance of the time-dependent model. Was this corrected for in the time-dependent model? It would be useful to include an additional sentence or paragraph describing the potential impact of this parameterization when used in the time-dependent scenario, or whether there

are any changes made to formula 2 for the steady-state or time dependent model.

5. P. 1926 Lines 15-17: It might be useful to state the length of the spin-up period.

6. P. 1927 Line 8: Should be referred to as the “average accumulation rate”? If so, is it the annual or 6-hourly rate, or does it change based on the scenario?

7. P. 1928 Line 3: Mention the source of the data from the 48 drilling sites.

8. P.1928 Lines 10-11: Is there an explanation for the success of the model at the South Pole? Is this associated with low accumulation rates there? It might enhance the arguments presented later to suggest this possibility somewhere in this section.

9. Figure 5: Add r2 values to the figure if possible.

10. P. 1929 Line 4: Change “coefficient” to “exponent”.

11. P. 1930 Lines 25-28: The sentence would be clearer if it read “. . .the pattern is somewhat different; while z550 is small, z830 shows relatively high values. This is caused by. . .” Change comma after “regions” to a semicolon.

12. P. 1931 Line 11: I suggest adding a sentence for clarification along the lines of: “. . .edges of the ice sheet (not shown). Therefore, a deeper firn column is not necessarily denser, and will contain more air.”

13. P. 1931 Lines 20-22: Note the source of the “total ice column” thickness data. Define “BEDMAP”; it is not defined earlier.

14. P. 1931 Line 24: Clarify that the time dependent model is also corrected with the updated expression used for the steady state model.

15. P. 1932 Line 3: Change “Table 2:” to “Table 2.”

16. P. 1933 Line 22: Change “outspoken” to another word, such as “obvious” or “evident”.

17. P. 1934 Line 11: “Everywhere in Antarctica” might be an overstatement based on

the results presented here; replace with “within three very different climatic zones in Antarctica” or a similar sort of statement.

Interactive comment on The Cryosphere Discuss., 5, 1921, 2011.