

Response to review #1

We would first like to thank the reviewer for his useful and detailed comments which have helped a lot to improve the readability of our manuscript.

General comments

This manuscript is a sound evaluation of the surface mass balance (SMB) and energy balance (SEB) simulated by the regional climate model HIRHAM5 over Vatnajökull ice cap, Iceland. Here HIRHAM5 is run at 5.5 km resolution for the period 1981-2014, using an updated albedo scheme that calculates snow albedo as a function of surface temperature and snow ageing, and prescribes ice albedo from MODIS records. Comparison of HIRHAM5 output with SMB measurements (1995-2014), meteorological data, and observed radiative and turbulent heat fluxes (2001-2014) collected at 5 automatic weather stations (AWS) shows good agreement. However, the authors find a winter mass balance overestimation in the ablation zone, resulting from overestimated surface albedo in HIRHAM5. This is attributed to both the formation of a too thick snow layer covering the ice in winter and the fact that snow darkening from dust events or volcanic eruptions is not accounted for in the model.

This study investigates the climate of an Icelandic ice cap, for which little research has been conducted.

Actually, much research has been conducted on this ice cap, which is part of what makes this study possible. For example, mass balance measurements have been conducted since 1991-92 glaciological year and weather stations have been operated on the glacier since 1994. However, it is correct that not much research has been done on this ice cap using a Regional Climate model.

Through model evaluation, the authors highlight the importance of well representing impurities deposition, e.g. from dust and volcanic ashes, to realistically capture snow/ice albedo and hence accurately model SMB changes. They also present a 1981-2014 SMB data set that will be valuable for forthcoming studies. However, further clarifications, shortening, and copy editing are necessary to improve the manuscript readability (see **Point Comments**). I judge that **minor revisions** are required before acceptance in The Cryosphere.

Substantive Comments

- a) The authors use multiple terminologies for surface mass balance (SMB), which is confusing. For consistency, the authors should refer to “winter or summer mass balance” and “SMB or net SMB”.

Thanks for bringing this to our attention. We have changed the manuscript so we only use one terminology.

- b) In the abstract and conclusions, the authors introduce results that are not discussed in the main manuscript. Examples can be found at **L14-15** of page 1 and **L3-10** of page 17. As the paper focuses on model evaluation, I would advise to remove these lines.

We think this is an important point to get across, but you are right that it perhaps does not belong in the abstract and conclusion. We have removed the lines from the abstract

and added L3-10 in the conclusion to section 4.7 instead, so it is still included in the paper but not as prominently.

- c) Ice albedo records from AWS stations are sometimes extremely low, e.g. 0.03 (L12 of page 10) and 0.01 (L26 of page 10). Are these measurements valid, i.e. deposition of dust or ashes darkening the surface, or do they result from AWS malfunction, e.g. low solar zenith angle, riming of the sensors, ...? Could the authors provide references for such low albedo records or verify that all measurements used in this study are valid?

Very low values of the ice albedo have regularly been observed in the ablation zone in Vatnajökull, down to values of 0.05. These low values have also been observed in MODIS measurements, with the MCD43A MODIS product e.g. observing values at Brúarjökull down to 0.03. In the case of extremely low values (lower than 0.05), there are some years where the stations have been placed on a layer of tephra or sand, and therefore the very low albedo values may not represent the albedo of the ice but more likely the albedo of the tephra. A sentence to this effect has been added to the paper (after the 0.03 mention).

- d) In Section 4.5, the authors should describe the “total energy balance” using an equation:

$$E = LW_{net} + SW_{net} + Hs+I + Gh$$

Where LW_{net} and SW_{net} are the net short/longwave radiation, $Hs+I$ are the turbulent heat fluxes and Gh is the ground heat flux. I would advise to refer to “melt energy” instead of “energy balance” in the discussion.

The surface energy balance equation has been added to the section

Point Comments

Page 1

L1: “carried out” instead of “made”.

L2-3: I would suggest “[...] of the glacier surface mass balance (SMB). This simulation uses a new snow albedo parameterization that describes the albedo using an exponential [...] surface temperature dependent”.

L6: “in situ SMB measurements”. See also my **Substantive Comment a**).

L6: “The model agrees well with observations at the AWS sites [...]”.

L5-6: “for 2001-2014” and “for 1995-2014”.

L9: “[...] and not taking the surface darkening from dirt and [...]”.

L10-14: “balance for the whole of Vatnajökull (1995-2014) [...], with a small mass balance underestimation of [...] on average, whereas the winter mass balance is overestimated by 0.5 m w. eq. due to too large precipitation [...] the ice cap. A simple correction [...]”.

L14-18: I would reformulate as “Here, we use HIRHAM5 to simulate the evolution of the SMB of

Vatnajökull for the period 1981-2014, and show the importance [...] ice albedo to model realistic SMB and that processes such as dust storms, currently not accounted for in RCMs, are an important [...]”. See also my **Substantive Comment b**).

Thanks for the suggestions. These have all been changed.

Page 2

L5: “contribute to rise the sea level by 1 cm”.

L6: You should move the following sentence here “Runoff from Vatna. ice cap is economically important for hydropower [...] and future surface mass balance (SMB) changes are thus of keen interest.”.

L9: “However, to carry out reliable future projections, or reconstruct the past climate, it is important to evaluate how well models simulate the present climate.”.

L11-14: You could also refer to the work of Fettweis et al. 2017 (The Cryosphere Discussion) after Langen et al. 2016 at L13.

L16-22: I would suggest “Therefore, Icelandic glaciers are excellent candidates for evaluating modelled meteorological and SMB components. Compared to Greenland, observations are recorded in a relatively small area, offering a good [...] HIRHAM5 model on a regional scale. As albedo in Iceland is significantly different from that of [...], model evaluation over Iceland provides important [...] on the glacier energy balance.”

L23-26: I would suggest: “Here we present a 1981-2014 SMB data set of the Vatna. ice cap modelled by HIRHAM5 at 5.5 km resolution. HIRHAM5 is a state-of-the-art, high resolution RCM that has been well validated over Greenland (e.g. ...). In this study, HIRHAM5 incorporates an updated albedo scheme, using a background MODIS ice albedo field, in the aim of capturing the effect of dust and tephra on ice albedo in the ablation zone. Model simulations results [...]”

L30: This sentence can be removed.

Done.

Page 3

L5: Could you mention the period of observation in brackets?

Of course. It's been added

L13: I would suggest: “The turbulent fluxes, combining sensible and latent heat fluxes, and [...]”.

L25: “weighting”

L27: Remove “the” before 1995.

Thanks, it has been corrected

L30-: As the MODIS ice albedo product is described in this Section, the authors should move **L14-**

22 of page 6 here. The authors do not mention the period over which minimum autumn MODIS

albedo is averaged nor the range of values obtained. This should be clarified.

The lines have been moved to the observations section. The range of values (0.03-0.3) and the period used has been added to the text.

L30: Replace “domain” by “spectrum”.

L32: Replace “have been shown t be” by “are”.

Done. Thanks.

Page 4

L6: Replace “has implemented” by “implements”.

L18: Replace “calculated results” by “calculated turbulent fluxes”.

Page 5

L18: For consistency, I would suggest to refer to “dry regime” instead “cold regime”, to match the regime names at **L25**.

L19: “In a dry regime, [...]”

L30: “Refreshment of the snow albedo to its minimum value [...]. A partial refreshment is possible as the snow albedo is only reset to the [...]”.

Page 6

L1: Replace “value” by “threshold”.

L9: I would suggest: “In the case of shallow snow cover, [...]”.

L18: I suggest: “Additional tephra or dust deposition will [...]”.

Okay, thanks. All suggestions have been added

L19: Washed off by runoff or wind? Could you provide a reference here?

Washed off by runoff. This has not been published, but it has been observed during field visits to e.g. Langjökull and Brúarjökull over the summer during the last 20+ years, but of course there is a chance that some of the particles remain. However, these have a small effect compared to the tephra layers. That this is based on field observations has been clarified in the text.

L26: Move “(equivalent to ~5.5 km)” after “0.05°”. Insert “for the period 1981-2014” after “rotated pole grid”.

Done

Page 7

L9: Could you provide a reference in which this previous HIRHAM5 data set is used?

Yes, I've added a reference to Langen et al, 2017, which also use this HIRHAM5 data set

L11: You could remove the sentence “Running the model [...] cost of the model”.

L12: You should insert **L19-24** here.

Done

L14: “effect on upward short and longwave radiation ”.

The albedo scheme will have an effect on the upward shortwave radiation, so the sentence remains “effect on upward longwave radiation”

L30: What do the authors mean by “four surrounding”, do they mean the four closest grid-cells?

Yes, we do. It has been changed.

L32: For consistency, temperature should be expressed in °C.

We would prefer to keep the temperature in SI units. Previous mentions of temperature in °C have instead been changed to Kelvin.

L32: “Pressure is corrected using Eq. 1 decreasing the bias down to 0.1 to 0.5 hPa”.

L33: Replace “[...], it is not large [...]” by “[...], and the resulting differences are not large [...]”.

Page 8

L12: Replace “made by AWSs” by “collected at AWSs”.

Done

L14: Do you mean “bi-linearly interpolating”?

Yes, we do

L16: Replace “given in this study” by “listed in Tables 2-4”.

Ok, done

Section 4.1: Here you could include scatterplots of the 4 meteorological variables to highlight how HIRHAM5 performs on a daily basis.

Sure. The figure has been added as Fig. 2

L20-21: You could remove the sentence “Before validating [...] are simulated in the model.”.

L22: “2 m temperature”.

L25: I suggest “The comparison of modelled and observed mean daily [...] from 2001-2014 is shown in Table 2.”.

L27: You could remove “is generally forecast with a high degree of skill;”

L27-29: I would suggest “At each station [...] correlation ($r > 0.9$) between modelled and estimated pressure (Eq. 1), for the entire time series and for each individual year.”.

L31: “by 0.8 °C overall.”

Corrected, except we decided to use K instead of °C in L31.

Page 9

L1: Replace “remaining” by “other” and “but with less than 0.6 K” by “by at most 0.6 °C”.

L2: Insert “($r \sim 0.9$)” after “all five stations”.

L17-21: I would suggest “As a result, a similar underestimation of incoming longwave radiation is obtained at all five stations, with the largest difference occurring at the BAB station (Fig. 2). The average percentage [...] (see Table 3), and falls well within the 10 % [...]. However, Fig. 2a also shows that 25-30 % of the simulated days have larger errors than 10 %.”.

L28: “[...] reproduces the daily values well ($r \sim \dots$).”.

L30: Replace “and only” by “combined with”.

L31: I would suggest “[...] at all AWS locations (-7.9Wm^{-2}).”

Page 10

L10-11: I suggest: “[...] in the model, while snow cover persists longer in reality. One exception occurs in 2001, where the modelled albedo never drops down to the ice value, whereas observations [...]”.

Thanks, these have all been changed

L14: Which period? I also suggest: “which contributes to delay the albedo drop [...]”.

The measurement period (2001-2014). And the suggestion has been added.

L15: “[...] a too thick snow cover in winter is also the cause [...]”.

L15: You could move **L20-23** here, followed by “As a result, the ice surface is never exposed [...] any of the modelled years [...] during all but two years, i.e. ... and During these two years, the simulated albedo fits well [...]”.

L19-20: You could remove these sentences.

L20: Comparisons with mass balance [...] at this station. An overestimation of the snow thickness [...] fluxes, lead to persistent snow cover at the end of summer.”.

Corrected. Thanks

L26: See my *Substantive Comment c*).

See answer under *Substantive Comments c*)

L29-30: I suggest “Close to the equilibrium line, the albedo is highly [...] spatially, e.g. there is a large [...]”.

L33: “meaning that”.

Done

Page 11

L3: I suggest “The smallest difference between modelled and observed albedo is found [...]”.

L5: “An exception to this is found in 2010 [...]”.

L8: I would suggest “For instance, the very low albedo values obtained at the TAC station (Fig.

3b) are due to tephra deposition [...]”.

L12: I suggest “Such discrepancy could be explained by dust events, advancing or delaying the drop in surface albedo. Dragosics et al. (2016) investigated [...]”.

L15: “[...] all events and showed that the dust storms have a [...]”.

L16: Remove “, of course,”.

L21-25: I would suggest “As both the incoming and outgoing SW radiation are underestimated at most stations, the net SW shows a negative bias of ~ -6 to 12 Wm^{-2} at stations AB and ELA, and of -22 and -28 Wm^{-2} at the two AC stations. The resulting average model error at all five stations is -15.5 Wm^{-2} .”.

L27: I suggest “As HIRHAM5 underestimates meteorological variables at all stations, similar underestimation is obtained for the turbulent fluxes (Table 3 and Fig. 4). The two AC stations [...] between the AWS estimate and [...]”.

All suggested changes to this page have been added. Thanks

Page 12: See my **Substantive Comment d)**

See answer under **Substantive Comment d)**

L5: “inaccurate cloud representation cannot be the only [...] error. Errors in the interaction of clouds and radiation, e.g. error in the optical thickness of the clouds, or in the clear sky fluxes, could partly explain these discrepancies.”

L10: I suggest “Since the simulated outgoing [...] a small negative bias, the deviation in net LW radiation is governed by the incoming radiation. Errors in the simulated albedo mean [...] the deviation in net SW radiation. These errors can be partly attributed to [...] storms, which are not taken into account in HIRHAM5. In addition, errors in the simulated albedo also stem from snow cover that disappears too slowly compared to AWS records in the ablation zone. As a result, modelled albedo drops [...]”.

L16: I suggest “of the net SW and LW radiation and the turbulent fluxes leads to underestimated

melt energy, which contributes to overestimate the modelled snow thickness.”

L21: “the mean difference between modelled and observed energy components [...] is shown for each station (Fig. 5)”.

L25: “net SW radiation”.

Thanks for the suggestions. They have been implemented

L26-28: These explanations are unclear to me, could you reformulate?

We have reformulated as; *The mean difference between observations and the simulations of the SW radiation for non-eruption years is -3 W m^{-2} whereas the radiation difference in 2010 is -106 W m^{-2} . Assuming the larger deviation from the mean in 2010 is only due to the volcanic eruption, the increase in available energy due to the eruption is 103 W m^{-2} . If it is further assumed that the surface was always at melting point, the increase in melt due to the 2010 Eyjafjallajökull eruption over the 128 day measuring period would be $\sim 3.1 \text{ m w.eq.}$ at this station.*

L32: “Modelled longwave radiation is consistently underestimated by 10 Wm^{-2} .”

L34: “the albedo comparison. Depending on [...] the albedo is generally [...]”.

Page 13

L6: “As previously discussed, this albedo bias, and hence underestimated SW radiation, occurs [...] proximity of the equilibrium line. An underestimation of the incoming [...]”.

L19: Replace “offers an evaluation” by “allows to evaluate”.

L20: Here the authors could mention the specific year.

Page 14

L2: “SMB is also measured at 25-120 non-AWS sites, depending on the year (Fig. 1b).”.

L8: “receives a large amount of precipitation. However, since HIRHAM5 [...]”.

L13: Replace “particularly significant process” by “key process”.

L15: I would suggest “Removing this location from the comparison, the total difference drops to one-third [...]”.

Thanks, the above changes have all been added

L16-18: This sentence is difficult to read, could you reformulate?

We have reformulated as: *The reason the difference is smaller than for the [AWS](#) sites only is that more sites close to the edge of the ice cap are included. The winter balance at the measurement points in the ablation area of the icecap generally is overestimated in the model, and therefore these points partly offset the underestimation in the middle of the ice cap.*

L26: I would suggest “HIRHAM is used to estimate the mean SMB of Vatna. for 1981-2014. The winter, summer and net mass balances [...]”.

changed

L29: “manually interpolating”, what do the authors mean by this? Please clarify

Manually interpolated might not be the right description. They are created using Kriging interpolation of the mass balance measurements. On glaciers where no measurements are available, the mass balance is approximated using known correlations with the mass balance on other glaciers. Skerðarárjökull e.g. has no mass balance measurements, but it is known to have a similar mass balance as Breiðamerkurjökull, which is measured. The Breiðamerkurjökull balance is therefore used to estimate the Skerðarárjökull balance. The manual has been removed from the sentence, and if more info is needed about the interpolation scheme, more info is given in the reference (Pálsson, 2016).

L31: “The largest deviations are obtained in 1995, where ablation is overestimated in the simulation [...] 2010-2012, where ablation is underestimated [...]”.

changed

Page 15

L16-18: I would advise to swap Fig. 10 and Fig. 9, and to discuss these mass balance maps earlier in this Section.

Done, the two figures and the sections discussing them have been switched

L21: “a previous run using a constant ice albedo of 0.3.”.

L26: Replace “appears to be on the” by “are found on the”.

L27: “are located in areas”.

L28: “The TAB station is located in the ablation area, where the ice surface is never exposed in the model due to an overestimation of the winter accumulation.”.

Changed

Page 16: Present tense should be used in the conclusions.

L1: “[...] ice cap allows us to evaluate the model performance.”

L21: “[...] into the model is to implement a stochastic [...]”.

L31: “by 0.06 m”.

changed

Page 17

L3-10: See my *Substantive Comment a*).

See comment under *Substantive Comment a*).

L10: “HIRHAM5 is therefore a useful tool to expand [...]”.

L15: “[...] lateral boundary, e.g. output of a general circulation model.”.

Changed

Figures and Tables

Tables 2-4: I would advise to show average observations at the AWS stations instead of HIRHAM values in the second column.

Ok, the values have been changed in the tables

Table 2: For consistency, temperature should be expressed in °C.

We would prefer to use SI units. Previous uses of °C have been changed to K for consistency.

Figure 1a: Could you rename the different stations so that they match the labels used in the main manuscript, e.g. T acc. → T-AC.

Of course. This has been changed

Figures 2-4: Could you use similar symbols for both locations (B and T stations), the large crosses you use make the deviations appear larger than they really are.

Definitely. Both locations now use dots in the scatter plots.

Figure 4: Remove the last sentence in the caption and insert a similar legend (symbols) as in Figs. 2 and 3

Done

Figure 5: In the legend, could you write “Hs+l” instead of “Hs + Hl”?

No problem. It has been changed

Figure 6 caption: I suggest: “Comparison of the winter [...] 2014 between the mass [...]”.

Figure 7 caption: “see Fig. 1b”.

Figure 10 caption: Replace “placement” by “location”.

Figure 11 caption: “Difference in a) mean albedo, and b) mean SMB in m w. eq. for 2001-2014 between two runs with [...]”.

All caption suggestions have been added. Thanks