The Cryosphere Discuss.,
https://doi.org/10.5194/tc-2017-88-RC2, 2017

The Cryosphere Discussions

Interactive comment on "The modelled liquid water balance of the Greenland Ice Sheet" *by* Christian R. Steger et al.

C.ÂăM. Stevens (Referee)

maxstev@uw.edu

Received and published: 22 July 2017

Summary:

This paper presents results of a investigation of the liquid water balance (LWB) of the Greenland Ice Sheet using firn/snow-model (SNOWPACK). The authors' goals are to quantify the components of the LWB spatially and how those quantities have changed in recent decades; to investigate temporal and spatial patterns in refreezing and how those affect the firn; and to assess the models' ability to simulate firn aquifers. The authors force their model using climatic data from the regional climate model RACMO.

Observations of LWB components are unfortunately scarce, but the authors use available data (GRACE data, firn temperatures, firn-aquifer extents) to evaluate their model

performance. The model results compare to GRACE data very well. The model does not reproduce firn temperatures as well, but the results do still compare to the data favorably.

General Comments:

The paper is written and organized well and is a topic of wide interest to the cryospheric-science community. Understanding the LWB is important, as the authors identify, because uncertainty in the runoff component of surface mass balance is a large contributor to sea-level-change estimates. Accurate model simulations are an essential contribution to this scientific issue. Additionally, the authors do a good job of discussing potential sources of model error. I recommend this manuscript for publication with minor revisions.

General points to address:

- The authors mention firn "structure" numerous times. I think to many in the firn community "firn structure" refers to microstructural properties such as grain size, coordination number, etc. In this case, the authors refer specifically to firn temperature and porosity. It may be appropriate to call them by name specifically or use "firn physical properties" as the terminology.

- The authors ignore any lateral flow and also any heterogeneous flow (i.e. piping). I would like a bit more discussion on how those might affect the results, or if it is even possible to know at this point. Section 2.1 asserts that pore space downhill is often filled, but can enough hydraulic head be generated to drive a significant amount of flow? Is there enough data on piping available to do an easy scale analysis of how much heat could be delivered (how deep, how fast?)

- Section 3.2 and figure 4 compares model results to observations. The authors identify biases in the model and discuss lower elevation sites, but what about the higher elevation sites? The model shows a somewhat uniform temperature increase over the

period, but the observations are not as spatially coherent, e.g. sites 4-050 and 4-000. Also, the model gets the lower-elevation structure correct for the modern, but does not as well for 1960. Why is this? Does your assumption that 1952/55 would be the same as 1960 break down (I do think that is a very reasonable assumption, however.)

- Section 3.2 (end): If the different parameterization for fresh-snow density works better, why did you not just use that one? How does this uncertainty affect the results for the higher elevation sites? When you say, “An improved fresh snow density parameterisation seems therefore essential to address this inaccuracy”, do you mean an entirely new parameterization is needed, or just a new-to-your-model parameterization? Does the Langen (2017) parameterization fit the criteria of an improved parameterization?

- Section 4.1: Please clarify: You say “changes in the retained liquid mass (dM_ret/dt) are even smaller. . .”. Equation 1 defines dM_ret/dt as the liquid water balance. Is retained liquid mass the same as the LWB? In that sentence, does the quantity in parentheses (dM_ret/dt) refer to ‘changes in retained liquid mass’ or to ‘retained liquid mass’? I don’t doubt the science here but it was confusing to read. If changes in LWB, defined as dM_ret/dt, are indeed small, then it might imply that is it not an important term in changes in SMB.

- End of page 8, start of page 9,and Figure 8: Please clarify your language: Basin 4 shows a very large increase in firn temperature (due to refreezing I believe), but then you talk about how changes in t_skin are also important (but basin 4 does not show increase in t_skin). Adding a few sentences to clarify this would help – which phenomena is important where?

Specific/technical corrections:

- Use of units throughout: in some places the authors use units of kg/mˆ2/a (e.g. Figure 5) and in others w.e./a (e.g. Figure 6). It would be good to have consistency throughout. I slightly prefer m w.e./a in this context because it is slightly more intuitive.

- Use of vague language throughout: several instances of “it seems” or “apparently”. Just say what you mean directly. E.g. page 5 line 19: change to “it is reasonable”.

- Page 1, Line 5: “good model performance” is vague; perhaps “indicate good model-observation agreement” or something along those lines

- P1L7: “increases with” change to “increases at”

- P1L13: be aware that upward could also mean forming at a shallower depth “migration of firn aquifers to higher elevations”

-P1L20-21: put the e.g. section in parentheses to break up the sentence more clearly; change to “and the darkening”

- P1L24: change to “suggest that modeled refreezing”

- P3L15: perhaps a new paragraph at “The Greenland mass . . .”

- P4L1: please clarify: do you mean densification scheme, as in how density changes with time, or the parameterization for new snow density that you use?

- P4L9: get rid of word Futhermore.

- P4L19: it is a bit unclear what you mean by “indirectly”. “over” is probably not the best word here.

- P4L25: start new paragraph at “A comparison”, rather than at line 28.

- P5L3: do you mean delaying runoff by 18 days in the model? Please clarify.

- P5L7: mean seasonal amplitude in what?

- P5L7: change to “A too-early modeled snow. . .”

- P5L13-14: remove semi-colon and e.g., change to “. . .et al. 2015), or accumulating . . .”

- P5L20-21: change to “Figure 4 shows that SNOWPACK. . .”

- P6L5: I think you have not definded IMAU-FDM acronym prior to this use.

- P6L8: The sentence starting “Due to a different. . .” is a bit awkward to read – try to rephrase to be active voice.

- P7L12: 47% refreezes – how has this changed since 1960?

- P7L17: list the four most relevant components in parentheses.

- P7L20: “Remarkably” – why is this remarkable? Would you have expected other regions to also have more rain? Is there more precipitation in total in that region, or higher rainfall as a percentage of total precipitation – how does that compare to other areas?

- P7L27: change “does” to “do”

- P7L31: change “one” to “trend”

- P8L6: Is melt climate? I might suggest that temperature is climate, and melt is a result (but maybe I am wrong or nit-picking or both)

- P8L13: do you mean “the seasonal decrease in refreezing at higher elevations is caused by . . .”?

- P8L23-26: Are these sentences about hysteresis needed? They seem distracting and not relevant to me, but if they are relevant, include some discussion about how it affects your results and conclusions.

- P8L29: get rid of word “even”

- P8L30: change to “causes melt and refreezing. . .”

- P9L18: change “higher” to “larger”

- P9L18 and Figure 10: perhaps adding a panel to figure 10 to show pore space across the transect?

- P10L10: get rid of word “apparently”

- P10L16: get rid of apparently, say something like, “Instead, in these regions liquid water drains into . . .”

- P10L20: Change to: “Comparing the modeled depth of the firn-aquifer top to observations is difficult . . .”

- P10L23: change to “unsaturated wet layer”

- P10L26: unclear what you mean by advection of cold interior ice here – please expand on the physics of what is going on.

- P10L28: would initializing the model with lower temperatures be a physical thing do to? Is there any reason to believe that firn temperatures were lower in 1960 (assuming that is the start of the simulation)?

- P10L32: Specify the time period over which that expansion is occurring.

- P11L4-5: are these trends or just changes?

- P11L11: hyphen in ice-sheet margin

- P11L12: s in aquifers; change “i.e.” to “specifically”

- P11L14: no comma after simulation

- P11L16: get rid of word “the” before aquifer formation

- P11L26: get rid of word “intuitively”

- P13, end: also mention piping perhaps

- Figure 3 caption: change to “shaded areas illustrate”

- Figure 5: It might be nice to have basin numbers labeled or on this figure to avoid flipping to figure 2. Why is refreezing the only parameter you show fraction for? You could, for each LWB component, show the value (as you do) with the fraction of total in

parentheses. So, for example, basin 1 in panel e would have the value 14 (30%). That way the reader could see the fraction for all of the components. Also on this figure: The outlines of the basins are tough to see (make them darker and make the ELA a dashed dark line?). The color scales make it tough to see what is going on near the margins – not sure how to fix that.

- Figure 6: the legend could be larger at the bottom, especially with the thickness of the lines

- Figure 8: Perhaps move the x-labels to the bottom so that the numbers and labels are next to one another. It is a bit confusing – is this showing the change in the average values for 1960-1989 subtracted from the average values for 1990 – 2014? Also on this figure: legend could be larger

- Figure 10: An additional panel showing the elevation/surface profile of the ice sheet could be useful here.

- Figure 11: inset panels are quite small.

- Figure 13: Put a label along the color bar: Firn Air Content (m). The dots here make this a bit tough to understand. Perhaps making the aquifer dots more contrasting colors? Or use crosses? The grey dots are tough to see.

- Table 1: The units are difficult to understand here. Does m w.e. aˆ-1 (25a)ˆ-1 refer to melt, rainfall, runoff, and refreezing? Since you state in the caption that these trends are 1990 – 2014, does it not suffice to say the trend is in m w.e. per year?

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