

Response to reviewers

Dear reviewers,

To start with, we would like to thank you for your useful and constructive comments. Below, our responses to the individual reviewers comments are displayed in blue to facilitate readability.

The main revision is an extension of the evaluation of modeled SMB to include data from the GrIS accumulation zone. We did this to assess whether the changes in precipitation distribution over the GrIS, as simulated by the updated model RACMO2.3, improved on the previous model version.

Review#1: Graham Cogley

Substantive Comments

P1178 L6 What does the adjectival “upper air” mean here? And from what direction do the temperatures “reach” the freezing point? (I.e. say either “rise to” or “fall to”.)

This is confusing and we removed the end of this sentence: “... this especially favours snowfall in summer.”

P1179 L10-14 “once snow melts” is rather misleading. The rate of metamorphism increases progressively as the temperature rises towards the freezing point. Presumably the rate of grain growth then remains high (until an episode of refreezing complicates the situation), but the appearance of liquid water is an immediate complication as far as the albedo is concerned. These sentences should be clarified – perhaps by shortening, because it is not clear that this discussion is essential for the purposes of the paper.

We reformulated the sentence as follow: “In the accumulation zone, it is proposed that higher temperatures lead to enhanced snow metamorphism and surface darkening (Box et al., 2012), resulting in enhanced melt through the positive melt-albedo feedback (Stroeve, 2001).”

P1181 L24 What is an “auto-conversion coefficient”? It may be accepted jargon among regional-scale climate modellers, but is unintelligible to me. (What is being converted into what? And why is the prefix “auto” needed?)

Auto-conversion is rather misleading, although this term is used in the ECMWF documentation, we reformulated the sentence as follow: “Furthermore, the cloud water-to-snowfall conversion coefficient now remains constant for liquid ($> 0^{\circ}\text{C}$) and mixed phase clouds (-23°C to 0°C) whereas it decreases with temperature for ice clouds ($< -23^{\circ}\text{C}$), resulting in slower snowfall production.”

P1182 L5 Should this begin with “In the polar version of RACMO2.3, ...”?

We modified the beginning of this sentence accordingly.

P1184 L13-16 This is confusing and needs rethinking. I think it means “causes moisture-bearing depressions to propagate eastwards towards south Greenland”. But in that case why

don't they produce a topographic precipitation maximum in *southwest* Greenland? Comma after the first "Greenland" in any case.

We reformulated the sentence to make it less confusing: "In addition, the vicinity of the polar front, which predominantly produces easterly flow to its north, causes depressions to propagate eastward towards southern Greenland. This leads to a pronounced topographically forced precipitation maximum along the southeastern coast."

L26-28 This enhanced northwesterly advection of drier air needs to be reconciled with the eastward advection of *moister* air at L13-16. It seems that you are summarizing average patterns, but forgetting that at any point the wind does not blow in two directions at once. The same problem seems to arise at L27-28, where it may be that "reinforced ... weakened" should be "more frequent ... less frequent".

In this section, we first discuss the average patterns of wind and precipitation as modeled by RACMO2.3 (L11-16). The second paragraph highlights the average differences between the new and old version of RACMO2. Therefore, we noted "enhanced northwesterly advection of drier air " in RACMO2.3 with respect to version 2.1. We reformulated as follows: "In south Greenland, RACMO2.3 simulates decreased precipitation **with respect to the previous model version**; this is related to enhanced north-westerly advection of colder and drier air masses and consequently weakened onshore flow (Noël et al., 2014)."

P1185 L11 "enhanced" should be "improved" and "conversion" should (probably) be "transition". Presumably the transition is from rain at the surface in warmer weather to snow in colder weather. But if the simulated phenomenon is the melting of snow flakes as they fall through the air column then the sentence needs to be expanded.

Here, we meant to say that the conversion of cloud water into snowfall is more pronounced at higher temperature in RACMO2.3 relative to the old model version. We reformulated as follow: "Owing to an increase of the cloud water-to-snowfall conversion coefficient, the revised physics in RACMO2.3 favours solid precipitation at the expense of liquid precipitation, especially for cloud temperatures between -7 °C and -1 °C."

P1186 L10-15 There is no sign convention for components of the energy balance. The reader "just has to know" what you are talking about. Tables 1 to 3 suggest that the convention is "all fluxes positive except for latent heat", which is absurd; for example the observed Table-1 melt according to the equation is 737.2, not 42.8. Make all fluxes positive towards the surface, or positive upward or downward, but do not oblige the reader to work out which of your plus signs should actually be minus signs. The "ground" heat flux is oddly named and could perhaps be called the "subsurface heat flux". But why, having been introduced here, is it not mentioned again? You could say, for example, that its annual averages do not exceed $X \text{ W m}^{-2}$ in magnitude.

Apologies for this confusion; we now adopt the convention of a positive sign for fluxes towards the surface, this is clarified in the text. We also replaced "ground heat flux" by subsurface heat flux and mentioned its annual average value accordingly.

L19 "2010-2012 (S10)": the AWS began operating in 2011 according to P1183 L10. Clarify.

You are correct, the AWS at S10 was installed in 2011 by Utrecht University staff. However,

we used AWS observations from GEUS site “KAN_U” to extend the time series backward to include 2010. This is now clarified in the manuscript. “Since 2011, an AWS is also operated in the accumulation zone at S10 (~ 1850 m), about 140 km from the ice sheet margin. At this location, data consist of a merged time series collected at KAN U in 2010 and S10 for 2011-2012.”

P1188 L2-8 Some clarification is needed here of what “prescribed” (L3) and “restricted to” (L8) mean. I think this would be achieved by moving “No ice albedo ... (Fig. 5f)” to L3, and continuing with “, and so RACMO2 prescribes the albedo as 0.55. In recent summers, ...”. The “In fact, both ...” sentence could be deleted because it is out of place and unhelpful.

We rewrote these sentences to make it clearer: “The bias in surface albedo between model and observations (Fig. 5f) can be explained by the too high prescribed bare ice albedo (Fig. 1). No ice albedo could be derived from MODIS imagery for this location, in which case we prescribe a constant ice albedo of 0.55. However, in recent warm summers, the surface at S9 showed lower surface albedo values of ~0.43 and ~0.45 in 2010 and 2012, respectively. As a consequence, both RACMO2 versions fail to capture this ongoing decline of summer ice albedo.”

P1191 L14-15 Unclear. Should this be “because in inward-propagating air masses this change delays cloud formation to higher elevations further inland”?

To make it clearer, we rephrased this sentence as follow: “The inclusion of ice supersaturation in RACMO2.3 might aggravate this problem over the ablation zone, because, for inland-propagating air masses, this process delays cloud condensation to higher ice sheet elevations, as was also seen in simulations of Antarctic climate ...”.

Stylistic Comments

Thank you for these language and stylistic corrections, we applied them accordingly.

P1178

L9 “snowfalls” [OK](#)

L10 “have the potential to” is a verbose way of saying “can”. Delete the unnecessary “locally”. [OK](#)

L19 Do not hyphenate the names of decades (such as “the 1990s”). [OK](#)

L22-22 Commas needed at either end of the “and solid ice ... Rignot et al, 2011)” clause. [OK](#)

P1179

L15 “have the potential to” again, but here it needs to be deleted altogether. [OK](#)

P1180

L1 Change “the use of an explicit” to “an explicit model of”. [OK](#)

L20 Capitalize “Research”. [OK](#)

P1181

L6 There is no need to capitalize terms simply because you are about to turn them into acronyms ... [OK](#)

L7 ... and in fact this acronym is not used again so it is unnecessary. [OK](#)

L10-11 Do not capitalize “independent column approximation”. And again, do not bother to

define an acronym you are not going to use. There are too many acronyms in the paper already. [OK](#)

L12-13 “between ... and” or “of ... with”. [OK](#)

P1182

L12 “RACMO2.1”. [OK](#)

L22 “0.30”, and use equal numbers of decimal digits in similar contexts below. [OK](#)

L26 Yet another unused acronym. This is the second definition of this one. Delete both it and the one on P1180. [OK](#)

P1183

L22 “gradient”. [OK](#)

L23 Delete “of”. [OK](#)

L25-26 “decreased/increased SMB in the west/east” is easy for the writer and hard for the reader. Say “decreased SMB in the west and increased SMB in the east”. [OK](#)

P1184

L11 “from southwest to northeast”. [OK](#)

L17 “Relative to RACMO2.1, RACMO2.3 is 0.1 to 0.3 °C cooler in ...”. [OK](#)

L23 “precipitation in”. [OK](#)

L24-25 “in the northwest, on the lee side of” (or “in the lee of”). [OK](#)

L26 Delete the meaningless “overall”. [OK](#)

L28 “subsequently” should be “consequently”. [OK](#)

P1185

L18-19 Again, easy to write but much harder to read. Say “The reduced summer snowfall in the centre and southeast and the increase in the southeast are not compensated by opposite and equivalent rainfall changes;”. [OK](#)

L28 “significantly exceeds in magnitude”. [OK](#)

P1186

L9 “where there are significant differences in SMB between the two model versions”. [OK](#)

L10-15 *M* is not defined (it cannot be the SEB.) “radiation” (or “radiation fluxes”) in three places. [OK](#)

L22 “show”. [OK](#)

P1187

L13 Delete “values”. [OK](#)

L25 Insert “simulated” before “summer snowfall”. [OK](#)

P1188

L13-14 “too large. However,”. [OK](#)

L20 I am not sure what “a partial recovery” means. Perhaps “longer persistence”? [OK](#)

P1189

L15 I am not sure what “determined” means here. “selected”? [OK](#)

L26 Change “Solving” to “Correcting”. [OK](#)

P1190

L2 “in combination with”. Comma needed after “LWd”. [OK](#)

L12 “least-squares”. [OK](#)

P1191

L16-17 “Another change that is simpler to implement is improvement of the ...”. [OK](#)

Tables & Figures

Table 1 “mean annual”, not “monthly mean”. Presumably you have averaged the 12 monthly means and then the nine annual means. In L5 of the header, say “between RACMO2 and S5 observations” (as at L3). [OK](#)

Tables 2,3 “annual mean”, not “monthly mean”. [OK](#)

Table 4 “annual mean cumulated” is not correct; you mean “mean annual”. The fact that it is “cumulated” over the year is irrelevant. Save space by deleting the S5-S10 unit column and putting the units after “SMB” in the header. [OK](#)

Figures 2,3 “mean annual”, not “annual mean cumulated” (in four places in all). [OK](#)

Figure 4 “cumulated” is unnecessary. [OK](#)

Figure 5 Delete “Absolute value of” and “, respectively”. [OK](#)

Figure 6 Change “combined with absolute” to “, and”. [OK](#)

Figure 7 Perhaps the lines for Stake data and RACMO2.3 could be made thicker, so as to distinguish them from the single-stake lines. [OK](#)

Figure 8 Add the stake identifiers along the top axis of the graph to make it easier to interpret the caption. [OK](#)

Review#2: Anonymous Referee

Improvements:

1. The paper reads more like a model evaluation paper than a study into the effects of summer snowfall on the ice sheet. I suggest updating the title to reflect this.

We modified the title as follow: "Evaluation of the updated regional climate model RACMO2.3: summer snowfall impact on the Greenland Ice Sheet"

2. Given that the focus of the paper is very much on evaluating the different RACMO simulations, it is a little disappointing that only the K-transect AWS data is used, although no doubt for good reasons. Nonetheless, the GC-Net and PROMICE networks of AWS have freely available measurements of the usual meteorological variables, even if only for a short period compared to the simulations here. It would be nice to see at least a few of these used as well since we would expect the biases within and between the models to be spatially varying and using one or two other observation locations would help to tease this out.

Obtaining reliable surface energy balance (SEB) components from AWS measurements represents a considerable effort: it requires an SEB model, multiple data corrections and assumptions, e.g. about snow density and snow accumulation. Moreover, AWS data do not provide information about precipitation rate, which is the focus of this paper. Therefore instead we chose to extend the model evaluation using additional accumulation data from ice cores across the ice sheet (see reply to comment 3 below).

3. The authors also assert that precipitation (and cloud cover) is improved without showing any evidence for this. While recognizing this is not easy to measure in Greenland, I note there are observations from shallow cores and the DMI coastal stations which could be useful for this purpose and again just a few key locations compared with the two simulations would help to show this. Cloud cover is also observed at Summit and some coastal stations and this could be interesting to compare too since the LW/SW fluxes are a crucial part of the story and the conclusion asserts, again without offering evidence, that the new RACMO has improved clouds. I emphasise this point as getting accumulation right is crucial for e.g. ice sheet modelling.

We agree with the reviewer that accumulation is a crucial parameter for this paper. Precipitation data from coastal stations are notoriously unreliable, as ordinary precipitation gauges which are used suffer from considerable undercatch. Moreover, these stations are situated in very heterogeneous terrain which hampers a comparison using model data with limited resolution. So instead, we decided to expand the model evaluation using 87 accumulation data derived from ice cores drilled on the ice sheet (new Figure 8). This figure confirms the general improvement of RACMO2.3 over RACMO2.1. Note that the evaluation only includes sites with observations that overlap in time with both model runs.

An evaluation of cloud cover is beyond the scope of this study; this particular topic is addressed in another paper by Kristof van Tricht et al. (currently under review), where a comparison is made with satellite cloud and derived surface radiation products.

4. Similarly for the SMB estimates from stake measurements around the ice sheet, although the K-transect measurements are pretty much the gold standard in Greenland, it would be nice to include a few other data sets from different locations (eg NEEM, Summit, NGRIP, Promice stations etc). The authors mention an ongoing study along these lines, but I see no reason why at least some of these other datasets could not also be combined here as it would strengthen the argument for the improved RACMO setup.

See previous answer: an additional 87 accumulation observations around the GrIS have been used to extend the model evaluation (new Figure 8). Recently, a new ablation dataset has been compiled by Horst Machguth and will be published in the Journal of Glaciology. Unfortunately, because these data are not yet published, we can not use these to expand the comparison. That is why a specific comparison of ablation measurements with a 1 km, downscaled product of RACMO2.3 will be discussed in a forthcoming paper.

Alternatively, perhaps a comparison of the new model with the old using the runoff data into the Nuuk fjords presented in Van As et al. 2014 would be instructive as this includes a region that certainly would see the effect of the different partitioning of snow and rainfall.

In this case, comparing the runoff simulated by both model versions with observations does not provide additional information. The main reason is that the differences in runoff between both model versions are rather small (~200 mm we at most) and well inside the observational uncertainty range.

5. Section 3.2 on large scale changes in circulation, is not very clear. What causes the change in 500 hPa height? The paragraph implies that this is a response to the cooling in the upper troposphere? How do you know? Some fairly large changes appear to have been included in boundary layer, turbulence and radiation schemes which may also partly account for this.

We agree that many other processes could contribute to this modelled cooling. However, we only clearly identified a progressive reduction of condensation with altitude, which is likely related to the introduction of supersaturation, in turn cooling gradually the upper-atmosphere by reducing the release of latent heat. We reformulated as follow: "Among other processes, reduced upper-air condensation, attributed to the introduction of ice supersaturation in the updated physics, contributes to this cooling."

Minor comments:

P1180 L7,11 write "section" in full **OK**

P1183 L25-26 also **OK**

P1185 L18-19 I share Graham Cogley's dislike of this kind of sentence structure. Please make it into two sentences as it is much easier to read. **OK**

P1184 L13-15 This sentence needs revising to make it simpler to read

We reformulated the sentence to make it less confusing: “In addition, the vicinity of the polar front, which predominantly produces easterly flow to its north, causes depressions to propagate eastward towards southern Greenland. This leads to a pronounced topographically forced precipitation maximum along the southeastern coast.”

P1186 Section 4 please state which grid cell you used to make the comparison with. Was it the same procedure as when comparing SMB? This is a non-trivial problem when comparing point observations with 11x11 model grids as the authors acknowledge elsewhere.

We decided to add a paragraph in the “Observational data” section to explain more clearly the selection method we used and in which conditions. “To compare model to observations, we apply a distinct selection method in the ablation and accumulation zones of the GrIS. In the accumulation zone, modelled SMB is obtained by selecting the closest RACMO2 grid cell. Due to significant dependence of ablation terms on elevation, modelled SMB and SEB components were retrieved by successively selecting the nearest grid cell and then applying an altitude correction. To do so, we select a grid cell, among the closest pixel and its 8 adjacent neighbours, which minimizes the elevation bias between the model and the stations.”

Tables & Figures

Figure text (at least on my print out) was mostly unreadably tiny, especially in Figure 5. [OK](#)

On figure 1 the change in background albedo was also difficult to see, perhaps this could be enlarged or an alternative colour scheme used? [OK](#)

Apparently, cumulated is an English word as I looked it up in the OED. Stylistically I prefer accumulated or cumulative but this is a matter for the editor as it is personal preference! I should say that given all authors are non-native speakers the grammar, spelling and English usage is exceptionally good (though not surprising!). [Thank you.](#)