

Response to reviewers:

Dear reviewers, we would like to thank you for your constructive comments on our manuscript. We tried to address most of the concerns you raised, and to apply corrections where appropriate to improve our manuscript.

To facilitate readability, our responses to reviewers are displayed in blue and modifications in the manuscript are highlighted in red. These suggested changes, together with additional minor corrections, are also displayed in red in the attached revised manuscript.

Reviewer #1:

This paper presents an updated version of the polar version of the RACMO2 regional climate model (RACMO2p2), evaluated over the Greenland ice sheet against various observational datasets. Model updates include changes to the concentration of impurities assumed to be deposited onto the snowpack, the grain size of snow that has experienced meltwater refreezing, the albedo of superimposed ice, and the saltation coefficient for drifting snow. These changes generally result in an improved agreement between modeled and observed atmospheric variables, radiative fluxes and SMB. Some biases persist and can be corrected by future improvements to model physics and parameterizations and/or downscaling of model outputs.

General Comments

The paper is well written and the presentation is generally clear. The paper is not novel in the sense of presenting new model physics or parameterizations, but the changes to RACMO2 that are presented seem to have a significant impact on representation of the Greenland ice sheet surface and the agreement between modeled and observed SMB. A detailed validation of this updated version of the model has been conducted. The paper is therefore likely to be of interest to the cryospheric and climate modeling communities, and is important in providing details about and validation of a new version of RACMO that will be used for future studies of Greenland mass balance. I feel that the paper should be published in the Cryosphere after some relatively minor concerns are addressed below.

One general concern is the use of net surface energy balance to indicate energy available for melting. If the snow temperature is below 0°C, this energy must first be used to warm the snowpack before contributing to melting. In the ablation zone during summer where temperatures are close to freezing, most of the net energy goes to melting, but some of it must go into warming the snow/ice. The authors should revise the manuscript to refer to the net energy balance rather than melt energy, or explain why they can assume that the net energy balance can be considered melt energy.

In RACMO2, the skin temperature (T_{skin}) of snow and ice is derived by closing the surface energy budget (SEB), using the linearized dependencies of all fluxes to T_{skin} and further assuming, as a first approximate, that no melt occurs at the surface ($M = 0$). If the obtained T_{skin} exceeds the melting point, T_{skin} is set to 0°C; all fluxes are then recalculated and the melt energy flux (M) is estimated by closing the SEB using Eq. 1. Therefore, snow melt is possible even though the upper snow layer remains below the melting point. In that case, the generated meltwater refreezes directly in this upper snow layer, rapidly warming it to 0°C. This is now clarified in the manuscript: “In RACMO2, the skin temperature (T_{skin}) of snow and ice is derived by closing the surface energy budget (SEB), using the linearized dependencies of all fluxes to T_{skin} and further assuming, as a first approximate, that no melt occurs at the surface ($M = 0$). If the obtained T_{skin} exceeds the melting point, T_{skin} is set to 0°C; all fluxes are then recalculated and the melt energy flux ($M > 0$) is estimated by closing the SEB in Eq. 1., assuming that no solar radiation can directly penetrate the snow or ice interface.” As the term “melt energy” is commonly used in multiple publications, e.g. Van den Broeke et al. (2017), Van Wessem (2013, 2017), Ettema et al. (2010), and to remain consistent with previously published RACMO2 papers, we decided to keep M to refer to melt energy.

Regarding comparisons between RACMO2.3p1 and observations for some of the plots, it would be useful to see how much RACMO2.3p2 improves on the previous version with respect to meteorological variables. Adding RACMO2.3p1 to Figs. 3, 4, and 5 could potentially make them difficult to interpret, but I think that the authors should at least provide some statistics with regard to the meteorological comparison (corresponding to statistics for Figs. 3 and 4). It would be nice to see the corresponding figures for RACMO2.3p1 in the supplementary material as well. For RACMO2.3p1 outputs corresponding to Fig. 5, there is a similar figure in Noël et al. (2015) as the authors mention, and I think the tables provide enough information to understand the improvement.

As RACMO2.3p1 only covers the period 1958-2015, a direct comparison with RACMO2.3p2 (including 2016) cannot be conducted without discarding a substantial amount of data. Therefore, we decided to keep Figs. 3 and 4 as are and included similar figures for RACMO2.3p1 (1958-2015) in a Supplementary Material (see Figs. S5 and S10). These figures also list statistics for the radiative fluxes and meteorological data. We included a new table (Table 1) summarizing the main statistics in the revised manuscript together with the following sentences in Section 3.1 and 3.2, respectively. “Table 1 and Fig. S5 compare the agreement of RACMO2.3p2 and version 2.3p1 with in situ measurements. We find an overall improvement in the updated model version, showing a smaller bias and RMSE as well as an increased variance explained. Notably, the remaining negative bias in 2-m temperature (Fig. S5a) and the systematic dry bias (Fig. S5b) in RACMO2.3p1 have almost vanished in the updated model version (Figs. 3a and b).”

“Compared to the previous model version (Table 1), changes in the cloud scheme have significantly improved the representation of LWd (Figs. 4c and S10c), showing a reduced negative bias and RMSE. These modifications have also somewhat decreased the positive bias in SWd (Fig. 4a), relative to RACMO2.3p1 (Fig. S10a). In addition, LWu is notably improved in RACMO2.3p2: the remaining negative bias in LWu has almost vanished (Figs. 4d and S10d). This can be partly explained by the much better resolved 2-m temperature in RACMO2.3p2.”

In Section 3.3 and Tables 1-5, the signs of biases for upward and downward fluxes and interpretation in the text are confusing and sometimes inconsistent. It seems that the biases are generally considered with respect to the absolute value of fluxes (e.g. a negative bias for an upward flux is an underestimate of the upward flux) but this is not always the case. The calculation of net fluxes is also inconsistent. Mostly, the upward flux bias is subtracted from the downward flux bias, but not always. The authors should make sure that the signs for all biases are consistent, and that the text interprets the direction of the biases correctly. The authors could use the same conventions for both fluxes and biases, but this should be made clear in the figure captions and in the text, to remind the reader that a positive bias for an upward flux is an underestimate of the upward flux. For example, if SWu (Obs) is -70.9, and the RACMO2.3p2 bias (RACMO2.3p2 – obs) is 4.5, the authors can indicate that the magnitude of SWu is underestimated by 4.5 in RACMO2.3p2. Alternately the authors could define upward fluxes as being positive, which is more intuitive, and Eq. 1 could be changed so that upward fluxes are subtracted rather than added.

As suggested, we decided to adopt the convention that all SEB fluxes are set positive. We corrected equation 1, values in the main text and in the tables accordingly. We also noticed a small bug in the script calculating statistics at site S10; this has been corrected in the text and associated table. We also made sure that LWN and SWN biases are correctly defined, and clarified when necessary if fluxes are underestimated.

The section on the Northeast Greenland ice stream seems a bit out of place with respect to other sections. The authors should provide some more background at the beginning of Section 4.2 discussing how the ice discharge measurements can be used to evaluate SMB. The discharge measurements should also be mentioned in Section 2.5. Also, the authors should provide a rationale for their assumption of equilibrium between SMB and discharge for the northeast Greenland basin for the 1958-2015 period. The better agreement with discharge measurements suggests an improvement to SMB, but doesn't necessarily prove that SMB is accurate. This should be clarified in Section 4.2.

We clarified as follows, in Section 2.5: “In addition, we compare modelled SMB with annual glacial ice discharge (D) retrieved from the combined Zachariae Isstrøm and Nioghalvfjærdsbrae glacier catchments in northeast Greenland (1975-2015; yellow line in Fig. 6a), presented in Mouginot et al. (2015).”.

In Section 4.2: “For northeast Greenland's two main glaciers, Zachariae Isstrøm and Nioghalvfjærdsbrae (79N glacier; yellow line in Fig. 6a), solid ice discharge (D) estimates are available for the period 1975-2015 (Mouginot et al., 2015). Assuming that this glacier catchment draining ~12% of the GrIS area remained in approximate balance until ~2000 (Mouginot et al., 2015), i.e. $D = SMB$, measurements of D at the grounding line of these marine-terminating glaciers can be used to evaluate modelled SMB.”.

Followed by: “However, it is important to note that, while good agreement is obtained between averaged SMB and D before 2001, suggesting a glacier catchment in approximate balance as in Mouginot et al. (2015), this does not necessarily confirm that spatial and temporal variability of northeast Greenland SMB is accurately resolved by the model.”.

Specific Comments

P. 1, Line 10: Be more specific here. How are the patterns “better resolved”?

We reformulated as: “[...] better resolves the spatial patterns and temporal variability of SMB compared with the previous [...]”.

P. 1, Line 13: “future climate scenario projections” is unclear. Do the authors mean “projections of GrIS climate and SMB in response to future climate scenarios”?

We reformulated accordingly. Thank you.

P. 2, Line 19: Change “model simulations” to “RCM simulations”

Thank you.

P. 2, Lines 25-26: This phrase is confusing. Also, I don't believe the Box (2013) approach used data assimilation. Suggest revising “and data assimilation ... accumulation measurements...” to read: “and reconstruction of SMB obtained by combining RCM outputs with temperature and ice core accumulation measurements...”

We reformulated accordingly.

P. 2, Lines 27-28: Add reference detailing CESM future simulations (Vizcaíno et al., 2014): Vizcaíno, M., Lipscomb, W. H., Sacks, W. J., and van den Broeke M.: Greenland surface mass balance as simulated by the Community Earth System Model. Part II: Twenty-first-century changes, Journal of Climate, 27, 215-226, doi: 10.1175/JCLI-D-12-00588.1, 2014. The authors might consider citing this study that presents a simulation of SMB from the GEOS-5 model: Cullather, R. I., Nowicki, S. I., Zhao, B., and Suarez, M. J.: Evaluation of the surface representation of the Greenland ice sheet in a general circulation model, Journal of Climate, 27, 4835-4856, doi: 10.1175/JCLI-D-13-00635.1, 2014.

Thank you, reformulated as follows: “Vizcaíno et al. (2013, 2014) and Cullather et al. (2014) respectively used the Community Earth System Model (CESM) at 1° resolution (~100 km) and the Goddard Earth Observing System model version 5 (GEOS-5) at 0.5° resolution (~50 km) to estimate recent and future mass losses of the GrIS.”

P. 2 Line 49 – P. 3 Line 1: There are likely also improvements that could be made regardless of resolution, that a high-resolution simulation could not fix. Perhaps mention this also.

To clarify this, we inserted the following sentence: “Important modelling challenges and limitations still need to be addressed in RACMO2 regardless of the spatial resolution used: e.g. cloud representation (Van Tricht et al., 2016), surface albedo and turbulent heat fluxes (Section 6).”

P. 3, Line 56: Could the authors provide a reference for RACMO2.3p1?

We added a reference to Noël et al. (2015).

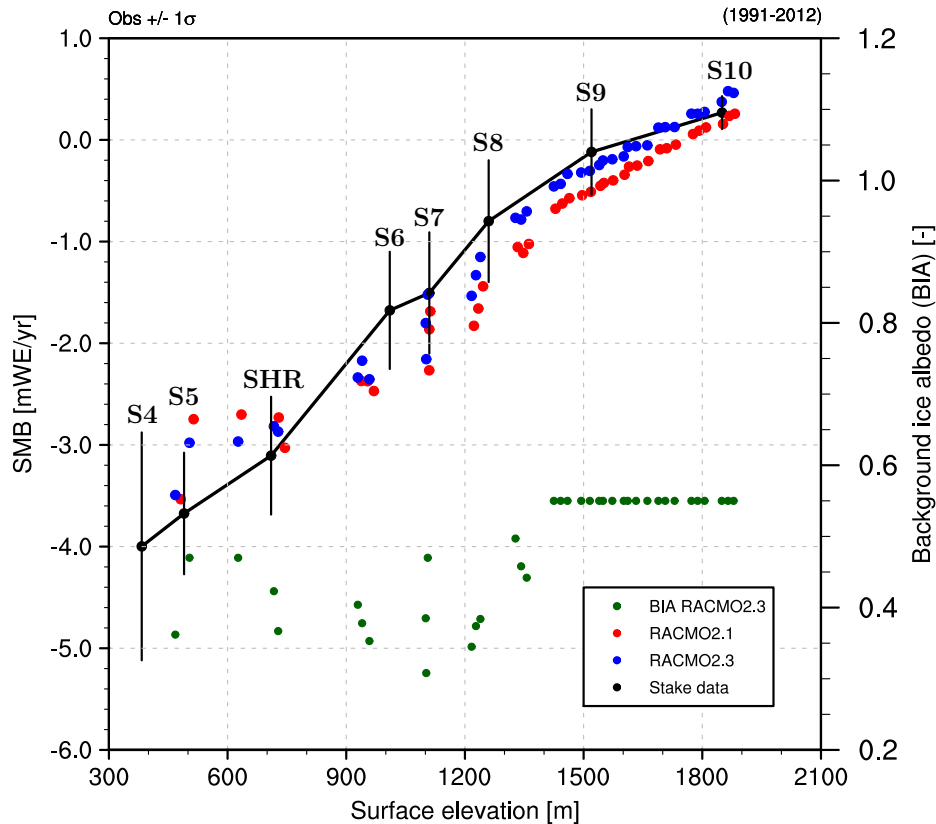
P. 4, Lines 82-84: As noted above, the net energy absorbed by the snowpack must be used to raise the surface temperature to the melting point before it can be used for melting. “M” should therefore be changed to “Enet” and this sentence should be revised accordingly.

See our previous response to General comments.

P. 4, Line 87: Add “net” before “sensible and latent turbulent heat fluxes” for clarity. Done.

P. 5, Lines 109-111: The corrections that have been made also can affect the ablation zone, though they probably have less of an impact there. Were similar biases found in the ablation zone previously?

From Fig. 9 in Noël et al. (2015) (see below), you can clearly see that compared to observations along the K-transect (black dots) SMB in RACMO2.3p1 (blue) is overestimated in the ablation zone, due to too low melt (ablation) rates.



P. 5, Lines 116-118: If possible, can the authors provide evidence that supports decreasing the size of refrozen snow grains?

We could not find a proper reference that validates our assumption. However, Kuipers Munneke et al. (2011) suggest that the grain size of refrozen snow should be ascribed a value larger or equal to 1000 μm . We therefore chose to set the grain size of refrozen snow to 1000 μm : this value minimizes the positive melt bias in the model across the GrIS percolation zone.

P. 5, Lines 136-137: Can the authors be a bit more specific about the levels or height at which upper atmosphere nudging is applied?

See our response to Reviewer #2.

P. 5, Lines 139-141: Provide a few more details about this. What are the “best” profiles and how are they derived?

We clarified this by reformulating as: “The model has about 40 active [...] 1957 using estimates of temperature and density profiles derived from the offline [...] (Ligtenberg et al., 2011). These profiles are obtained by repeatedly running IMAU-FDM over 1960-1979 forced by the outputs of the previous RACMO2.3p1 climate simulation until the firn column reaches an equilibrium.”

P. 6, 149-151: Are fractional areas of ice vs. tundra allowed in a RACMO grid box? If so, it would be useful to have this information here.

To clarify this, we inserted the following sentence: “In RACMO2, a grid-cell with an ice fraction ≥ 0.5 is considered fully ice-covered.”

P. 6, Line 156: Please specify the version number. Is this version 5 or version 6?

We now mention version 5 in the revised manuscript.

P. 6, Lines 157-160: These sentences are a bit unclear. I think the authors are saying that MODIS values for bare ice albedo below 0.3 are replaced by a value of 0.3, and MODIS values above 0.55 are replaced with 0.55. Any grid cells without a valid MODIS estimate are assigned a value of 0.55. Please clarify.

Your interpretation is right, except for non-valid MODIS estimates which are set to 0.47. For clarity, we reformulated as: "In RACMO2, minimum ice albedo is set to 0.30 for [...], and a maximum value of 0.55 [...].".

P. 7, Lines 201-202: Are these biases statistically significant? It might be useful for the reader to have this information.

We calculated the significance of the biases in Figs. 3-4 by comparing the mean bias listed in each scatter plot with 2 standard deviations of the biases (95% interval). None of the biases were larger than 2 standard deviations, so that these biases are determined as insignificant. As the biases are relatively small and negligible compared to the absolute value of the meteorological data and radiative fluxes, we deem that this is not necessary to mention in the manuscript.

P. 7, Lines 209-210: Can the authors be sure that the LWd underestimation leads to the LWu underestimation?

We reformulated as: "The negative biases in LWd and 2-m temperature partly lead to LWu underestimation of [...].".

P. 8, Line 214: Can the authors elaborate here? Is there a difference because of heterogeneity in fresh snow distribution leading to differences between the model estimate and local measurements?

We elaborated as follows: "In RACMO2, precipitation falls vertically, i.e. no horizontal transport is allowed, and is assumed to be instantly deposited at the surface. Consequently, the spatial distribution of summer snow patches may be locally inaccurate, resulting in large albedo discrepancies when compared to point albedo measurements.".

P. 8, Lines 229-231: It's a bit unclear that the values in parentheses are biases and not absolute magnitude of the quantities. Clarify here and where applicable elsewhere in the text, e.g. "... between overestimated SWn (bias of 16.2 W m⁻²)".

Done.

P. 8, Line 231: Make clear whether SWu is over- or underestimated. I believe it's underestimated. (See general comments.)

Done.

P. 8, Lines 236-237: I believe the newest MCD43A3 product includes a correction for sensor deterioration, but if v5 is used here, this still applies. Perhaps clarify with "underestimated surface albedo for the MCD43A3 v5 product".

We reformulated accordingly.

P. 8, Lines 238-239: Again this is confusing because of sign conventions. If the signs of the biases follow the conventions, the net bias should be -23.9 W m⁻² and not 0.3 W m⁻².

This is now corrected. See also our response to General comments.

P. 9, Line 252: Also add reference to Table 2 here.

Done.

P. 9, Line 253: Clarify under- vs. overestimated, use "~4 W m⁻²" to indicate that the value is approximate.

Done. See also our response to General comments.

P. 9, Lines 269-270: According to most of the previous calculations of net flux, these terms don't compensate. There is underestimated downward flux and overestimated upward flux, so the net flux is underestimated.

Both Swd and SWu are underestimated. Thank you.

P. 9, Line 271: Add reference to Table 4.

Done.

P. 9, Lines 272-273: Again, here the biases have been added rather than subtracted to get the net flux, in contrast with calculations for other sections.

This is now corrected.

P. 10, Line 289: Here the SWu bias, shown as positive in Table 1, is referred to as negative, which would make sense if conventions are followed everywhere, but is not consistent with earlier discussion (e.g. p. 9, line 264, where a positive bias for SWu is referred to as an overestimation).

At line 289, we mention site S6 showing a SWu underestimate of 3.8 W/m², while line 264 refers to site S9 close to the equilibrium line where SWu is overestimated by 3.5 W/m². We clarified this by replacing “Here, [...]” by “At site S6, [...]”.

P. 11, Line 316: The increase in refreezing is attributed to an increase in precipitation, but along the west coast, there is a decrease in precipitation in some areas. Perhaps another factor could be persistence of snow cover as a result of reduced melting.

Thank you. We reformulated as follows: “[...] a result of combined enhanced precipitation and reduced summer melt (delaying the disappearance of the seasonal snow cover), that increased [...] (Fig. 7f).”.

P. 12, Lines 353-354: Show numbers for both model versions for comparison.

The numbers previously shown were incorrect, we revised accordingly based on bias and RMSE listed in Table 6: “[...] shows a decreased bias from 606 mm w.e. in RACMO2.3p1 to 424 mm w.e. in version 2.3p2, and reduced RMSE from -133 mm w.e. to -54 mm w.e., and an increased R2 from 0.92 to 0.97.”

P. 12, Lines 358-362: Is this correction applied to the values in Fig. 9?

This correction is applied to both RACMO2 versions in Figs. 9a and c. It is now mentioned in the figure caption as: “At S10, modelled SMB is estimated as the difference between total precipitation and melt.”.

P. 13, Lines 402-405: Provide some numbers to illustrate that the new version performs as well as the previous version.

We included the following numbers: “[...] as well as the previous version, i.e. bias of 1.20 m w.e. yr-1 and RMSE of 0.47 m w.e. yr-1 (Noël et al., 2016), although [...]”.

P. 13, Lines 419-420: What are the new values for RMSE, bias, and error at QAS_L?

We calculated a model (RACMO2.3p2) RMSE and bias of 2.35 m w.e. and 2.21 m w.e. at QAS_L, respectively. This is now mentioned in the revised manuscript.

Tables 1-5: The term ME is used here for melt energy, but the term M is used in the text. These should be consistent. As noted in the general comments I believe this should really refer to the net energy balance. Captions for Tables 2-5 can be reduced to “Same as Table 1 for Station...”

Please, see our previous response in the General comments. We replaced ME in Tables 2-6 by M.

Figure 11: The red points in (a) indicate something different from (b) and (c). I feel that the authors should include RACMO2.3p2 for (a), (b) and (c), and use the same color scheme. A different color could be used to show the measurements from QAS_L.

We judge that showing RACMO2.3p1 data in Fig. 11b and c would make the scatter plots unclear and confusing. A similar comparison using RACMO2.3p1 data is already conducted in Noël et al. (2016). We now display QAS_L data in orange and we modified the caption accordingly.

Units for statistics should be the same for all figures if possible, and should correspond to the units in the text.

We deem that units should remain mm w.e. in Fig. 11a as bias and RMSE are relatively small. However, we think that m w.e. is more adequate for Figs. 11 b and c due to the larger bias and RMSE (2 orders of magnitude). Therefore, we decided not to change the units in the revised manuscript.

Also, I believe the third line of caption: “version 2.3 (red)” should read “version 2.3p1 (red)”.

Done.

Technical Corrections

P. 1, Line 10: Change “than the previous model version” to “compared with the previous model version”. OK.

P. 2, Line 29: Change “to explicitly resolve” to “of explicitly resolving”. OK.

P. 2, Line 33: Change “evaluate and improve” to “evaluating and improving”. OK.

P. 2, Line 45: “If the authors are still referring to previous versions of the model, change to “is underestimated” to “was underestimated”.

We kept “is underestimated” as this is still valid in version 2.3p2.

P. 2, Line 50: Change “near-kilometre” to “near-kilometre-scale” We replaced by “near-kilometre scale”.

P. 3, Line 55: Change “all over Greenland.” to “across the GrIS.” [OK](#).

P. 5, Line 132: Add “an” before “11 km horizontal...” [OK](#).

P. 5, Lines 134-135: Mention that the model domain is shown in Fig. 1 to make clear what Fig. 1 is showing. [We reformulated as: “\[...\] 6-hourly basis over the model domain shown in Fig. 1.”](#)

P. 7, Line 191: Change “of 23 AWS” to “from 23 AWS” [OK](#).

P. 7, Line 192: Change “output” to “outputs”. [OK](#).

P. 7, Line 194: Add “and” after “10-m wind speed,” [OK](#).

P. 7, Line 201: change “with a small negative bias” to “with the model exhibiting a small negative bias” for clarity. [OK](#).

P. 8, Line 231 and Line 239: Change “too low cloud cover” to “underestimated cloud cover”. [OK](#).

P. 8, Line 241: The van den Broeke (2008) reference seems to be missing from the reference list. [This reference is actually Smeets and van den Broeke \(2008\). This has been corrected.](#)

P. 9, Line 258: Change “too large SHF” to “SHF to be overestimated”. [OK](#).

P. 10, Lines 295 – 298: The language could be improved here. Suggested revision: “In Section 3, we discussed the overall good ability of RACMO2.3p2 to reproduce the contemporary climate of the GrIS, which is essential for estimating realistic SMB patterns. Here we compare SMB from RACMO2.3p2 and RACMO2.3p1 over the GrIS. For further evaluation, we focus on three regions where there are large differences in SMB between the two versions.” [Thank you, we revised accordingly.](#)

P. 11, Line 318: Change “very GrIS margins” to “extreme margins of the GrIS”. [OK](#).

P. 12, Lines 360-362: This sentence is a bit wordy... suggest changing “decreasing the bias...” to “decreasing the bias by 260 mm w. e. yr-1 to -40 mm w. e. yr-1 and the RMSE by 200 mm w. e. yr-1 to 210 mm w. e. yr-1.” [OK, thank you.](#)

P. 12, Line 378: Change “3 months” to “3 month”. [OK](#).

P. 14, Line 426: Add “an” before “11 km resolution”. [OK](#).

P. 14, Line 434: change “narrow ablation zones” to “the narrow ablation zone”. [OK](#).

P. 14, Line 444: Change “to capture” to “to capturing”. [OK](#).

P. 15, Line 455: Change “cryoconites” to “cryoconite”. [OK](#).

P. 15, Line 467: Change “proves to accurately capture” to “accurately captures”. [OK](#).

Figure 2: Although it is not necessary since the caption provides a description, a legend on Fig. 2a would be useful for the reader. [Done](#).

Figure 5: The dashed lines on the legend are hard to distinguish from solid lines. [Although relatively small, we judge that Fig. 5 is readable as is. We did not modify this figure in the revised manuscript.](#)

Figure 9: The black and blue colors are a bit hard to distinguish. Can the blue color be made slightly brighter? In caption, remove “the” in “for the S5”. [We decided to display observed data in light gray, and kept dark blue for RACMO2.3p2 data to remain consistent with other figures. Thank you.](#)

Figure 10: The yellow line is difficult to see. The color could be made slightly darker. Add “and” after “a) daily snow albedo”. [As in Fig. 9, observational data are now displayed in light gray.](#)

Fix references to follow format for The Cryosphere. [We hope that the references are now suitable.](#)

Reviewer #2:

This is a very nice well-written and detailed paper describing the revised RACMO2.3p2 model and the effect of improved model tuning on the Greenland ice sheet surface mass balance estimates. This kind of paper is extremely important for users of SMB data to read and digest in order to understand the likely biases and uncertainties within model output and the thorough analysis, while not really presenting much novel scientific research is an important addition to the scientific canon. It is very well structured and easy to read and the authors are to be congratulated on a thorough overview. That said I have some issues, which I feel should be addressed before final publication.

Points for consideration

In section 2.3 Model Updates, it is noted that there have been some changes to the cloud scheme but these are not discussed in much detail and it is not clear how the large adjustments to the l_{crit} in mixed phase and ice clouds were reached. This is a pretty serious adjustment of the model as many of the other model parametrizations in the radiation scheme are likely to be tuned to these kind of values, possibly giving erroneous results or different compensating biases. However little detail is given as to how or why the particular values for these adjustments were chosen. Nor are the effects of this adjustment alone described in any detail – for instance on lines 398 to 400 reference is made to a precipitation bias in the SE compared to observations, but it is not clear if this bias is reduced or increased from RACMO2.3p1 and if this is a result of the cloud scheme changes or for example the change in topography caused by moving to the GIMP DEM. More information on how this change in cloud parametrizations has altered precipitation in particular would be helpful, as the differences in the topography shown in figure 2 seem also to be related to the change in distribution of precipitation, at least in some locations as shown in figure 7.

We agree that the cloud scheme updates, i.e. tuning of the critical cloud content (l_{crit}), is not described in sufficient detail. The goal of this tuning was to obtain a uniform increase in precipitation over Greenland in order to minimize the inland dry bias observed in RACMO2.3p1.

To that end, we carried out a series of sensitivity experiments, i.e. one-year simulations, to test changes in spatial distribution as well as in the time scale of precipitation formation. From these experiments, we found a linear relationship between the critical cloud content (l_{crit}) for mixed and ice clouds, the vertical integrated cloud content (liquid and ice water paths that also affect the SEB through changes in cloud optical thickness), and the integrated precipitation over Greenland. Increasing l_{crit} for mixed (2x) and ice clouds (5x) uniformly enhances precipitation, except for some high accumulation regions in southeast Greenland (see Section 5.1 and Fig. 11a).

These new settings were then tested for a longer period. This approximately cancelled the dry bias observed in RACMO2.3p1. This also led to larger but realistic vertical integrated cloud content and did not strongly affect the SEB and surface climate of the GrIS. Note that l_{crit} is also strongly adjusted in the ECMWF physics compared to commonly used values in the literature. For example, for snow clouds modelled by a cloud parcel model, Lin et al. (1983) set l_{crit} to $1 \cdot 10^{-3} \text{ kg kg}^{-1}$, while the ECMWF physics uses a value of $0.3 \cdot 10^{-4} \text{ kg kg}^{-1}$. The justification for this is provided at p. 90 of ECMWF-IFS (2008): “A lower value (of l_{crit}) is appropriate for a GCM sized grid box (unless subgrid cloud variability is explicitly taken into account)”. As RACMO2 employs much smaller grid boxes than GCMs, higher values of l_{crit} , typically $\sim 10^{-4} \text{ kg kg}^{-1}$, are not unreasonable.

In brief, changes in precipitation shown in Fig. 7a are mostly driven by the tuning of l_{crit} . Locally, large changes in mountainous areas, i.e. notably in southeast Greenland, are due to changes in the topography. Likewise, tuned l_{crit} is the main driver of changes in SWd and LWd through changes in cloud optical thickness, which of course slightly impact the other SEB components. However, these are even more affected by other changes applied in the new model version, i.e. changes in ice and snow albedos. To clarify this, we added the following sentences: “The values of l_{crit} adopted in RACMO2 were obtained

after conducting a series of sensitivity experiments, i.e. one-year simulations, to test the dependence of precipitation formation efficiency, spatial distribution and cloud moisture content on l_{crit} and other cloud tuning parameters. From these experiments, we found a linear relationship between l_{crit} for mixed and ice clouds, the vertical integrated cloud content, i.e. liquid and ice water paths that also affect the SEB through changes in cloud optical thickness, and the integrated precipitation over Greenland. These new settings were then tested for a longer period and proved to almost cancel the dry bias observed in RACMO2.3p1 (see Section 5.1). This led to larger but realistic vertical integrated cloud content and did not strongly affect the SEB and surface climate of the GrIS. For instance, the induced changes of surface downward shortwave and longwave radiation are only about -4 W m^{-2} and 7 W m^{-2} , respectively, peaking in central Greenland. While the obtained increase in l_{crit} is relatively large, especially for ice clouds, it is important to note that it is also strongly adjusted in the original ECMWF physics compared to commonly used values in the literature: e.g. Lin et al. (1983) set l_{crit} to $1 \cdot 10^{-3} \text{ kg kg}^{-1}$ for ice clouds, while the ECMWF physics, tuned for GCM sized grid cells, uses a value of $0.3 \cdot 10^{-4} \text{ kg kg}^{-1}$ (ECMWF-IFS, 2008). As l_{crit} depends on model grid resolution, i.e. GCMs running at lower spatial resolution require lower value of l_{crit} (ECMWF-IFS, 2008), the use of a larger l_{crit} for e.g. ice clouds ($1.5 \cdot 10^{-4} \text{ kg kg}^{-1}$) in RACMO2 is deemed reasonable. In addition, this value remains well within the range of values previously presented in the literature (Lin et al., 1983)."

On a similar theme, I note that the small improvement in LWd and SWd on the K-transect is reasonably attributed to the change in the cloud scheme. It would be very interesting to see if this improvement is consistent across Greenland at stations other than the K-transect. There is some reason to believe that western Greenland is often modelled well but in other regions RCMs do a less good job of reproducing observed climate variables, possibly due to biases in cloud schemes as well as the complex topography in other areas. As there is now a fairly large amount of data available from Promice stations it would be nice to see some geographical spread in the figures presented in figure 5 and tables 1-5, perhaps limited to maybe 3-4 extra stations in north, south and east Greenland to determine if the positive results from western Greenland are replicated elsewhere.

To provide a regional evaluation of meteorological and radiation data, we decided to add individual scatterplots for four different sectors of the ice sheet (NE [Figs. S3-4], NW [Figs. S5-6], SE [Figs. S7-8], SW [Figs. S9-10]). These scatterplots are similar to Figs. 3 and 4. They list statistics for the four regions, respectively, and clearly stress that RACMO2.3p2 agrees as well with observations in these four sectors. See also our response to the General comments 2) of reviewer #1. We also added the following sentences in the revised manuscript; in Section 3.1: "To provide some regional insight on the model performance, Table S1 and Figs. S1-S4 compare modelled meteorological data from RACMO2.3p2 with AWS measurements (green dots in Fig. 1) clustered in four sectors of the GrIS, i.e. NW, NE, SW and SE, respectively. These sectors correspond to the four quadrants delimited by longitude 40°W and latitude 70°N , respectively. These regional scatter plots unambiguously show that RACMO2.3p2 performs as good in each of these four sectors of the GrIS."

In Section 3.2: "Clustering AWS measurements within four sectors of the GrIS (Figs. S6-S9 and Table S1), RACMO2.3p2 shows good and equivalent agreement in NW, NE, SW and SE Greenland, respectively."

Upper atmosphere relaxation is mentioned on line 136-7 but no details are given. I would like to see this expanded with details on which fields are nudged and at which levels in the atmosphere as this is important for interpreting the atmospheric model output.

We elaborated as follows: "To better capture SMB interannual variability in this new model version, upper atmosphere relaxation (UAR or nudging) of temperature and wind fields is applied every 6 hours for model atmospheric levels above 600 hPa, i.e. $\sim 4 \text{ km a.s.l.}$ (Van de Berg and Medley [2016]). UAR is not applied to atmospheric humidity fields in order not to alter clouds and precipitation formation in RACMO2."

The authors acknowledge that boundary forcing is important for results (line 20) but the differences between results from ERA40 and ERA-Interim forced years are not explored at all. It would be

helpful to have a time series of SMB and the components for the full 1958-2015 averaged over the full ice sheet for the full period. This would show if, for example, there is a marked change in precipitation or melt potentially resulting from the switch in boundary forcing in 1979 is visible in more detail.

Time series of RACMO2.3p1 have been already published in e.g. Van den Broeke et al. (2016) [11 km] and Noël et al. (2017) [1 km] and show no abrupt changes (larger than the interannual variability) between 1978 and 1979, i.e. when the re-analysis forcing switches from ERA-40 to ERA-Interim. The same also applies to RACMO2.3p2 simulation.

It would also give a better sense of the interannual and decadal scale variability in SMB of Greenland. Plotting these with model version p1 masked with the same ice mask would also allow us to assess the differences in SMB over the full ice sheet that result from the improvements introduced here.

As discussed in Section 5.1, trends and time series cannot be directly derived from the new RACMO2.3p2 version as “correct” precipitation and underestimated runoff, i.e. due to unresolved high melt rates over low-lying marginal outlet glaciers and narrow ablation zone, lead to overestimated GrIS SMB at 11 km resolution, highlighting the need for further statistical downscaling. In addition, relevant climatological averages (1958-2016) for the main SMB components are already listed in Sections 5.1 [11 km] and 5.2 [1 km]. At the discretion of the editor, we are happy to include time series of annual downscaled SMB components from RACMO2.3p2 at 1 km.

I am not quite clear if the improvements to the snow module are part of the online RACMO model or the offline firn model – I assume the former, but please clarify this in sections 2.1 and 2.3.

RACMO2 (climate model including a snow/firn module) and FDM-IMAU (firn model) are two different models. As mentioned, IMAU-FDM is run offline and is forced by the climate data of RACMO2. In Section 2.1 and 2.3, we only refer to RACMO2 settings and updates and do not discuss FDM-IMAU. FDM-IMAU is only mentioned in Section 2.1 to clarify how a snowpack initialization has been obtained for the 1st of September 1957, date at which the RACMO2.3p2 simulation starts. FDM-IMAU simulations forced by RACMO2.3p2 will be discussed in a forthcoming paper. See also our response to reviewer #1.

“The model has about 40 active [...] 1957 using estimates of temperature and density profiles derived by the offline [...] (Ligtenberg et al., 2011). These profiles are obtained by repeatedly running IMAU-FDM over 1960-1979 forced by the outputs of the previous RACMO2.3p1 climate simulation until the firn column reaches an equilibrium.”

On line 216 you note that AWS data is sometimes spurious, Ryan et al 2017 in GRL also showed that the siting of stations (for very good reasons!) also leads to spurious underestimation of albedo – this should probably be referenced. [This reference has been included in the revised manuscript.](#) Thank you.

Modelling the climate and surface mass balance of polar ice sheets using RACMO2, Part 1: Greenland (1958-2016)

Brice Noël¹, Willem Jan van de Berg¹, J. Melchior van Wessem¹, Erik van Meijgaard², Dirk van As³, Jan T. M. Lenaerts⁴, Stef Lhermitte⁵, Peter Kuipers Munneke¹, C. J. P. Paul Smeets¹, Lambertus H. van Ulf², Roderik S. W. van de Wal¹, and Michiel R. van den Broeke¹

¹Institute for Marine and Atmospheric research Utrecht, University of Utrecht, Utrecht, Netherlands.

²Royal Netherlands Meteorological Institute, De Bilt, Netherlands.

³Geological Survey of Denmark and Greenland (GEUS), Copenhagen, Denmark.

⁴Department of Atmospheric and Oceanic Sciences, University of Colorado, Boulder, USA.

⁵Department of Geoscience & Remote Sensing, Delft University of Technology, Delft, Netherlands.

Correspondence to: Brice Noël (B.P.Y.Noel@uu.nl)

Abstract.

We evaluate modelled Greenland ice sheet (GrIS) near-surface climate, surface energy balance (SEB) and surface mass balance (SMB) from the updated regional climate model RACMO2 (1958-2016). The new model version, referred to as RACMO2.3p2, incorporates updated glacier outlines, topography and ice albedo fields. Parameters in the cloud scheme governing the conversion of cloud condensate into precipitation have been tuned to correct inland snowfall underestimation; snow properties are modified to reduce drifting snow and melt production in the ice sheet percolation zone. The ice albedo prescribed in the updated model is lower at the ice sheet margins, increasing ice melt locally. RACMO2.3p2 shows good agreement compared to in situ meteorological data and point SEB/SMB measurements, and better resolves the spatial patterns and temporal variability of SMB compared with the previous model version, notably in the northeast, southeast, and along the K-transect in southwestern Greenland. This new model version provides updated, high-resolution gridded fields of the GrIS present-day climate and SMB, and will be used for projections of the GrIS climate and SMB in response to future climate scenario in a forthcoming study.

Keywords. RACMO, SMB, SEB, Greenland

1 Introduction

Predicting future mass changes of the Greenland ice sheet (GrIS) using regional climate models (RCMs) remains challenging (Rae et al., 2012). The reliability of projections depend on the ability of RCMs to reproduce the contemporary GrIS climate and surface mass balance (SMB), i.e. snowfall accumulation minus ablation from meltwater runoff, sublimation and drifting snow erosion (Van Angelen et al., 2013a; Fettweis et al., 2013). In addition, **RCM** simulations are affected by the quality of the re-analysis used as lateral forcing (Fettweis et al., 2013, 2017; Bromwich et al., 2015) and by the accuracy of the ice sheet mask and topography prescribed in models (Vernon et al., 2013).

Besides direct RCM simulations, the contemporary SMB of the GrIS has been reconstructed using various other methods, e.g. Positive Degree Day (PDD) models forced by statistically downscaled re-analyses (Hanna et al., 2011; Wilton et al., 2016), mass balance models forced by the climatological output of an RCM (HIRHAM4) (Mernild et al., 2010, 2011), **and reconstruction of SMB obtained by combining RCM outputs** with temperature and ice core accumulation measurements (Box, 2013). **In addition, Vizcaíno et al. (2013) and Cullather et al. (2014) respectively used the Community Earth System Model (CESM) at 1° resolution (~100 km) and the Goddard Earth Observing System model version 5 (GEOS-5) at 0.5° resolution (~50 km) to estimate recent and future mass losses of the GrIS.**

Polar RCMs have the advantage **of explicitly resolving** the relevant atmospheric and surface physical processes at high spatial (5 to 20 km) and temporal (sub-daily) resolution. Nonetheless, good RCM performance often results from compensating errors between poorly parameterized processes, e.g. cloud physics (Van Tricht et al., 2016) and turbulent fluxes (Noël et al., 2015; Fausto et al., 2016). Therefore, considerable efforts have been dedicated to **evaluating and improving** polar RCM output in Greenland (Ettema et al., 2010b; Van Angelen et al., 2013b; Lucas-Picher et al., 2012; Fettweis et al., 2017; Noël et al., 2015; Langen et al., 2017), using in situ SMB observations (Bales et al., 2001, 2009; Van de Wal et al., 2012; Machguth et al., 2016), airborne radar measurements of snow accumulation (Koenig et al., 2016; Overly et al., 2016; Lewis et al., 2017) and meteorological records (Ahlstrøm et al., 2008; Kuipers Munneke et al., 2017; Smeets et al., 2017), including radiative fluxes that are required to close the ice sheet surface energy balance (SEB), and hence quantify surface melt energy.

For more than two decades, the polar version of the Regional Atmospheric Climate Model (RACMO2) has been developed to simulate the climate and SMB of the Antarctic and Greenland ice sheets. In previous versions, snowfall accumulation was systematically underestimated in the GrIS interior, while melt was generally overestimated in the percolation zone (Noël et al., 2015). At the ice sheet margins, meltwater runoff is underestimated over narrow ablation zones and small outlet glaciers that are not accurately resolved in the model's ice mask at 11 km. Locally, this underestimation can exceed several m w.e. yr⁻¹, e.g. at automatic weather station (AWS) QAS.L installed at the southern tip of Greenland (Fausto et al., 2016). These biases can be significantly reduced by statistically

downscaling SMB components to 1 km resolution (Noël et al., 2016). Computational limitations currently hamper direct near-kilometre **scale** simulations of the contemporary GrIS climate, making it essential to further develop RACMO2 model physics at coarser spatial resolution. **Important modelling challenges and limitations still need to be addressed in RACMO2 regardless of the spatial resolution used: e.g. cloud representation (Van Tricht et al., 2016), surface albedo and turbulent heat fluxes (Section 6).**

Here, we present updated simulations of the contemporary GrIS climate and SMB at 11 km resolution (1958-2016). The updated model incorporates multiple adjustments, notably in the cloud scheme and snow module. Model evaluation is performed using in situ meteorological data and point SEB/SMB measurements collected **across the GrIS**. We then compare the SMB of the updated model version (RACMO2.3p2) with its predecessor (RACMO2.3p1), **discussed in Noël et al. (2015)**, for the overlapping period between the two simulations (1958-2015). Section 2 discusses the new model settings and initialisation, together with observational data used for model evaluation. Modelled climate and SEB components are evaluated using in situ measurements in Section 3. Changes in SMB patterns between the new and old model versions are discussed in Section 4, as well as case studies in northeast, southwest and southeast Greenland. Section 5 introduces and evaluates the updated downscaled daily, 1 km SMB product. Section 6 discusses the remaining model uncertainties, followed by conclusions in Section 7. This manuscript is part of a tandem model evaluation over the Greenland (present study) and Antarctic ice sheets (Van Wessem et al., 2017).

2 Model and observational data

2.1 The Regional Atmospheric Climate Model RACMO2

The polar ('p') version of the Regional Atmospheric Climate Model (RACMO2) (Van Meijgaard et al., 2008) is specifically adapted to simulate the climate of polar ice sheets. The model incorporates the dynamical core of the High Resolution Limited Area Model (HIRLAM) (Undén et al., 2002) and the physics package cycle CY33r1 of the European Centre for Medium-range Weather Forecasts Integrated Forecast System (ECMWF-IFS, 2008). It also includes a multi-layer snow module that simulates melt, liquid water percolation and retention, refreezing and runoff (Ettema et al., 2010b), and accounts for dry snow densification following Ligtenberg et al. (2011). RACMO2 implements an albedo scheme that calculates snow albedo based on prognostic snow grain size, cloud optical thickness, solar zenith angle and impurity concentration in snow (Kuipers Munneke et al., 2011). In RACMO2, impurity concentration, i.e soot, is prescribed as constant in time and space. The model also simulates drifting snow erosion and sublimation following Lenaerts et al. (2012b). Previously, RACMO2 has been used to reconstruct the contemporary SMB of the Greenland ice sheet (Van Angelen et al., 2013a,b; Noël et al., 2015, 2016) and peripheral ice caps (Noël et al., 2017a), the Canadian Arctic Archipelago (Lenaerts et al., 2013; Noël et al., 2017b), Patagonia (Lenaerts et al.,

2014) and Antarctica (Van Wessem et al., 2014a,b).

2.2 Surface energy budget and surface mass balance

90 In RACMO2, the skin temperature (T_{skin}) of snow and ice is derived by closing the surface energy budget (SEB), using the linearized dependencies of all fluxes to T_{skin} and further assuming, as a first approximate, that no melt occurs at the surface ($M = 0$). If the obtained T_{skin} exceeds the melting point, T_{skin} is set to 0°C ; all fluxes are then recalculated and the melt energy flux ($M > 0$) is estimated by closing the SEB in Eq. 1, assuming that no solar radiation can directly penetrate the snow or ice interface.

$$\begin{aligned} M &= SW_d - SW_u + LW_d - LW_u + SHF + LHF + G_s \\ &= SW_n + LW_n + SHF + LHF + G_s \end{aligned} \quad (1)$$

where SW_d and SW_u are the shortwave down/upward radiation fluxes, LW_d and LW_u are the long-wave down/upward radiation fluxes, SHF and LHF are the **net** sensible and latent turbulent heat fluxes, and G_s is the subsurface heat flux. SW_n and LW_n are the net short/longwave radiation at the surface. All fluxes are expressed in W m^{-2} and are defined positive.

In the percolation zone of the GrIS, liquid water mass from melt (ME) and rainfall (RA) can percolate through the firn column, and is either retained by capillary forces as irreducible water (RT) or refreezes (RF). Combined with dry snow densification, this progressively depletes firn pore space until the entire column turns into ice (900 kg m^{-3}). The fraction not retained is assumed to immediately run off (RU) to the ocean:

$$RU = ME + RA - RT - RF \quad (2)$$

The climatic mass balance (Cogley et al., 2011), hereafter referred to as SMB, is estimated as:

$$SMB = P_{tot} - RU - SU_{tot} - ER_{ds} \quad (3)$$

where P_{tot} is the total amount of precipitation, i.e. solid and liquid, RU is meltwater runoff, SU_{tot} is the total sublimation from drifting snow and surface processes, and ER_{ds} is the erosion by the process of drifting snow. All SMB components are expressed in mm w.e. (water equivalent) for point 'specific' SMB values, or in Gt yr^{-1} when integrated over the GrIS.

2.3 Model updates

In the cloud scheme, parameters controlling precipitation formation have been modified to reduce the negative snowfall bias in the GrIS interior (~ 40 mm w.e. yr^{-1}) (Noël et al., 2015). To correct for this, the critical cloud content (l_{crit}) governing the onset of effective precipitation formation for liquid-mixed and ice clouds has been increased by a factor 2 (Eqs. 5.35 and 6.39 in ECMWF-IFS (2008)) and 5 (Eq. 6.42 in ECMWF-IFS (2008)), respectively. As a result, moisture transport is prolonged to higher elevations and precipitation is generated further inland. The values of l_{crit} adopted in RACMO2 were obtained after conducting a series of sensitivity experiments, i.e. one-year simulations, to test the dependence of precipitation formation efficiency, spatial distribution and cloud moisture content on l_{crit} and other cloud tuning parameters. From these experiments, we found a linear relationship between l_{crit} for mixed and ice clouds, the vertical integrated cloud content, i.e. liquid and ice water paths that also affect the SEB through changes in cloud optical thickness, and the integrated precipitation over Greenland. These new settings were then tested for a longer period and proved to almost cancel the dry bias observed in RACMO2.3p1 (see Section 5.1). This led to larger but realistic vertical integrated cloud content and did not strongly affect the SEB and surface climate of the GrIS. For instance, the induced changes of surface downward shortwave and longwave radiation are only about -4 W m^{-2} and 7 W m^{-2} , respectively, peaking in central Greenland. While the obtained increase in l_{crit} is relatively large, especially for ice clouds, it is important to note that it is also strongly adjusted in the original ECMWF physics compared to commonly used values in the literature: e.g. Lin et al. (1983) set l_{crit} to $1 \cdot 10^{-3} \text{ kg kg}^{-1}$ for ice clouds, while the ECMWF physics, tuned for GCM sized grid cells, uses a value of $0.3 \cdot 10^{-4} \text{ kg kg}^{-1}$ (ECMWF-IFS, 2008). As l_{crit} depends on model grid resolution, i.e. GCMs running at lower spatial resolution require lower values of l_{crit} (ECMWF-IFS, 2008), the use of a larger l_{crit} for e.g. ice clouds ($1.5 \cdot 10^{-4} \text{ kg kg}^{-1}$) in RACMO2 is deemed reasonable. In addition, this value remains well within the range of values previously presented in the literature (Lin et al., 1983).

Furthermore, the previous model version overestimated snow melt in the percolation zone of the GrIS (Noël et al., 2015). With the aim of minimizing this bias, the following parameters have been tuned in the snow module:

a) The model soot concentration, accounting for dust and black carbon impurities deposited on snow, has been reduced from 0.1 ppmv to 0.05 ppmv, more representative of observed values (Doherty et al., 2010). A lower soot concentration yields a higher surface albedo, hence decreasing melt (Van Angelen et al., 2012).

b) The size of refrozen snow grains has been reduced from 2 to 1 mm (Kuipers Munneke et al., 2011). Consequently, the surface albedo of refrozen snow increases, as smaller particles enhance scattering of solar radiation back to the atmosphere (Kaasalainen et al., 2006).

c) In previous model versions, the albedo of superimposed ice, i.e. the frozen crust forming at the firn surface, was set equal to the albedo of bare ice (~ 0.55), underestimating surface albedo

and hence overestimating melt. The snow albedo scheme now explicitly calculates the albedo of superimposed ice layers (~ 0.75), following Kuipers Munneke et al. (2011).

d) The saltation coefficient of drifting snow has been approximately halved from 0.385 to 0.190 (Lenaerts et al., 2012b). Saltation occurs when near surface wind speed is sufficiently high to lift snow grains from the surface. In RACMO2, this coefficient determines the depth of the saltation layer, i.e. typically extending 0 to 10 cm above the surface, that directly controls the mass of drifting snow transported in the suspension layer aloft (above 10 cm). This revision does not affect the timing and frequency of drifting snow events, which are well modelled (Lenaerts et al., 2012b,a), but only reduces the horizontal drifting snow transport and sublimation, preventing a too early exposure of bare ice during the melt season, especially in the dry and windy northeastern GrIS (Section 4.2).

2.4 Initialisation and set up

To enable a direct comparison with previous runs, RACMO2.3p2 is run at an 11 km horizontal resolution for the period 1958-2016, and is forced at its lateral boundaries by ERA-40 (1958-1978) (Uppala et al., 2005) and ERA-Interim (1979-2016) (Dee et al., 2011) re-analyses on a 6-hourly basis over the model domain shown in Fig. 1. The forcing consists of temperature, specific humidity, pressure, wind speed and direction being prescribed at each of the 40 vertical atmosphere hybrid model levels. To better capture SMB inter-annual variability in this new model version, upper atmosphere relaxation (UAR or nudging) of temperature and wind fields is applied every 6 hours for model atmospheric levels above 600 hPa, i.e. ~ 4 km a.s.l. (Van de Berg and Medley, 2016). UAR is not applied to atmospheric humidity fields in order not to alter clouds and precipitation formation in RACMO2. As the model does not incorporate a dedicated ocean module, sea surface temperature and sea ice cover are prescribed from the re-analyses (Fiorino, 2004; Stark et al., 2007). The model has about 40 active snow layers that are initialised in September 1957 using estimates of temperature and density profiles derived from the offline IMAU Firn Densification Model (IMAU-FDM) (Ligtenberg et al., 2011). These profiles are obtained by repeatedly running IMAU-FDM over 1960-1979 forced by the outputs of the previous RACMO2.3p1 climate simulation until the firn column reaches an equilibrium. The data spanning the winter season up to December 1957 serve as an additional spin up for the snowpack and are therefore discarded in the present study.

Relative to previous versions, the integration domain extends further to the west, north and east (Fig. 1). This brings the northernmost sectors of the Canadian Arctic Archipelago and Svalbard well inside the domain interior, and further away from the lateral boundary relaxation zone (24 grid cells, black dots in Fig. 1). In addition, RACMO2.3p2 utilises the 90-m Greenland Ice Mapping Project (GIMP) Digital Elevation Model (DEM) (Howat et al., 2014) to better represent the glacier outlines and the surface topography of the GrIS. Compared to the previous model version, which used the 5 km DEM presented in Bamber et al. (2001), the GrIS area is reduced by 10,000 km² (Fig. 2a). This mainly results from an improved partitioning between the ice sheet and peripheral ice caps, for which

the ice-covered area has, in equal amounts, decreased and increased, respectively. In RACMO2, a grid-cell with an ice fraction ≥ 0.5 is considered fully ice-covered. The updated topography shows significant differences compared to the previous version, especially over marginal outlet glaciers where surface elevation has considerably decreased (Fig. 2b). Bare ice albedo is prescribed from the
190 500 m MODerate-resolution Imaging Spectroradiometer (MODIS) 16-day Albedo version 5 product (MCD43A3v5), as the 5% lowest surface albedo records for the period 2000-2015 (vs. 2001-2010 in older versions; Fig. 2c). In RACMO2, minimum ice albedo is set to 0.30 for dark ice in the low-lying ablation zone, and a maximum value of 0.55 for bright ice under perennial snow cover in the accumulation zone. In previous RACMO2 versions, bare ice albedo of glaciated grid cells without
195 valid MODIS estimate were set to 0.47 (Noël et al., 2015).

2.5 Observational data

To evaluate the modelled contemporary climate and SMB of the GrIS, we use daily average meteorological records of near-surface temperature, wind speed, relative humidity, air pressure and down/upward short/longwave radiative fluxes, retrieved from 23 AWS for the period 2004-2016
200 (green dots in Fig. 1). Erroneous radiation measurements, caused e.g. by sensor riming, were discarded by removing daily records showing $SW_d bias > 6 \sigma_{bias}$, where $SW_d bias$ is the difference between daily modelled and observed SW_d and σ_{bias} is the standard deviation of the daily SW_d bias for all measurements. In addition, measurements affected by sensor heating in summer, i.e. showing $LW_u > 318 \text{ W m}^{-2}$, were eliminated as these values represent $T_s > 0^\circ\text{C}$ for $\epsilon \approx 0.99$, where T_s is
205 the surface temperature and ϵ the selected emissivity of snow or ice. We only used daily records that were simultaneously available for each of the four radiative components. Eighteen of these AWS sites are operated as part of the Programme for Monitoring of the Greenland Ice Sheet (PROMICE, www.promice.dk) covering the period 2007-2016 (Van As et al., 2011). Four other AWS sites, namely S5, S6, S9 and S10 (2004-2016), are located along the K-transect in southwest Greenland
210 (67°N , $47\text{-}50^\circ\text{W}$) (Smeets et al., 2017). Another AWS (2014-2016) is situated in southeast Greenland (66°N ; 33°W) at a firn aquifer site (Forster et al., 2014; Koenig et al., 2014). The latter five sites are operated by the Institute for Marine and Atmospheric research at Utrecht University (IMAU).

We also use in situ SMB measurements collected at 213 stake sites in the GrIS ablation zone (yellow dots in Fig. 1; Machguth et al. (2016)) and at 182 sites in the accumulation zone (white dots
215 in Fig. 1) including snow pits, firn cores (Bales et al., 2001, 2009), and airborne radar measurements (Overly et al., 2016). We exclusively selected measurements that temporally overlap with the model simulation (1958-2016). To match the observational period, daily modelled SMB is cumulated for the exact number of measuring days at each site.

For model evaluation, we select the grid cell nearest to the observation site in the accumulation
220 zone. In the ablation zone, an additional altitude correction is applied by selecting the model grid cell with the smallest elevation bias among the nearest grid cell and its eight adjacent neighbours.

One ablation site and seven PROMICE AWS sites presented an elevation bias in excess of > 100 m compared to the model topography and were discarded from the comparison.

In addition, we compare modelled SMB with annual glacial ice discharge (D) retrieved from the combined Zachariae Isstrøm and Nioghalvfjærdsbrae glacier catchments in northeast Greenland (1975-2015; yellow line in Fig. 6a), presented in Mougnot et al. (2015).

3 Results: near-surface climate and SEB

We evaluate the modelled present-day near-surface climate of the GrIS in RACMO2.3p2 using data from 23 AWS sites (see Section 2.5). Then, we discuss in more detail the model performance at 4 AWS along the K-transect and compare RACMO2.3p2 outputs to those of RACMO2.3p1.

3.1 Near-surface meteorology

Figure 3 compares daily mean values of 2-m temperature, 2-m specific humidity, 10-m wind speed, and air pressure collected at 23 AWS sites with RACMO2.3p2 output. The modelled 2-m temperature is in good agreement with observations ($R^2 = 0.95$) and with a RMSE of $\sim 2.4^\circ\text{C}$ and a small cold bias of $\sim 0.1^\circ\text{C}$ (Fig. 3a). As specific humidity is not directly measured at AWS sites, it is calculated from measured temperature, pressure and relative humidity following Curry and Webster (1999). The obtained 2-m specific humidity is accurately reproduced in the model ($R^2 = 0.95$) with a RMSE $\sim 0.35 \text{ g kg}^{-1}$ and a negative bias of 0.13 g kg^{-1} (Fig. 3b). The same holds for daily records of 10-m wind speed ($R^2 = 0.68$; Fig. 3c), with the model exhibiting a small negative bias and RMSE of $\sim 2 \text{ m s}^{-1}$. Surface pressure is also well represented ($R^2 = 0.99$) with a small negative bias of 0.8 hPa and RMSE $< 6 \text{ hPa}$ (Fig. 3d). A systematic pressure bias at some stations results from the (uncorrected) elevation difference with respect to the model, which can be as large as 100 m . To provide some regional insight on the model performance, Table S1 and Figs. S1-S4 compare modelled meteorological data from RACMO2.3p2 with AWS measurements (green dots in Fig. 1) clustered in four sectors of the GrIS, i.e. NW, NE, SW and SE, respectively. These sectors correspond to the four quadrants delimited by longitude 40°W and latitude 70°N , respectively. These regional scatter plots unambiguously show that RACMO2.3p2 performs as good in each of these four sectors of the GrIS.

Table 1 and Fig. S5 compare the agreement of RACMO2.3p2 and version 2.3p1 with in situ measurements. We find an overall improvement in the updated model version, showing a smaller bias and RMSE as well as an increased variance explained. Notably, the remaining negative bias in 2-m temperature (Fig. S5a) and the systematic dry bias (Fig. S5b) in RACMO2.3p1 have almost vanished in the updated model version (Figs. 3a and b).

3.2 Radiative fluxes

Figure 4 shows scatter plots of modelled and measured daily mean radiative fluxes, i.e. short/longwave down/upward radiation. Radiative fluxes are also well reproduced by the model with R^2 ranging from 0.83 for LW_d to 0.95 for SW_d (Fig. 4), showing relatively small biases of -7.1 W m^{-2} and 3.8 W m^{-2} , and RMSE of 21.2 W m^{-2} and 27.1 W m^{-2} , respectively. The negative biases in LW_d and 2-m temperature partly lead to LW_u underestimation of 4.4 W m^{-2} with a small RMSE of 12.1 W m^{-2} , in combination with positive bias in SW_d suggests an underestimation of cloud cover in the ice sheet marginal regions, where most stations are located. The larger bias and RMSE in SW_u of 6.8 W m^{-2} and 32.1 W m^{-2} , respectively, can be ascribed to overestimated surface albedo, especially during summer snowfall episodes, when a bright fresh snow cover is deposited over bare ice. In RACMO2, precipitation falls vertically, i.e. no horizontal transport is allowed, and is assumed to be instantly deposited at the surface. Consequently, the spatial distribution of summer snow patches may be locally inaccurate, resulting in large albedo discrepancies when compared to point albedo measurements. Note that these AWS radiation measurements are also prone to potentially large uncertainties due to preferred location on ice hills, sensor tilt, riming and snow/rain deposition on the instruments, leading to spurious albedo and SW_u data (Ryan et al., 2017), e.g. the upper left dots in Fig. 4b. Clustering AWS measurements within four sectors of the GrIS (Figs. S6-S9 and Table S1), RACMO2.3p2 shows good and equivalent agreement in NW, NE, SW and SE Greenland, respectively.

Compared to the previous model version (Table 1), changes in the cloud scheme have significantly improved the representation of LW_d (Figs. 4c and S10c), showing a reduced negative bias and RMSE. These modifications have also somewhat decreased the positive bias in SW_d (Fig. 4a), relative to RACMO2.3p1 (Fig. S10a). In addition, LW_u is notably improved in RACMO2.3p2: the remaining negative bias in LW_u has almost vanished (Figs. 4d and S10d). This can be partly explained by the much better resolved 2-m temperature in RACMO2.3p2.

3.3 Seasonal SEB cycle along the K-transect

The K-transect comprises four AWS sites located in different regions of the GrIS: S5 and S6 are installed in the lower and upper ablation zone, respectively, S9 is situated close to the equilibrium line and S10 in the accumulation zone. Figure 5 shows monthly mean modelled (continuous lines, RACMO2.3p2) and observed (dashed lines) SEB components, i.e. net short/longwave radiation (SW_n/LW_n), latent and sensible heat fluxes (LHF/SHF), surface albedo and melt measured at these four AWS sites for the period 2004-2015. Tables 2-5 list statistics calculated at each individual AWS and for the two model versions.

3.3.1 Low ablation zone

At station S5 (490 m a.s.l.), surface melt is well reproduced in RACMO2.3p2, with a small negative bias of 0.4 W m^{-2} (Table 2; Fig. 5b). However, this good agreement results from significant error compensation between overestimated SW_n (bias of 16.2 W m^{-2}) and underestimated SHF in summer (15.3 W m^{-2} ; Fig. 5a). The bias in SW_n is mostly driven by overestimated SW_d (20.7 W m^{-2} ; Table 2) and to a lesser extent by underestimated SW_u (4.5 W m^{-2}), resulting from underestimated cloud cover and ice albedo (Fig. 5b), respectively. AWS are often installed on snow covered promontories, i.e. hummocks, that maintain higher albedo in summer (~ 0.55) than their surroundings where impurities collect. Mixed reflectance from bright ice cover (~ 0.55) and neighbouring darker tundra, exposed nunataks or meltwater ponds (< 0.30), located within the same MODIS grid cell, likely explains this underestimation. Another explanation stems from the deterioration of MODIS sensors in time, resulting in underestimated surface albedo records for the MCD43A3v5 product (Polashenski et al., 2015; Casey et al., 2017).

LW_n is well reproduced in the model due to similar negative biases in LW_d and LW_u ($\sim 12 \text{ W m}^{-2}$), indicating again underestimated cloud cover. The large negative bias in SHF is attributed to an inaccurate representation of surface roughness in the lowest sectors of the ablation zone. Smeets and van den Broeke (2008) show that observed surface roughness for momentum has a high temporal variability at site S5, with a minimum of 0.1 mm in winter, when a smooth snow layer covers the rugged ice sheet topography, and a peak in summer (up to 50 mm), when melting snow exposes hummocky ice at the surface. In RACMO2, surface aerodynamic roughness is prescribed at 1 mm for snow-covered grid cells and at 5 mm for bare ice, hence significantly underestimating values over ice in summer and thus causing too low SHF (Ettema et al., 2010a). This bias in SHF at S5 is also partly ascribable to too cold conditions (2°C). Although not negligible, LHF contributes little to the energy budget and shows a positive bias of 3.4 W m^{-2} , notably in winter.

3.3.2 Upper ablation zone

Station S6 is located at 1010 m a.s.l. in the GrIS upper ablation zone. There, summer melt is overestimated by $\sim 8 \text{ W m}^{-2}$ owing to both too high SW_n and SHF (9.8 W m^{-2} and 7 W m^{-2} , respectively; Fig. 5c and Table 3). As for S5, the bias in SW_n results from overestimated SW_d (6 W m^{-2}) and underestimated SW_u (3.8 W m^{-2}). At the AWS location, surface albedo progressively declines from 0.60 to ~ 0.40 when bare ice is exposed in late summer, whereas RACMO2.3p2 simulates bare ice at the surface throughout summer, with an albedo of 0.40. As a result, modelled surface albedo is systematically underestimated in summer, especially in July (Fig. 5d). Likewise, a small negative bias in LW_n (2.3 W m^{-2}) is obtained as LW_d and LW_u are both slightly underestimated (Table 3). Here, 2-m temperature is on average 0.7°C too high, causing SHF to be overestimated (7 W m^{-2}).

3.3.3 Equilibrium line

Close to the equilibrium line, RACMO2.3p2 slightly underestimates summer melt (2.4 W m^{-2} ; Fig. 5f and Table 4). At station S9 (1520 m a.s.l.), a perennial snow cover maintains a minimum albedo of 0.65 in summer, i.e. when melt wets the snow. A small positive bias in modelled snow albedo (0.03) combined with a slightly underestimated SW_d (1.5 W m^{-2}) lead to an overestimated SW_u (3.5 W m^{-2}), hence underestimating SW_n (5 W m^{-2}). Although LW_d is underestimated by 3.1 W m^{-2} and LW_u is overestimated by 0.5 W m^{-2} , especially in winter, LW_n agrees well with measurements. The 2-m surface temperature shows a 0.5°C positive bias, in turn causing slightly too large SHF (5.2 W m^{-2} ; Fig. 5e and Table 4).

3.3.4 Accumulation zone

All SEB components are well reproduced at site S10 (1850 m a.s.l.). Compensation of minor errors between underestimated SW_d and SW_u ($\sim 2 \text{ W m}^{-2}$) provides a good agreement with observed SW_n (Fig. 5g and Table 5). Modelled surface albedo also compares well with measurements, with only a small positive bias (0.01; Fig. 5h). LW_n is underestimated by $\sim 9 \text{ W m}^{-2}$; this is mainly driven by a too low LW_d and a too large LW_u (Table 5). The turbulent fluxes are well captured although a significant positive bias in SHF persists ($\sim 5 \text{ W m}^{-2}$), especially in winter when LW_d is underestimated. As biases in SHF and LW_d are almost equal, modelled melt matches well with observations despite a small negative bias ($\sim 0.2 \text{ W m}^{-2}$).

3.4 Model comparison along the K-transect

Tables 2-5 compare statistics of SEB components between RACMO2.3p2 and 2.3p1. Although differences are relatively small, the new model formulation shows general improvements. The increased cloud cover over the GrIS reduced the bias in SW_d and LW_d . Improvements in the representation of turbulent fluxes is partly attributed to the new topography prescribed in RACMO2.3p2 and the better resolved SW_d/LW_d , although significant biases remain at all stations.

At site S5 located in the low ablation zone (Table 2), smaller SW_d and lower ice albedo significantly reduce the SW_u bias in RACMO2.3p2, and enhanced LW_d decreases the negative bias in LW_u . As a result, melt increases substantially, reducing the negative bias compared to version 2.3p1. Note that SW_d remains overestimated in RACMO2.3p2. This is compensated by underestimated SHF, i.e. partly caused by underestimated LW_d , providing realistic surface melt. In the upper ablation zone, similar improvements are obtained at site S6 (Table 3). At site S6, all SEB components show smaller biases except for SW_u , as underestimated surface albedo increases the negative SW_u bias.

Above the equilibrium line, enhanced cloud cover also reduces the SW and LW biases at sites S9 and S10 (Tabs. 4 and 5). However, surface albedo overestimation in RACMO2.3p2 causes a small

355 increase in melt underestimation.

4 Results: regional SMB

In Section 3, we discussed the overall good ability of RACMO2.3p2 to reproduce the contemporary climate of the GrIS, which is essential for estimating realistic SMB patterns. Here we compare SMB from RACMO2.3p2 and RACMO2.3p1 over the GrIS. For further evaluation, we focus on three
360 regions where there are large differences in SMB between the two versions.

4.1 Changes in SMB patterns

Figure 6a shows SMB from RACMO2.3p2 for the overlapping model period 1958-2015. Differences with the previous version 2.3p1 are shown in Fig. 6b and the changes in individual SMB components are depicted in Fig. 7. Owing to the modifications in the cloud scheme, clouds are sustained to higher
365 elevations, enhancing precipitation further inland, while it decreases in low-lying regions. Changes are especially large in southeast Greenland where the decrease locally exceeds $300 \text{ mm w.e. yr}^{-1}$. Precipitation in the interior increases by up to $50 \text{ mm w.e. yr}^{-1}$ (Fig. 7a). This pattern of change is clearly recognisable in the SMB difference (Fig. 6b). In addition, the shallower saltation layer in the revised drifting snow scheme is responsible for reduced sublimation ($\sim 50 \text{ mm w.e. yr}^{-1}$; Fig. 7b)
370 that reinforces the overall increase in SMB (Fig. 6b). Although drifting snow erosion changes locally, patterns are heterogeneous and the changes remain small when integrated over the GrIS (Fig. 7c). This process has only a limited contribution to SMB ($\sim 1 \text{ Gt yr}^{-1}$) resulting from drifting snow being transported away from the ice sheet towards the ice-free tundra and ocean.

In the percolation zone, the decrease in runoff (Fig. 7d) is governed by reduced surface melt
375 (Fig. 7e), mostly resulting from the smaller grain size of refrozen snow and the lower soot concentration in snow that have increased surface albedo (not shown), further increasing SMB (Fig. 6b). In west and northeast Greenland, this decrease in runoff even exceeds that of melt by 50 to 100 mm w.e. yr^{-1} , a result of combined enhanced precipitation and reduced summer melt (delaying the disappearance of the seasonal snow cover), that increased the snow refreezing capacity (Fig. 7f). At
380 higher elevations, the decrease in refreezing is exclusively driven by melt reduction (Figs. 7e and f), while at the extreme margins of the GrIS, the lower ice albedo used in RACMO2.3p2 (Fig. 2c) locally increases runoff (Fig. 7d), in turn decreasing SMB (Fig. 6b).

4.2 Northeast Greenland

For northeast Greenland's two main glaciers, Zachariae Isstrøm and Nioghalvfjærdsbrae (79N glacier;
385 yellow line in Fig. 6a), solid ice discharge (D) estimates are available for the period 1975-2015 (Mouginot et al., 2015). Assuming that this glacier catchment draining $\sim 12\%$ of the GrIS area remained in approximate balance until ~ 2000 (Mouginot et al., 2015), i.e. $D \approx \text{SMB}$, measurements

of D at the grounding line of these marine-terminating glaciers can be used to evaluate modelled SMB.

In these two catchments, model updates significantly improve the representation of SMB, that was substantially underestimated in the previous version. Figure 8a compares ice discharge (black dots) with modelled SMB (RACMO2.3p2 as blue dots and 2.3p1 in red) integrated over the two glacier basins for 1958-2015. In a balanced system, i.e. before discharge accelerated in 2001, SMB equals ice discharge. Averaged over 1975-2001, modelled SMB in RACMO2.3p2 (20.5 Gt yr^{-1}) is similar to the estimated glacial discharge of 21.2 Gt yr^{-1} , significantly improving upon version 2.3p1 (15.8 Gt yr^{-1}). The negative bias in RACMO2.3p2 (0.7 Gt yr^{-1} ; dashed blue line) is reduced by almost a factor of eight relative to the previous version (5.4 Gt yr^{-1}) and SMB now equals discharge within the uncertainty. However, it is important to note that, while good agreement is obtained between averaged SMB and D before 2001, suggesting a glacier catchment in approximate balance as in Mouginot et al. (2015), this does not necessarily confirm that spatial and temporal variability of northeast Greenland SMB is accurately resolved by the model. Averaged over 2001-2015, basin mass loss accelerated due to enhanced surface runoff, decreasing SMB by 4.2 Gt yr^{-1} , and increased ice discharge (2.8 Gt yr^{-1}).

Figures 8b and c show mean SMB for 1958-2015 as modelled by RACMO2.3p2 and 2.3p1, respectively. In the percolation zone, the difference between the two model versions primarily results from the smaller refrozen snow grain size that reduces melt and runoff through increased surface albedo in RACMO2.3p2. To a smaller extent, reduced soot concentration delays the onset of melt in summer. In the ablation zone, snow cover persists longer before bare ice is exposed in late summer, in turn reducing runoff (Fig. 7d). Superimposed on this, precipitation has increased over the whole glacier basin (Fig. 7a), allowing for enhanced refreezing in snow (Fig. 7f) hence increasing SMB by 4.7 Gt yr^{-1} in RACMO2.3p2 (Fig. 6b). Note the large inter-annual variability in modelled SMB showing a maximum and minimum value of approximately 30 Gt yr^{-1} and 8.5 Gt yr^{-1} in RACMO2.3p2 vs. 25 Gt yr^{-1} and 0 Gt yr^{-1} in the previous version, stressing the importance of accurately modelling individual SMB components. In this dry region, underestimation of snowfall accumulation in RACMO2.3p1 initiated a pronounced feedback decreasing SMB: active drifting snow processes erode the shallow snow cover, exposing bare ice prematurely and moving the equilibrium line too far inland (Figs. 8b and c).

4.3 K-transect

The K-transect in southwest Greenland consists of eight stake sites where SMB is measured annually (yellow dots in Fig. 6a) (Van de Wal et al., 2012; Machguth et al., 2016). Figure 9a compares modelled (RACMO2.3p2 as blue dots and RACMO2.3p1 in red), with observed SMB (black dots) along the transect, averaged for the period 1991-2015. Using mean annual SMB at each station, the updated model shows a decreased bias from 606 mm w.e. in RACMO2.3p1 to 424 mm w.e. in

version 2.3p2, and reduced RMSE from -133 mm w.e. to -54 mm w.e., and an increased R^2 from

425 0.92 to 0.97. In the low ablation zone (< 600 m a.s.l.), the lower ice albedo increases runoff in summer, locally reducing SMB. Decreased runoff in the upper ablation zone, i.e. between 600 and 1500 m a.s.l., increases SMB, improving the agreement at all sites except SHR. A negative bias in SMB remains at site S6 where ice albedo in summer (0.45 in July) is underestimated by up to 0.1 (Fig. 5d). Above the equilibrium line (> 1500 m a.s.l.), in situ stake SMB measurements systemat-
430 ically underestimate climatic SMB, as they do not or only partly account for internal accumulation, i.e. refreezing in the firn. For comparison at S10, we therefore use the difference between modelled total precipitation and melt instead of SMB, decreasing the bias by 260 mm w.e. yr^{-1} to -40 mm w.e. yr^{-1} and the RMSE by 200 mm w.e. yr^{-1} to 210 mm w.e. yr^{-1} . Measured and modelled SMB-to-elevation gradients are estimated using a linear regression: 3.21 mm w.e. m^{-1} from observations,
435 2.62 mm w.e. m^{-1} in RACMO2.3p1, and 3.16 mm w.e. m^{-1} in RACMO2.3p2, indicating a notable improvement in model performance along the K-transect.

Figures 9b and c show time series of measured (dashed lines) and modelled SMB (continuous lines; RACMO2.3p2) at each site along the K-transect for the period 1991-2016. The model realistically captures inter-annual variability in the SMB signal although substantial biases remain at
440 stations SHR and S6 (Table 6).

4.4 Southeast Greenland

Southeast Greenland experiences topographically forced precipitation maxima in winter, followed by high melt rates in summer, allowing for the formation of perennial firn aquifers (Forster et al., 2014; Koenig et al., 2014). In April 2014, an AWS was installed in the aquifer zone of the southeast
445 GrIS (yellow dot in Fig. 6a). In August 2015, the AWS was relocated from 1563 m a.s.l (66.18°N and 39.04°W) to 1663 m a.s.l (66.36°N and 39.31°W). Figure 10 shows time series of snow albedo and cumulative snow melt energy (expressed in mm w.e.) modelled by RACMO2.3p2 (blue lines) and RACMO2.3p1 (red lines), and calculated from the AWS data (gray lines) for the summer of 2014. The comparison is limited to 2014 because of a 3 month data gap in summer 2015.

450 As melt wets the snow in summer, surface albedo gradually decreases from values typical for dry fresh snow (0.85) to wet old snow (~ 0.75) in late summer, before sharply increasing again when a new fresh snow cover is deposited (gray line in Fig. 10a). In the previous model version, surface albedo could drop to values as low as ~ 0.66 in summer (JJA), e.g. days 152 to 243, underestimating albedo by 0.04 on average. The bias is reduced to 0.01 in RACMO2.3p2 as combined lower soot
455 concentration and decreased grain size of refrozen snow increase the surface albedo. The remaining small negative bias is mostly ascribable to a too rapid snow metamorphism from fresh to old snow that leads to a premature drop in surface albedo, e.g. days 140 to 160. Sporadic fresh snow deposition over older snow, characterised by sharp peaks in surface albedo during summer, are well timed by the model. Consequently, the cumulative melt obtained at the end of summer (702 mm w.e.; blue

line in Fig. 10b) is reduced by ~ 100 mm w.e. relative to RACMO2.3p1 (red line), a significant improvement when compared to observations (639 mm w.e.; gray line).

5 Results: SMB of the contiguous ice sheet

5.1 Modelled SMB at 11 km

In Figure 11, we evaluate modelled SMB in RACMO2.3p2 using 182 measurements collected in the GrIS accumulation zone (white dots in Fig. 1) and 1073 stake observations from 213 sites located in the ablation zone (yellow dots in Fig. 1). The increased precipitation in the GrIS interior reduces the negative bias in the 11 km product (blue dots in Fig. 11a) compared to the previous model version (red dots in Fig. 11a). For the full data set, a significant bias of -22 mm w.e. yr^{-1} and RMSE of 72 mm w.e. yr^{-1} remain in RACMO2.3p2. Sites experiencing the highest precipitation rates on the steep slopes of southeast Greenland (> 0.5 m w.e. yr^{-1}) primarily contribute to this bias. If only values < 0.5 m w.e. yr^{-1} are considered (156 measurements), the bias and RMSE decrease from -26 mm w.e. yr^{-1} and 52 mm w.e. yr^{-1} in RACMO2.3p1 to only -7 mm w.e. yr^{-1} and 49 mm w.e. yr^{-1} in RACMO2.3p2. In the ablation zone (Fig. 11b), the updated model performs as well as the previous version, i.e. bias of 1.20 m w.e. yr^{-1} and RMSE of 0.47 m w.e. yr^{-1} (Noël et al., 2016), although SMB remains overestimated in the lower sectors, caused by inaccurately resolved steep slopes, low ice albedo and relatively large turbulent fluxes at the GrIS margins, which require further downscaling (see Section 5.2).

Integrated over the GrIS, modelled SMB has increased by 66 Gt yr^{-1} (415 Gt yr^{-1} ; $+19\%$) compared to the previous version. This difference is dominated by a significant increase in SMB in the percolation zone of the GrIS, driven by reduced meltwater runoff (61 Gt yr^{-1} or -22%) and reduced sublimation (10 Gt yr^{-1} or -24%), while precipitation decreased by less than 1% (5 Gt yr^{-1}); the latter can be explained by the smaller GrIS area ($\sim 10,000$ km 2 or 0.6%) in the new ice mask. We deem these changes in the 11 km fields to be realistic. For the poorly resolved marginal areas, the SMB product requires further statistical downscaling to reproduce the high melt rates in these rugged regions at the ice sheet margins. At 11 km resolution, runoff is locally underestimated by up to 6 m w.e. yr^{-1} , e.g. station QAS.L in southern Greenland (orange stars in Fig. 11b).

5.2 Downscaled SMB to 1 km

To solve these issues at the margins, we apply the downscaling technique described in Noël et al. (2016), which includes elevation and ice albedo corrections. As a result, modelled runoff increases by 82 Gt yr^{-1} ($\sim 37\%$) to 305 Gt yr^{-1} for the period 1958-2015, compared to the 11 km product, and the SMB bias and RMSE in the GrIS ablation zone are reduced by 480 and 460 mm w.e. yr^{-1} , respectively. The error at QAS.L is reduced to ~ 2 m w.e. yr^{-1} (orange stars in Fig. 11c), i.e. bias and RMSE of 2.21 m w.e. yr^{-1} and 2.35 m w.e. yr^{-1} , respectively. A major improvement upon Noël

et al. (2016) is that no additional precipitation correction is required here as the remaining negative
495 bias in the GrIS interior has been almost eliminated in RACMO2.3p2 (Fig. 11a). At 1 km resolution,
precipitation contributes 693 Gt yr^{-1} to GrIS SMB. Relative to the 11 km product, GrIS-integrated
SMB at 1 km decreases by 59 Gt yr^{-1} (-14%) to 356 Gt yr^{-1} , in line with our previous estimate
of 338 Gt yr^{-1} (+5%) (Noël et al., 2016). This confirms once more that an 11 km resolution is
insufficient to resolve runoff patterns over narrow ablation zones and small outlet glaciers, and that
500 further downscaling is essential to obtain realistic GrIS SMB.

6 Remaining limitations and challenges

6.1 Model resolution

Extensive model evaluation confirms that RACMO2.3p2 realistically reproduces the contemporary
climate and SMB of Greenland, although significant biases remain. However, while a 11 km grid
505 is sufficient to resolve large-scale inland SMB patterns, it does not well resolve irregular, low-lying
regions at the GrIS margins where runoff peaks. There, the main issue remains to accurately resolve
total runoff of meltwater from the narrow ablation zone and small outlet glaciers. This demonstrates
the need for higher resolution (statistically or dynamically) downscaled products, e.g. the 1 km
product as presented here, for regional mass balance studies.

510 An alternative approach is to carry out a dedicated Greenland simulation at higher spatial resolu-
tion, e.g. 5.5 km (Langen et al., 2017; Mottram et al., 2017). This increase in resolution does lead
to better resolved SMB gradients over marginal glaciers, without exceeding the physics constraints
of a hydrostatic model like RACMO2. Subsequently applying the statistical downscaling technique
to this 5.5 km product would likely result in further improvements.

6.2 Turbulent fluxes

Another model limitation stems from the turbulent fluxes scheme. While LHF remains generally
small and contributes little to the energy budget, accurate SHF is crucial to capturing extreme melt
events along the GrIS margins (Fausto et al., 2016), such as those that occurred in summer 2012
(Nghiem et al., 2012). However, SHF shows significant biases in RACMO2.3p2 in low-lying re-
520 gions at the GrIS margins. Improving the representation of the GrIS surface roughness and surface
elevation using higher spatial resolution could reduce these biases.

6.3 Surface albedo

Snow melt rate is highly sensitive to soot concentration in snow (Van Angelen et al., 2012). Although
assumed to be constant in time and space in RACMO2, Takeuchi et al. (2014) show a heterogeneous
525 distribution of impurities (soot, dust, microbiological material) over the GrIS, with a gradual in-
crease towards lower elevations due to a) the proximity of dust sources in the tundra region and, b)

downslope transport of previously deposited soot by meltwater runoff.

Over bare ice, the accumulation of cryoconite and the growth of algae play a major role in reducing surface albedo (Musilova et al., 2016; Stibal et al., 2017). Therefore, explicitly modelling
530 impurity concentration on ice, as described in Cook et al. (2017a,b), could substantially improve melt estimates. Future climate projections should include such a bio-darkening feedback (Tedesco et al., 2016).

7 Conclusions

We present a detailed evaluation of the regional climate model RACMO2.3p2 (1958-2016) over the
535 Greenland ice sheet (GrIS). The updated model generates more inland precipitation at the expense of marginal regions, reducing the dry bias in the GrIS interior. Impurity concentration in snow, i.e. soot, has been decreased by a factor of two, minimising the melt rate overestimation in the GrIS percolation zone. We demonstrate that the model successfully reproduces the contemporary climate of the GrIS compared to daily meteorological records and radiative energy flux measurements from
540 23 AWS sites. Apart from the ultimate margins, the model also accurately captures the seasonal cycle of radiative and turbulent heat fluxes as well as surface albedo along the K-transect in southwest Greenland. Compared to SMB observations, RACMO2.3p2 generally improves on the previous version, especially in the extensive GrIS interior. SMB improvements are also found along the K-transect as well as in northeast and southeast Greenland. This model version will be used for future
545 climate scenario projections at 11 km resolution. Nonetheless, since runoff from narrow glaciers in the GrIS margins remains poorly resolved at this resolution, it is necessary to further statistically downscale present-day and future SMB fields to higher spatial resolutions for use in regional mass balance studies.

8 Author contribution

550 B. N., W. J. B., J. M. W. and M. R. B. conceived this study, decided on the new model settings and performed the analysis and synthesis of the data sets. B. N. performed the model simulations and led the writing of the manuscript. J. T. M. L., E. M., P. K. M. and L. H. U. contributed to the development of the model. D. A., S. L., C. J. P. P. S. and R. S. W. W. processed and provided observational data sets. All authors contributed to discussions in writing this manuscript.

9 Data availability

RACMO2.3p2 data at 11 km (1958-2016), and a daily downscaled product at 1 km resolution are available from the authors without conditions.

Acknowledgements. B. Noël, W. J. van de Berg, J. M. van Wessem, R. S. W. van de Wal and M. R. van den Broeke acknowledge support from the Polar Programme of the Netherlands Organization for Scientific Research
560 (NWO/ALW) and the Netherlands Earth System Science Centre (NESSC), as well as the European Centre for Medium-range Weather Forecasts (ECMWF) for hosting simulations and providing computation time.

References

- A. P. Ahlstrøm, P. Gravesen, S. B. Andersen, D. van As, M. Citterio, R. S. Fausto, S. Nielsen, H. F. Jepsen, S. S. Kristensen, E. L. Christensen, L. Stenseng, R. Forsberg, S. Hanson, and D. Petersen. A new Programme for Monitoring the Mass Loss of the Greenland Ice Sheet. *Geologic survey of Denmark and Greenland bulletin*, 15:61 – 64, 2008. doi:www.geus.dk/publications/bull.
- R. C. Bales, J. R. McConnell, E. Mosley-Thompson, and B. Csatho. Accumulation over the Greenland ice sheet from historical and recent records. *Journal of Geophysical Research*, 106(D24):33813 – 33825, 2001. doi:10.1029/2001JD900153.
- R. C. Bales, Q. Guo, D. Shen, J. R. McConnell, G. Du, J. F. Burkhart, V. B. Spikes, E. Hanna, and J. Cappelen. Annual accumulation for Greenland updated using ice core data developed during 2000-2006 and analysis of daily coastal meteorological data. *Journal of Geophysical Research*, 114(D6):D06116, 2009. doi:10.1029/2008JD011208.
- J. L. Bamber, S. Ekholm, and W. B. Krabill. A new, high-resolution digital elevation model of Greenland fully validated with airborne laser altimeter data. *Journal of Geophysical Research*, 106:6733 – 6745, 2001. doi:10.1029/2000JB900365.
- J. E. Box. Greenland Ice Sheet Mass Balance Reconstruction. Part II: Surface Mass Balance (1840-2010). *Journal of Climate*, 26:6974 – 6989, 2013. doi:10.1175/JCLI-D-12-00518.1.
- D. H. Bromwich, A. B. Wilson, L.-S. Bai, G. W. K. Moore, and P. Bauer. A comparison of the regional Arctic System Reanalysis and the global ERA-Interim Reanalysis for the Arctic. *Quarterly Journal of the Royal Meteorological Society*, 142(695):644 – 658, 2015. doi:10.1002/qj.2527.
- K. A. Casey, C. M. Polashenski, J. Chen, and M. Tedesco. Impact of MODIS sensor calibration updates on Greenland Ice Sheet surface reflectance and albedo trends. *The Cryosphere*, 11:1781 – 1795, 2017. doi:10.5194/tc-11-1781-2017.
- J. G. Cogley, R. Hock, L. A. Rasmussen, A. A. Arendt, A. Bauder, R. J. Braithwaite, P. Jansson, G. Kaser, M. Möller, L. Nicholson, and M. Zemp. Glossary of glacier mass balance and related terms. Technical Report IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, UNESCO-IHP, Paris, 2011. Springer New York.
- J. M. Cook, A. J. Hodson, A. S. Gardner, M. Flanner, A. J. Tedstone, C. Williamson, T. D. Irvine-Fynn, R. Bryant J. Nilsson, and M. Tranter. Quantifying bioalbedo: a new physically based model and discussion of empirical methods for characterising biological influence on ice and snow albedo. *The Cryosphere*, 11: 2611 – 2632, 2017a. doi:https://doi.org/10.5194/tc-11-2611-2017.
- J. M. Cook, A. J. Hodson, A. J. Taggart, S. H. Mernild, and M. Tranter. A predictive model for the spectral "bioalbedo" of snow. *Journal Geophysical Research Earth Surface*, 122:434 – 454, 2017b. doi:10.1002/2016JF003932.
- R. I. Cullather, S. M. J. Nowicki, B. Zhao, and M. J. Suarez. Evaluation of the Surface Representation of the Greenland Ice Sheet in a General Circulation Model. *Journal of Climate*, 27:4835 – 4856, 2014. doi:10.1175/JCLI-D-13-00635.1.
- J. A. Curry and P.J. Webster. *Thermodynamics of Atmospheres and Oceans*. Academic Press, London, United Kingdom, 1999.
- D. P. Dee, S. M. Uppala, A. J. Simmons, P. Berrisford, P. Poli, S. Kobayashi, U. Andrae, M. A. Balmaseda,

- G. Balsamo, P. Bauer, P. Bechtold, A. C. M. Beljaars, L. van de Berg, J. Bidlot, N. Bormann, C. Delsol, R. Dragani, M. Fuentes, A. J. Geer, L. Haimberger, S. B. Healy, H. Hersbach, E. V. Hölm, L. Isaksen, P. Kållberg, M. Köhler, M. Matricardi, A. P. McNally, B. M. Monge-Sanz, J.-J. Morcrette, B.-K. Park, C. Peubey, P. de Rosnay, C. Tavalato, J.-N. Thépaut, and F. Vitart. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137:553 – 597, 2011. doi:10.1002/qj.828.
- S. J. Doherty, S. G. Warren, T. C. Grenfell, A. D. Clarke, , and R. E. Brandt. Light-absorbing impurities in Arctic snow. *Atmos. Chem. Phys.*, 10:11647 – 11680, 2010. doi:10.5194/acp-10-11647-2010.
- ECMWF-IFS. Part IV : PHYSICAL PROCESSES (CY33R1). *Technical Report*, 2008.
- J. Ettema, M. R. van den Broeke, E. van Meijgaard, and W. J. van de Berg. Climate of the Greenland ice sheet using a high-resolution climate model - Part2: Near-surface climate and energy balance. *The Cryosphere*, 4: 529 – 544, 2010a. doi:10.5194/tc-4-529-2010.
- J. Ettema, M. R. van den Broeke, E. van Meijgaard, W. J. van de Berg, J. E. Box, and K. Steffen. Climate of the Greenland ice sheet using a high-resolution climate model - Part 1: Evaluation. *The Cryosphere*, 4:511 – 527, 2010b. doi:10.5194/tc-4-511-2010.
- R. S. Fausto, D. van As, J. E. Box, W. Colgan, P. L. Langen, and R. H. Mottram. The implication of nonradiative energy fluxes dominating Greenland ice sheet exceptional ablation area surface melt in 2012. *Geophysical Research Letters*, 43:1944 – 8007, 2016. doi:10.1002/2016GL067720.
- X. Fettweis, B. Franco, M. Tedesco, J. H. van Angelen, J. T. M. Lenaerts, M. R. van den Broeke, and H. Gallée. Estimating the Greenland ice sheet surface mass balance contribution to future sea level rise using the regional atmospheric climate model MAR. *The Cryosphere*, 7:469 – 489, 2013. doi:10.5194/tc-7-469-2013.
- X. Fettweis, J. E. Box, C. Agosta, C. Amory, C. Kittel, C. Lang, D. van As, H. Machguth, and H. Gallée. Reconstructions of the 1900-2015 Greenland ice sheet surface mass balance using the regional climate MAR model. *The Cryosphere*, 11:1015 – 1033, 2017. doi:10.5194/tc-11-1015-2017.
- M. Fiorino. A multi-decadal daily sea surface temperature and sea ice concentration data set for the era-40 reanalysis. In *ERA-40 Project Report Series*, No. 12, page 16 pp. European Centre for Medium Range Weather Forecasts (ECMWF), 2004.
- R. R. Forster, J. E. Box, M. R. van den Broeke, C. Miège, E. W. Burgess, J. H. van Angelen, J. T. M. Lenaerts, L. S. Koenig, J. Paden, C. Lewis, S. P. Gogineni, C. Leuschen, and J. R. McConnell. Extensive liquid meltwater storage in firn within the Greenland ice sheet. *Nature Geoscience*, 7(2):95 – 98, 2014. doi:10.1038/ngeo2043.
- E. Hanna, P. Huybrechts, J. Cappelen, K. Steffen, R. C. Bales, E. Burgess, J. R. McConnell, J. P. Steffensen, M. Van den Broeke, L. Wake, G. Bigg, M. Griffiths, and D. Savas. Greenland Ice Sheet surface mass balance 1870 to 2010 based on Twentieth Century Reanalysis, and links with global climate forcing. *Journal of Geophysical Research*, 116:D24121, 2011. doi:10.1029/2011JD016387.
- I. M. Howat, A. Negrete, and B. E. Smith. The Greenland Ice Mapping Project (GIMP) land classification and surface elevation data sets. *The Cryosphere*, 8:1509 – 1518, 2014. doi:10.5194/tc-8-1509-2014.
- S. Kaasalainen, M. Kaasalainen, T. Mielonen, J. Suomalainen, J. I. Peltoniemi, and J. Näränen. Optical properties of snow in backscatter. *Journal of Glaciology*, 52(179):574 – 584, 2006.
- L. S. Koenig, C. Miège, R. R. Forster, and L. Brucker. Initial in situ measurements of perennial

meltwater storage in the Greenland firn aquifer. *Geophysical Research Letters*, 41:81 – 85, 2014. doi:10.1002/2013GL058083.

- 645 L. S. Koenig, A. Ivanoff, P. M. Alexander, J. A. MacGregor, X. Fettweis, B. Panzer, J. D. Paden, R. R. Forster, I. Das, J. R. McConnell, M. Tedesco, C. Leuschen, and P. Gogineni. Annual Greenland accumulation rates (2009-2012) from airborne snow radar. *The Cryosphere*, 10:1739 – 1752, 2016. doi:10.5194/tc-10-1739-2016.
- 650 P. Kuipers Munneke, M. R. van den Broeke, J. T. M. Lenaerts, M. G. Flanner, A. S. Gardner, and W. J. van de Berg. A new albedo parameterization for use in climate models over the Antarctic ice sheet. *Journal of Geophysical Research*, 116:D05114, 2011. doi:10.1029/2010JD015113.
- P. Kuipers Munneke, C. J. P. P. Smeets, C. H. Reijmer, J. Oerlemans, R. S. W. van de Wal, and M. R. van den Broeke. The K-transect in West-Greenland: long-term (2003-2016) surface energy balance observations. *Arctic, Antarctic and Alpine Research*, 2017. submitted.
- 655 P. L. Langen, R. S. Fausto, B. R. M. Vandecrux, R. H. Mottram, and J. E. Box. Liquid Water Flow and Retention on the Greenland Ice Sheet in the Regional Climate Model HIRHAM5: Local and Large-Scale Impacts. *Frontiers in Earth Science*, 4(110):18 pp., 2017. doi:10.3389/feart.2016.00110.
- J. T. M. Lenaerts, M. R. van den Broeke, J. H. Angelen, E. van Meijgaard, and S. J. Déry. Drifting snow climate of the Greenland ice sheet: a study with a regional climate model. *The Cryosphere*, 6:891 – 899, 2012a. doi:10.5194/tc-6-891-2012.
- 660 J. T. M. Lenaerts, M. R. van den Broeke, S. J. Déry, E. van Meijgaard, W. J. van de Berg, Stephen P. Palm, and J. Sanz Rodrigo. Modeling drifting snow in antarctica with a regional climate model: 1. methods and model evaluation. *Journal of Geophysical Research - Atmospheres*, 117(D5):D05108, 2012b. doi:10.1029/2011JD016145.
- 665 J. T. M. Lenaerts, J. H. van Angelen, M. R. van den Broeke, A. S. Gardner, B. Wouters, and E. van Meijgaard. Irreversible mass loss of Canadian Arctic Archipelago glaciers. *Geophysical Research Letters*, 40(5):1 – 5, 2013. doi:10.1002/grl.50214.
- J. T. M. Lenaerts, M. R. van den Broeke, J. M. van Wessem, and W. J. van de Berg. Extreme Precipitation and Climate Gradients in Patagonia Revealed by High-Resolution Regional Atmospheric Climate Modeling. *American Meteorological Society*, 27:4607 – 4621, 2014. doi:10.1175/JCLI-D-13-00579.1.
- 670 G. Lewis, E. Osterberg, R. Hawley, B. Whitmore, H. P. Marshall, and J. Box. Regional Greenland accumulation variability from Operation IceBridge airborne accumulation radar. *The Cryosphere*, 11:773 – 788, 2017. doi:10.5194/tc-11-773-2017.
- S. R. M. Ligtenberg, M. M. Helsen, and M. R. van den Broeke. An improved semi-empirical model for the densification of Antarctic firn. *The Cryosphere*, 5:809 – 819, 2011. doi:10.5194/tc-5-809-2011.
- 675 Y.-L. Lin, R. D. Farley, and H. D. Orville. Bulk Parameterization of the Snow Field in a Cloud Model. *Journal of Applied Meteorology*, 22:1065 – 1092, 1983. doi:10.1175/1520-0450(1983)022<1065:BPOTSF>2.0.CO;2.
- P. Lucas-Picher, M. Wulff-Nielsen, J. H. Christensen, Gudfinna Adalgeirsdóttir, and Ruth M. and S. B. Simonson. Very high resolution regional climate model simulations over Greenland: Identifying added value. *Journal of Geophysical Research*, 117:D02108, 2012. doi:10.1029/2011JD016267.
- 680 H. Machguth, H. Thomsen, A. Weidick, A. P. Ahlstrøm, J. Abermann, M. L. Andersen, S. Andersen, A. A. Bjørk, J. E. Box, R. J. Braithwaite, C. E. Bøggild, M. Citterio, P. Clement, W. Colgan, R. S. Fausto, K. G. S.

- Gubler, B. Hasholt, B. Hynek, N. Knudsen, S. Larsen, S. Mernild, J. Oerlemans, H. Oerter, O. Olesen, C. Smeets, K. Steffen, M. Stober, S. Sugiyama, D. van As, M. van den Broeke, and R. S. van de Wal. Greenland surface mass balance observations from the ice sheet ablation area and local glaciers. *Journal of Glaciology*, pages 1 – 27, 2016. doi:10.1017/jog.2016.75.
- 685 S. H. Mernild, G. E. Liston, C. A. Hiemstra, and J. H. Christensen. Greenland Ice Sheet Surface Mass-Balance Modeling in a 131-Yr Perspective, 1950-2080. *American Meteorological Society*, 11:3 – 22, 2010. doi:10.1175/2009JHM1140.1.
- 690 S. H. Mernild, G. E. Liston, C. A. Hiemstra, J. H. Christensen, M. Stendel, and B. Hasholt. Surface Mass Balance and Runoff Modeling Using HIRHAM4 RCM at Kangerlussuaq (Søndre Strømfjord), West Greenland, 1950-2080. *American Meteorological Society*, 24:609 – 623, 2011. doi:10.1175/2010JCLI3560.1.
- R. Mottram, F. Boberg, P. Langen, S. Yang, C. Rodehacke, J. H. Christensen, and M. S. Madsen. Surface Mass balance of the Greenland ice Sheet in the Regional Climate Model HIRHAM5: Present State and Future Prospects. *Low Temperature Science*, 75(105):105 – 115, 2017. doi:10.14943/lowtemsci.75.105.
- 695 J. Mouginot, E. Rignot, B. Scheuchl, I. Fenty, A. Khazendar, M. Morlighem, A. Buzzi, and J. Paden. Fast retreat of Zachariae Isstrøm, northeast Greenland. *Science*, 350(6266):1357 – 1361, 2015. doi:10.1126/science.aac7111.
- M. Musilova, M. Tranter, J. L. Bamber, N. Takeuchi, and A. M. Anesio. Experimental evidence that microbial activity lowers the albedo of glaciers. *Geochemical Perspectives Letters*, 2:106 – 116, 2016. doi:10.7185/geochemlet.1611.
- 700 S. V. Nghiem, D. K. Hall, T. L. Mote, M. Tedesco, M. R. Albert, K. Keegan, C. A. Shuman, N. E. DiGirolamo, and G. Neumann. The extreme melt across the Greenland ice sheet in 2012. *Geophysical Research Letters*, 39(20):L20502, 2012. doi:10.1029/2012GL053611.
- 705 B. Noël, W. J. van de Berg, E. van Meijgaard, P. Kuipers Munneke, R. S. W. van de Wal, and M.R. van den Broeke. Evaluation of the updated regional climate model RACMO2.3: summer snowfall impact on the Greenland Ice Sheet. *The Cryosphere*, 9:1831 – 1844, 2015. doi:10.5194/tc-9-1831-2015.
- B. Noël, W. J. van de Berg, H. Machguth, S. Lhermitte, I. Howat, X. Fettweis, and M. R. van den Broeke. A daily, 1 km resolution data set of downscaled Greenland ice sheet surface mass balance (1958-2015). *The Cryosphere*, 10(5):2361 – 2377, 2016. doi:10.5194/tc-10-2361-2016.
- 710 B. Noël, W. J. van de Berg, S. Lhermitte, B. Wouters, H. Machguth, I. Howat, M. Citterio, G. Moholdt, J. T. M. Lenarets, and M. R. van den Broeke. A tipping point in refreezing accelerates mass loss of Greenland’s glaciers and ice caps. *Nature Communications*, 8:14730, 2017a. doi:10.1038/ncomms14730.
- B. Noël, W. J. van de Berg, S. Lhermitte, B. Wouters, N. Schaffer, and M. R. van den Broeke. Six decades of glacial mass loss in the Canadian Arctic Archipelago. *Journal of Geophysical Research Earth Surface*, 2017b. in review.
- 715 T. B. Overly, R. L. Hawley, V. Helm, E. M. Morris, and R. N. Chaudhary. Greenland annual accumulation along the EGIG line, 1959-2004, from ASIRAS airborne radar and neutron-probe density measurements. *The Cryosphere*, 10:1679 – 1694, 2016. doi:10.5194/tc-10-1679-2016.
- C. M. Polashenski, J. E. Dibb, M. G. Flanner, J. Y. Chen, Z. R. Courville, A. M. Lai, J. J. Schauer, M. M. Shafer, and M. Bergin. Neither dust nor black carbon causing apparent albedo decline in Greenland’s dry snow zone: Implications for MODIS C5 surface reflectance. *Geophysical Research Letters*, 42(21):9319 –
- 720

9327, 2015. doi:10.1002/2015GL065912.

- J. G. L. Rae, G. Aðalgeirsdóttir, T. L. Edwards, X. Fettweis, J. M. Gregory, H. T. Hewitt, J. A. Lowe, P. Lucas-Picher, R. H. Mottram, A. J. Payne, J. K. Ridley, S. R. Shannon, W. J. van de Berg, R. S. W. van de Wal, and M. R. van den Broeke. Greenland ice sheet surface mass balance: evaluating simulations and making projections with regional climate models. *The Cryosphere*, 6:1275 – 1294, 2012. doi:10.5194/tc-6-1275-2012.
- J. C. Ryan, A. Hubbard, T. D. Irvine-Fynn, S. H. Doyle, J. M. Cook, M. Stibal, and J. E. Box. How robust are in situ observations for validating satellite-derived albedo over the dark zone of the Greenland Ice Sheet? *Geophysical Research Letters*, 44(12):6218 – 6225, 2017. doi:10.1002/2017GL073661.
- C. J. P. P. Smeets and M. R. van den Broeke. Temporal and Spatial Variations of the Aerodynamic Roughness Length in the Ablation Zone of the Greenland Ice Sheet. *Boundary Layer Meteorology*, 128:315 – 338, 2008. doi:10.1007/s10546-008-9291-0.
- C. J. P. P. Smeets, P. Kuipers Munneke, D. van As, M. R. van den Broeke, W. Boot, J. Oerlemans, H. Snellen, C. H. Reijmer, and R. S. W. van de Wal. The K-transect in west Greenland: twenty-three years of weather station data. *Arctic, Antarctic and Alpine Research*, 2017. in press.
- J. D. Stark, Exeter Met Office, C. J. Donlon, M. J. Martin, and M. E. McCulloch. OSTIA: An operational, high resolution, real time, global sea surface temperature analysis system. *OCEANS 2007 - Europe*, pages 1 – 4, 2007. doi:10.1109/OCEANSE.2007.4302251. Conference Publications.
- M. Stibal, J. E. Box, K. A. Cameron, P. L. Langen, M. L. Yallop, R. H. Mottram, A. L. Khan, N. P. Molotch, N. A. M. Christmas, F. C. Quaglia, D. Remias, C. J. P. P. Smeets, M. R. van den Broeke, J. C. Ryan, A. Hubbard, M. Tranter, D. van As, and A. P. Ahlstrøm. Algae Drive Enhanced Darkening of Bare Ice on the Greenland Ice Sheet. *Geophysical Research Letters*, 44:9 pp., 2017. doi:10.1002/2017GL075958.
- N. Takeuchi, N. Nagatsuka, J. Uetake, and R. Shimada. Spatial variations in impurities (cryoconite) on glaciers in northwest Greenland. *Bulletin of Glaciological Research*, 32:85 – 94, 2014. doi:10.5331/bgr.32.85.
- M. Tedesco, S. Doherty, X. Fettweis, P. Alexander, J. Jeyaratnam, and J. Stroeve. The darkening of the Greenland ice sheet: trends, drivers, and projections (1981-2100). *The Cryosphere*, 10:477 – 496, 2016. doi:10.5194/tc-10-477-2016.
- P. Undèn, L. Rontu, H. Järvinen, P. Lynch, J. Calvo, G. Cats, J. Cuxart, K. Eerola, C. Fortelius, J. A. Garcia-Moya, C. Jones, G. Lenderlink, A. McDonald, R. Mcgrath, B. Navascues, N. W. Nielsen, V. Degaard, E. Rodriguez, M. Rummukainen, K. Sattler, B. H. Sass, H. Savijarvi, B. W. Schreur, R. Sigg, and H. The. HIRLAM-5. *Scientific Documentation*, 2002. Technical Report.
- S. M. Uppala, P. W. Kållberg, A. J. Simmons, U. Andrae, V. Da Costa Bechtold, M. Fiorino, J. K. Gibson, J. Haseler, A. Hernandez, G. A. Kelly, X. Li, K. Onogi, S. Saarinen, N. Sokka, R. P. Allan, E. Andersson, K. Arpe, M. A. Balmaseda, A. C. M. Beljaars, L. Van De Berg, J. Bidlot, N. Bormann, S. Caires, F. Chevallier, A. Dethof, M. Dragosavac, M. Fisher, M. Fuentes, S. Hagemann, E. Hölm, B. J. Hoskins, L. Isaksen, P. A. E. M. Janssen, R. Jenne, A. P. McNally, J-F. Mahfouf, J-J. Morcrette, N. A. Rayner, R. W. Saunders, P. Simon, A. Ster, K. E. Trenberth, A. Untch, D. Vasiljevic, P. Viterbo, and J. Woollen. The ERA-40 re-analysis. *Quarterly Journal of the Royal Meteorological Society*, 131:2961 – 3012, 2005.
- J. H. Van Angelen, J. T. M. Lenaerts, S. Lhermitte, X. Fettweis, P. Kuipers Munneke, M. R. van den Broeke, E. van Meijgaard, and C. J. P. P. Smeets. Sensitivity of Greenland Ice Sheet surface mass balance to surface

albedo parameterization: a study with a regional climate model. *The Cryosphere*, 6:1175 – 1186, 2012. doi:10.5194/tc-6-1175-2012.

765 J. H. Van Angelen, J. T. M. Lenaerts, M. R. van den Broeke, X. Fettweis, and E. van Meijgaard. Rapid loss of
firn pore space accelerates 21st century greenland mass loss. *Geophysical Research Letters*, 40:2109 – 2113,
2013a. doi:10.1002/grl.50490.

J. H. Van Angelen, M. R. van den Broeke, B. Wouters, and J. T. M. Lenaerts. Contemporary (1969-2012)
evolution of the climate and surface mass balance of the Greenland ice sheet. *Surveys in Geophysics*, 35(5):
1155 – 1174, 2013b. doi:10.1007/s10712-013-9261-z.

770 D. Van As, R. S. Fausto, A. P. Ahlstrøm, S. B. Andersen, M. L. Andersen, M. Citterio, K. Edelvang, P. Gravesen,
H. Machguth, F. M. Nick, S. Nielsen, and A. Weidick. Temperature and ablation records from the Programme
for Monitoring of the Greenland Ice Sheet (PROMICE). *Geological Survey of Denmark and Greenland
Bulletin*, 23:73 – 76, 2011. URL www.geus.dk/publications/bull.

775 W. J. Van de Berg and B. Medley. Brief Communication: Upper-air relaxation in RACMO2 significantly
improves modelled interannual surface mass balance variability in Antarctica. *The Cryosphere*, 10:459 –
463, 2016. doi:<https://doi.org/10.5194/tc-10-459-2016>.

R. S. W. Van de Wal, W. Boot, C. J. P. P. Smeets, H. Snellen, M. R. van den Broeke, and J. Oerlemans. Twenty-
one years of mass balance observations along the K-transect, West Greenland. *Earth System Science Data*,
4:31 – 35, 2012. doi:10.5194/essdd-5-351-2012.

780 E. Van Meijgaard, L. H. van Ulf, W. J. van de Berg, F. C. Bosveld, B. van den Hurk, G. Lenderink, and A. P.
Siebesma. *Technical Report 302: The KNMI regional atmospheric climate model RACMO version 2.1*. Royal
Netherlands Meteorological Institute, De Bilt, 2008.

K. Van Tricht, S. Lhermitte, J. T. M. Lenaerts, I. V. Gorodetskaya, T. S. L'Ecuyer, B. Noël, M. R. van den
Broeke, D. D. Turner, and N. P. M. van Lipzig. Clouds enhance Greenland ice sheet meltwater runoff.
785 *Nature communications*, 7(10266), 2016. doi:10.1038/ncomms10266.

J. M. Van Wessem, C. H. Reijmer, J. T. M. Lenaerts, W. J. van de Berg, M. R. van den Broeke, and E. van
Meijgaard. Updated cloud physics in a regional atmospheric climate model improves the modelled surface
energy balance of Antarctica. *The Cryosphere*, 8:125 – 135, 2014a. doi:10.5194/tc-8-125-2014.

J. M. Van Wessem, C. H. Reijmer, M. Morlighem, J. Mouginot, E. Rignot, B. Medley, I. Joughin, B. Wouters,
790 M. A. Depoorter, J. L. Bamber, J. T. M. Lenaerts, W. J. van de Berg, M. R. van den Broeke, and E. van
Meijgaard. Improved representation of East Antarctic surface mass balance in a regional atmospheric climate
model. *Journal of Glaciology*, 60(222):761 – 770, 2014b. doi:10.3189/2014JoG14J051.

J. M. Van Wessem, W. J. van de Berg, B. P. Y. Noël, E. van Meijgaard, G. Birnbaum, C. L. Jakobs, K. Krüger,
J. T. M. Lenaerts, S. Lhermitte, S. R. M. Ligtenberg, B. Medley, C. H. Reijmer, K. van Tricht, L. D. Trusel,
795 L. H. van Ulf, B. Wouters, J. Wuite, and M. R. van den Broeke. Modelling the climate and surface mass
balance of polar ice sheets using RACMO2, Part 2: Antarctica (1979-2016). *The Cryosphere Discussions*,
2017. doi:<https://doi.org/10.5194/tc-2017-202>. in review.

C. L. Vernon, J. L. Bamber, J. E. Box, M. R. van den Broeke, X. Fettweis, E. Hanna, and P. Huybrechts.
Surface mass balance model intercomparison for the Greenland ice sheet. *The Cryosphere*, 7:599 – 614,
800 2013. doi:10.5194/tc-7-599-2013.

M. Vizcaíno, W. H. Lipscomb, W. J. Sacks, J. H. van Angelen, B. Wouters, and M. R. van den Broeke. Green-

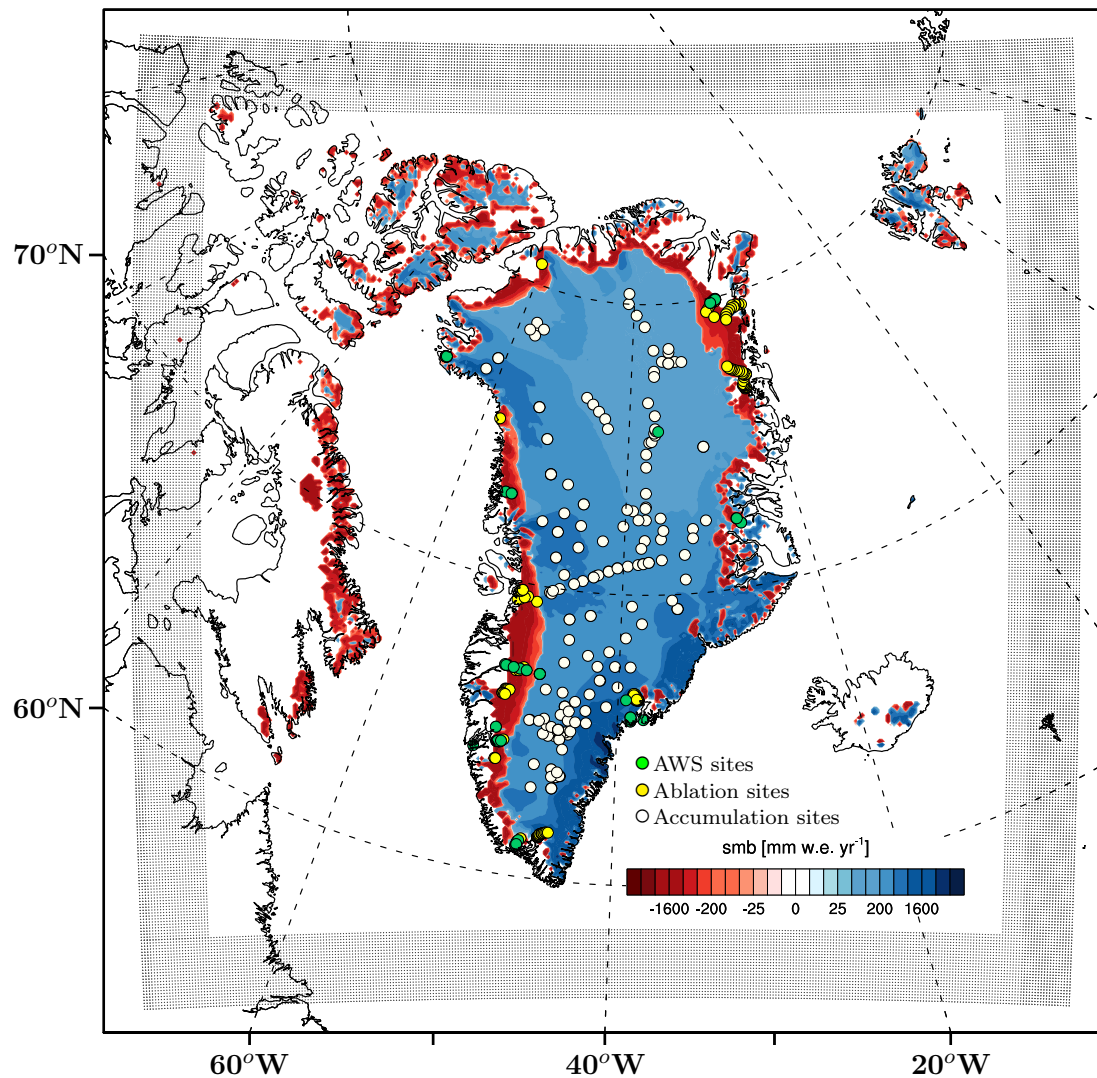


Fig. 1. SMB (mm w.e. yr⁻¹) modelled by RACMO2.3p2 at 11 km resolution for 2016. Black dots delineate the relaxation zone (24 grid cells) where the model is forced by ERA re-analyses. Ablation sites (213) are displayed as yellow dots, accumulation sites (182) as white dots, and AWS locations (23) are represented in green.

land Surface Mass Balance as Simulated by the Community Earth System Model. Part I: Model Evaluation and 1850-2005 Results. *Journal of Climate*, 26:7793 – 7812, 2013. doi:10.1175/JCLI-D-12-00615.1.

D. J. Wilton, A. Jowett, E. Hanna, G. R. Bigg, M. R. van den Broeke, X. Fettweis, and P. Huybrechts. High resolution (1 km) positive degree-day modelling of Greenland ice sheet surface mass balance, 1870-2012 using reanalysis data. *Journal of Glaciology*, 63(237):176 – 193, 2016. doi:10.1017/jog.2016.133.

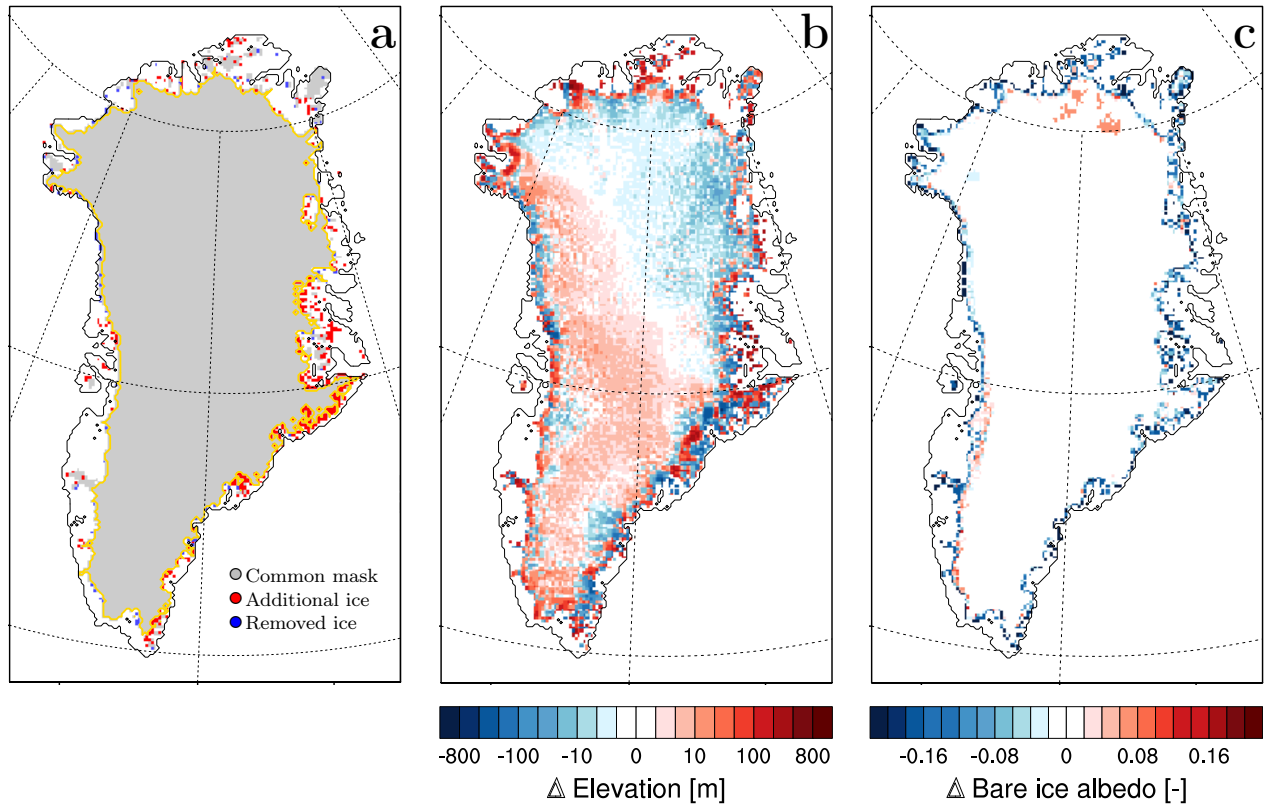


Fig. 2. Difference in a) ice mask b) surface elevation and c) bare ice albedo between RACMO2.3p2 and RACMO2.3p1. In Fig. 2a, the common ice mask for both model versions is displayed in grey, the ice sheet area is outlined in yellow; additional and removed ice-covered cells in RACMO2.3p2 are shown in red and blue, respectively.

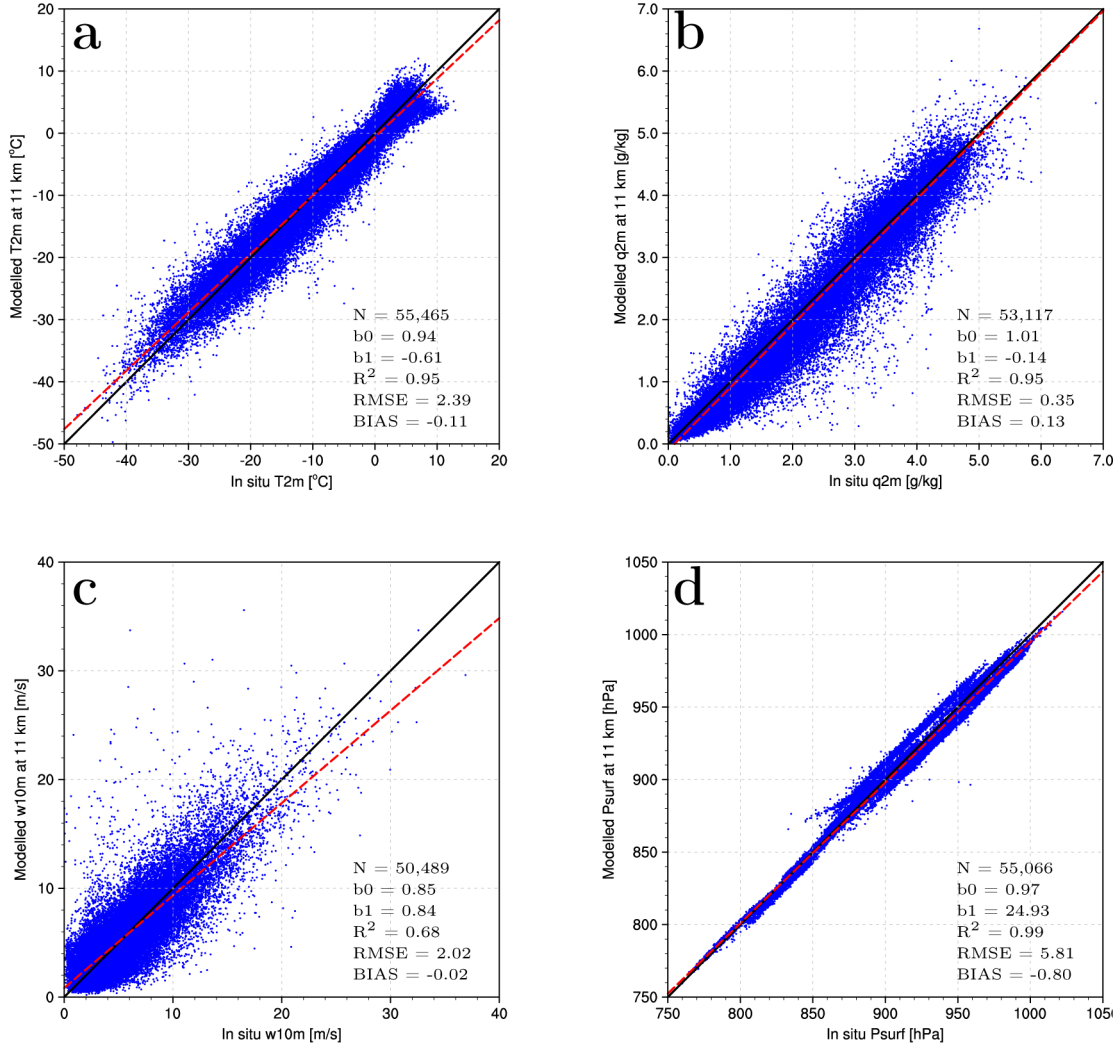


Fig. 3. Comparison between modelled (RACMO2.3p2, 2004-2016) and observed a) 2-m temperature (T_{2m} , °C), b) 2-m specific humidity (q_{2m} , g kg⁻¹), c) 10-m wind speed (w_{10m} , m s⁻¹) and d) surface pressure (Psurf, hPa) collected at 23 AWS (green dots in Fig. 1). For each variable, the linear regression including all records is displayed as red dashed line. Statistics including number of records (N), regression slope (b0) and intercept (b1), determination coefficient (R²), bias and RMSE are listed for each variable.

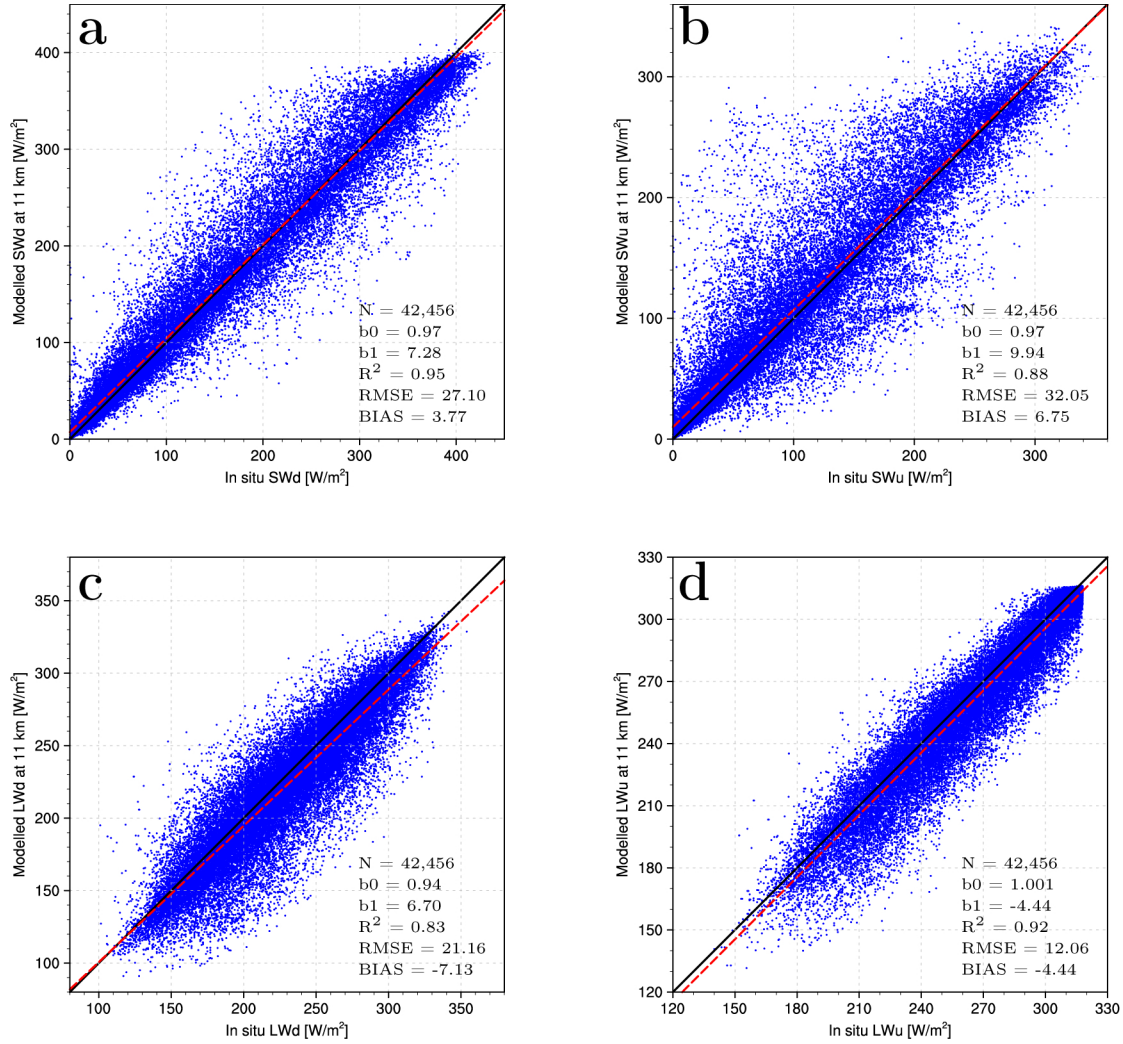


Fig. 4. Comparison between daily average modelled (RACMO2.3p2, 2004-2016) and observed a) shortwave downward, b) shortwave upward, c) longwave downward and d) longwave upward radiation (W m^{-2}) collected at 23 AWS (green dots in Fig. 1). For each variable, regression including all records is displayed as red dashed line. Statistics including number of records (N), the linear regression slope (b0) and intercept (b1), determination coefficient (R^2), bias and RMSE are listed for each variable.

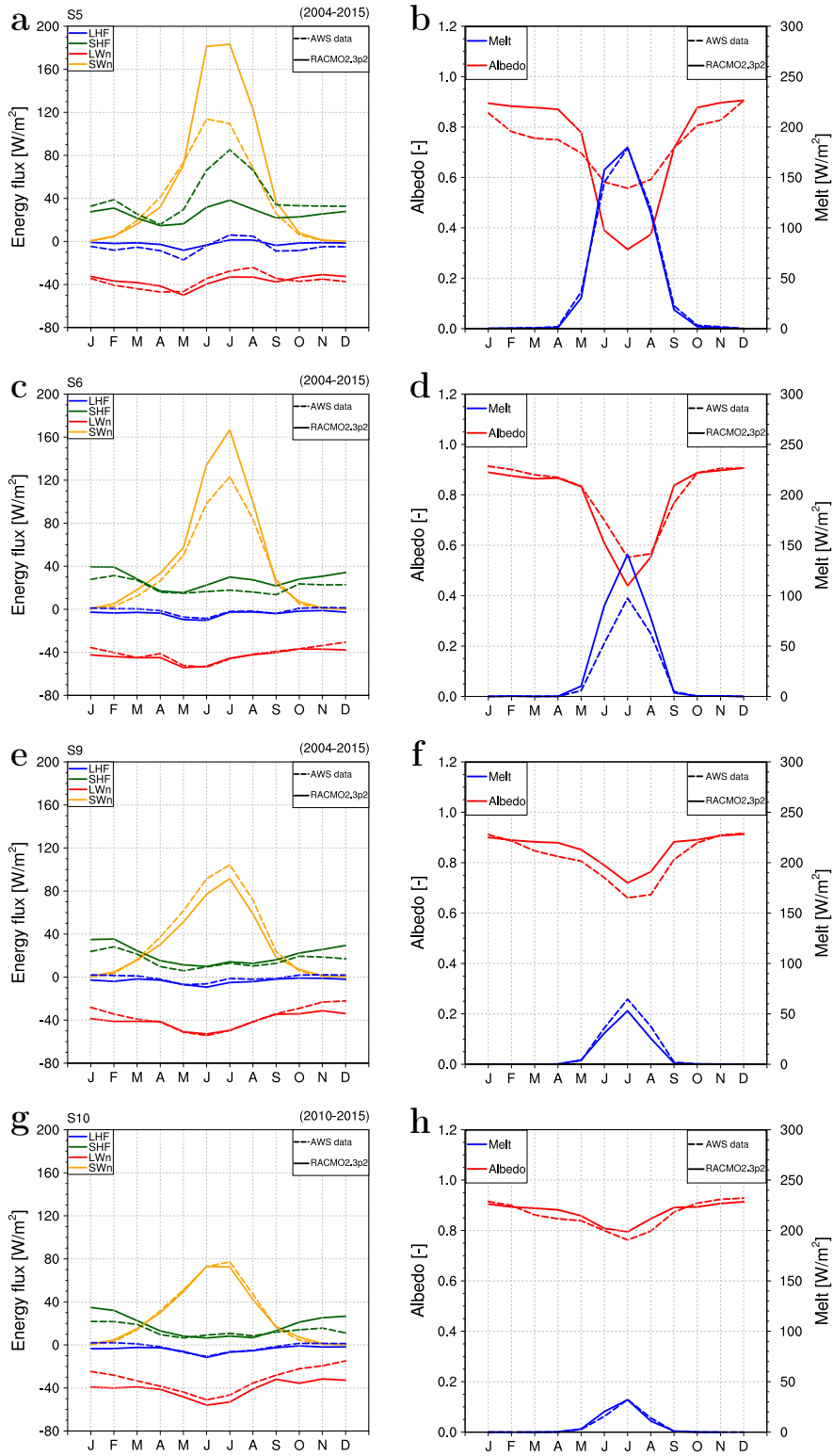


Fig. 5. Observed and modelled (RACMO2.3p2) monthly mean a) turbulent and net shortwave/longwave fluxes (W m^{-2}) and b) surface albedo and surface melt energy (W m^{-2}) at site S5 for 2004-2015. Similar results are shown at S6 for 2004-2015 (c and d), S9 for 2009-2015 (e and f) and S10 for 2010-2015 (g and h).

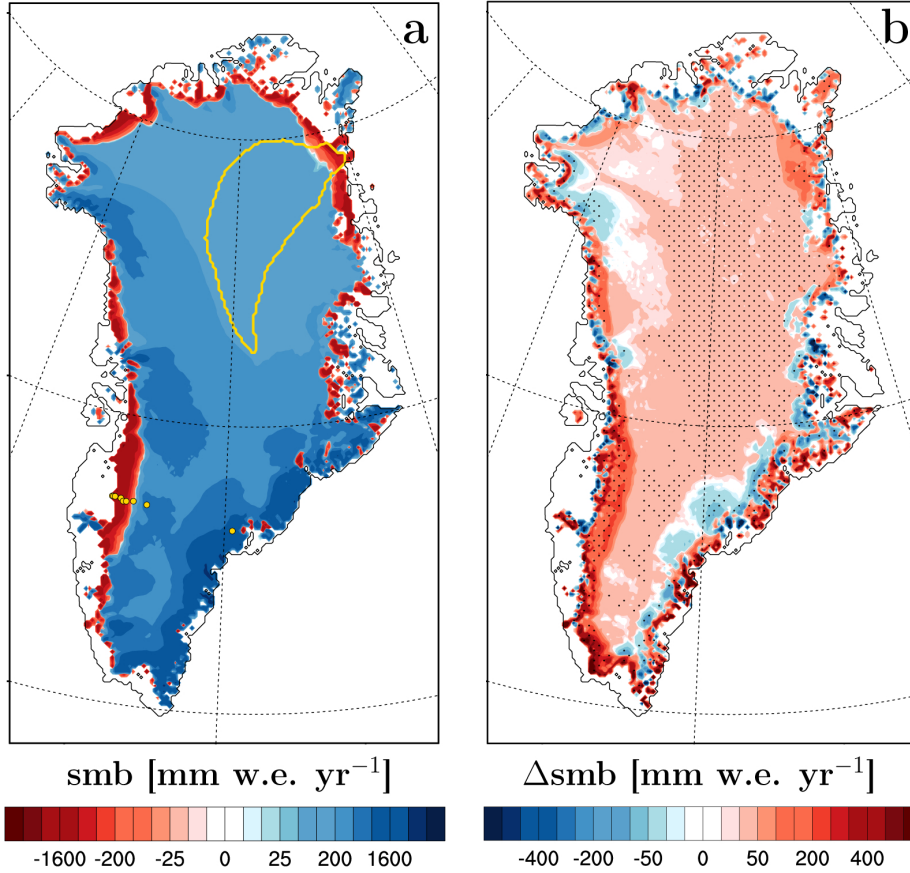


Fig. 6. a) SMB (mm w.e. yr⁻¹) averaged for the period 1958-2015. The combined Zachariae Isstrøm and Nioghalvfjærdsbrae (79N) glacier basins are delineated by the yellow line. Yellow dots locate the K-transect measurement sites in western Greenland and the single AWS operated in southeast Greenland. b) SMB difference (mm w.e. yr⁻¹) between RACMO2.3p2 and RACMO2.3p1 for the period 1958-2015. Areas showing significant difference are stippled in Fig. 6b: difference exceeds one unit of standard deviation of the difference between the two model versions.

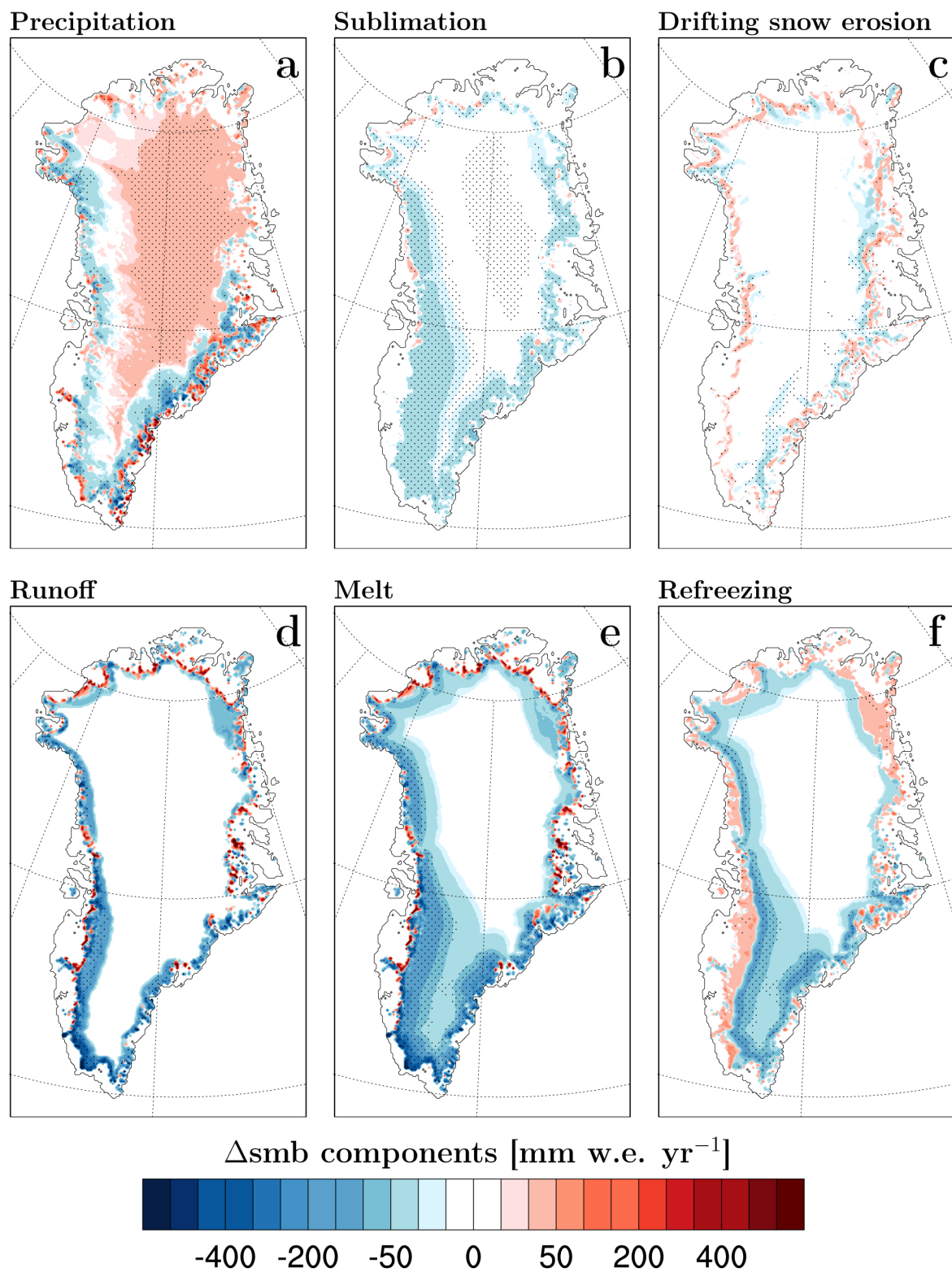


Fig. 7. Difference in SMB components (mm w.e. yr^{-1}) between RACMO2.3p2 and RACMO2.3p1 averaged for the period 1958-2015. Areas showing significant difference are stippled: the difference exceeds one unit of standard deviation of the difference between the two model versions.

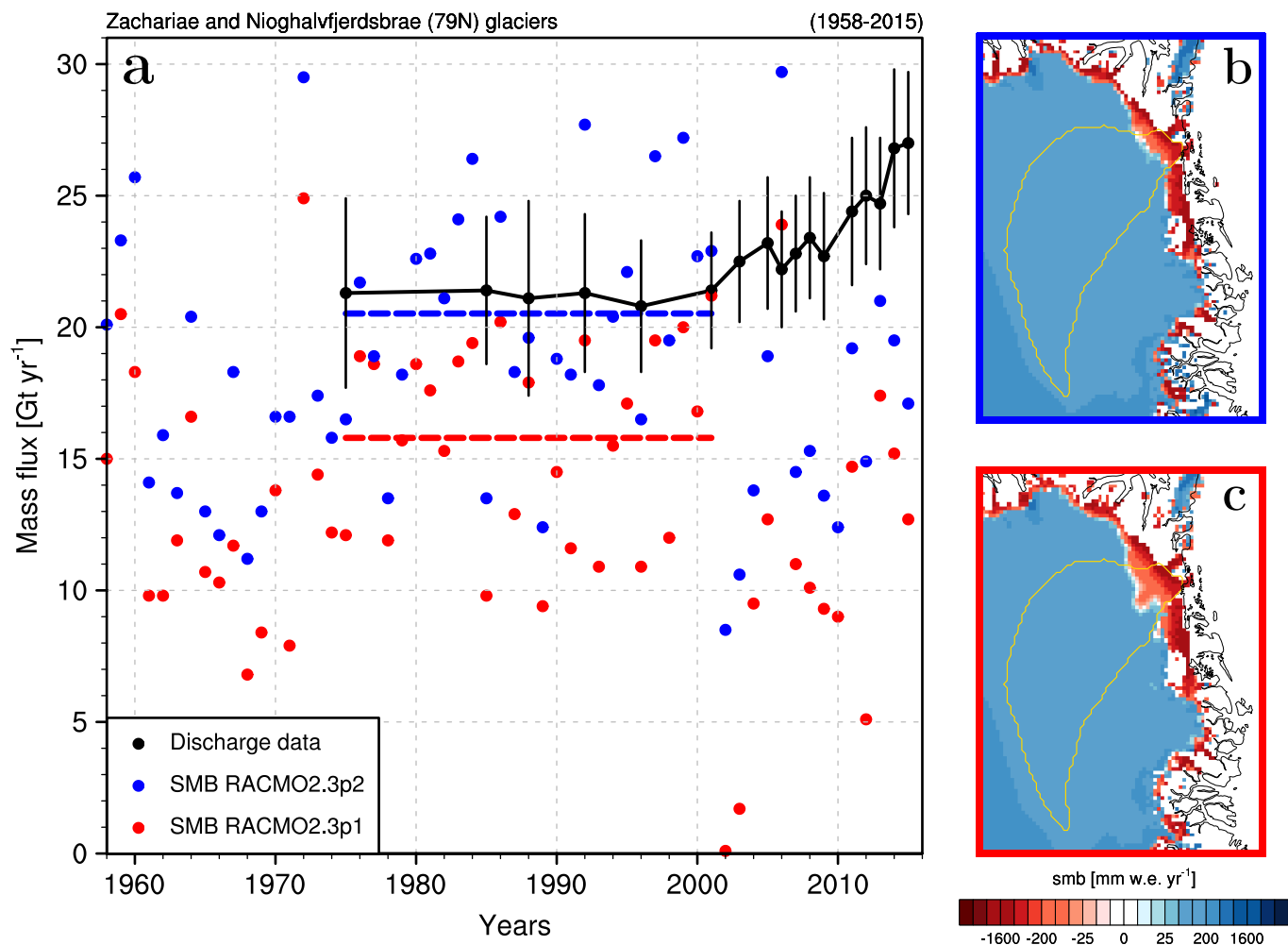


Fig. 8. a) Modelled basin-integrated SMB in RACMO2.3p2 (blue dots) and RACMO2.3p1 (red dots) and ice discharge estimates (black dots, Mougnot et al. (2015)) from the glacier basins of Zachariae Isstrøm and Nioghalvfjærdsbrae (79N) in northeast Greenland (yellow line in Figs. 8b and c) for the period 1975-2015. Dashed lines represent average SMB for 1975-2001. Mean SMB as modelled by b) RACMO2.3p2 and c) RACMO2.3p1 in northeast Greenland for the period 1958-2015.

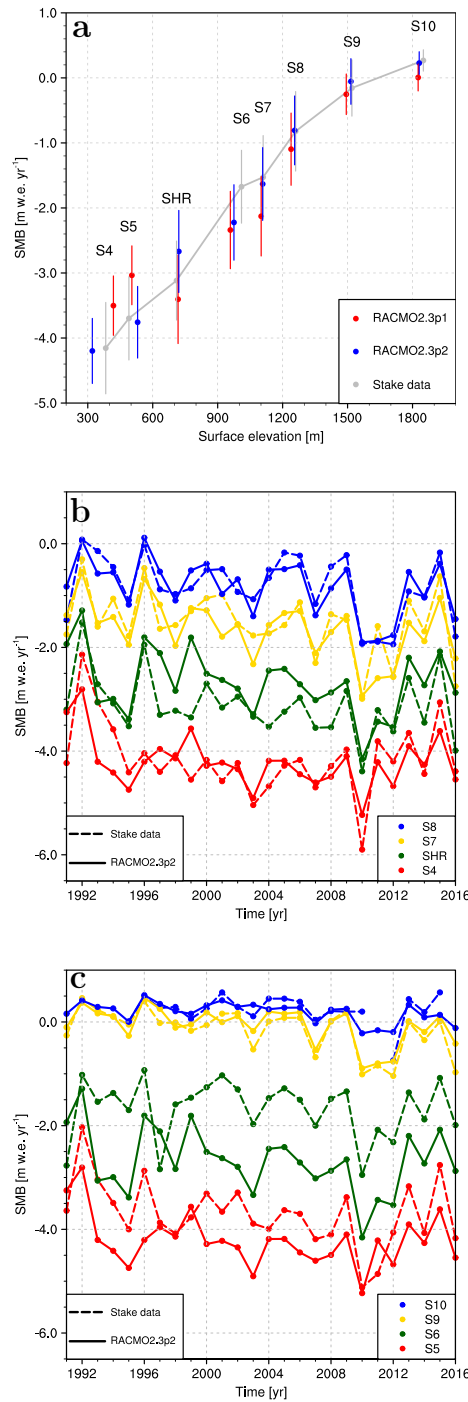


Fig. 9. a) Observed and simulated SMB (m w.e. yr⁻¹) along the K-transect in west Greenland (67°N), averaged for the period 1991-2015. The observed SMB (gray dots) at S4, S5, SHR, S6, S7, S8, S9 and S10 are based on annual stake measurements; S10 observations cover 1994-2015. The coloured bars represent the standard deviation (1σ) around the 1991-2015 modelled and observed mean value. Modelled SMB at stake sites are displayed for RACMO2.3p2 (blue dots) and RACMO2.3p1 (red dots). Fig. 9b shows time series of modelled (continuous lines) and observed (dashed lines) annual SMB at stakes S4, SHR, S7 and S8 for the period 1991-2016. Similar time series are shown for S5, S6, S9 and S10 in Fig. 9c. **At S10, modelled SMB is estimated as the difference between total precipitation and melt.**

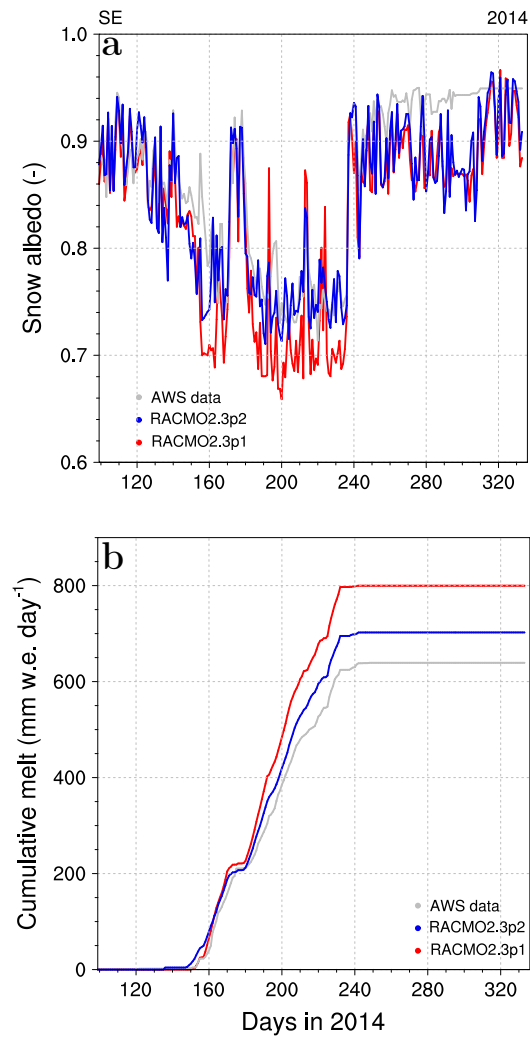


Fig. 10. Time series of a) daily snow albedo, and b) cumulative surface melt (mm w.e. per day) modelled by RACMO2.3p2 (blue lines), RACMO2.3p1 (red lines) and measured (gray lines) at the southeast AWS (66°N; 33°W; 1563 m a.s.l.) during summer 2014.

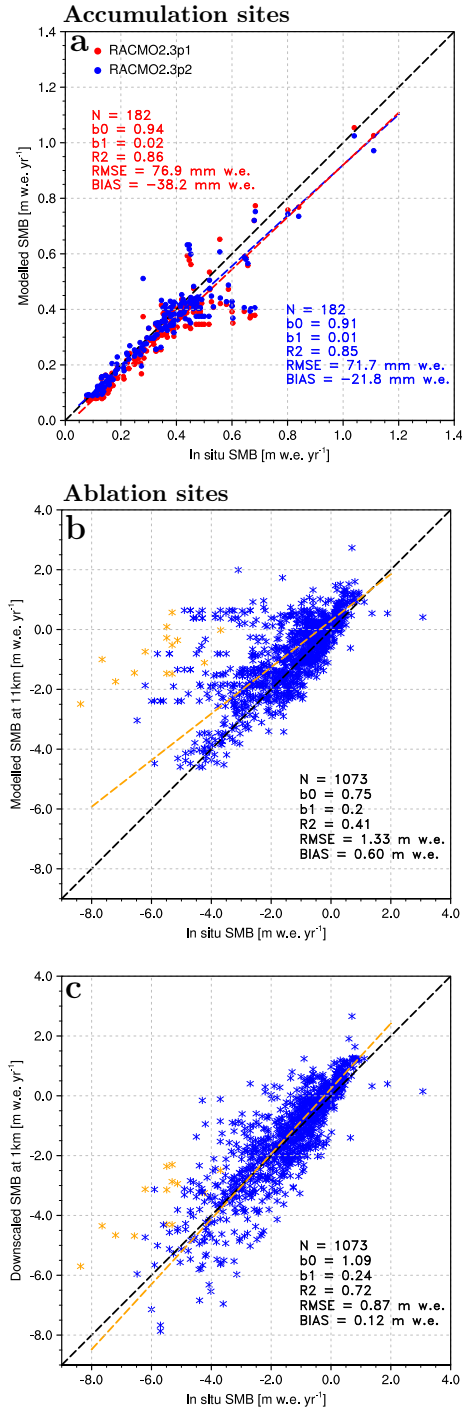


Fig. 11. Comparison between a) modelled, i.e. RACMO2.3p2 (blue) and RACMO2.3p1 (red) at 11 km, and observed SMB (m w.e. yr⁻¹) collected in the GrIS accumulation zone (white dots in Fig. 1). Regressions for RACMO2.3p2 (blue) and version 2.3p1 (red) are displayed as dashed lines. Comparison between SMB measurements from the GrIS ablation zone (yellow dots in Fig. 1) and b) original RACMO2.3p2 data at 11 km, c) downscaled product at 1 km. Orange stars correspond to measurements collected at station QAS.L at the southern tip of Greenland. Regression including all records is displayed as orange dashed line in Figs. 11b and c. Main statistics including number of records (N), regression slope (b0) and intercept (b1), determination coefficient (R²), bias and RMSE are listed for each graph.

PROMICE	23 AWS	RACMO2.3p1			RACMO2.3p2		
Variable	unit	bias	RMSE	R^2	bias	RMSE	R^2
T_{2m}	$^{\circ}\text{C}$	-0.8	2.9	0.93	-0.1	2.4	0.95
q_{2m}	g/kg	-0.2	0.4	0.93	0.1	0.4	0.95
w_{10m}	m/s	0.3	2.2	0.65	-0.02	2.0	0.68
Psurf	hPa	-0.2	7.7	0.98	-0.8	5.8	0.99
SW_d	W/m^2	6.5	26.7	0.96	3.8	27.1	0.95
SW_u	W/m^2	5.8	27.8	0.91	6.8	32.1	0.88
LW_d	W/m^2	-13.8	25.7	0.79	-7.1	21.2	0.83
LW_u	W/m^2	-7.4	14.6	0.91	-4.4	12.1	0.92

Table 1. Difference between daily modelled RACMO2.3p1 (2004-2015) or RACMO2.3p2 (2004-2016) and observed meteorological data and SEB components collected at 23 PROMICE AWS (green dots in Fig. 1). Statistics include model bias (RACMO2.3pX - observations), RMSE of the bias as well as the determination coefficient of daily mean data. All fluxes are set positive.

AWS	S5	Obs.	RACMO2.3p1			RACMO2.3p2		
Variable	unit	mean	bias	RMSE	R^2	bias	RMSE	R^2
SW_d	W/m^2	109.5	26.2	33.1	0.99	20.7	27.2	0.98
SW_u	W/m^2	70.9	15.8	25.0	0.93	4.5	34.3	0.74
LW_d	W/m^2	241.4	-17.0	18.5	0.97	-11.8	13.4	0.97
LW_u	W/m^2	278.3	-13.2	15.5	0.98	-12.1	14.2	0.98
SHF	W/m^2	41.1	-13.1	22.2	0.45	-15.3	22.4	0.66
LHF	W/m^2	5.3	2.6	5.6	0.72	3.4	6.5	0.64
M	W/m^2	42.6	-6.8	18.0	0.96	-0.4	11.9	0.97
ALB	(-)	0.74	0.03	0.09	0.75	-0.004	0.14	0.72
T_{2m}	$^{\circ}\text{C}$	-6.4	-2.3	2.6	0.99	-2.0	2.2	0.992

Table 2. Modelled and observed mean SEB components and statistics of the differences (2004-2015) at station S5 in the lower ablation zone (490 m a.s.l.). Statistics include means of measurements collected at S5, model bias (RACMO2.3pX - observations), RMSE of the bias as well as the determination coefficient of monthly mean data. All fluxes are set positive.

AWS	S6	Obs.	RACMO2.3p1			RACMO2.3p2		
Variable	unit	mean	bias	RMSE	R^2	bias	RMSE	R^2
SW_d	W/m^2	131.6	9.7	12.7	0.997	6.0	9.1	0.997
SW_u	W/m^2	95.8	-2.9	16.3	0.97	-3.8	16.3	0.97
LW_d	W/m^2	222.3	-8.7	11.4	0.96	-2.7	6.5	0.97
LW_u	W/m^2	263.6	-1.6	4.0	0.991	-0.4	3.1	0.992
SHF	W/m^2	20.8	9.8	11.4	0.67	7.0	8.7	0.70
LHF	W/m^2	1.6	-3.9	5.2	0.42	-2.4	3.3	0.64
M	W/m^2	18.7	10.6	22.0	0.96	8.3	18.0	0.97
ALB	(-)	0.81	-0.02	0.06	0.89	-0.02	0.06	0.89
T_{2m}	$^{\circ}\text{C}$	-10.9	0.4	0.8	0.994	0.7	1.0	0.995

Table 3. Modelled and observed mean SEB components and statistics of the differences (2004-2015) at station S6 in the upper ablation zone (1010 m a.s.l.). Statistics include means of measurements collected at S6, model bias (RACMO2.3pX - observations), RMSE of the bias as well as the determination coefficient of monthly mean data. All fluxes are set positive.

AWS Variable	S9 unit	Obs. mean	RACMO2.3p1			RACMO2.3p2		
			bias	RMSE	R^2	bias	RMSE	R^2
SW _d	W/m ²	141.2	2.2	6.6	0.998	-1.5	7.8	0.997
SW _u	W/m ²	106.5	3.5	9.4	0.991	3.5	7.6	0.995
LW _d	W/m ²	217.8	-10.1	14.1	0.93	-3.1	8.9	0.94
LW _u	W/m ²	255.2	-1.9	4.9	0.99	0.5	3.5	0.991
SHF	W/m ²	15.8	7.0	9.2	0.68	5.2	7.3	0.74
LHF	W/m ²	0.8	-3.8	5.4	0.20	-2.8	4.0	0.42
M	W/m ²	12.0	-0.7	7.8	0.89	-2.4	7.0	0.96
ALB	(-)	0.82	0.02	0.05	0.79	0.03	0.06	0.83
T _{2m}	°C	-13.3	-0.04	0.7	0.994	0.5	0.8	0.996

Table 4. Modelled and observed mean SEB components and statistics of the differences (2009-2015) at station S9 close to the equilibrium line (1520 m a.s.l.). Statistics include means of measurements collected at S9, model bias (RACMO2.3pX - observations), RMSE of the bias as well as the determination coefficient of monthly mean data. **All fluxes are set positive.**

AWS Variable	S10 unit	Obs. mean	RACMO2.3p1			RACMO2.3p2		
			bias	RMSE	R^2	bias	RMSE	R^2
SW _d	W/m ²	141.5	1.7	7.0	0.998	-2.1	8.3	0.998
SW _u	W/m ²	113.8	-2.7	12.0	0.991	-1.7	7.3	0.997
LW _d	W/m ²	220.4	-14.4	17.2	0.93	-6.5	10.7	0.94
LW _u	W/m ²	252.5	-1.0	4.8	0.99	2.1	4.1	0.991
SHF	W/m ²	11.9	7.6	10.8	0.57	4.9	8.3	0.62
LHF	W/m ²	-2.7	-3.5	5.6	0.22	-2.1	3.5	0.62
M	W/m ²	8.9	2.5	6.6	0.89	-0.2	3.1	0.92
ALB	(-)	0.86	-0.01	0.04	0.69	0.01	0.03	0.73
T _{2m}	°C	-14.6	0.5	1.0	0.991	1.1	1.3	0.995

Table 5. Modelled and observed mean SEB components and statistics of the differences (2010-2015) at station S10 in the accumulation zone (1850 m a.s.l.). Statistics include means of measurements collected at S10, model bias (RACMO2.3pX - observations), RMSE of the bias as well as the determination coefficient of monthly mean data. **All fluxes are set positive.**

Stakes SMB	Obs. mean	RACMO2.3p1			RACMO2.3p2			Coordinates		
		bias	RMSE	R^2	bias	RMSE	R^2	lon. (°W)	lat. (°N)	elev. (m a.s.l.)
S4	-4.2	0.64	0.84	0.40	-0.05	0.51	0.47	-50.20	67.10	383
S5	-3.7	0.64	0.79	0.45	-0.08	0.46	0.50	-50.09	67.10	490
SHR	-3.1	-0.32	0.57	0.53	0.41	0.62	0.51	-49.94	67.10	710
S6	-1.7	-0.68	0.87	0.30	-0.56	0.78	0.29	-49.40	67.08	1010
S7	-1.5	-0.65	0.75	0.64	-0.15	0.37	0.68	-49.15	66.99	1110
S8	-0.8	-0.31	0.49	0.62	-0.03	0.28	0.76	-48.88	67.01	1260
S9	-0.2	-0.13	0.21	0.83	0.07	0.16	0.88	-48.25	67.05	1520
S10	0.3	-0.25	0.33	0.44	-0.04	0.21	0.45	-47.02	67.00	1850

Table 6. Modelled and observed mean annual SMB (m w.e. yr⁻¹) and statistics of the differences at S4, S5, SHR, S6, S7, S8 and S9 over 1991-2015; measurements at S10 are compared to modelled total precipitation minus melt for the period 1994-2015. Spatial coordinates of each site are listed.

Supplementary Material: Modelling the climate and surface mass balance of polar ice sheets using RACMO2, Part 1: Greenland (1958-2016)

Brice Noël¹, Willem Jan van de Berg¹, J. Melchior van Wessem¹, Erik van Meijgaard², Dirk van As³, Jan T. M. Lenaerts⁴, Stef Lhermitte⁵, Peter Kuipers Munneke¹, C. J. P. Paul Smeets¹, Lambertus H. van Ulft², Roderik S. W. van de Wal¹, and Michiel R. van den Broeke¹

¹Institute for Marine and Atmospheric research Utrecht, University of Utrecht, Utrecht, Netherlands.

²Royal Netherlands Meteorological Institute, De Bilt, Netherlands.

³Geological Survey of Denmark and Greenland (GEUS), Copenhagen, Denmark.

⁴Department of Atmospheric and Oceanic Sciences, University of Colorado, Boulder, USA.

⁵Department of Geoscience & Remote Sensing, Delft University of Technology, Delft, Netherlands.

Correspondence to: Brice Noël (B.P.Y.Noel@uu.nl)

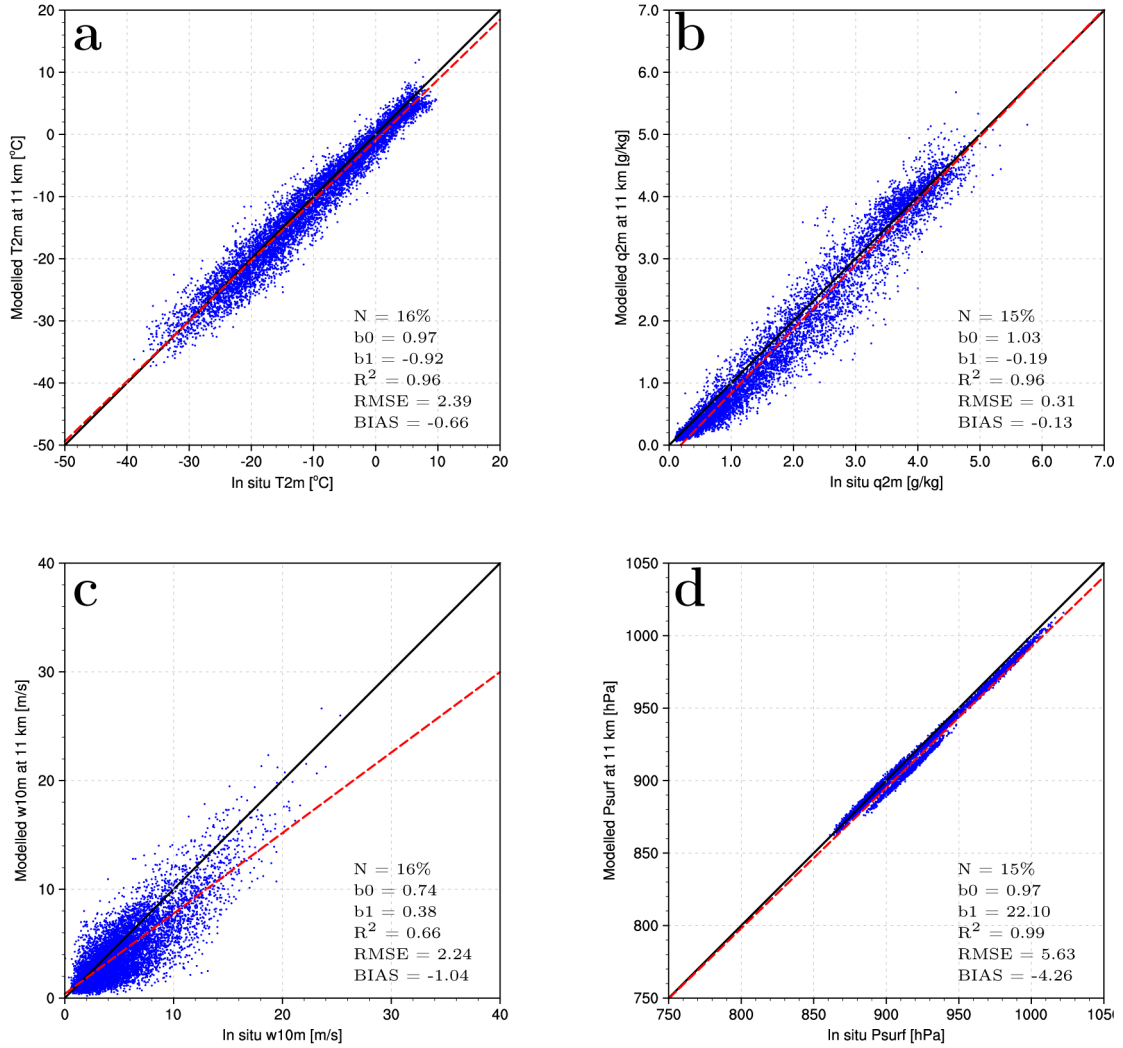


Fig. S1. North West Greenland (NW): comparison between modelled (RACMO2.3p2, 2004-2016) and observed a) 2-m temperature (T_{2m} , $^{\circ}\text{C}$), b) 2-m specific humidity (q_{2m} , g kg^{-1}), c) 10-m wind speed (w_{10m} , m s^{-1}) and d) surface pressure (P_{surf} , hPa) at 4 AWS located in NW Greenland (green dots in Fig. 1). For each variable, the linear regression including all records is displayed as red dashed line. Statistics including the percentage of measurements located in the NW sector (N), regression slope (b_0) and intercept (b_1), determination coefficient (R^2), bias and RMSE are listed for each variable.

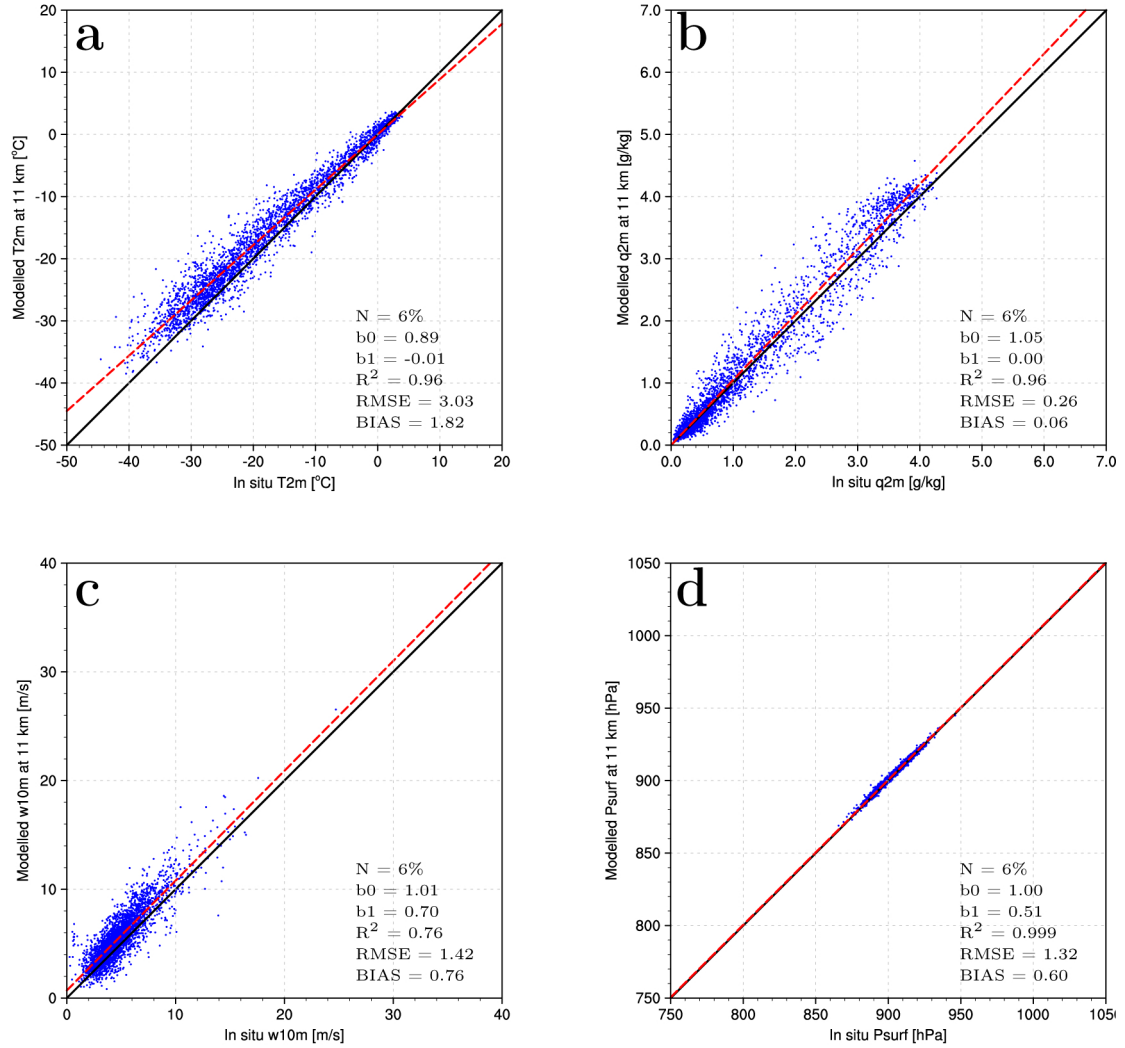


Fig. S2. North East Greenland (NE): comparison between modelled (RACMO2.3p2, 2004-2016) and observed a) 2-m temperature (T_{2m} , $^{\circ}\text{C}$), b) 2-m specific humidity (q_{2m} , g kg^{-1}), c) 10-m wind speed (w_{10m} , m s^{-1}) and d) surface pressure (P_{surf} , hPa) at 2 AWS located in NE Greenland (green dots in Fig. 1). For each variable, the linear regression including all records is displayed as red dashed line. Statistics including the percentage of measurements located in the NE sector (N), regression slope (b_0) and intercept (b_1), determination coefficient (R^2), bias and RMSE are listed for each variable.

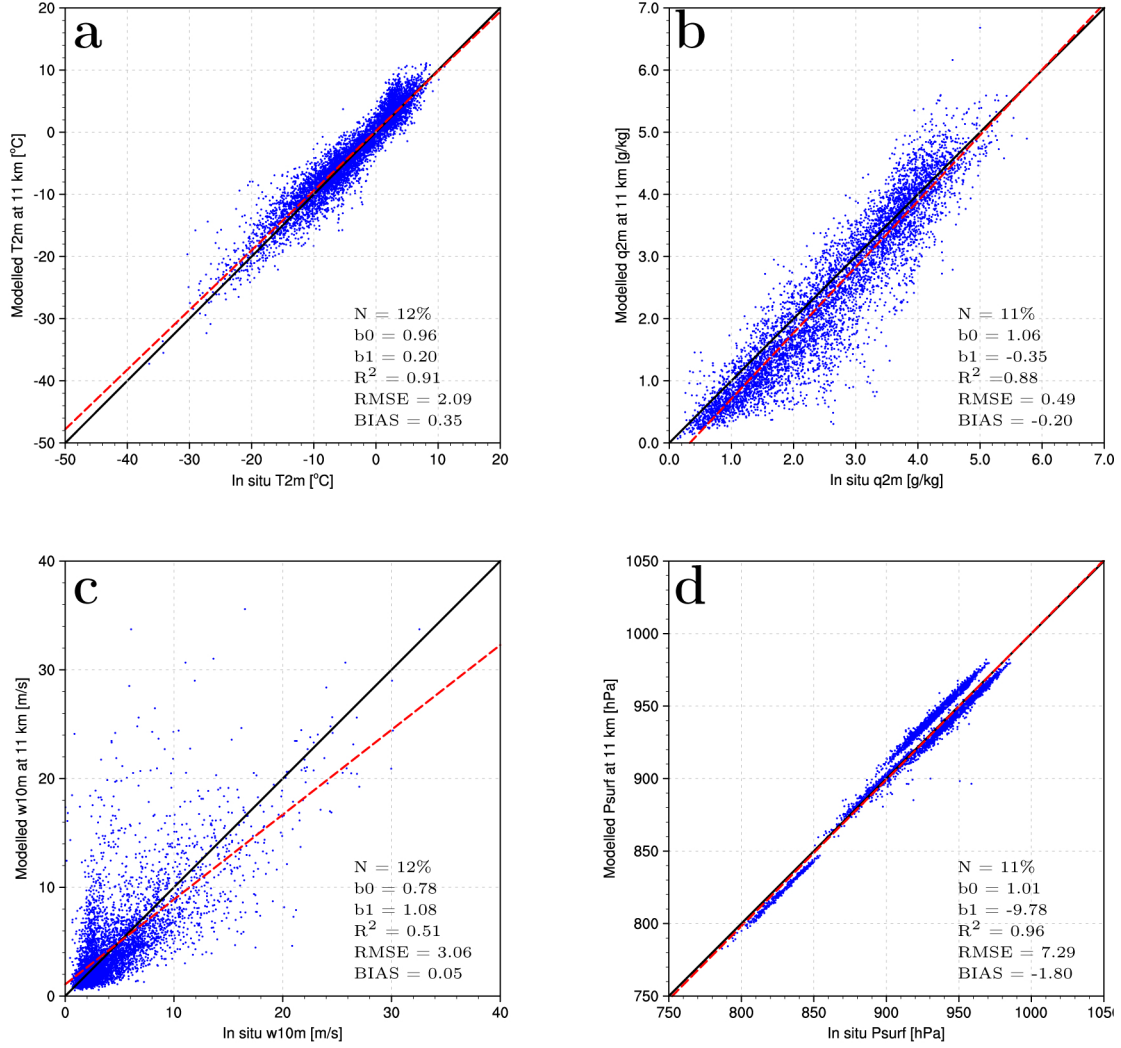


Fig. S3. South East Greenland (SE): comparison between modelled (RACMO2.3p2, 2004-2016) and observed a) 2-m temperature (T_{2m} , °C), b) 2-m specific humidity (q_{2m} , g kg^{-1}), c) 10-m wind speed (w_{10m} , m s^{-1}) and d) surface pressure (P_{surf} , hPa) collected at 4 AWS located in SE Greenland (green dots in Fig. 1). For each variable, the linear regression including all records is displayed as red dashed line. Statistics including the percentage of measurements located in the SE sector (N), regression slope (b0) and intercept (b1), determination coefficient (R^2), bias and RMSE are listed for each variable.

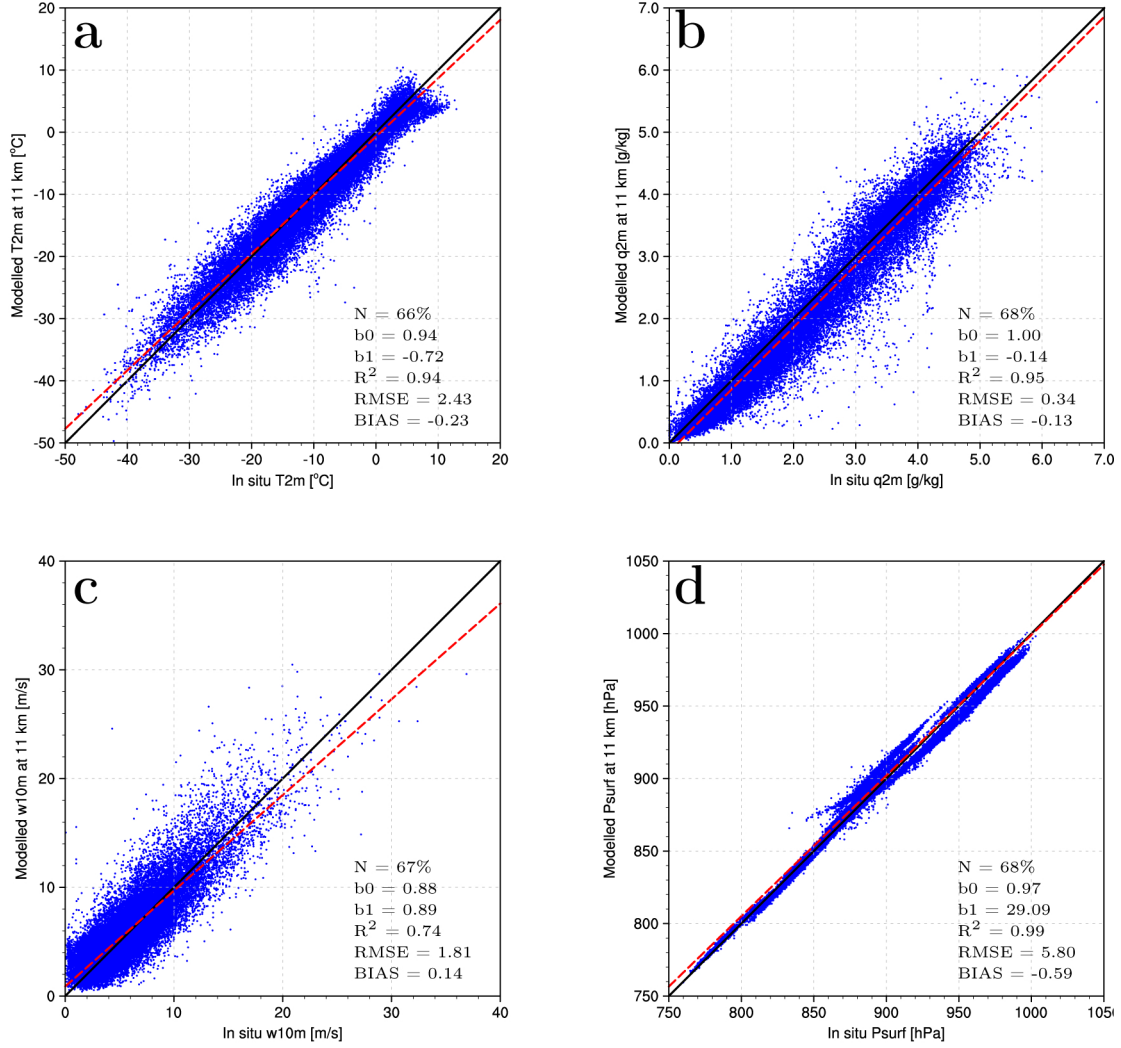


Fig. S4. South West Greenland (SW): comparison between modelled (RACMO2.3p2, 2004-2016) and observed a) 2-m temperature (T_{2m} , $^{\circ}\text{C}$), b) 2-m specific humidity (q_{2m} , g kg^{-1}), c) 10-m wind speed (w_{10m} , m s^{-1}) and d) surface pressure (P_{surf} , hPa) collected at 13 AWS located in SW Greenland (green dots in Fig. 1). For each variable, the linear regression including all records is displayed as red dashed line. Statistics including the percentage of measurements located in the SW sector (N), regression slope (b_0) and intercept (b_1), determination coefficient (R^2), bias and RMSE are listed for each variable.

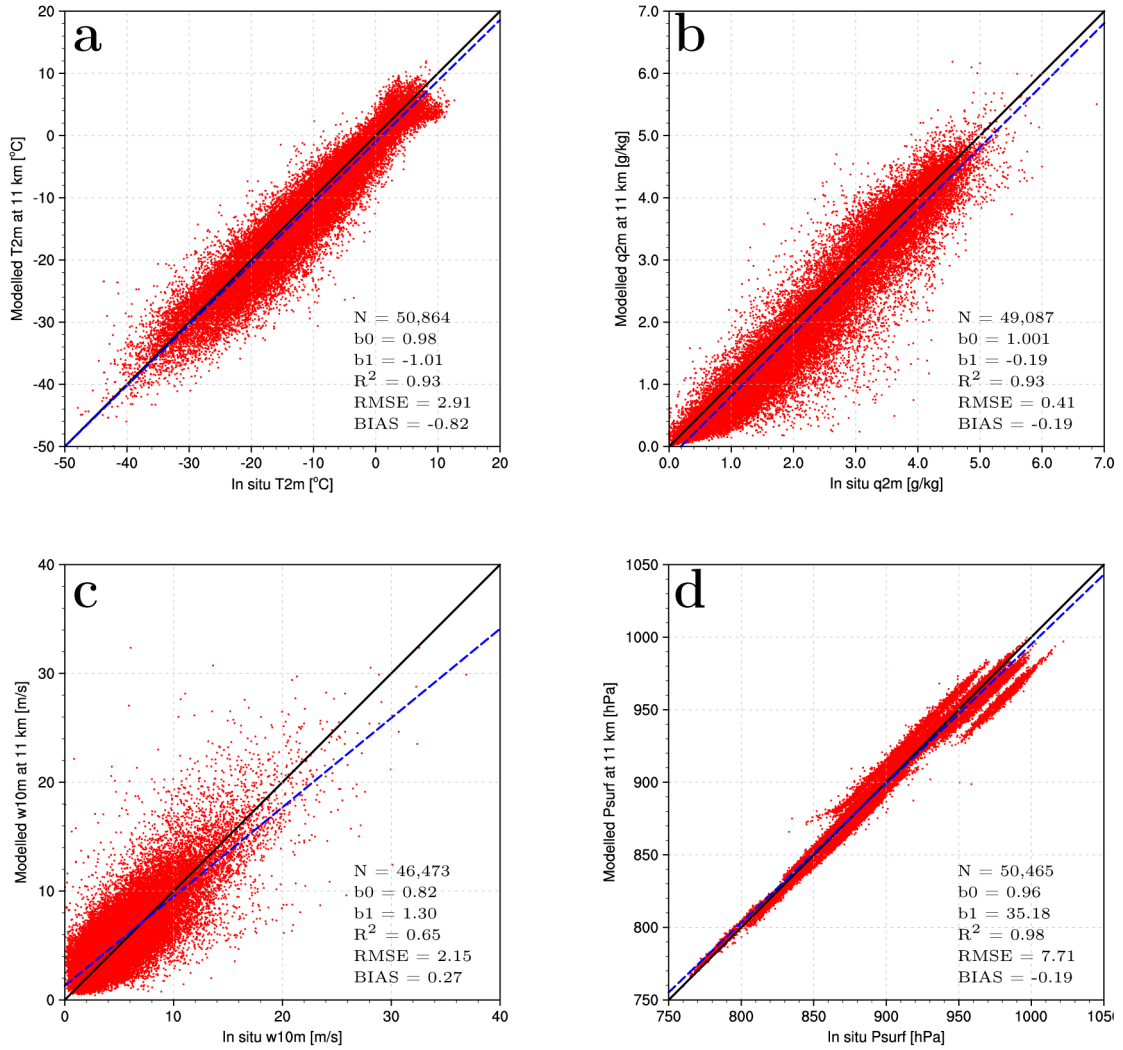


Fig. S5. Comparison between modelled (RACMO2.3p1, 2004-2015) and observed a) 2-m temperature (T_{2m} , °C), b) 2-m specific humidity (q_{2m} , g kg⁻¹), c) 10-m wind speed (w_{10m} , m s⁻¹) and d) surface pressure (P_{surf} , hPa) collected at 23 AWS (green dots in Fig. 1). For each variable, the linear regression including all records is displayed as blue dashed line. Statistics including number of records (N), regression slope (b_0) and intercept (b_1), determination coefficient (R^2), bias and RMSE are listed for each variable.

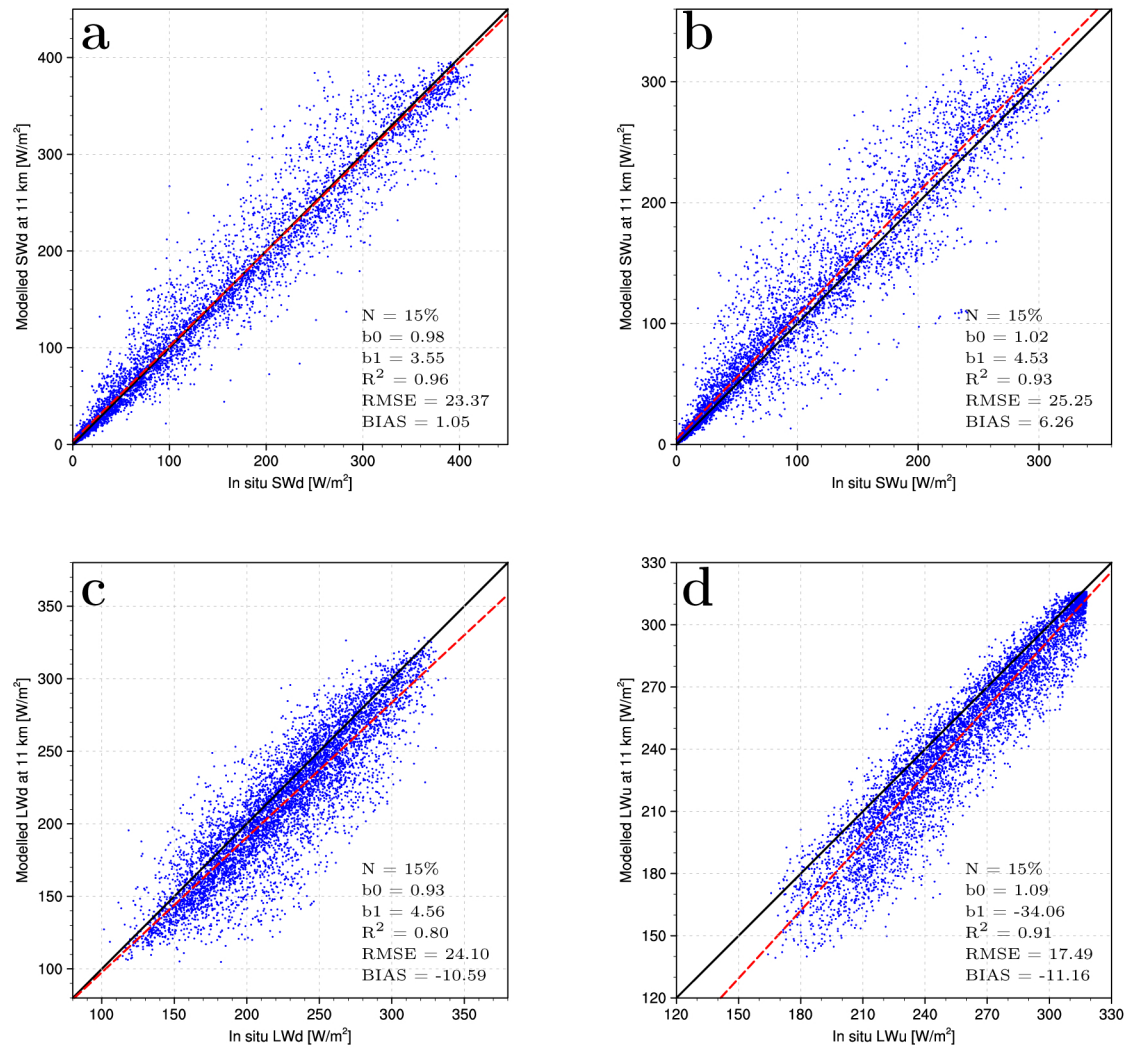


Fig. S6. North West Greenland (NW): comparison between daily average modelled (RACMO2.3p2, 2004-2016) and observed a) shortwave downward, b) shortwave upward, c) longwave downward and d) longwave upward radiation (W m^{-2}) collected at 4 AWS located in NW Greenland (green dots in Fig. 1). For each variable, regression including all records is displayed as red dashed line. Statistics including the percentage of measurements located in the NW sector (N), the linear regression slope (b_0) and intercept (b_1), determination coefficient (R^2), bias and RMSE are listed for each variable.

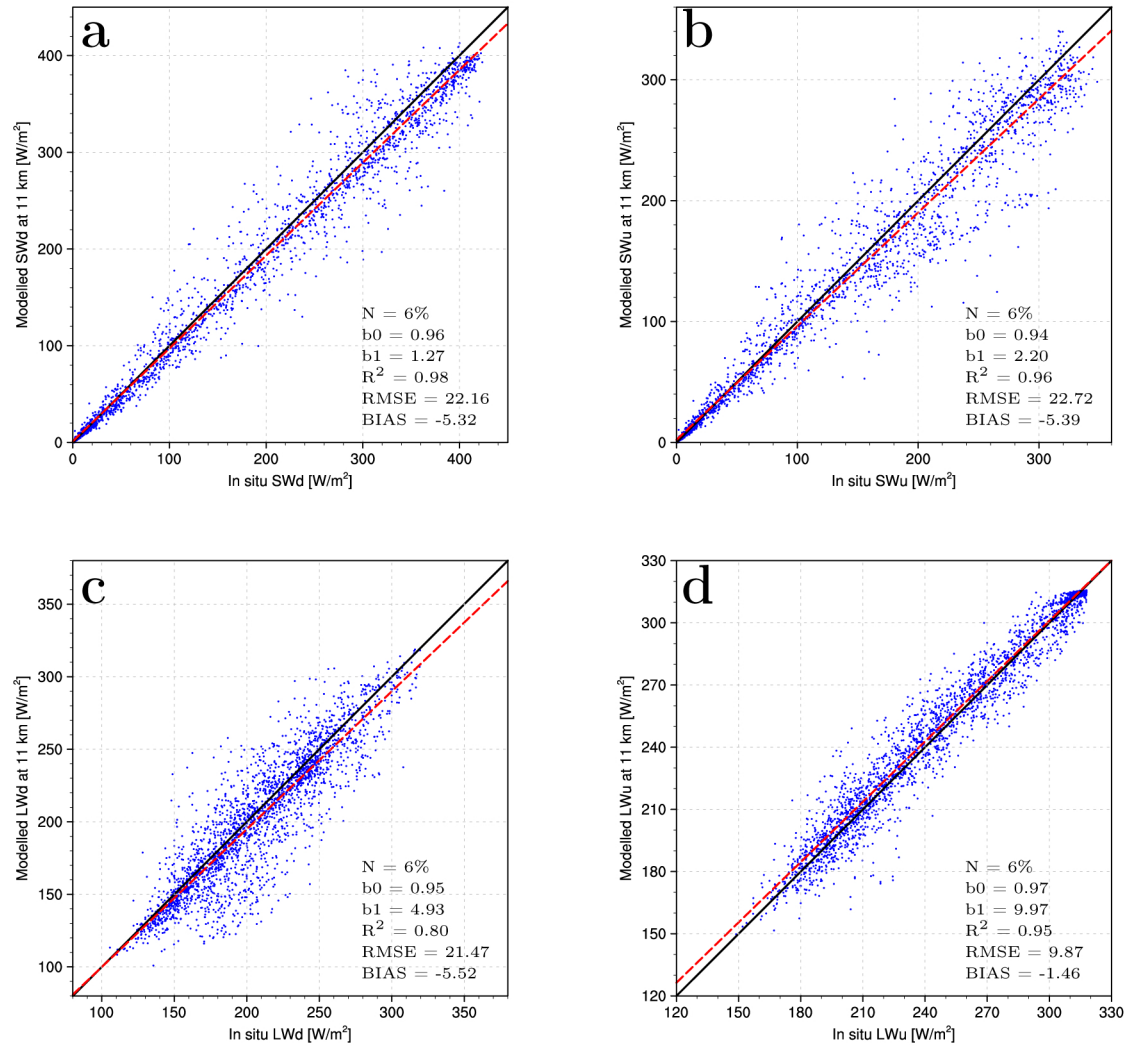


Fig. S7. North East Greenland (NE): comparison between daily average modelled (RACMO2.3p2, 2004-2016) and observed a) shortwave downward, b) shortwave upward, c) longwave downward and d) longwave upward radiation (W m^{-2}) collected at 2 AWS located in NE Greenland (green dots in Fig. 1). For each variable, regression including all records is displayed as red dashed line. Statistics including the percentage of measurements located in the NE sector (N), the linear regression slope (b0) and intercept (b1), determination coefficient (R^2), bias and RMSE are listed for each variable.

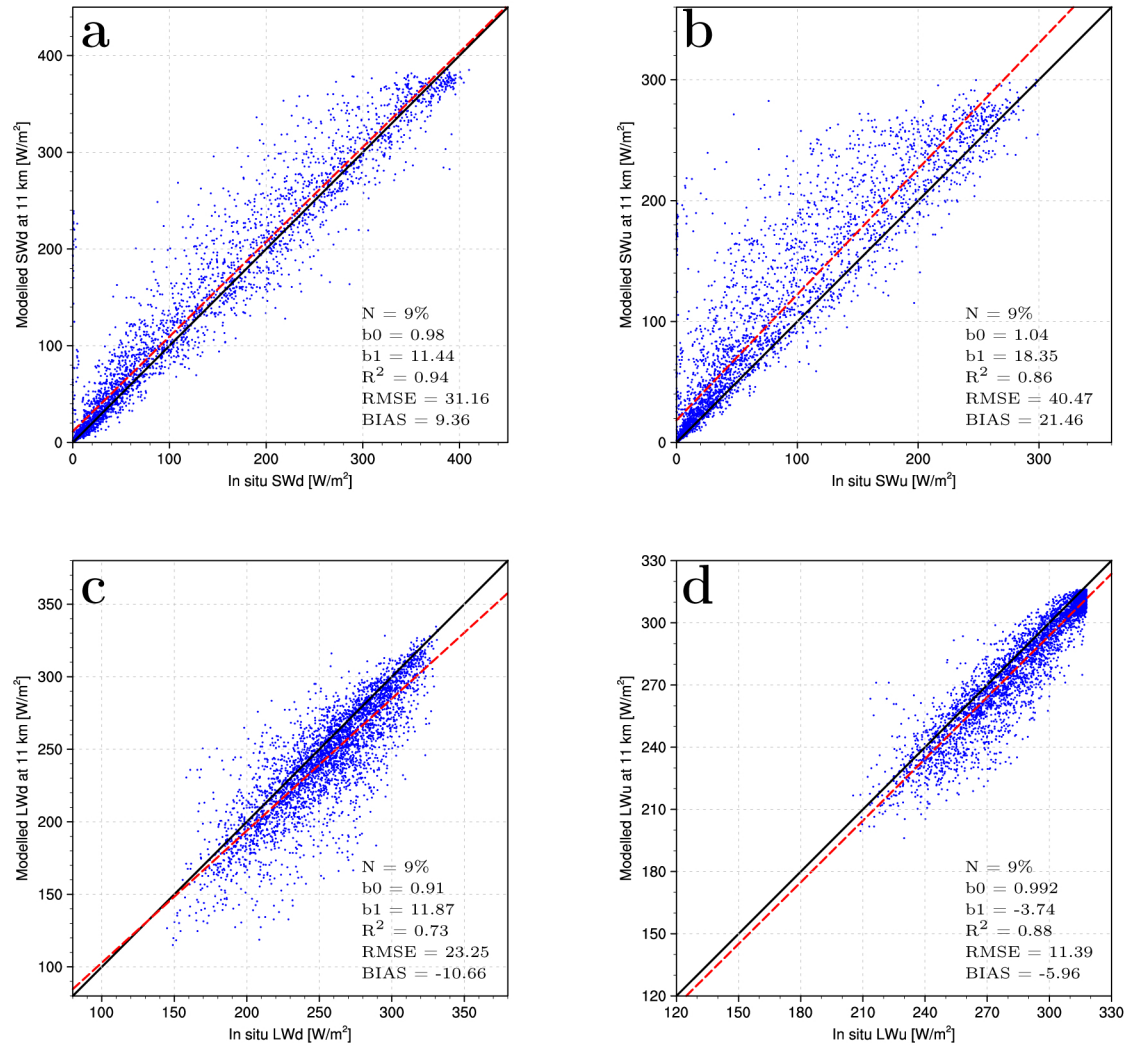


Fig. S8. South East Greenland (SE): comparison between daily average modelled (RACMO2.3p2, 2004-2016) and observed a) shortwave downward, b) shortwave upward, c) longwave downward and d) longwave upward radiation (W m^{-2}) collected at 4 AWS located in SE Greenland (green dots in Fig. 1). For each variable, regression including all records is displayed as red dashed line. Statistics including the percentage of measurements located in the SE sector (N), the linear regression slope (b0) and intercept (b1), determination coefficient (R^2), bias and RMSE are listed for each variable.

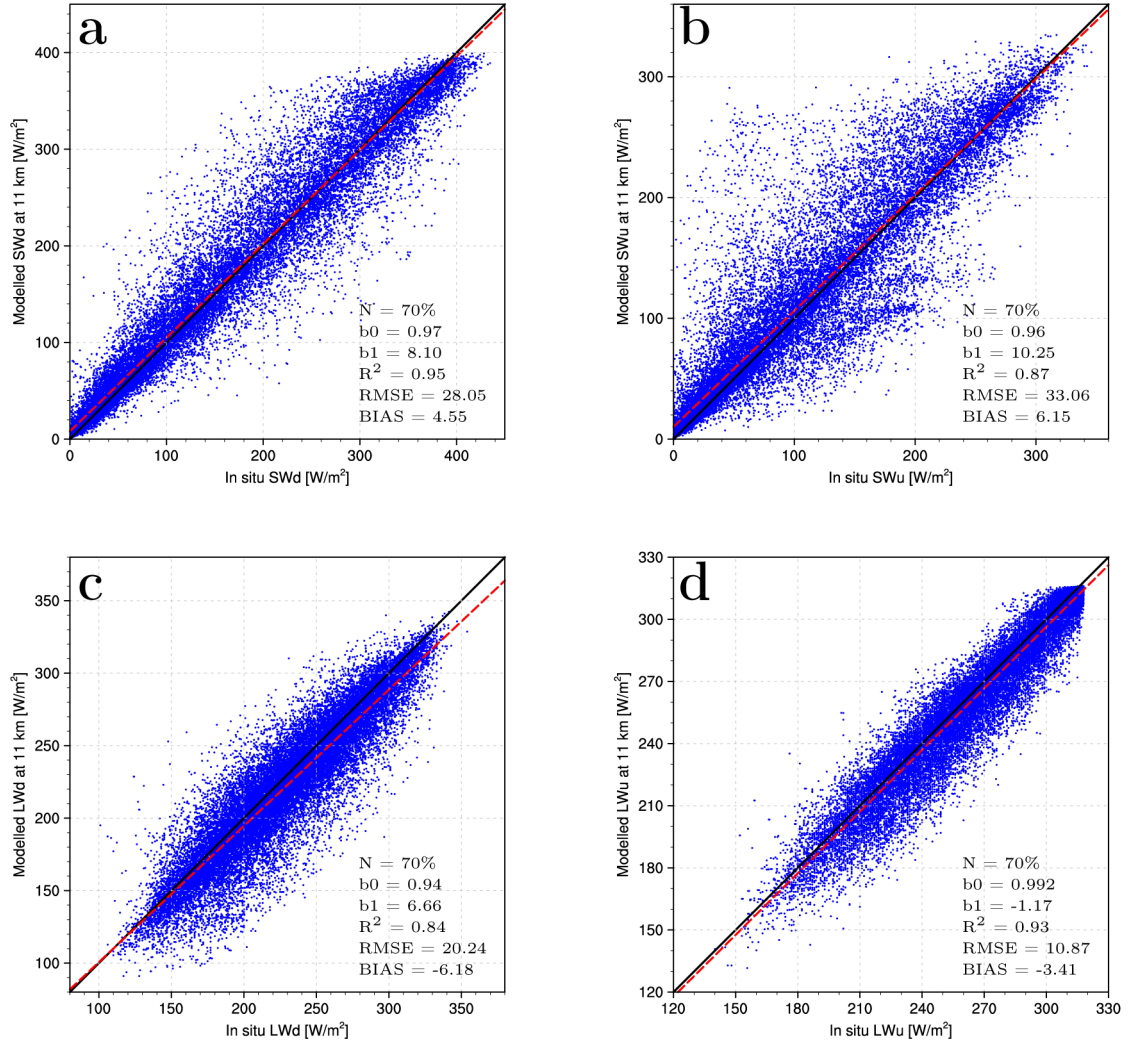


Fig. S9. South West Greenland (SW): comparison between daily average modelled (RACMO2.3p2, 2004-2016) and observed a) shortwave downward, b) shortwave upward, c) longwave downward and d) longwave upward radiation (W m^{-2}) collected at 13 AWS located in SW Greenland (green dots in Fig. 1). For each variable, regression including all records is displayed as red dashed line. Statistics including the percentage of measurements located in the SW sector (N), the linear regression slope (b_0) and intercept (b_1), determination coefficient (R^2), bias and RMSE are listed for each variable.

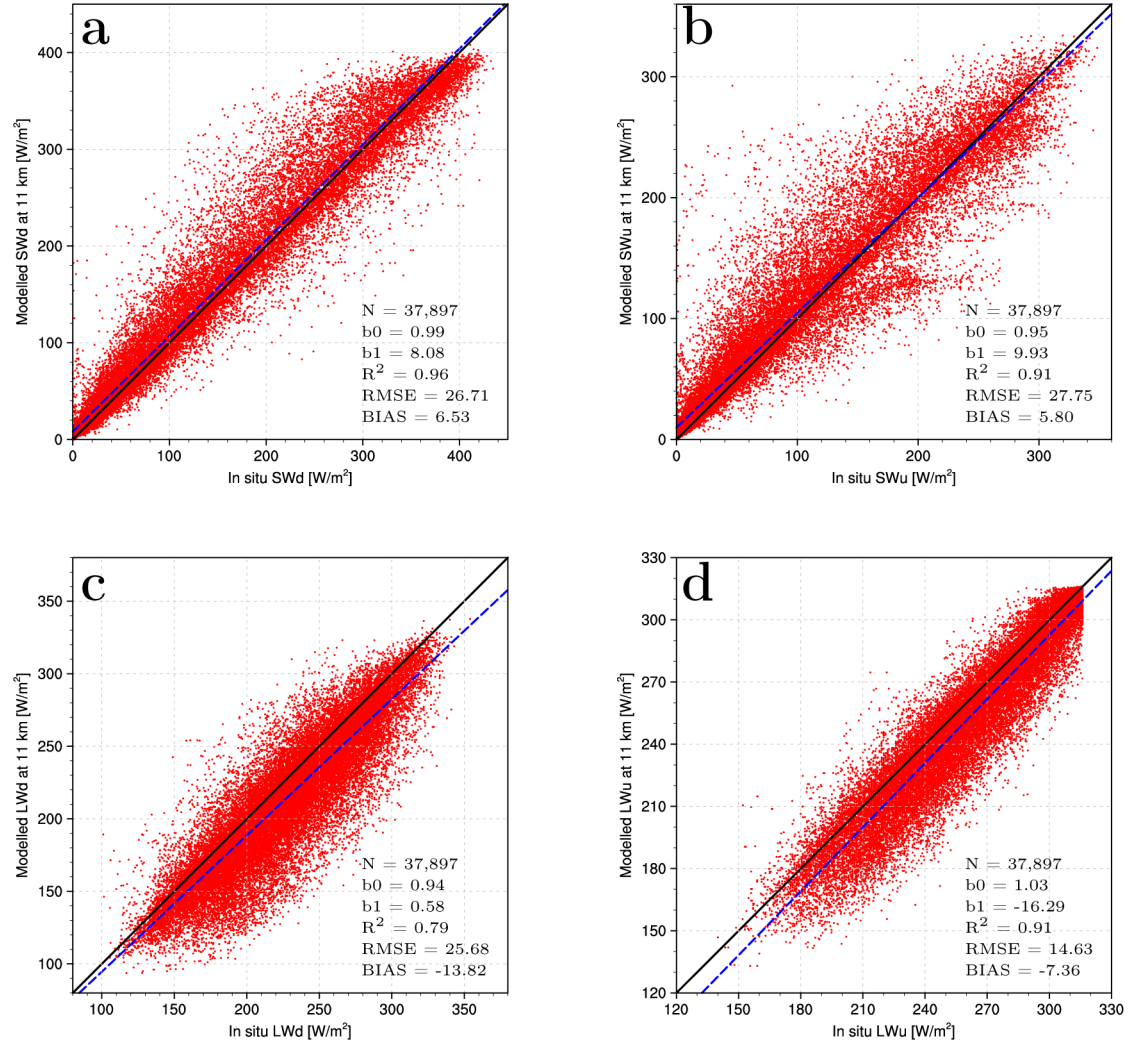


Fig. S10. Comparison between daily average modelled (RACMO2.3p1, 2004-2015) and observed a) shortwave downward, b) shortwave upward, c) longwave downward and d) longwave upward radiation (W m^{-2}) collected at 23 AWS (green dots in Fig. 1). For each variable, regression including all records is displayed as blue dashed line. Statistics including number of records (N), the linear regression slope (b0) and intercept (b1), determination coefficient (R^2), bias and RMSE are listed for each variable.

PROMICE	23 AWS	NW (4 AWS)			NE (2 AWS)			SE (4 AWS)			SW (13 AWS)		
Variable	unit	bias	RMSE	R^2	N (%)	bias	RMSE	R^2	N (%)	bias	RMSE	R^2	N (%)
T_{2m}	°C	-0.7	2.4	0.96	16	1.8	3.0	0.96	6	0.4	2.1	0.91	12
q_{2m}	g/kg	-0.1	0.3	0.96	15	0.1	0.3	0.96	6	-0.2	0.5	0.88	11
w_{10m}	m/s	-1.0	2.2	0.66	16	0.8	1.4	0.76	6	0.1	3.1	0.51	12
Psurf	hPa	-4.3	5.6	0.99	15	0.6	1.3	0.999	6	-1.8	7.3	0.96	11
SW_d	W/m^2	1.1	23.4	0.96	15	-5.3	22.2	0.98	6	9.4	31.2	0.94	9
SW_u	W/m^2	6.3	25.3	0.93	15	-5.4	22.7	0.96	6	21.5	40.5	0.86	9
LW_d	W/m^2	-10.6	24.1	0.80	15	-5.5	21.5	0.80	6	-10.7	23.3	0.73	9
LW_u	W/m^2	-11.2	17.5	0.91	15	-1.5	9.9	0.95	6	-6.0	11.4	0.88	9

Table S1. Difference between daily modelled RACMO2.3p2 (2004-2016) and observed meteorological data and SEB components collected at 23 AWS (green dots in Fig. 1) and clustered within four GrIS sectors: NW ($>40^\circ W$, $>70^\circ N$; 4 AWS), NE ($<40^\circ W$, $>70^\circ N$; 2 AWS), SE ($<40^\circ W$, $<70^\circ N$; 4 AWS) and SW ($>40^\circ W$, $<70^\circ N$; 13 AWS) Greenland. Statistics include model bias (RACMO2.3p2 - observations), RMSE of the bias, the determination coefficient of daily mean data as well as the percentage of measurements located in each GrIS sector. All fluxes are set positive.