

Response to review #2

We would first like to thank the reviewer for his useful suggestions which have helped a lot to improve our manuscript.

The importance of accurate glacier albedo for estimates of surface mass balance on Vatnajökull: Evaluating the surface energy budget in a Regional Climate Model with automatic weather station observations

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Summary:

The authors present a simulation of mass balance for the Vatnajökull ice cap using the HIRHAM5 regional climate model, with an updated albedo scheme that simulates albedo as a function of snow age and surface temperature. The simulated mass and energy balance are compared with observations from automatic weather stations on the ice cap. There is a fairly good agreement between observed and measured mass and energy balance, with the largest differences being associated with errors in simulated albedo. These errors are associated with inaccuracies in simulating snow cover extent during summer, as well as the lack of a scheme for accounting for impurity deposition in the model.

General Comments:

The paper is well written, well thought out, and scientifically sound. The paper is an important contribution as it focuses on regional climate model simulation of albedo over an ice cap and identifies challenges that can be addressed by future work. I believe the paper should be accepted for publication in the Cryosphere after relatively minor revisions discussed below. The points below are mostly very minor changes.

Some general points are:

1. Since a main focus of the paper is on albedo and how it influences mass balance, some papers discussing the importance of albedo to glacier and ice sheet mass balance and challenges in modeling albedo should be mentioned in the introduction.

A small section has been added about this with references to a few papers

2. Though this is not essential, I feel that the methods section could benefit by being reorganized. Since the main focus of the paper is validating the regional model results, the RCM could be described first, followed by the description of observational data, followed by the description of methods of comparison (including AWS point models – section 3.1, validation methods 3.2.2, and elevation-based corrections 3.2.5). This would require some editing to ensure that the text is consistent with the new order.

You're right, writing about the RCM first would be more logical. The sections have been reorganised in the manner you suggest

3. Figure 10 is hardly discussed in section 4.7. There should be more discussion of this figure. In particular, the model – measured differences for the weather station measurements are consistent with the

differences shown in Figs. 10 d, e, and f; for example there is a low SMB bias at high elevations and high SMB bias at low elevations. These consistencies should be discussed.

The discussion of the figure has been expanded. Now it reads; *“Spatial maps of the (uncorrected) average winter, summer, and net SMB from the 1980-81 glaciological year until 2013-14 are shown in Figure 9. The approximate location of the average ELA is marked on the figure. The model captures the position of the ELA fairly well, but at e.g. Brúarjökull, where the average ELA is at 1200 m, the position of the average ELA is at a too high elevation. The average deviation between observation and model over the observation period at each measurement location is also shown in Figure 9 in order to give an indication of the average error of the model at different parts of the ice cap. The winter balance (Fig. 9e) is generally overestimated at low elevations and underestimated at high elevations, except for at Öraefajökull where there is a large overestimation of the winter balance, as discussed in the previous section. As can be seen in Figure 9e, there is generally a low SMB bias at high elevations and a high SMB bias at low elevations during the summer. This is consistent with the comparisons with AWS stations, as we found that the bias in the energy available for melt was smaller at high elevation than at low elevation (see Table 2) This was partly due to a smaller albedo bias for stations in the ablation zone than for stations in the accumulation zone”.*

4. Section 4.8 also seems very short. The authors could provide more discussion of how the albedo differences affect SMB, and how this relates to the biases discussed in other parts of the study.

A few lines have been added discussing the change in specific SMB when changing the albedo scheme and we refer to the specific SMB figure. Lines 16-21, page 16.

Specific Comments:

- 1. P. 1, Line 14:** Suggest changing “specific mass balance” to “specific surface mass balance” for clarity.

Has been changed to SMB

- 2. P. 1, Line 16:** Add “through 2014” after “from 1981” to make the time period clear.

Has been changed to „for the period 1981-2014“ after suggestion from the referee #1

- 3. P. 1, Lines 16-18:** The second part of the sentence doesn't fit with the first part, and contradicts it somewhat. I think the point the authors are trying to make here is that the model can provide a reasonable representation of surface mass balance, but that a major source of uncertainty in this representation is the representation of surface albedo and how it evolves. Please clarify.

True, we agree that the second part of the sentence sounds like a contradiction and you are right about your interpretation of the sentence. We have tried to clarify by dividing the sentence and adding some further explanation: *Here, we use HIRHAM5 to simulate the evolution of the SMB of Vatnajökull for the period 1981-2014 and show that the model provides a reasonable representation of the SMB for this period. However, a major source of uncertainty in the representation of the SMB is the representation of the albedo, and processes currently not accounted for in RCMs, such as dust storms, are an important source of uncertainty in estimates of snow melt rate.*

- 4. P. 2, Line 18:** “Good records” is a bit vague. What is good about them?

We have tried to clarify by changing the sentence to; “Compared to Greenland, observations are recorded in a relatively small area, offering a good opportunity to evaluate the spatial and temporal variability of the HIRHAM5 model on a regional scale“

5. **P. 2, Line 25:** Change “background albedo” to “background bare ice albedo” for clarity.

changed

6. **P. 2, Lines 24-26:** I believe van Angelen et al. (2012) was the first to use this approach. This paper should be cited: van Angelen, J. H., Lenaerts, J. T. M., Lhermitte, S., Fettweis X., Kuipers Munneke, P., van den Broeke, M. R., van Meijgaard, and Smeets, C. J. P. P.: Sensitivity of Greenland Ice Sheet surface mass balance to surface albedo parameterization: a study with a regional climate model, *The Cryosphere*, 6, 1175-1186, doi: 10.5194/tc-6-1175-2012, 2012.

The paper has been cited and the following sentence has been added; *‘This method determining the ice albedo has previously been used by e.g. Angelen et al (2012)’*

7. **P. 3, Line 6:** Note that Brúarjökull and Tungnaárjökull are glaciers that make up part of the Vatnajökull ice cap.

A sentence making this clear has been added

8. **P. 3, Line 25:** How is the summer surface identified?

The summer surface is identified by finding the summer melt layer in snow cores, which is generally easily determined due to a significant amount of dust in the layer.

9. **P. 3, Line 30:** Which MODIS product is used here?

MODIS product MCD43A3 v006 is used. This has been added to the text

10. **P. 4, Line 5:** add “from AWS measurements” after “The turbulent energy fluxes were calculated” for clarity.

Added

11. **P. 6, Lines 20-21:** How is it known that the new particles are generally washed off? Isn't it possible that some of the impurities are scavenged at the surface? (e.g. Doherty et al., 2013) Doherty, S. J., Grenfell, T. C., Forsström, S., Hegg, D. L., Brandt, R. E., and Warren, S. G.: Observed vertical distribution of black carbon and other insoluble light-absorbing particles in melting snow, *J. Geophys. Res.*, 118, 1-17, doi: 10.1002/jgrd.50235, 2013.

This is known from field observations at e.g. Langjökull and Brúarjökull, which has been visited during the summer for the last 20 years. There is a possibility that some of the impurities remain, yes, but most of the particles are washed off and the effect of what might remain is expected to be small compared to the effect of the tephra layers. That this assumption is based on field observations has been clarified in the text.

- 12. P. 7, Line 31:** I suggest noting here that the correction was applied so that model results could be compared to AWS measurements at AWS locations.

The sentence was altered to mention this. Now it reads; “The temperature was corrected for the elevation bias in order to compare the model results to the AWS measurements at AWS locations“

- 13. P. 8, Lines 14-15:** This repeats some information from section 3.2.3. Since the corrections made in section 3.2.3 are done for the purpose of validation, perhaps the material from section 3.2.3 can be merged into this section.

Section 3.2.3 has been merged with this section (3.2.5).

- 14. P. 8, Line 16:** It is unclear what “components” refers to here.

The sentence has been changed so it makes clear that it is the energy balance components

- 15. P. 8, Line 22:** Change “temperature, T2m” to “air temperature at 2 m, T2m” for clarity.

changed

- 16. P. 9, Line 7:** What is the temperature gradient between?

The atmosphere and the surface. This has been clarified in the sentence.

- 17. P. 9, Lines 12-14:** Can the author’s elaborate briefly on this? Why are the winds interpolated rather than being calculated within the model?

The wind speeds are interpolated because the lowest atmospheric layer in HIRHAM5 is 10 m. The 2m temperature is interpolated to that height within the model, but the wind speed is not. Therefore we must interpolate it to the AWS height in order to compare it to measurements.

- 18. P. 9, Line 31:** Suggest changing “total LW” to “net LW (incoming-outgoing)” radiation

changed

- 19. P. 10, Line 10:** By “generally exposed” do the authors mean “every year”?

No, it is not exposed in 2001 and 2011-2013. This has been clarified in the sentence.

- 20. P. 10, Line 19:** Since the difficulties in modeling the ELA station have not been elaborated on yet, perhaps the difficulties should be briefly summarized, e.g. “some of the modelling difficulties which affect the ELA station (discussed below), associated with errors in simulating the presence or absence of snow cover...”

Sentence has been deleted due to suggestion from referee #1

- 21. P. 11, Line 7:** I believe “underestimating the albedo” should be changed to “overestimating the albedo”.

You’re right, it should. It has been changed

- 22. P. 12, Line 2:** Suggest changing “total energy was estimated” to “total energy balance was estimated”.

Done

- 23. P. 13, Line 1:** “the summer surface was reached” is a bit unclear. Are the authors referring to exposure of bare ice at this location?

Yes, we are. The sentence has been changed to “bare ice was exposed“ for clarity.

- 24. P. 13, Line 5:** Change “SW radiation” to “net SW radiation” for clarity.

Changed

- 25. P. 13, Line 8:** Again “net SW radiation” would be clearer.

Changed

- 26. P. 16, Line 4:** Be more clear about what is underestimated.

Done. We have added that the underestimation is of the energy balance components.

- 27. P. 16, Line 12:** It is known that the model simulates surface temperatures well, as discussed in the previous paragraph. Perhaps it is better to say that the accuracy of outgoing longwave radiation is consistent with the ability of the model to capture surface temperatures.

The sentence has been changed to reflect this. It now reads; “Whereas the modelled outgoing LW radiation component is within the uncertainty of the LW observations at the five stations, *which is consistent with the ability of the model to capture surface temperatures*, there was a larger difference between the modelled and measured outgoing SW radiation”

- 28. P. 16, Lines 15-16:** The better agreement with observations as compared with a fixed albedo, though obvious given the wide spread of observed values, is not mentioned in the results section. If mentioned here, it should also be mentioned in Section 4.3.

You’re right, it wasn’t. That part of the sentence has been deleted.

- 29. P. 16, Lines 30-31:** This sentence is confusing. It makes it seem as if the average modeled mass balance for 1981-2014 is being compared with the average for 1995-2014 from observations.

Rather, the model results for 1995-2014 were compared with observations for 1995-2014. Please clarify.

You're right. We have tried to clarify this by changing the sentence to; *'The mean specific summer, winter and net mass balances are reconstructed for all of Vatnajökull from 1981-2014, and estimates of the specific SMB based on in situ SMB measurements are compared to the reconstructed specific SMB for the period 1995-2014.'*

- 30. Table 2:** In the caption, the meaning of the parameters in column 1 should be explained, as is done for Table 3.

The meaning of the parameters has been added to the beginning of the caption

- 31. Figure 1:** The weather station names are not consistent with the names in the text. For example "B-ab1" should be "B-AB" to be consistent with the text. Also, in the caption, it should be pointed out that the unlabeled sites in Fig. 1a were not used in the study. Optionally, the symbols could be a different color to emphasize this. Perhaps Brúarjökull and Tungnaárjökull could also be labeled on the map for clarity. The lines on Fig. 1b are not explained. I suppose these connect mass balance sites collected along a transect. Finally, the labels (a) and (b) should be added for the sub-plots.

The names of the stations have been changed in the figure, and we point out in the label that only labeled AWSs are used in this study. A description of the colored lines has also been added (they do connect mass balance sites collected along a transect), and the labels (a) and (b) has been added to the plots.

- 32. Figure 10:** (Caption) Add the years of the observational period for clarity.

Added

Technical Corrections:

- P. 1, Line 3:** Suggest changing "describes the albedo with an exponential decay with time..." to "allows albedo to exponentially decay with time..."
- P. 4, Line 1:** Change "lat/lon" to "latitude-longitude coordinates"
- P. 5, Line 28:** Change "The found best-fit values were..." to "The best-fit values were found to be..."
- P. 5, Line 30:** Change "Refreshment of albedo to the maximum value only occurs..." to "Albedo is only refreshed to the maximum value if.."

Changed! Thanks

- 5. P. 6, Line 11:** I believe there is a typo in the equation. Should "dn+1" be "dt+1"?

You're right, it should be. It has been changed.

- 6. P. 6, Line 23:** Change "How much this" to "The extent to which"

Changed

- 7. P. 7, Line 4:** Change “The model is here run” to “For this study, the model is run”

The sentence has been deleted and the period added to the first line after suggestion from referee #1

- 8. P. 7, Line 10:** Change “allows a quick and thorough” to “allows for a quick and thorough”
- 9. P. 8, Line 5:** Change “like for example that of the albedo” to “including, for example, the albedo parameterization,”
- 10. P. 8, Line 31:** Change “with 0.8 K overall” to “by 0.8 K on average”

Done

- 11. P. 9, Line 1:** Change “but with less than 0.6 K” to “by less than 0.6 K”; change “it for example” to “for example, it”
- 12. P. 9, Line 20:** Change “larger errors-” to “larger errors;”
- 13. P. 10, Line 12:** Change “down to 0.03” to “as low as 0.03”; Change “the total overestimation” to “the average overestimation”
- 14. P. 10, Line 27:** Change “that low in situ...” to “that a low in situ...”.
- 15. P. 11, Line 28:** Change “comparisons statistics” to “comparison statistics”.
- 16. P. 12, Lines 10-12:** This sentence is rather long. I suggest splitting it into two sentences.
- 17. P. 14, Line 16:** Change “one-third that of the AWS sites...” to “one-third the difference with respect to the AWS sites...”

Done

- 18. P. 14, Line 27:** Change “back to 1981” to “extending back to 1981”.

Changed to “for 1981-2014“

- 19. P. 16, Line 6:** Change “comparisons only uses” to “comparisons only use”.
- 20. P. 16, Line 12:** Change “there was a larger differences” to “there was a larger difference”.
- 21. P. 16, Line 19:** Change “and that the model does not account” to “and the fact that the model does not account”
- 22. P. 16, Line 20:** Change “way to include” to “means of capturing”
- 23. P. 17, Line 21:** Change “could be including a stochastic...” to “could be to include a stochastic...”
- 24. P. 17, Line 31:** Change “with 0.06 m” to “by 0.06 m”.
- 25. P. 18, Line 13:** Change “like for example ERA-20C” to “for example, with the ERA20C reanalysis”.

Done

- 26. Figure 3:** The axis for Fig. 3b is a bit confusing. I suggest removing the 100, and leaving 0 for all plots.

Changed

- 27. Figure 4:** suggest adding “from AWS stations” after “fluxes calculated” for clarity.
- 28. Figure 6:** The caption seems to be erroneously in italics.
- 29. Figure 11:** Change “used AWS” to “AWS stations used in this study”

Done! thanks