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 = LWnet + SWnet + Hs+l + Gh

Where LWnet and SWnet are the net short/lonwave radiation, Hs+l 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 depend**e**nt".
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 199**5**-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: "weigh**t**ing"

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 "0.05º". 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 ºC.

We would prefer to keep the temperature in SI units. Previous mentions of temperature in ºC 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 ºC overall."

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

Page 9
L1: Replace "remaining" by "other" and "but with less than 0.6 K" by "by at most 0.6 ºC".
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 ($r \sim$ …).".
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 ~3.1 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 be in the reference (Palsson, 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 ºC.

We would prefer to use SI units. Previous uses of ºC 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. à 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

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

Louise Steffensen Schmidt, Guðfinna Aðalgeirsdóttir, Sverrir Guðmundsson, Peter L. Langen, Finnur Pálsson, Ruth Mottram, Simon Gascoin, and Helgi Björnsson

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 Öræfajökull 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 Meijgaad, 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-abl" 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 Tungnaárjokull 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:

1. **P. 1, Line 3:** Suggest changing "describes the albedo with an exponential decay with time…" to "allows albedo to exponentially decay with time…"
2. **P. 4, Line 1:** Change "lat/lon" to "latitude-longitude coordinates"
3. **P. 5, Line 28:** Change "The found best-fit values were…" to "The best-fit values were found to be…"
4. **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

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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Abstract. A simulation of the surface climate of Vatnajökull ice cap, Iceland, ~~made~~ carried out with the Regional Climate Model HIRHAM5 for the period 1980-2014, is used to estimate the evolution of the glacier ~~mass balance. A~~ surface mass balance (SMB). This simulation uses a new snow albedo ~~parametrization is used for the simulation that describes the albedo with an exponential~~ parameterization that allows albedo to exponentially decay with time and is surface temperature ~~dependant~~dependent. The albedo scheme utilizes a new background map of the ice albedo created from observed MODIS data. The simulation is evaluated against observed daily values of weather parameters from five Automatic Weather Stations (AWSs) from 2001-2014, as well as in situ ~~mass balance measurements from 1994-2014~~SMB measurements from 1995-2014. The model ~~simulates the observed parameters well at the station~~ agrees well with observations at the AWS sites, albeit with a general underestimation of the net radiation. This is due to an underestimation of the incoming radiation and a general overestimation of the albedo. The average modelled albedo is overestimated in the ablation zone, which we attribute to an overestimation of the thickness of the snow layer and not taking the surface darkening from dirt and volcanic ash deposition during dust storms and volcanic eruptions into account. A comparison with the specific summer, winter, and net mass balance for ~~all~~ the whole of Vatnajökull ~~from 1994-2014~~ (1995-2014) shows a good overall fit during the summer, with ~~the model underestimating the balance by only~~ a small mass balance underestimation of 0.04 m w.eq. on average, ~~but a too large winter balance due to an overestimation of the~~ whereas the winter mass balance is overestimated by on average 0.5 m w. eq. due to too large precipitation at the highest areas of the ice cap. ~~The average overestimation of the winter balance is 0.5 m w.eq., but a~~ A simple correction of the accumulation at the highest points of the glacier reduces this to 0.15 m w.eq. ~~The model captures~~ Here, we use HIRHAM5 to simulate the evolution of the ~~specific mass balance well, for example capturing a shift in the balance in the mid-1990s, which gives us confidence in the results for the entire model run. The model is therefore used to provide an estimate of~~ SMB of Vatnajökull for the ~~evolution of the specific surface mass balance of Vatnajökull from 1981, and we show the importance of bare glacier ice albedoto modelled mass balance and that processes not currently~~ 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.

Keywords: glacier; albedo; energy balance; HIRHAM5

1 Introduction

Worldwide, glaciers and ice caps are losing mass at increasing rates as a response to climate change (e.g. Vaughan et al., 2013). Major changes in the dimensions of glaciers are expected to affect the sea level and climate throughout the world, and it is therefore important to describe and understand the glacier climate. Glacier retreat and mass loss at significantly increasing rates are also observed for Icelandic glaciers (Björnsson et al., 2013), which could potentially contribute to sea level rise the rise in sea level by 1 cm (Björnsson and Pálsson, 2008; Björnsson et al., 2013). The runoff from Vatnajökull ice cap is economically important to hydropower production in Iceland and the present and future mass balance is thus of keen interest. Numerical high-resolution Regional Climate Models (RCMs), such as MAR (Gallée and Schayes, 1994), RACMO2 (Meijgaard et al., 2008), or HIRHAM5 (Christensen et al., 2006), are valuable tools for estimating the meteorological parameters and mass balance variability at the surface of glaciers. However, in order to have confidence in the result of future model to carry out reliable future projections, or model reconstructions of reconstruct the past climate, it is important to evaluate how well they models simulate the present climate . .

Evaluation of RCMs is important, not only because it reveals possible biases in the model, but also because it could yield recommendations for model improvements. Much work has gone into evaluating RCMs over Greenland (e.g. Box and Rinke, 2003; Noël et al. Antarctica (e.g. Lenaerts and Van Den Broeke, 2012; Agosta et al., 2015), but less effort has gone into evaluating them over Iceland (e.g. Ágústsson et al., 2013; Nawri, 2014).

However, since a long term meteorological monitoring programme has been conducted on Icelandic glaciers since the 1991-92 glaciological year (e.g. Björnsson et al., 1998). Therefore, Icelandic glaciers make an excellent evaluation site for the meteorological and mass balance componentssimulated by a RCM. The runoff from Vatnajökull ice cap is economically important to hydropower production in Iceland and the present and future mass balance is thus of keen interest. Furthermore, the good records over are excellent candidates for evaluating modelled meteorological and SMB components. Compared to Greenland, observations are recorded in a relatively small area, compared to Greenland, offer offering a good opportunity to evaluate the spatial and temporal variability of the HIRHAM5 model . As the albedo may be significantly different in Iceland than on a regional scale. As albedo in Iceland is significantly different from that of Greenland or Antarctica, e.g. due to frequent dust storms and occasional volcanic eruptions, model evaluations over Iceland can provide provides important insight into the effect of albedo changes on the glacier energy balanceon a regional scale.

The RCM used in this study is HIRHAM5, which is a state of the art, high-resolution RCM that has been well validated over Greenland (e.g. Box and Rinke, 2003; Lucas-Picher et al., 2012; Rae et al., 2012; Langen et al., 2017). Here we present a

HIRHAM5 simulation with an updated albedo scheme which uses a background albedo map in an attempt to take the effects of dust and tephra on the glacier Due to the large spatial and temporal variation in albedo of Icelandic glaciers (spanning from less than 0.1 for dirty ice in the ablation zone into account. Model simulation results are compared to observations from Automatic Weather Stations (AWS) and in situ mass balance observations, in an effort to improve the performance of the model. The possible physical reasons for any model biases are discussed, and recommendations for corrections are made where possible.

Furthermore, the mass balance of Vatnajökull is reconstructed back to 1981 using the model, keeping in mind the identified model errors. to 0.9-0.95 for new snow), and the large sensitivity of melt to variations in albedo, it is crucial to have correct estimates of the albedo when modelling the surface mass balance. However, accurate modelling of the albedo can be challenging. E.g. volcanic eruptions and dust storms can significantly lower the glacier albedo, and thus increase the amount of melt (e.g. Conway et al., 1996; Gascoin et al., 2017; Dragosics et al., 2016), but are difficult to include in albedo models. Accurate simulations of the ice albedo is also problematic, as for some glaciers it varies with elevation (e.g. Knap et al., 1999) but not for others (e.g. Greuell et al., 1997). In addition, the ice albedo may decrease with time (e.g. Reijmer et al., 1999), increase with time (e.g. Oerlemans and Knap, 1998), or remain constant (e.g. Greuell et al., 1997) depending on the glacier.

2 Observational data

The primary observational dataset used in this study was collected by AWSs at selected locations on Here we present a 1981-2014 SMB data set of Vatnajökull . Since 1994, 1-13 stations have been operated on the ice cap during the summer months (e.g. Oerlemans et al., 1999; Guðmundsson et al., 2006). The temperature, relative humidity, wind speed, and wind direction at 2 above the surface have been measured during the entire period, while the radiation components have been measured since 1996. For this study, data from five AWSs were considered - three on Brúarjökull (B) and two on Tungnaárjökull (T) (see Figure 1). Two stations are situated in the ablation zone (henceforth referred to as the AB stations), one station is situated near the equilibrium line altitude (ELA station), and two stations are in the accumulation zone (AC stations). The average elevation of each station is shown in Table 1. All five stations have been operated on the glacier every year during the period 2001-2014. Observations of 2 temperature, humidity, wind speed, and radiative fluxes were used to validate ice cap modelled by HIRHAM5 over Vatnajökull.

The uncertainties of the AWS observations vary depending on the sensor. The temperature and humidity sensors have an accuracy of 0.2 and 2 % for temperature and humidity, respectively, while the accuracy of the wind speed is 0.2 (Guðmundsson et al., 2009). The radiative fluxes were measured using either Kipp and Zonen CM14, CNR1 or CNR4 sensors that have a maximum manufacturer-reported uncertainty of ±10 % for daily totals (e.g. Kipp and Zonen, 2002). However, the uncertainty has independently been evaluated to be lower (3-5 %) when used in an ice sheet environment (van den Broeke et al., 2004; Guðmundsson et al., 2009). The turbulent fluxes and surface pressure were not measured at the stations, but were estimated using the methods described in Section 3.1. In additionto AWS data, in situ mass balance measurements were used to evaluate the simulated surface mass balance (SMB) at several sites on Vatnajökull. Conventional in situ mass balance measurements have been carried out every glaciological year since 1991-92, with 60 stations measured each year on average. The measurement sites are shown in Figure 1. The uncertainty of the mass balance measurements has been estimated to be ±0.3

The SMB measurements are conducted at the beginning and end of the accumulation season in order to measure both the winter and summer balance. The winter balance is measured in the beginning of the melt season by drilling down to the previous summer layer and weighing the snow column. The summer surface is used as the reference level even if some snow accumulation had occurred by the time the summer balance measurements were conducted. The snow thickness on top of the summer surface at the time of the autumn survey has been measured since the 1995. This is needed when comparing with the simulation of snow accumulation. Observations of the broadband albedo in the shortwave domain (0.3-5.0μm) from the MODerate Resolution Imaging Spectroradiometer (MODIS) was used to create a background map of the ice albedo at all glacier gridpoints in HIRHAM5, which was used in the implemented at 5.5 km resolution. HIRHAM5 is a state-of-the-art, high resolution RCM that has been well validated over Greenland (e.g. Box and Rinke, 2003; Lucas-Picher et al., 2012; Rae et al., 2012; Langer In this study, HIRHAM5 albedo scheme. The MODIS estimates of incorporates an updated albedo scheme, using a background MODIS ice albedo field, in the albedo on Vatnajökull have been shown to be in good agreement with AWS data (Gascoin et al., 2017). The MODIS data were extracted in geographical coordinates (lon/lat) at a resolution of 0.005°, i.e. close to the original MODIS resolution of 500 m. This was done using the MODIS reprojection tool with the bilinear interpolation method . These MODIS data in lat/lon were then resampled to match the rotated HIRHAM5 lon/lat grid coordinates by bilinear interpolation using Matlab's interpn function (MATLAB, 2015).

2 Model description

1.1 AWS point models

The turbulent energy fluxes were calculated using a one-level eddy flux model (Björnsson, 1972; Guðmundsson et al., 2009) which uses Monin-Obukhov similarity theory (Monin and Obukhov, 1954) and has implemented different roughness lengths for the vertical profiles of wind, temperature, and water vapour (Andreas, 1987). The model is described in detail in Guðmundsson et al. (2009). Uncertainties of this model for example pertain to the aerodynamic roughness length for momentum z_0. The majority of z_0 values recorded over melting glacier surfaces vary over two orders of magnitude (between 1 aim of capturing the effect of dust and tephra on ice albedo in the ablation zone. This method of determining the ice albedo has previously been used by e.g. van Angelen et al. (2012). Model simulation results are compared to observations from Automatic Weather Stations (AWS) and 10 mm) , but over fresh snow or smooth ice surfaces the roughness length is generally around 0.1 mm (Brock et al., 2006). An order of magnitude increase in z_0 can more than double the estimated turbulent fluxes (Brock et al., 2000), so the chosen roughness length parametrization can greatly affect the performance of the model. Generally, a constant value of z_0 is prescribed for snow and /or ice surfaces (Brock et al., 2006), which is an oversimplification as the roughness may vary significantly over the ablation season (e.g. Grainger and Lister, 1966).

However, since measurements of the evolution of z_0 over the entire measurement period are not available, a constant roughness length of 1 mm was chosen in the calculation of the non-radiative fluxes. Sensitivity tests were conducted to estimate how large an error this choice of roughness length could lead to at the used AWS sites. A roughness length of 0.1 mm would decrease the calculated results by 16-22 %, while using a roughness length of 10 mm would increase the calculated fluxes by 10-19 %, depending on the station. Since the contribution of the turbulent fluxes to the total energy balance is generally low, this translates into an increase or a decrease in the total energy balance at the stations by a maximum of 7 %. The surface air pressure at the station is also needed to calculate the turbulent fluxes, but it is not measured at the AWS sites. Instead it is estimated at the relevant elevation h using synoptic observations from meteorological stations operated by the Icelandic Met Office and the following relationship:

$$P(h) = P(h_0)\left(1 - \frac{0.0065(h-h_0)}{T(h_0)}\right)^{5.25}$$

where $P(h_0)$ in situ mass balance observations, in an effort to improve the performance of the model. The possible physical reasons for any model biases are discussed, and $T(h_0)$ are the air pressure and air temperature, respectively, observed at an elevation h_0 (e.g Wallace et al., 2006). This method has previously been applied successfully at various locations on Vatnajökull and Langjökull (e.g. Guðmundsson et al., 2006, 2009)recommendations for corrections are made where possible.

2 Model description

2.1 HIRHAM5

In this study we employed the regional climate model HIRHAM5 (Christensen et al., 2006), which was developed at the Danish Meteorological Institute. It is a hydrostatic RCM which combines the dynamical core of the HIRLAM7 numerical forecasting model (Eerola, 2006) and physics schemes from the ECHAM5 general circulation model (Roeckner et al., 2003). Model simulations have been successfully validated over Greenland using AWS and ice core data (e.g. Box and Rinke, 2003; Stendel et al., 2008; Lucas-Picher et al., 2012; Langen et al., 2015; Rae et al., 2012; Langen et al., 2017)

While the original HIRHAM5, as described in Christensen et al. (2006), used unchanged ECHAM physics, an updated model version, which includes a dynamic surface scheme that explicitly calculates the surface mass budget on the surface of glaciers and ice sheets, is used in this study. This new scheme takes melting of snow and bare ice into account and resolves the retention and refreezing of liquid water in the snow pack (Langen et al., 2015, 2017). In addition, the 5 layer surface scheme in ECHAM has been expanded to 25 layers.

2.1.1 New albedo parametrization

The updated model also features a more sophisticated snow albedo scheme (Nielsen-Englyst, 2015) than that used in the original HIRHAM5; whereas the previous scheme was purely temperature dependent, the new scheme depends both on the age of the snow and the surface temperature. The scheme is similar to that used in Oerlemans and Knap (1998), which assumes that the albedo decays exponentially as it ages, but in this study an additional temperature component is applied. If there is snow on the surface, the change in the snow albedo from one time step to the next depends on whether the surface is in a cold dry (<-2 271 K) or wet regime (≥ −2 ≥ 271 K). In the cold dry regime, the surface temperature is too low for any melting to occur, while in the wet regime the temperature in the surface layer is high enough for the surface to be melting. The snow albedo changes over a timestep, δt, as

$$\alpha^{t}_{snow} = (\alpha^{t-1}_{snow} - \alpha_{mx}) \cdot e^{-\delta t/\tau_x} + \alpha_{mx} \tag{1}$$

where α_{mx} is the minimum snow albedo value that can be reached from ageing of the snow and τ_x is a timescale which determines how fast the albedo reaches its minimum value. These two variables take on different values depending on whether the snow is in the dry (d) or wet (w) regime.

Observations from the AC and ELA stations were used to determine α_{mx} and τ_x. The optimal variables were found by minimizing the weighted mean RMSE between the modelled and measured albedo by varying the values of α_{mx} and τ_x. The found best-fit values were found to be α_{md}=0.65, α_{mw}=0.41, τ_{md}=5 days, and τ_{mw}=10 days.

Refreshment of the albedo Albedo is only refreshed to the maximum value only occurs if snowfall constitutes more than 95 % of the total precipitation. It is possible to have a partial refreshment , A partial refreshment is possible as the albedo is only refreshed reset to the maximum allowed value if the amount of snowfall on that day (S_0) is higher than 0.03 m w.eq. This value threshold was chosen to provide the best fit with the AWS observations. The rate of refreshment b is given by

$$b = min\left[1, \frac{S_f}{S_0}\right] \tag{2}$$

where S_f is the amount of snowfall during the model time step in m w.eq. and S_0 is the critical amount of snowfall in m w.eq. per model time step needed to completely refresh the albedo. Using this rate, the albedo is then refreshed using

$$\alpha^{t+1}_{snow} = \alpha^{t}_{snow} + b \cdot (\alpha_{max} - \alpha^{t}_{snow}) \tag{3}$$

where α_{max} is the maximum albedo for freshly fallen snow, set equal to 0.85 as this provides the best average fit with the observations.

In the case of small snow depthsshallow snow cover, the surface albedo will be affected by the albedo of the underlying ice. A smooth transition between the snow and bare ice albedo is therefore implemented, and the final albedo is thus expressed as

$$\alpha^{t+1} = \alpha^{t+1}_{snow} + (\alpha_{ice} - \alpha^{t+1}_{snow}) \cdot exp(\frac{-d^{n+1}}{d_s} \frac{-d^{t+1}}{d_s}) \tag{4}$$

where d is the snow depth, and d_s is a characteristic scale for snow depth. Following Oerlemans and Knap (1998), the characteristic scale is set to 3.2 cm snow depth. If no snow is present, the albedo is set to the bare ice albedo.

~~In order to determine the~~ The bare ice albedo ~~at each gridpoint, daily MODIS data over Iceland from 2001-2012 were used. Years with volcanic eruptions were discarded, as the volcanic ash lowered the albedo values far below the average. The minimum autumn albedo value was then determined in each grid point and that value used to create a bare~~ is determined from a background ice albedo map ~~of the glaciers. The spectral properties of ice in the ablation zone are controlled by tephra layers in the ice, which are exposed as the glacier melts (Larsen et al., 1996). New falling tephra or dust will therefore only have a small effect on the spectral properties of the ice, as the ice surface is already covered in dark bands. In addition, the new particles are generally washed off from year to year. Applying one background map for the entire period should therefore provide the same results as applying a map created for each year. In addition, it allows us to run the model for years where no MODIS observations are available or where the amount of observations over the ice cap are sparse due to e.g. clouds~~which was created using MODIS observations from 2001-2012. How this map was created is described in section 3.

~~How much~~ The extent to which this bare ice MODIS albedo map improves the simulations will be estimated by comparing the results with those from a model simulation using a constant ice albedo in Section 4.8.

2.1.2 Experimental design

In this study, HIRHAM5 is run at a resolution of 0.05° ~~on a rotated pole grid~~ (equivalent to ∼5.5 km) on a rotated pole grid for the period 1980-2014. The model uses 31 irregularly spaced vertical atmospheric levels from the surface to 10 hPa with a model time step of 90 seconds in the dynamical scheme. The model is configured for a domain containing all of Greenland and Iceland. The model is forced at the lateral and lower boundaries by the ECMWF ERA-Interim reanalysis dataset (Dee et al., 2011), which uses observations from satellites, weather balloons, and ground stations to create a comprehensive reanalysis of the atmosphere. The model is forced by temperature, wind, relative humidity and surface pressure at the lateral boundary, and sea surface temperature and sea ice fraction at the lower boundary at 6 hour intervals.~~The model is here run from 1980 to 2014.~~

The new snow/ice surface scheme discussed above is run offline in this study, meaning that the subsurface scheme is run separately from the atmospheric code. This is done by forcing the subsurface scheme every 6 hours by radiative and turbulent surface fluxes, as well as snow, rain, evaporation, and sublimation data from a HIRHAM5 experiment with a previous version of the albedo and refreezing schemes (e.g. Langen et al., 2017). While a full, high-resolution HIRHAM5 run is computationally very expensive, the offline model offers a fast and flexible option to test new model implementations and allows for a quick and thorough spin-up of the subsurface. ~~Running~~ The offline model was initialized with values from a previous offline model run with a different albedo scheme and then a model spin-up was performed by integrating the model for ~~a smaller domain which only contains Iceland further reduces the computational cost of the model~~150 years repeating the forcing from 1980. The largest adjustments occurred during the first 75 years of the spin-up, after which the variation was much smaller than the interannual variability. At the end of the run, the solar radiation, surface mass balance, runoff, snow depth, and refreezing had all converged, as had the temperature, liquid and snow content in all 25 subsurface layers. The final state of the spin-up was then used as the initial condition for the 1980-2014 model simulation. The reported values of albedo, upward longwave and shortwave radiation, and surface mass balance in the following are all from the offline run.

A disadvantage of this method is that it neglects feedbacks between the atmospheric circulation and the surface conditions like e.g. the albedo and temperature. However, since the surface temperature of Vatnajökull is typically near the melting point during the summer, both in reality and in the model, changes in the albedo should not have a large effect on ~~the~~ upward longwave radiation and the turbulent fluxes. Thus while the updated surface scheme is important for the mass balance components, the error due to the neglected feedbacks is likely small in the model calculations.

~~The offline model was initialized with values from a previous offline model run with a different albedo scheme and then a model spin-up was performed by integrating the model for 150 years repeating the forcing from 1980. The largest adjustments occurred during the first 75 years of the spin-up, after which the variation was much smaller than the interannual variability. At the end of the run, the solar radiation, surface mass balance, runoff, snow depth, and refreezing had all converged, as had the temperature, liquid and snow content in all 25 subsurface layers. The final state of the spin-up was then~~

2.1.3 Model uncertainty

Due to nonlinearities in the HIRHAM5's model dynamics and physics, it has an implicit uncertainty due to internal model variability originating from nonlinear processes (e.g. Giorgi and Bi, 2000; de Elía et al., 2002). This variability is caused by numerical sensitivity, uncertainty in the boundary and initial conditions, and errors due to model parametrizations (e.g. Box and Rinke, 2003) including, for example, the albedo parameterization, the vertical gradients in the boundary layer, or cloud radiative effects. In addition, using a constant value of z_0 for both snow and bare ice could lead to large errors in the turbulent fluxes (e.g. Brock et al., 2000).

3 Observational data

The primary observational dataset used in this study was collected by AWSs at selected locations on Vatnajökull. Since 1994, 1-13 stations have been operated on the ice cap during the summer months (e.g. Oerlemans et al., 1999; Guðmundsson et al., 2006). The temperature, relative humidity, wind speed, and wind direction at 2 m above the surface have been measured during the entire period (1992-present), while the radiation components have been measured since 1996. For this study, data from five AWSs were considered - three on Brúarjökull (B) and two on Tungnaárjökull (T) (see Figure 1). Both Brúarjökull and Tungnaárjökull are outlet glaciers of Vatnajökull ice cap. Two stations are situated in the ablation zone (henceforth referred to as the AB stations), one station is situated near the equilibrium line altitude (ELA station), and two stations are in the accumulation zone (AC stations). The average elevation of each station is shown in Table 1. All five stations have been operated on the glacier every year during the period 2001-2014. Observations of 2 m temperature, humidity, wind speed, and radiative fluxes were used to validate HIRHAM5 over Vatnajökull.

The uncertainties of the AWS observations vary depending on the sensor. The temperature and humidity sensors have an accuracy of 0.2 K and 2 % for temperature and humidity, respectively, while the accuracy of the wind speed is 0.2 ms^{-1}

(Guðmundsson et al., 2009). The radiative fluxes were measured using either Kipp and Zonen CM14, CNR1 or CNR4 sensors that have a maximum manufacturer-reported uncertainty of ±10 % for daily totals (e.g. Kipp and Zonen, 2002). However, the uncertainty has independently been evaluated to be lower (3-5 %) when used in an ice sheet environment (van den Broeke et al., 2004; Guðn The turbulent fluxes, combining sensible and latent heat fluxes, and surface pressure were not measured at the stations, but were estimated using the methods described in Section 3.1.

In addition to AWS data, in situ mass balance measurements were used to evaluate the simulated surface mass balance (SMB) at several sites on Vatnajökull. Conventional in situ mass balance measurements have been carried out every glaciological year since 1991-92, with 60 stations measured each year on average. The measurement sites are shown in Figure 1. The uncertainty of the mass balance measurements has been estimated to be ±0.3 m w.eq.

The SMB measurements are conducted at the beginning and end of the accumulation season in order to measure both the winter and summer balance. The winter balance is measured in the beginning of the melt season by drilling down to the previous summer layer and weighting the snow column. The summer surface is used as the ~~initial condition for the 1980-2014 model simulation.~~

3.0.1 ~~Elevation-based corrections~~

reference level even if some snow accumulation had occurred by the time the summer balance measurements were conducted. The snow thickness on top of the summer surface at the time of the autumn survey has been measured since 1995. This is needed when comparing with the simulation of snow accumulation.

Observations of the broadband albedo in the shortwave spectrum (0.3-5.0μm) from the MODerate Resolution Imaging Spectroradiometer (MODIS) were used to create a background map of the ice albedo at all glacier gridpoints in HIRHAM5, which was used in the implemented HIRHAM5 ~~uses an elevation model over Iceland which has been interpolated onto the 5.5 km model grid. Since errors in the elevation of the glacier surface can introduce significant biases in temperature and pressure which are not caused by physical model errors (Box and Rinke, 2003), any elevation bias in the model has to be taken into account. The elevation bias was calculated as the difference between the model elevation, which was interpolated to the AWS sites using bilinear interpolation of the elevation at the four surrounding model grid points, and GPS observations at each site (Table 1).~~

~~The temperature was corrected for the elevation bias using a constant lapse rate of 6.5 , which resulted in temperature corrections on the order of 0.1-0.3 K. Correcting for the pressure was done using Eq. (5) and amounted to corrections on the order of 1 to 5 kPa. Thus although the~~ albedo scheme. MODIS product MCD43A3 v006 was used for the background map. The MODIS estimates of the albedo on Vatnajökull are in good agreement with AWS data (Gascoin et al., 2017). The MODIS data were extracted in geographical coordinates (lon/lat) at a resolution of 0.005°, i.e. close to the original MODIS resolution of 500 m. This was done using the MODIS reprojection tool with the bilinear interpolation method. These MODIS data in latitude-longitude coordinates were then resampled to match the rotated HIRHAM5 ~~elevation is consistently overestimated,~~

it is not large enough to introduce significant biases in temperature and surface pressure. lon/lat grid coordinates by bilinear interpolation using Matlab's interpn function (MATLAB, 2015).

3.0.1 Model uncertainty

Due to nonlinearities in the HIRHAM5's model dynamics and physics, it has an implicit uncertainty due to internal model variability originating from nonlinear processes (e.g. Giorgi and Bi, 2000; de Elía et al., 2002). This variability is caused by numerical sensitivity, uncertainty in the boundary and initial conditions, and errors due to model parametrizations (e.g. Box and Rinke, 2003 like for example that of the albedo, In order to determine the bare ice albedo at each gridpoint, daily MODIS data over Iceland from 2001-2012 were used. Years with volcanic eruptions were discarded, as the volcanic ash lowered the albedo values far below the average. The minimum autumn albedo value was then determined in each grid point using values from Juli-September and that value used to create a bare ice albedo map of the glaciers. The final albedo map had ice albedo values in the vertical gradients in range 0.03-0.3 for Vatnajökull. The spectral properties of ice in the ablation zone are controlled by tephra layers in the ice, which are exposed as the glacier melts (Larsen et al., 1996). Additional tephra or dust deposition will therefore only have a small effect on the spectral properties of the boundary layer, or cloud radiative effects. In addition, using ice, as the ice surface is already covered in dark bands. In addition, field observations suggest that the new particles are generally washed off from year to year. Applying one background map for the entire period should therefore provide the same results as applying a map created for each year. In addition, it allows us to run the model for years where no MODIS observations are available or where the amount of observations over the ice cap are sparse due to e.g. clouds.

3.1 AWS point models

The turbulent energy fluxes were calculated from AWS measurements using a one-level eddy flux model (Björnsson, 1972; Guðmundsson e uses Monin-Obukhov similarity theory (Monin and Obukhov, 1954) and implements different roughness lengths for the vertical profiles of wind, temperature, and water vapour (Andreas, 1987). The model is described in detail in Guðmundsson et al. (2009). Uncertainties of this model for example pertain to the aerodynamic roughness length for momentum z_0. The majority of z_0 values recorded over melting glacier surfaces vary over two orders of magnitude (between 1 and 10 mm), but over fresh snow or smooth ice surfaces the roughness length is generally around 0.1 mm (Brock et al., 2006). An order of magnitude increase in z_0 can more than double the estimated turbulent fluxes (Brock et al., 2000), so the chosen roughness length parametrization can greatly affect the performance of the model. Generally, a constant value of z_0 for both snow andbare ice is prescribed for snow and/or ice surfaces (Brock et al., 2006), which is an oversimplification as the roughness may vary significantly over the ablation season (e.g. Grainger and Lister, 1966).

However, since measurements of the evolution of z_0 over the entire measurement period are not available, a constant roughness length of 1 mm was chosen in the calculation of the non-radiative fluxes. Sensitivity tests were conducted to estimate how large an error this choice of roughness length could lead to large errors in the turbulent fluxes (e.g. Brock et al., 2000). at the used AWS sites. A roughness length of 0.1 mm would decrease the calculated turbulent fluxes by 16-22 %, while using a roughness length of 10 mm would increase the calculated fluxes by 10-19 %, depending on the station. Since the contribution of the turbulent fluxes to the total energy balance is generally low, this translates into an increase or a decrease in the total energy balance at the stations by a maximum of 7 %.

The surface air pressure at the station is also needed to calculate the turbulent fluxes, but it is not measured at the AWS sites. Instead it is estimated at the relevant elevation h using synoptic observations from meteorological stations operated by the Icelandic Met Office and the following relationship:

3.1.1 ~~Validation method~~

$$P(h) = P(h_0)\left(1 - \frac{0.0065(h-h_0)}{T(h_0)}\right)^{5.25} \quad (5)$$

where $P(h_0)$ and $T(h_0)$ are the air pressure and air temperature, respectively, observed at an elevation h_0 (e.g Wallace et al., 2006). This method has previously been applied successfully at various locations on Vatnajökull and Langjökull (e.g. Guðmundsson et al., 2006, 2

3.2 Validation method

AWS data from 2001-2014 for three Brúarjökull stations and two Tungnaárjökull stations are considered, as well as SMB point measurements from 1995-2014. All stations were operated during the summer months, but since 2006 the lowest Brúarjökull station has been operated year round. Comparisons are made between daily averages from the HIRHAM5 model and the in situ observations ~~made by~~ collected at the AWSs. HIRHAM5 daily means are calculated from 6 hourly outputs, while the AWS daily means are calculated from observations at 10 minute intervals.

Comparisons between station values and model values are made by ~~bilinear interpolation of~~ bi-linearly interpolating the model output to the measurement position using the four closest model grid points and using only glacier-surface type grid cells.

In order to remove the effect of seasonally varying magnitudes of the energy balance components, the percent errors ~~given in this study~~ listed in Tables 2-4 are calculated as the Root Mean Square Error (RMSE) divided by the observations.

HIRHAM5 uses an elevation model over Iceland which has been interpolated onto the 5.5 km model grid. Since errors in the elevation of the glacier surface can introduce significant biases in temperature and pressure which are not caused by physical model errors (Box and Rinke, 2003), any elevation bias in the model has to be taken into account before validating the results. The elevation bias was calculated as the difference between the model elevation and GPS observations at each site (Table 1).

4 ~~Results and discussion~~

3.1 ~~Meteorological variables~~

~~Before validating the surface energy balance components, a comparison of four near-surface variables with observations was made~~ The temperature was corrected for the elevation bias in order to ~~assess how well they are simulated in the model .~~ compare the model results to the AWS measurements at AWS locations. This was done using a constant lapse rate of 6.5 K km^{-1}, which resulted in temperature corrections on the order of 0.1-0.3 K. Pressure is corrected using Eq. (5) decreasing the bias down to 0.1 to 0.5 hPa. Thus although the HIRHAM5 elevation is consistently overestimated, the resulting differences are not large enough to introduce significant biases in temperature and surface pressure.

4 Results and discussion

4.1 Meteorological variables

As the sensible and latent heat fluxes are computed using the surface pressure, p_{sl}, ~~temperature~~air temperature at 2 m, T_{2m}, relative humidity, r_{2m}, and wind speed, ~~w~~u, these model variables were evaluated at all five stations at the measurement height. How well these variables are simulated should indicate the model's ability to simulate the turbulent fluxes.

The comparison of ~~the~~ modelled and observed mean daily values during the summer months from 2001-2014 ~~with corresponding observations from the five stations~~ is shown in Fig. 2 and Table 2. The surface pressure, p_{sl}, which was not observed at the stations but estimated using Eq. (5), is generally forecast with ~~a high degree of skill, with~~ only a small error. At ~~every~~ each station there is a high positive correlation ~~between the HIRHAM5 simulated pressure and the pressure estimated using data from nearby meteorological stations~~ (r > 0.9) between modelled and estimated pressure (Eq. 5), ~~with correlation coefficients higher than 0.9 both~~ for the entire time series and for each individual year.

The model also captures the 2 m temperatures, T_{2m}, satisfactorily. The largest deviation from the observations is found at the B_{AB} station, which underestimates the temperature ~~with~~ by 0.8 ~~overall~~K on average. The temperature is also underestimated at the four ~~remaining~~ other stations, but ~~with less than~~ by at most 0.6 ~~K~~K. The model simulates the variation in temperature well; ~~it for example~~for example, it captures the temperature dampening over a melting glacier surface. This is expressed in the high correlation values for all five stations (r $\sim$ 0.9).

The measured relative humidity, r_{2m}, at all five stations is generally high, with only 1-3 % of the data points at each station falling below 70 %, and the minimum daily value between 42 and 58 %. The model simulates a lower mean humidity than the measured at all five stations, with 8-20 % of the points at each stations having values lower than 70 % and minimum daily values between 18 and 30 %. Since the exchange coefficient for moisture is a function of the atmospheric temperature profile, the underestimation of the relative humidity could be due to a too low temperature gradient between the atmosphere and the surface. This is consistent with the underestimation found in the 2 m temperature. The correlation of between 0.68-0.7 indicates that the model simulates the humidity fluctuations satisfactorily.

~~Since the~~ The lowest wind speed level in HIRHAM5 is at 10 m and the AWS wind speeds are measured at between 2-4 m, depending on the year, the HIRHAM5 wind speed is extrapolated to the measurement height using a logarithmic profile with a roughness length of 1 mm. At all five locations, HIRHAM5 simulates winds that are too weak on average. This could be due to the uncertainty arising from the interpolation of the model winds from second-lowest level (30 m) to the lowest level (10 m) under stable conditions, as the wind speed can change significantly over the 20 m interval.

4.2 Longwave radiation

As shown above, HIRHAM5 underestimates the temperature at all five stations, with the largest underestimation at the B$_{AB}$ station. ~~Therefore, it is to be expected that the~~ As a result, a similar underestimation of incoming longwave radiation is ~~underestimated~~ obtained at all five stations, with the largest difference occurring at the B$_{AB}$ station ~~. As shown in the scatter plots in Figure 3a, this is indeed the case~~3. The average percentage difference is approximately 8 % for all five locations (see Table 3), ~~so on average the results are~~ and falls well within the 10 % uncertainty of the AWS observations. However, ~~as can be seen in the figures, many of the simulated days have larger errors - between~~ Fig. 3a also shows that 25-30 % of the simulated ~~points have percent difference~~ days have errors larger than 10 %.

The incoming LW radiation is mainly emitted from clouds and atmospheric greenhouse gases, and therefore a source of the underestimation could be either that the model underrates cloud formation and/or simulates clouds that are too optically thin in the LW region of the spectrum. An underestimation of the temperature in the atmosphere could also be causing the underestimation.

Figure 3b shows the comparison of the modelled and measured outgoing LW radiation. There is a small overestimation at the T$_{AC}$ station, and a small underestimation of the other four stations, but in general the model reproduces the daily values well (r $\sim$ 0.76). The average percentage deviation between the modelled and measured values is only around 3 %, ~~and only~~ combined with between 0.5-2 % of the HIRHAM5 data points ~~have~~ having deviations larger than 10 %.

Due to an underestimation of the incoming LW radiation, and only small negative or positive biases in the outgoing LW, the ~~total LW~~ net LW (incoming-outgoing) radiation has a mean negative bias at all AWS locations ~~. The average model error for all five stations is~~ (-7.9 W m^{-2}).

4.3 Shortwave radiation and albedo

Figure 4 and Table 3 show the comparisons of the modelled and measured components of the shortwave (SW) radiation as well as the surface albedo. On average, the incoming SW radiation is underestimated at all five stations. This underestimation is also present in the means at all five stations for most years, except in 2002, 2004, 2005, and 2014 at the B$_{AB}$ station. This suggests that there are errors in either the modelling of the clouds, e.g. due to an overestimation of the cloud fraction, the amount of cloud formation, or the optical thickness of the clouds in the shortwave region, and/or because of errors in the clear-sky fluxes.

The albedo comparison is shown in Figure 4b. The modelled albedo at the two AB stations has the largest deviation from the observations; this is partly due to the modelled snow cover, which either does not completely disappear or disappears later in the year than the AWS data show. At the B$_{AB}$ station, the ice layer is generally exposed ~~in the model~~ the model (except in 2001 and 2011-2013), although the ~~ice surface is always exposed later~~ snow cover always persists longer than in reality. One exception ~~is~~ occurs in 2001, where the modelled albedo never drops down to the ice value~~in HIRHAM5, but the~~ , whereas observations show albedo values down to as low as 0.03. This one year therefore highly contributes to the total average overestimation of the albedo. This very low albedo value could be due to a layer of dust or tephra beneath the station, so it may not represent the ice albedo. However, very low ice albedo values down to 0.5 are not uncommon in the ablation zone of Vatnajökull (e.g. Gascoin et al., 2017). Comparisons with the mass balance measurements (discussed below in Section 4.6.1) show that the winter balance is overestimated during approximately half of the study period, which will contribute to the too slow measured years, which contributes to delay the albedo drop in the model.

At the T_{AB} station, the modelled winter snow cover a too thick modelled snow cover in winter is also the cause of some of the discrepancy. HereComparisons with mass balance measurements (Section 4.6.1) show that the winter balance is always overestimated at this station. An overestimation of the snow thickness at the beginning of summer, combined with an underestimation in the radiation and turbulent fluxes, lead to persistent snow cover at the end of summer. As a result, the ice surface is not never exposed in the model during any of the modelling modelled years, and the albedo never drops much below 0.4 (the minimum snow albedo), even though the AWS data shows that the ice surface was exposed during all but two years . However, during i.e. 2008 and 2010. During these two yearswhere the ice surface was not exposed, the simulated albedo fits well with observations. This station is only ~100 below the average ELA, and thus some of the same modelling difficulties which affect the ELA station (discussed below) may be found on this station, especially during years where the snow line is closer to the station. In addition, comparisons with mass balance measurements (Section 4.6.1) show that the winter balance is always overestimated at this station, and an overestimation of the snow layer at the beginning of summer, combined with an underestimation in the radiation and turbulent fluxes, is the likely reason for the overestimation of the snow layer at the end of summer.

Another issue which affects both stations is that the MODIS albedo at these points is not as low as the measured albedo. The MODIS ice albedo at these stations is 0.10 (B_{AB}) and 0.16 (T_{AB}), whereas the observations show the albedo can drop as low as 0.01 at both stations. The albedo drops below the MODIS value every year at the B_{AB}, and during 2001-2005 and 2011 at the T_{AB} stations. This is presumably due to the heterogeneity of the albedo in the ablation zone, which means that a low in situ albedo value at a point cannot be captured at the current HIRHAM5 resolution.

At the ELA station, the mean albedo value is underestimated (Table 3). This is due to the difficulty in modelling the albedo near the equilibrium line. In this areaClose to the equilibrium line, the albedo is highly variable both temporally and spatially. There is , e.g. there is a large difference in albedo depending on whether the previous year's summer surface was exposed or not. In general, the model overestimates the albedo during years where the summer surface was exposed, and underestimates the albedo during years where it was not. In addition, the winter mass balance at this station is always underestimated (Section 4.6.1), meaning that the thickness of snow layer in spring is underestimated and the effect of the underlying ice layer will therefore be overestimated, leading to the underestimation in albedo.

The difference between the model and the observations is smallest smallest difference between modelled and observed albedo is found at the two AC stations. The B_{AC} station generally provides the best fit with the observations, while the model tends to underestimate the albedo at the T_{AC} station. An exception to this is found in 2010 and 2011, where the albedo was overestimated by the model at both stations due to ash deposition from the Eyjafjallajökull and Grímsvötn eruptions (e.g. Gudmundsson et al., 2012).

A general reason for the model ~~underestimating~~ overestimating the albedo is that it does not take the albedo changes due to dust storms or volcanic dust deposition into account. ~~One example of this is~~ For instance, the very low albedo values ~~seen in Figure 4b~~ obtained at the T_{AC} station ~~(blue) which~~ Fig. 4b) are due to tephra ~~deposited~~ deposition on the glacier during the 2010 eruption of Eyjafjallajökull (e.g. Gudmundsson et al., 2012; Gascoin et al., 2017). Even though dust events do not cause as large changes in albedo as a volcanic eruption, they can still significantly lower the albedo (e.g. Painter et al., 2007; Dragosics et al., 2016) . As previously mentioned, the albedo in HIRHAM5 often reaches its yearly minimum value later in the summer than the observed~~, and~~ . Such discrepancy could be explained by dust events, ~~which cause the albedo to drop faster or earlier in the year than would otherwise be the case, could explain this discrepancy. A study by Dragosics et al. (2016) for example~~ advancing or delaying the drop in surface albedo. Dragosics et al. (2016) investigated 10 dust events which occurred at the B_{ELA} station in 2012, and found a lowering in the albedo during all events and showed that the dust storms ~~had~~ have a significant effect on the resulting energy balance.

The error in the outgoing shortwave radiation is ~~, of course,~~ caused by errors in the albedo and the incoming SW. At the B_{AB} station, the incoming radiation is slightly underestimated but the albedo is overestimated, hence the outgoing SW is overestimated. The values at the four other stations are all underestimated, due to larger underestimations of the incoming SW radiation and lower albedo errors.

~~Due to the underestimation of~~ As both the incoming and outgoing SW radiation are underestimated at most stations, the ~~two components partially offset each other. The net SW at the three highest stations is generally underestimated by between~~ net SW shows a negative bias of ~-6 ~~and~~ to -12 W m^{-2} ~~, while the values at the two AC stations are underestimated by between~~ at the AC and ELA stations, and of -22 and -28 W m^{-2} ~~. The~~ at the two AB stations. The resulting average model error at all five stations is ~~therefore negative at~~ -15.5 W m^{-2}.

4.4 Turbulent fluxes

~~Based on the comparison of the measured and modelled meteorological variables , one would expect~~ As HIRHAM5 ~~to forecast~~ underestimates meteorological variables at all stations, similar underestimation is obtained for the turbulent fluxes ~~with a significant model underestimation. As can be seen in the comparisons statistics in~~ (Table 3 and ~~the scatterplots in Figure 5, this appears to be the case~~ Fig. 5). The two AC stations have the largest differences and also the lowest correlation (0.45 and 0.49) between the AWS ~~model~~ estimate and the HIRHAM simulation. The other three stations also have significantly lower values in the HIRHAM5 model than in the AWS model, but with higher correlation coefficients (0.69-0.73).

It is important to bear in mind that this comparison is a model-model comparison, so while the eddy flux model may give a good estimate of the turbulent fluxes, model errors still affect the results e.g. due to the use of a constant roughness length.

4.5 Total energy balance

After the simulated components of the energy balance were evaluated against AWS observations, the total energy balance was estimated (see Table 3). The energy balance (E) is found using

$$E = LW_{net} + SW_{net} + H_{s+l} \tag{6}$$

where LW_{net} is the net LW radiation, SW_{net} is the net SW radiation, and H_{s+l} are the turbulent fluxes. Overall, the ~~energy balance~~ melt energy is underestimated, owing to all elements of the energy balance generally being underestimated. This is in large part due to the underestimation of the modelled incoming radiation. We attribute this to an error in the modelling of the clouds, but since both the incoming SW and LW radiation are underestimated, ~~the cloud cover~~ inaccurate cloud representation cannot be the the only source of the error. ~~An error in the cloud cover would have to be combined with an error~~ Errors in the interaction ~~between~~ of clouds and radiation, ~~for example in the form of an~~ e.g. error in the optical thickness of the clouds, or ~~errors~~ in the clear sky fluxes, ~~to explain these results~~could partly explain these discrepancies. The underestimation of the incoming LW radiation could also be due to errors in the vertical atmospheric temperature gradient.

~~Whereas~~ Since the simulated outgoing LW radiation generally only has a small ~~deviation from the measured, and~~ negative bias, the deviation in ~~the~~ net LW radiation is ~~therefore mostly due to~~ governed by the incoming radiation~~, the errors~~ . Errors in the simulated albedo ~~means~~ mean that both the in- and outgoing SW radiation greatly contribute to the deviation in ~~the total~~ net SW radiation. ~~Some of the error can be~~ These errors can be partly attributed to ash and dust deposition during volcanic eruptions and dust storms, which ~~the model does not take into account and we therefore cannot expect these events to be reflected in the model results. However, as mentioned above, another issue with~~ are not taken into account in HIRHAM5. In addition, errors in the simulated albedo ~~stems from a snow layer~~ also stem from snow cover that disappears too slowly compared to AWS ~~results at stations~~ records in the ablation zone~~, which means that the simulated~~ . As a result, modelled albedo drops too slowly compared to the measured albedo. The underestimation of the net SW and LW radiation and the turbulent fluxes ~~also~~ leads to underestimated melt energy. This contributes to the overestimation of the modelled snow ~~layer, as they all contribute to the underestimation of energy available for melt~~thickness.

In order to estimate how much the different components contribute to the energy difference on a year-to-year basis, the mean difference ~~of the~~ between modelled and observed energy components during each summer (Apr-Oct) ~~was plotted~~ is shown for each station (Fig. 6).

At the B_{AC} station, the contribution of the long- and shortwave radiation and turbulent fluxes to the energy difference is consistent for the entire period, with the error of each component being almost equal, varying between -25 and 0 W m^{-2}. At the T_{AC} station, the error due to the three components is also of the same order of magnitude, except in 2010 and 2011 where there error in the net SW radiation is much larger than that in the other components. This is due to a large drop in the albedo as a result of the Eyjafjallajökull (2010) and Grímsvötn (2011) eruptions. The mean difference ~~in~~ between observations and the simulations of the SW radiation for non-eruption years is -3 W ~~/m^2~~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 ~~contribution to the~~

~~energy is -103~~ increase in available energy due to the eruption is 103 W m^{-2}~~over a 128 day measurement period~~. 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 ∼3.1 m w.eq. at this station.

At the ELA site, the contribution from the modelled turbulent fluxes to the energy balance deviation generally varies between ±10 W m^{-2}, except in 2013 where the bias is around -25 W m^{-2}. ~~The difference in modelled and measured~~ Modelled longwave radiation is consistently ~~at about~~ underestimated by -10 W m^{-2}. The deviation in the shortwave radiation is more variable, as expected from the results of the albedo comparison~~; depending on whether the previous years summer surface~~ . Depending on whether bare ice was exposed or not, the albedo ~~was~~ is generally either over- or underestimated. For example, at B_{ELA}, the ~~summer~~ ice surface was reached in ~~for~~ e.g. 2007 and 2012, resulting in an overestimation of the albedo. In e.g. 2002 and 2009, however, the albedo was high the entire summer as ~~the previous summer surface was not~~ no ice was exposed, resulting in an underestimation of the predicted albedo.

At the T_{AB} station, both the net LW radiation and the turbulent fluxes agree well with observations for the entire period. The net SW radiation, however, is always underestimated, especially in 2001-2003 and 2011. These years, the measured albedo at the station goes below 0.1, while the HIRHAM5 albedo stays around 0.4. As previously discussed, this albedo bias, and hence underestimated net SW radiation, occurs because of an overestimation of the snow cover at the station due to an overestimation of the winter accumulation and possibly also the proximity ~~to~~ of the equilibrium line~~, and it is the main reason for the large underestimation of the SW radiation~~. An underestimation of the incoming SW radiation, which we attribute to an error in cloud cover amount of clear-sky fluxes, also contributes to this error.

At the B_{AB} station, the longwave radiation bias is relatively constant with values close to 0 W/m^2 for much of the measurement period. The absolute deviation due to the turbulent fluxes is less than 10 W m^{-2} for most of the period, although with slightly larger deviations from 2007-2010. The SW radiation is always underestimated at this station, mostly due to the previously discussed overestimation of the albedo.

4.6 Surface mass balance

4.6.1 At AWS sites

Scatter plots of measured and HIRHAM5 simulated SMB are shown in Figure 7 and the average deviations are shown in Table 4.

The winter mass balance comparison ~~offers an evaluation~~ allows to evaluate of the winter precipitation in HIRHAM5. The simulated mass balance at the B_{ELA} ~~,~~ and B_{AC} ~~, and~~ are always underestimated, while the T_{AC} stations is underestimated during all years but one~~, while the~~ (2012). The simulated value at the T_{AB} station is overestimated over the whole period. The modelled mass balance at the B_{AB} station has an almost equal amount of years which are over- and underestimated. Apparently the model either carries too much precipitation when the clouds reach the glacier, resulting in too much precipitation at the ice sheet margin, or more melting occurs at the ablation area stations during the winter months than the model estimates.

The summer SMB results are in good agreement with the results of the energy balance calculations. The summer SMB is generally overestimated, although it is underestimated occasionally at all stations except T_{AB}. The ELA station has the largest amount of underestimated points, which is consistent with the findings from the energy balance calculations. Besides the errors introduced due to the underestimation of the energy balance, possible over- or underestimations of the modelled summer accumulation contribute to these errors as well.

Due to the difference in the summer and winter balance, the net balance at the B_{AC}, T_{AC}, and B_{ELA} stations is generally underestimated in HIRHAM5, while the balance at the two AB stations is generally overestimated. This is due to a general overestimation of the winter balance in the ablation area, either due to an underestimation of the winter melt or an overestimation of precipitation, as discussed above.

4.6.2 At all measurement sites

The mass balance was not just measured at the AWS sites, but at between SMB is also measured at 25-120 sites on the ice capnon-AWS sites, depending on the year (Fig. 1). In order to estimate how well the model represents the SMB at non-AWS sites, the data from all the sites between 1995-2014 were compared with the HIRHAM5 simulation (Fig. 8; Table 4).

The winter balance at all measured points is slightly overestimated by HIRHAM5 on average. However, this is mostly due to a large difference between measured and simulated SMB at the ice covered, high elevated, central volcano Öræfajökull (the white dots in Fig. 8). Only one site has been measured on this glacier for a few years only (Guðmundsson, 2000), in a spot that always receives a large amount of accumulation, but precipitation. However, since HIRHAM5 consistently overestimates the accumulation by 100-200 %, this one point has a large effect on the mean error. This is a well known issue with hydrostatic models like HIRHAM5, as they characteristically overestimate the precipitation on the upslope and peaks in complex terrain. The reason for this is that the precipitation is calculated as a diagnostic variable, i.e. it is not governed by an equation that is a derivative of time, meaning that when the required conditions for precipitation are met in the local atmosphere, the precipitation appears instantaneously on the surface. Thus the scheme does not allow horizontal advection of snow and rain by atmospheric winds, which is a particularly significant key process in complex terrain, as it can force the precipitation downslope (e.g. Forbes et al., 2011). Without this effect, precipitation is generally overestimated at high peaks like Öræfajökull. If this point is removed Removing this location from the comparison, the total difference is about drops to one-third that of the difference with respect to the AWS sites only (-0.09 m w.eq.). This is due to the sites closer The reason the difference is smaller than for the AWS sites only is that more sites close to the edge of the ice cap , as are included. The winter balance at the measurement points at the outer parts of the icecap generally is overestimated in the model, while the balance at the sites and therefore these points partly offset the underestimation in the middle is underestimatedof the ice cap.

On average, the summer ablation is underestimated, which is consistent with the findings from the AWS stations that there is an average underestimation of the energy available for melt. The mean error and RMSE is only slightly larger than at the AWS sites.

The mean net balance is overestimated by approximately the same amount as the summer balance, partly due to the low mean deviation in the winter SMB. Due to the large deviation at Öræfajökull in the winter SMB, the Öræfajökull points clearly have the largest bias. If these points are excluded, a rmse closer to that for the AWS locations is found (1.1 m).

4.7 Reconstructing the SMB of Vatnajökull

~~Having assessed how wellthe model simulates the energy and mass balancecomponents at the measurement sites, the model was then used to estimate the mean specific mass balance of Vatnajökull back to 1981. The specific~~

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 Öræfajökull 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 3). This was partly due to a smaller albedo bias for stations in the ablation zone than for stations in the accumulation zone.

In addition to the spatial maps, the winter, summer ~~,~~ and net mass balances of Vatnajökull were calculated for the entire simulation period, and the results were compared with an estimate of the specific balance from 1995-2014, created by ~~manual~~ interpolation of the mass balance measurements (e.g. Pálsson et al., 2015), see Fig. 10. The model prediction of the mean specific summer mass balance generally fits well with the interpolated observations, with an overall difference of only 0.06 m w.eq. The largest deviations are obtained in 1995, where ~~there is too much ablation~~ ablation is overestimated in the simulation, and in 1997, 2005, and 2010-2012, where ~~there is too little ablation in the simulation~~ablation is underestimated, most likely due to ash depositions on the glacier following the 1996 Gjálp eruption, the 2004 and 2011 Grímsvötn eruptions or the 2010 Eyjafjallajökull eruption, which are not taken into account in the model.

Excluding the years where the albedo was affected by volcanic eruptions, the average difference becomes smaller but the model also predicts slightly too much ablation, as the difference becomes -0.02 m w.eq.

There is a shift in the summer and annual mass balance calculated by the model and the in situ MB measurements around 1996, with a generally more negative mass balance after 1996 than before. This is consistent with the increase of the annual mean temperature of Iceland in the mid-1990s, which resulted in a mean annual temperature ~ 1 K higher in the decade after than the decade prior to 1995. This is likely linked with atmospheric and ocean circulation changes around Iceland, as there was a rapid increase in ocean temperatures off the southern coast in 1996 (Björnsson et al., 2013).

The specific winter mass balance is larger overestimated in HIRHAM5 for the entire measurement period with an average of 0.54 m w.eq. Due to this difference, and only the small negative mean difference in summer mass balance, the annual mass balance of Vatnajökull is overestimated every year with an average difference of 0.50 m w.eq.

However, this is mostly due to the large overestimation of the winter accumulation on Öræfajökull; comparison with the mass balance measurements showed that the model overestimated the winter accumulation by 100-200 % compared with the obervations. In an attempt to estimate how much this error affects the results, a simple correction was added to the Öræfajökull points by reducing the simulated winter SMB by 50 %. The correction was added to four model grid points around Öræfajökull, due to the high (>10 m/yr) annual specific mass balance in these points (see Fig. 9a). The resulting modelled winter and annual specific balance are shown in Fig. 11. The winter balance is still overestimated, but the difference between modelled and interpolated values has been reduced to only 0.1 m w.eq. In addition, the average difference between the HIRHAM5 and interpolated annual SMB drops to only 0.08 m w.eq.

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 average deviation between observation and model over the observation period at each measurement location is also shown, in order to give an indication to the average error of the model at different parts of the ice cap.

4.8 Comparison with constant ice albedo simulation

In order to quantify the changes in the model performance resulting from the new albedo scheme used in this study, which utilizes an albedo map based on MODIS data (Gascoin et al., 2017), the results are compared to those of a run without MODIS albedo, which uses an previous run using a constant ice albedo of 0.3. The average difference in albedo and mass balance over the period 2001-2014 in each grid point are shown in Fig. 12, as well as the position of the AWS stations.

There is little to no difference between the two runs in the accumulation zone, due to the year-round snow cover. In the ablation zone, however, using the MODIS ice albedo map has a large effect on the simulated albedo. The largest difference appears to be differences are found on the southern outlet glacier Skeiðarárjökull, which is unfortunately a glacier where no mass balance or AWS measurements have been conducted. The B_{AB} and B_{ELA} stations are located in areas that are affected by the ice albedo, either because ice is exposed (B_{AB}) or because the underlying surface contributes to the albedo (B_{ELA}). The T_{AB} station is located in the ablation area, but for example due to an overestimation of the winter accumulation (Section 4.6.1) the ice surface is never exposed in the model due to an overestimation of the winter accumulation. The albedo estimate at this station was therefore not improved by using the MODIS albedo.

When the model is run with the constant ice albedo of 0.3, the amount of ablation will be lower and thus the specific summer balance will be higher. Compared to the simulation using the MODIS map (Fig. 11), the constant ice albedo simulation results in an increase in the specific summer SMB by an average of 0.37 m w.eq., or 18 %, per year for the period 1995-2014. The increase in the summer SMB ranges from 14 cm (in 2014) to 85 cm (in 2001) and the percentage increase varies between 8 % (in 2011) to 39 % (in 1995). As the winter balance is not dependant on the ice albedo, there are no changes in the specific winter SMB between the two simulations.

5 Conclusions

The comparison of a HIRHAM5 simulation with data from five AWSs on Vatnajökull ice cap allowed us to draw valid conclusions about ice cap allows us to evaluate the model performance. By comparing observations from April-October with model output, it was found that the model simulates the surface energy balance components and surface mass balance well, albeit with general underestimations of the energy balance components. Even though the energy balance was generally underestimated, the model simulated the near-surface temperature well. The reason for this is that the comparisons only uses use observations from the summer months, where the glacier surface is generally at the melting point, and thus the energy is used for melting and not for raising the temperature of the surface.

The modelled incoming radiation is underestimated on average in both the shortwave and longwave spectrum, which we suggest is due to biases in the modelling of the cloud cover combined with errors in the optical thickness in the short- or longwave spectrum, or errors in the clear-sky fluxes.

Whereas the modelled outgoing LW radiation component is within the uncertainty of the LW observations at the five stations, suggesting that the model simulates the surface temperatures wellwhich is consistent with the ability of the model to capture surface temperatures, there was a larger differences difference between the modelled and measured outgoing SW radiation. This is partly due to the underestimation of the incoming SW radiation and partly due to inaccuracies in the simulated albedo. The albedo , which was simulated using an iterative, temperature based albedo scheme (Nielsen-Englyst, 2015) with a bare ice albedo determined from MODIS data (Gascoin et al., 2017), was shown to provide a better fit with AWS albedo observations than when using a constant ice albedo. However, the . The simulated albedo was generally overestimated during the summer and did not reach the lowest yearly value as early in the year as the measured albedo, particularly in the ablation zone. This was attributed to an overestimation of the snow cover in the ablation zone, an overestimation in the MODIS ice albedo compared with AWS observations, and the fact that the model does not account for the effect of volcanic dust deposition during eruptions and dust events on the albedo. A possible way to include mean of capturing dust storms or eruptions into the model could be including is to implement a stochastic ashes or dust generator, which distributes dust onto the glacier. Including simulations of dust depositions and concentrations from a dust mobilization model could also be an option, as e.g. Dragosics et al. (2016) used the model FLEXDUST to simulate dust events on Vatnajökull in 2012, and found that the modelled dust events correspond well with albedo drops at two AWSs on Brúarjökull.

Due to the general underestimation of the energy balance components, the ablation during the summer months is underestimated on average. Comparison with mass balance measurements from the AWS sites and from sites scattered across Vatnajökull shows an overall overestimation of the summer balance by about 0.5 $\mathrm{m\,w.eq}$. The overestimation is largest in the ablation zone. The winter balance is on average underestimated at the survey sites, albeit with the highest measuring site (on Öræfajökull) having a large overestimation of the winter balance.

The mean specific summer, winter and net mass balances were are reconstructed for all of Vatnajökull from 1981-2014and compared to , and estimates of the mass balance from specific SMB based on in situ SMB measurements are compared to the reconstructed specific SMB for the period 1995-2014. The summer balance is overestimated with by 0.06 $\mathrm{m\,w.eq.}$ on average, i.e. there is generally too little ablation in the summer, with too much ablation in 1995 and too little ablation in years with, or following, volcanic eruptions. The winter balance is overestimated by 0.5 m w.eq., mostly due to a large overestimation at the high elevation glacier Öræfajökull. This overestimation of accumulation at high elevation is characteristic for hydrostatic RCMs (Forbes et al., 2011). If the overestimation at these points is corrected, we estimate that the simulated winter balance would fit well with the observations, as the overestimation of the balance would drop to around 0.1 m w.eq..

~~There is a shift in the summer and annual mass balance calculated by the model and the in situ MB measurements around 1996, with a generally more negative mass balance after 1996 than before. This is consistent with the increase of the annual mean temperature of Iceland in the mid-1990s, which resulted in a mean annual temperature ~ 1 higher in the decade after than the decade prior to 1995. This is likely linked with atmospheric and ocean circulation changes around Iceland, as there was a rapid increase in ocean temperatures off the southern coast in 1996 (Björnsson et al., 2013).~~ That the model catches the changes in the specific mass balance well over the mass balance measurement period, and also captures the shift in mass balance in the mid-90s, gives us confidence that the model estimates the specific mass balance of Vatnajökull well over the entire simulated period from 1980-2014. ~~The model~~ HIRHAM5 is therefore a useful tool to expand the time series of the specific SMB beyond the measurement years. However, as ERA-Interim reanalysis data only goes back to 1979, the model would need to be forced at the lateral ~~boundary by another dataset in order to estimate the mass balance before 1980, like for example ERA-20C (Poli et al., 2016)~~e.g. by output of a general circulation model. However using other reanalysis data probably leads to different errors; this needs further investigation. The model could also be a useful tool to estimate the future evolution of the SMB of the ice cap, but this would also require a different forcing at the lateral boundary like general circulation model output. This would most likely introduce larger biases than the ones found using ERA-Interim, and the magnitude of these biases would need to be estimated and corrected before using the model for future projections.

6 Data availability

HIRHAM5 output is freely accessible from http://prudence.dmi.dk/data/temp/RUM/HIRHAM/GL2/, as is MODIS data from https://modis.gsfc.nasa.gov/data/. Measurements from automatic weather stations and from in situ mass balance surveys are partially owned by the National Power Company of Iceland and are therefore not publicly available at this time.

Competing interests. The authors declare that they have no conflict of interest

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Tables and figures

Table 1. Average measured elevation and average bias of the interpolated HIRHAM5 elevation at each station for 2001-2014.

Station	Average elevation [m]	Average model elevation bias [m]
B_{AB}	839	22
T_{AB}	1089	47
B_{ELA}	1205	31
B_{AC}	1526	17
T_{AC}	1457	13

Table 2. Comparison of the surface pressure, p_{sl}, air temperature at 2 m, T_{2m}, relative humidity, r_{2m}, and wind speed, u, from HIRHAM5 simulations and AWS measurements during the summer months (Apr-Oct) for the period from 2001-2014. The HIRHAM5 bias (HIRHAM5-AWS), the ~~root-mean-sqaure~~ root-mean-square error (rmse), the percentage error, and the correlation (r) are shown.

Parameter	Station	~~HIRHAM5~~ AWS value	HIRHAM5 bias	rmse	% error	r
p_{sl} [hPa]	B_{AB}	~~911.7~~911.9	-0.2	2.8	0.3	0.96
	T_{AB}	~~883.8~~884.2	-0.4	3.0	0.3	0.95
	B_{ELA}	~~871.5~~872.1	-0.6	2.9	0.3	0.95
	B_{AC}	~~837.1~~837.0	0.1	2.2	0.3	0.97
	T_{AC}	~~844.2~~845.1	-0.9	2.7	0.3	0.96
T_{2m} [K]	B_{AB}	~~273.3~~274.1	-0.8	1.5	0.6	0.94
	T_{AB}	~~273.5~~274.0	-0.6	1.3	0.5	0.89
	B_{ELA}	272.9	-0.1	1.1	0.4	0.91
	B_{AC}	~~271.5~~271.6	-0.1	1.4	0.5	0.90
	T_{AC}	272.1	0.0	1.2	0.5	0.91
r_{2m}	B_{AB}	~~81.7~~87.9	-6.2	12.2	13.9	0.68
	T_{AB}	~~83.5~~89.6	-6.1	11.5	12.9	0.76
	B_{ELA}	~~88.0~~91.8	-3.8	9.8	10.7	0.73
	B_{AC}	~~90.4~~93.9	-3.5	9.6	10.2	0.68
	T_{AC}	~~87.4~~90.0	-2.6	9.7	10.7	0.72
u [m s^{-1}]	B_{AB}	~~3.9~~5.1	-1.2	2.0	39.0	0.80
	T_{AB}	~~5.0~~5.3	-0.3	1.8	33.0	0.87
	B_{ELA}	~~4.3~~4.4	-0.1	1.8	41.1	0.82
	B_{AC}	~~5.2~~5.9	-0.7	1.8	30.8	0.86
	T_{AC}	~~5.1~~5.2	-0.1	2.0	38.9	0.82

Table 3. Comparison of incoming and outgoing long- and shortwave radiation, albedo (α), turbulent fluxes (H_{s+l}), and total energy (E) from HIRHAM5 simulations and AWS measurements during summer months (Apr-Oct) from 2001-2014. The HIRHAM5 bias (HIRHAM5-AWS), the root-mean-square error (rmse), the percentage error, and the correlation (r) are shown.

Parameter	Station	~~HIRHAM5~~ AWS value	HIRHAM5 bias	rmse	% error	r
LW↓ [W m^{-2}]	B_{AB}	~~273.8~~290.6	-16.9	26.3	9.1	0.79
	T_{AB}	~~280.3~~287.3	-7.0	20.9	7.3	0.80
	B_{ELA}	~~274.9~~283.9	-9.0	21.7	7.7	0.79
	B_{AC}	~~271.8~~280.9	-8.5	24.4	8.7	0.79
	T_{AC}	~~270.3~~274.1	-3.8	20.4	7.4	0.83
LW↑ [W m^{-2}]	B_{AB}	~~307.3~~309.2	-1.9	7.3	2.4	0.87
	T_{AB}	~~309.5~~311.9	-2.5	7.4	2.4	0.78
	B_{ELA}	~~307.0~~309.9	-3.3	10.5	3.4	0.70
	B_{AC}	~~298.4~~299.9	-1.5	12.9	4.3	0.76
	T_{AC}	~~303.9~~301.4	2.6	11.6	3.9	0.68
SW↓ [W m^{-2}]	B_{AB}	~~185.2~~189.1	-4.0	55.5	29.3	0.81
	T_{AB}	~~185.7~~220.8	-35.2	72.2	32.7	0.79
	B_{ELA}	~~193.1~~229.3	-36.2	64.6	28.1	0.83
	B_{AC}	~~193.0~~236.8	-43.7	69.9	29.5	0.82
	T_{AC}	~~206.0~~247.2	-41.9	72.5	29.2	0.79
SW↑ [W m^{-2}]	B_{AB}	~~104.7~~86.6	18.1	61.0	70.4	0.64
	T_{AB}	~~105.6~~112.5	-6.9	54.7	48.7	0.73
	B_{ELA}	~~116.2~~146.1	-29.9	59.2	40.5	0.75
	B_{AC}	~~141.9~~173.2.9	-31.3	56.4	32.6	0.79
	T_{AC}	~~140.2~~173.5	-33.4	65.6	37.8	0.68
α [%]	B_{AB}	~~47.3~~34.6	12.7	23.6	68.2	0.75
	T_{AB}	~~54.5~~44.5	9.96	21.0	47.2	0.68
	B_{ELA}	~~57.8~~60.7	-2.9	18.4	30.2	0.57
	B_{AC}	~~73.0~~72.2	0.8	10.5	14.5	0.62
	T_{AC}	~~67.9~~70.1	-2.2	16.1	22.9	0.47
H_{s+l} [W m^{-2}]	B_{AB}	~~29.7~~34.7	-5.0	28.6	116	0.71
	T_{AB}	~~32.4~~36.2	-3.8	25.2	69.6	0.79
	B_{ELA}	~~22.5~~24.5	-2.0	26.2	107	0.71
	B_{AC}	~~8.4~~20.7	-12.3	28.2	136	0.31
	T_{AC}	~~14.5~~20.8	-6.3	23.0	110	0.49
E [W m^{-2}]	B_{AB}	~~87.2~~131.6	-44.4	82.8	62.9	0.67
	T_{AB}	~~83.4~~120.1	-36.7	98.0	72.3	0.58
	B_{ELA}	~~71.0~~84.4	-13.4	49.6	58.8	0.68
	B_{AC}	~~36.2~~64.8	-28.6	50.3	77.5	0.53
	T_{AC}	~~46.5~~67.7	-21.2	78.6	89.7	0.43

Table 4. Comparison of HIRHAM5 and mass balance measurements, both at AWS sites and for all measuring sites on Vatnajökull.

	Season	~~HIRHAM5~~ AWS value	HIRHAM5 bias	rmse	% error
AWS locations	Winter	~~1.11~~1.37	-0.26	0.71	51.6
	Summer	~~-1.86~~-2.34	0.48	0.81	-34.6
	Total	~~-0.75~~-0.98	0.23	1.15	-118
All locations	Winter	~~1.50~~1.46	0.04	1.21	82.9
	Summer	~~-1.76~~-2.28	0.52	0.94	-41.1
	Total	~~-0.27~~-0.83	0.56	1.56	-186

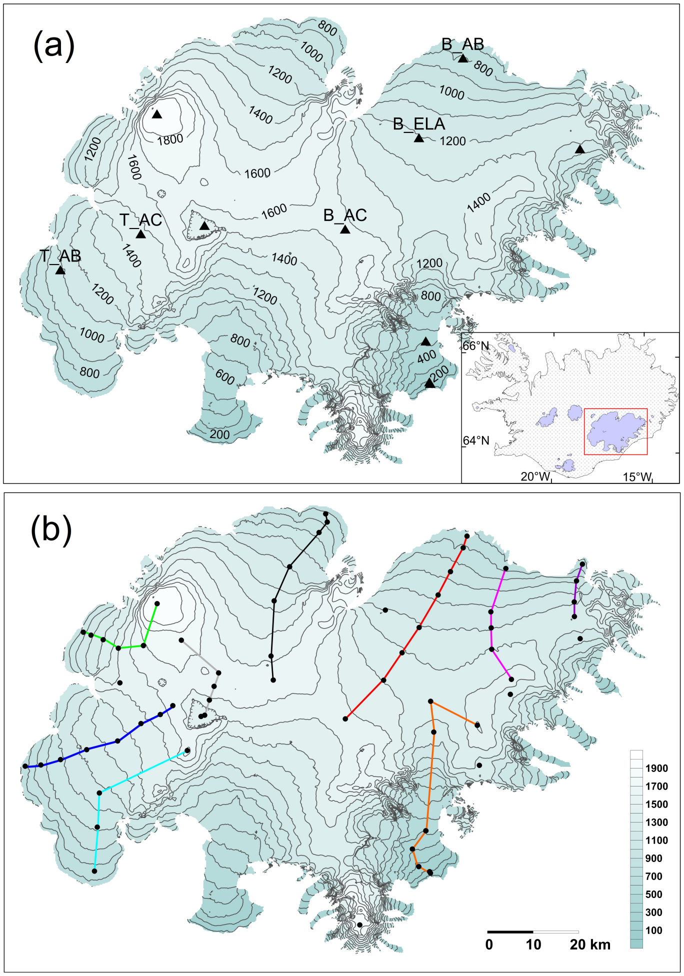


Figure 1. *a) the average location of the AWS sites. Only the labelled sites were used in this study. b) the average location of the mass balance sites from 1995-2014. The coloured lines connect mass balance sites along a transect. Not all mass balance sites were measured every year.*

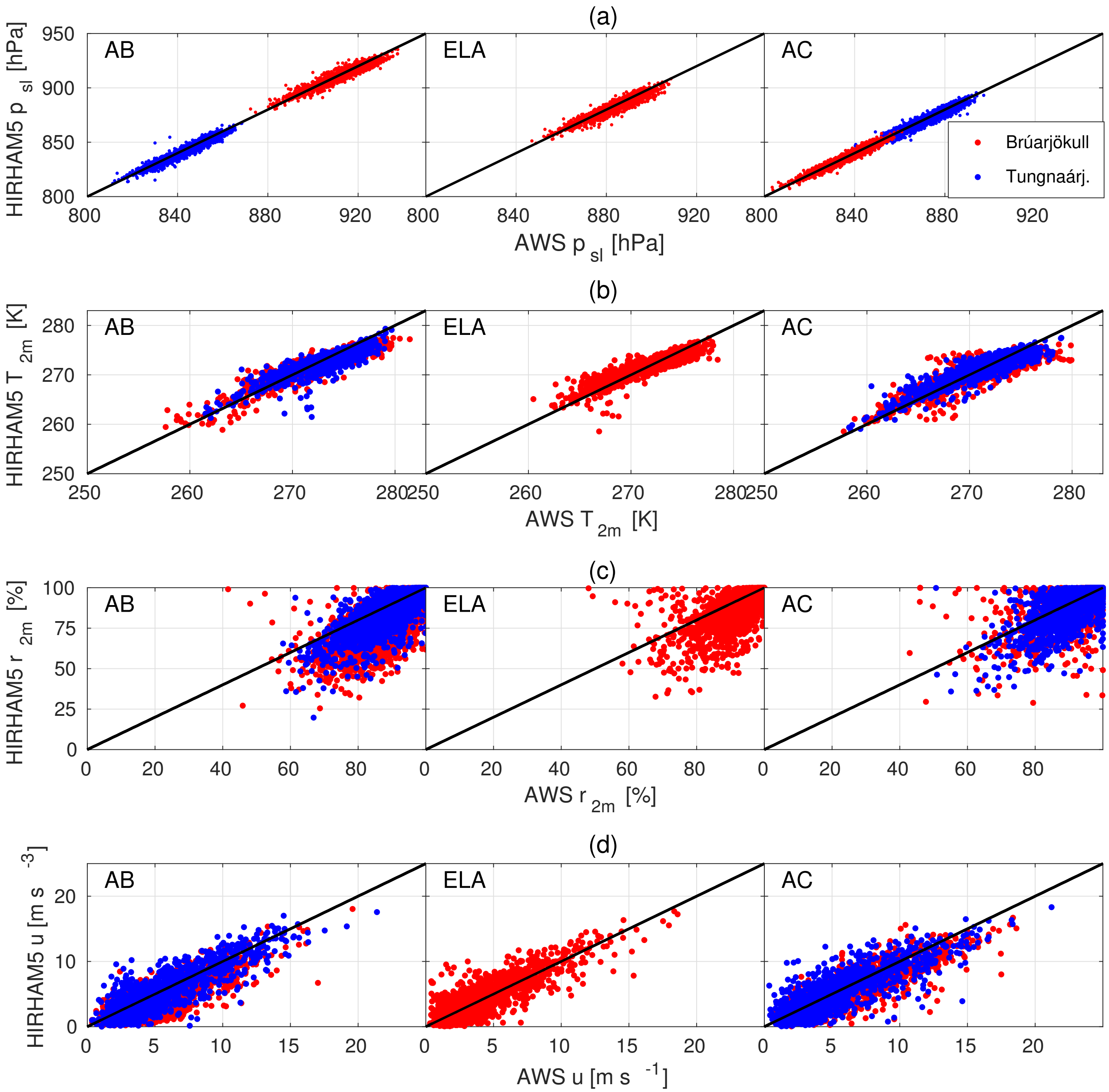


Figure 2. Scatter plots of the measured a) surface pressure, b), air temperature at 2 m, c) relative humidity at 2 m, and d) wind speed at 2 m, by stations on Bruarjökull (red) and Tungnaárjökull (blue) versus the same components simulated by HIRHAM5 at the same locations.

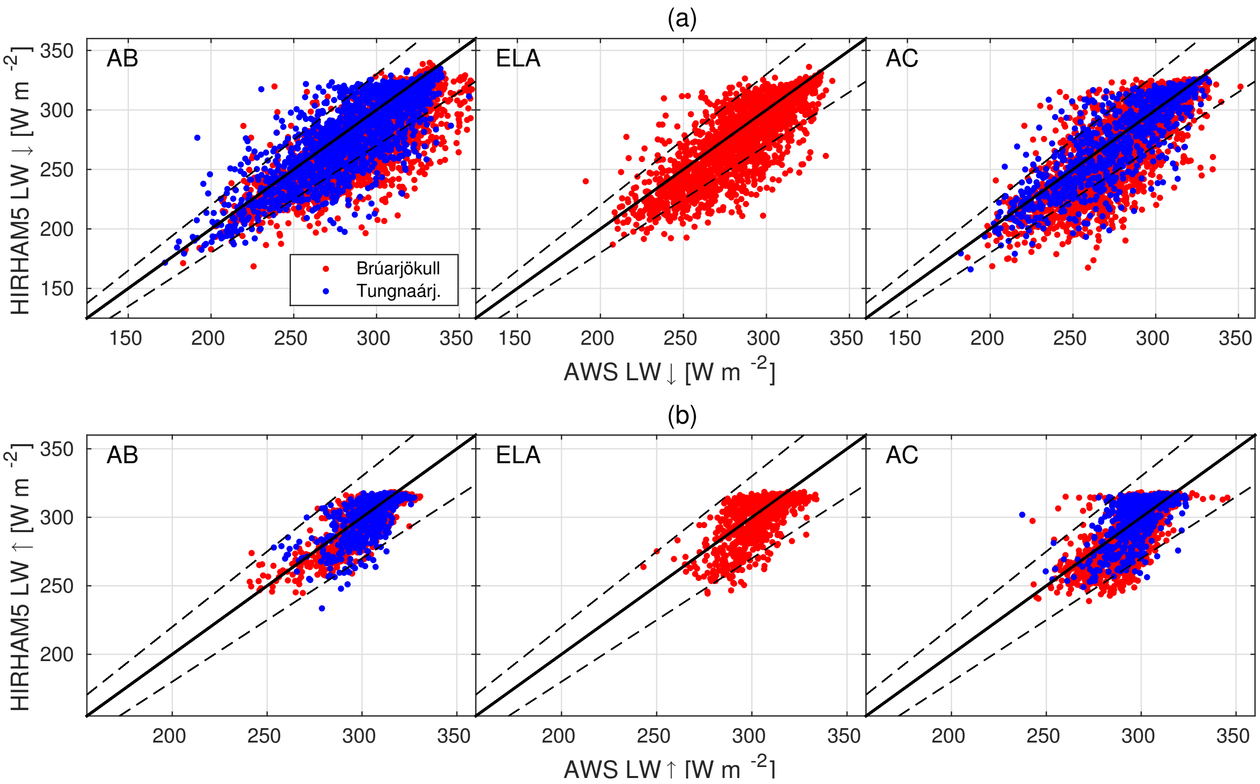


Figure 3. Scatter plots of the measured longwave radiation components, LW↓ and LW↑, by stations on Brúarjökull (red) and Tungnaárjökull (blue) versus the LW radiation components simulated by HIRHAM5 at the same locations. The dashed line corresponds to ±10%, *i.e.* the manufacturer reported uncertainty of the AWS measurements.

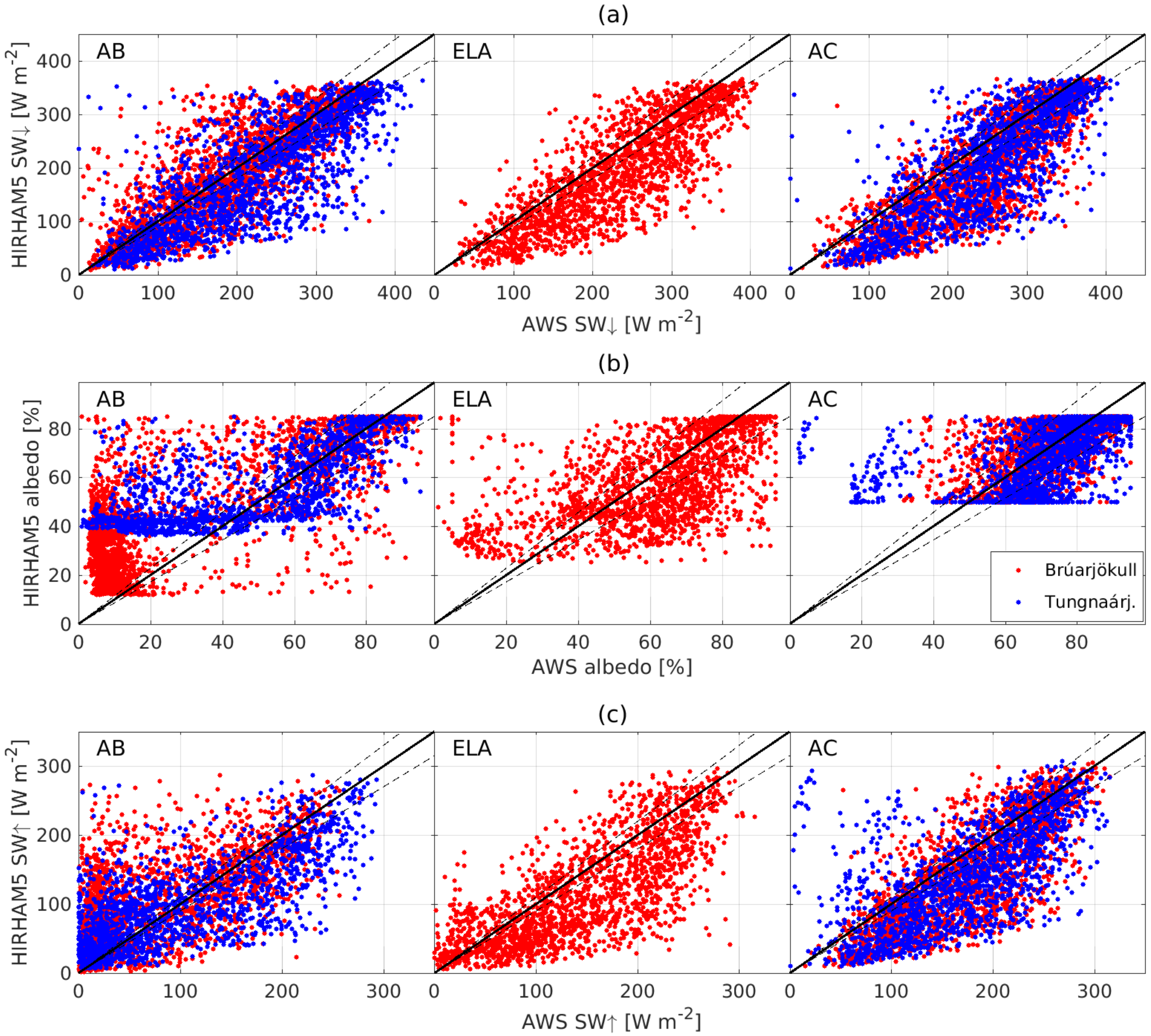


Figure 4. Scatter plots of the measured shortwave radiation components, a) SW↓, b) albedo, and c) SW↑, by stations on Bruarjökull (red) and Tungnaárjökull (blue) versus the shortwave radiation components simulated by HIRHAM5 at the same locations. The dashed line corresponds to the uncertainty of the measured AWS components.

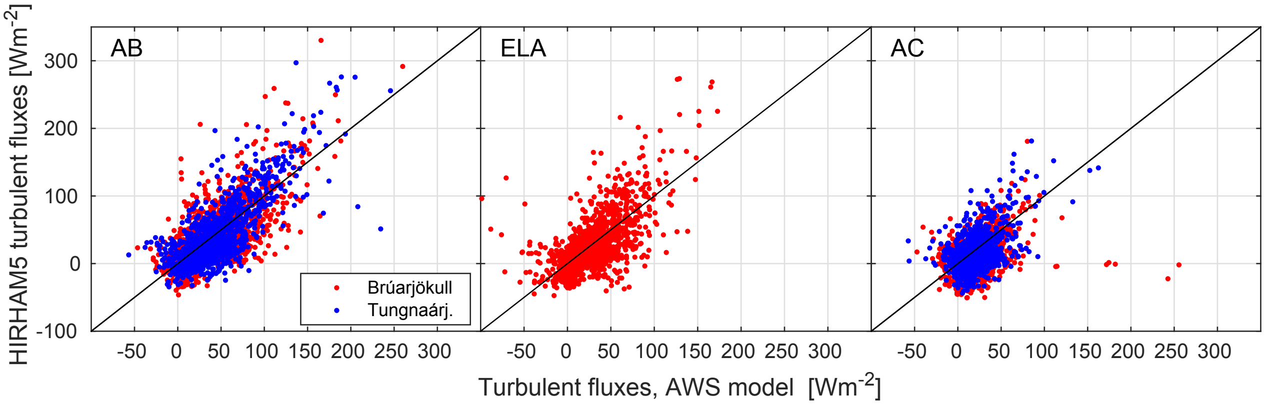


Figure 5. The total turbulent fluxes calculated from AWS stations using the a one-level flux model versus the HIRHAM5 simulated values.Red marks are the data from the Brúarjökull stations, and blue marks are for the Tungnaárjökull stations.

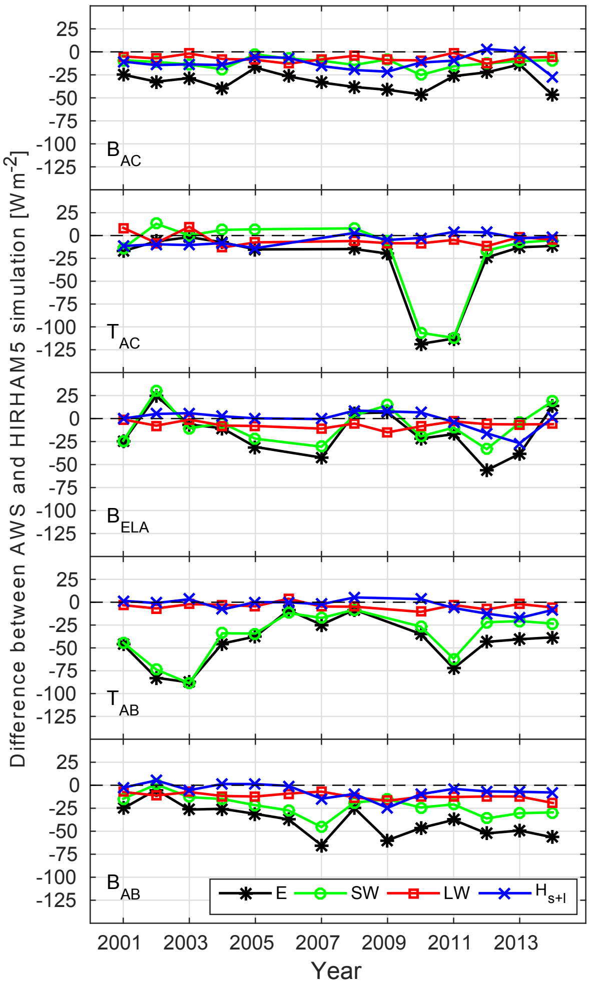
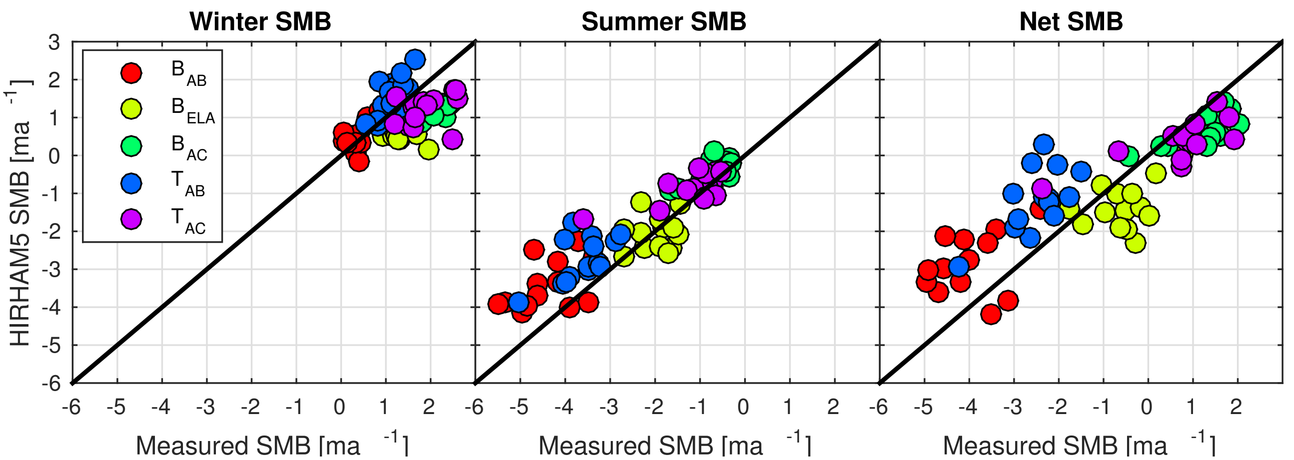


Figure 6. The average summer (Apr-Oct) bias of each energy balance component for the measurement period at each AWS site. The large deviation in the SW radiation at the Tunaárjökull sites in 2010-2011 is due to deposition of ash on the glacier during the 2010 Eyjafjallajökull and 2011 Grímsvötn eruptions.



~~The winter, summer, and net mass balance from 1995-2014 according to mass balance measurements at the five AWS sites and the HIRHAM5 simulation.~~

Figure 7. Comparison of the winter, summer, and net mass balance from 1995-2014 between the mass balance measurements at the five AWS sites and the HIRHAM5 simulation.

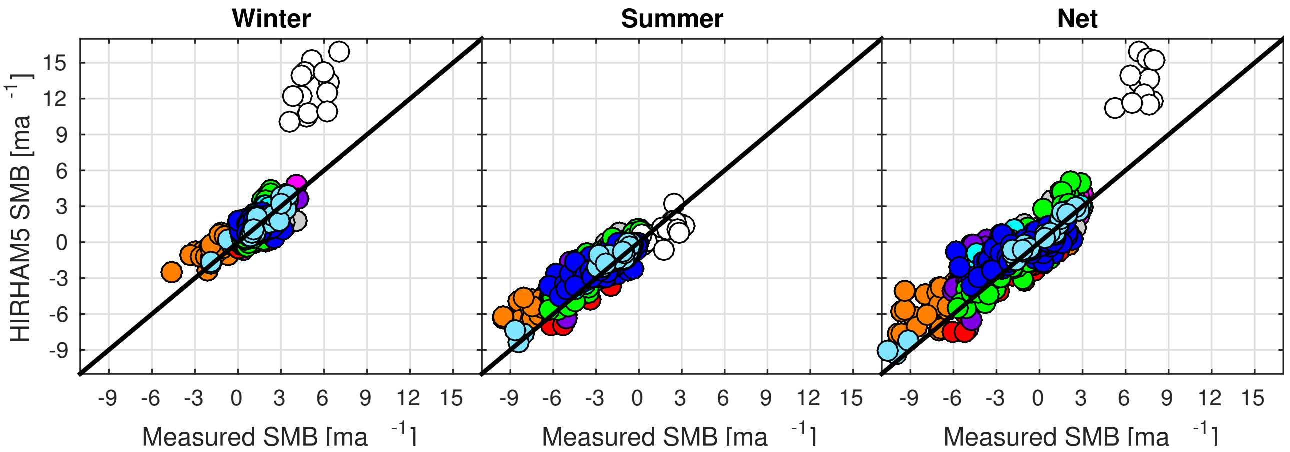


Figure 8. Comparison of SMB measurements from Vatnajökull ice cap from 1995-2014 and HIRHAM5 simulated values. Different colors represent different outlet glaciers, see Fig. 1b. The white dots are from a point on Öræfajökull.

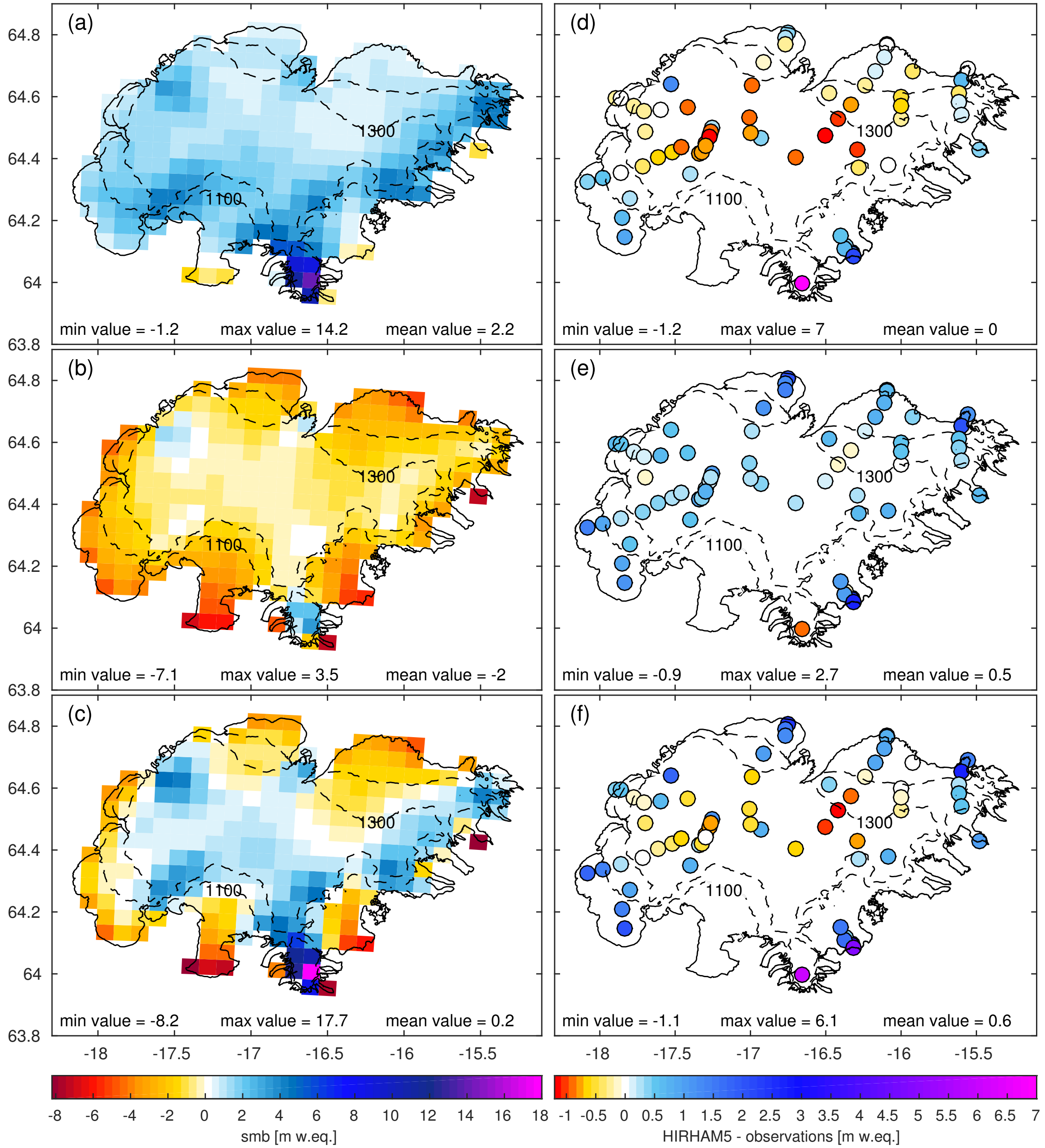


Figure 9. The average (a) winter, (b) summer, and (c) net SMB simulated by HIRHAM5 from the 1980-81 glaciological year to 2013-14. The contour lines marks the approximate location of the ELA, which generally lies between approximately 1100 and 1300 m elevation. Figures (d)-(f) show the average deviation between model and observations over the observation period (1992-2014) for each measurement location for the (d) winter, (e) summer, and (f) whole glaciological year.

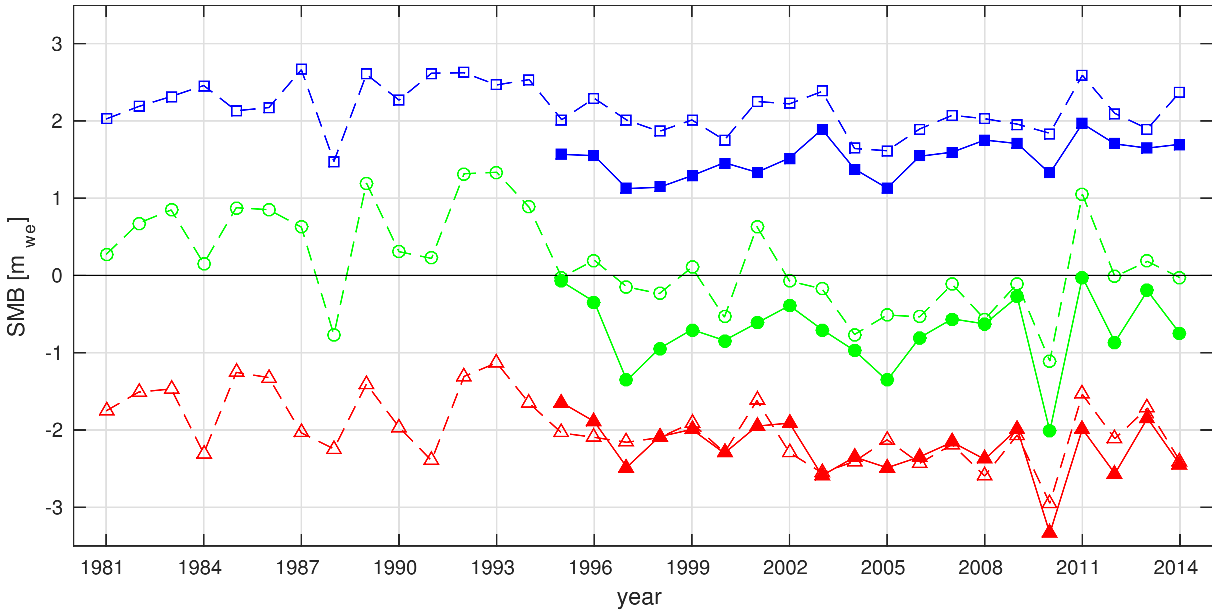


Figure 10. Average summer (red lines), winter (blue lines) and net (green lines) specific surface mass balance for the whole of Vatnajökull. The solid lines are the mass balance of Vatnajökull based on mass balance measurements and manual interpolation, while the dashed lines are the mass balance as simulated by HIRHAM5.

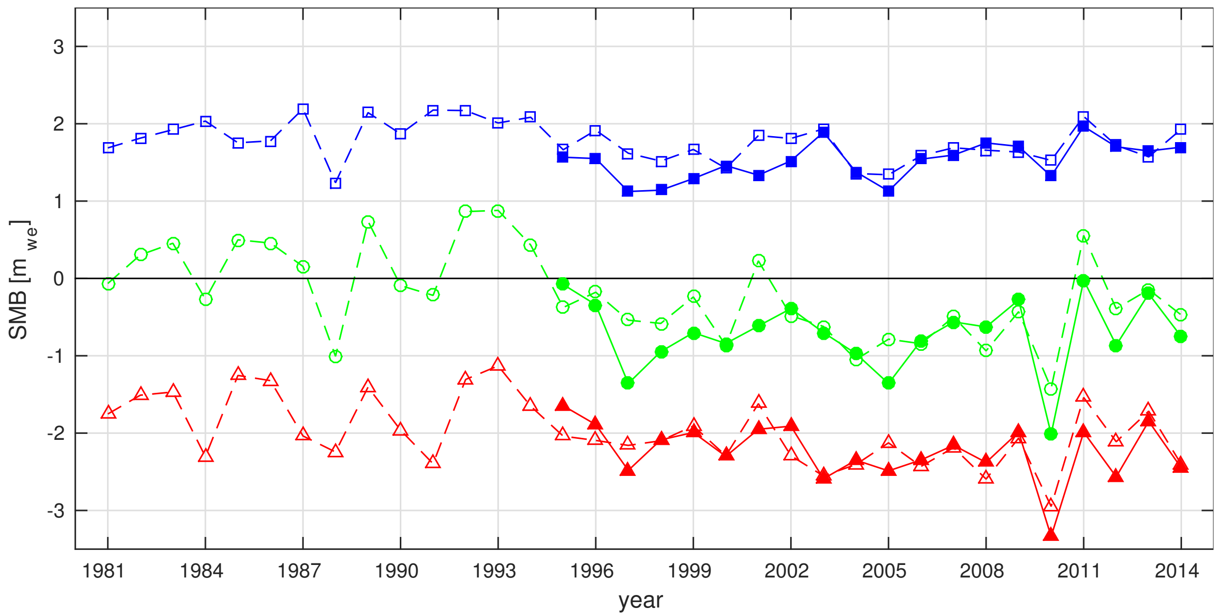


Figure 11. Same as Fig. 10, but corrected at the Öræfajökull area by reducing the HIRHAM5 simulated winter balance with 50%.

The average (a) winter, (b) summer, and (c) net SMB simulated by HIRHAM5 from the 1980-81 glaciological year to 2013-14. The contour lines marks the approximate placement of the ELA, which generally lies between approximately 1100 and 1300 m elevation. Figures (d)-(f) show the average deviation between model and observations over the observation period for each measurement location for the (d) winter, (e) summer, and (f) whole glaciological year.

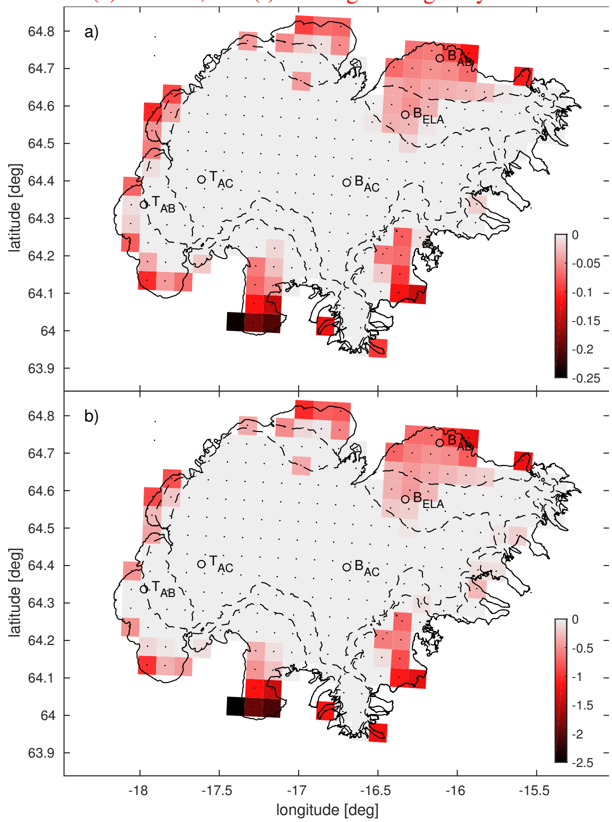


Figure 12. Difference in a) mean albedo, and b) mean SMB in m w. eq. for 2001-2014 between two runs with HIRHAM5, one using a MODIS bare ice albedo map and the other with a constant ice albedoin a) mean albedo and b) mean annual mass balance in from 2001-2014. The locations of the used AWS stations used in this study are shown with black circles.