

Authors response:

Dear reviewers and editor,

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 and modifications in the manuscript in orange to facilitate readability.

Main modifications:

To address the Reviewers' suggestions, we changed the title of Section 6 to *"Added value, limitations and uncertainties"* and included a new paragraph describing Figure 13 (see additional figure below). In this paragraph we discuss the added value of SMB v1.0 and how it improves on RACMO2.3 when compared to in-situ measurements. SMB v1.0 is an overall improvement on RACMO2.3 but most notably so in the lower ablation zone where the largest elevation and bare ice albedo corrections are applied. *"The downscaled SMB v1.0 is the first dataset to provide daily SMB estimates for all outlet glaciers of the GrIS at a 1-km resolution and for 58 years (1958-2015). Relative to the original RACMO2.3 output, this dataset improves local SMB values (Fig. 7) and produces more realistic SMB patterns over rugged glaciated areas along the GrIS margins (Figs. 9-12). Figs. 6 and 8 show that SMB v1.0 is an overall improvement on the original RACMO2.3. To further investigate this, Fig. 13 shows the annual mean SMB RMSE (model vs. observations) of the 11-km SMB field in RACMO2.3 (red), the downscaled product v0.2 (green) and v1.0 (blue) as a function of observed SMB, binned in 0.5 m w.e. intervals. In the ablation zone (SMB < 0), the SMB RMSE is reduced by 29-65% in v1.0 relative to the 11-km product, owing to the elevation correction in v0.2 (9-23%) and the additional albedo correction (20-42%). In the accumulation zone, the elevation dependence (9%) and the precipitation adjustment (19%) also contribute to reduce the SMB RMSE by 28% in v1.0. The largest RMSE reduction occurs in the lower GrIS ablation zone, where improvements in topography and bare ice albedo in v1.0 are greatest."*

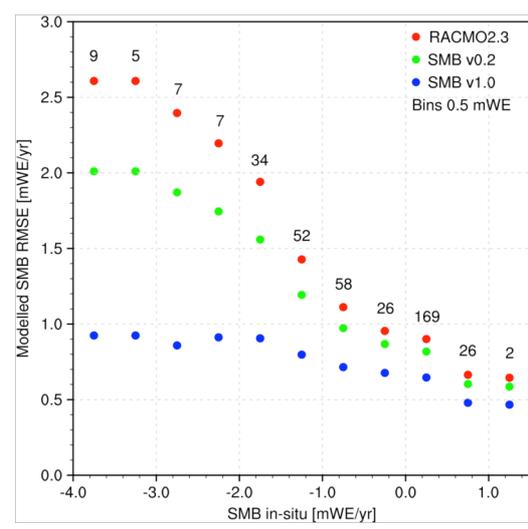


Fig. 13 Annual mean model SMB RMSE (model vs. observations) of the 11-km SMB field in RACMO2.3 (red dots), the downscaled SMB dataset v0.2 (green dots) and v1.0 (blue dots) as a function of observed SMB (395 observations). Modelled SMB is grouped in 0.5mWE/yr bins except for the first bin, which ranges from -6.00 to -3.75mWE/yr. Numbers indicate the amount of observations used in each bin.

We also improved the general figure display and modified the manuscript as suggested by the Reviewers. Fig. 6a-c were revised to correct for a small remaining mistake in the associated script. Related numbers in Section 4 were also corrected accordingly.

Referee#1: Anonymous

The main purpose of this paper is to present a new 1-km resolution RACMO2.3 dataset, describing the methods used and the successes and failures of the new data, particularly in comparison to the previous standard 11-km RACMO2.3 output. Certainly a 1-km dataset would be widely used and a great asset to the research community.

General comments:

Overall, I think the authors need to do a better job of making the readers job easy. A reader is going to be interested in this paper to learn about the 1-km product, the advantages and disadvantages it has, and how and when to trust the data. To do this, it's important that the authors do more to translate the technical methods into explanations of actual physical processes and mechanisms. Several examples are mentioned more explicitly below, but a primary example is the sentence at **L367**: "The extreme elevational SMB gradient that results over the narrow ablation zone is then poorly captured at 11-km, and hence also poorly represented at 1-km." This sentence raised a big red flag in my mind. Isn't the whole point of this downscaling that it can succeed at better representing things like a narrow ablation zone? With better explanation this might not seem so surprising or at least allay doubts the sentence raises about the broader success of downscaling.

We removed the sentence at **L367**, as it was unclear. Even at this location, most of the remaining bias that persists after the elevation correction in v0.2 (Fig. 6b) is removed in v1.0 when correcting for ice albedo (Fig. 6c).

The explanation of some of the downscaling methods is not clear. For example, around **L158**, the requirement of 6 adjacent ice-covered pixels is confusing. Please clarify: will a pixel only be considered if at least 6 of its neighbor points are ice-covered? In section 3.2, you've explained by 6 points are chosen, but need to provide an explanation for how you decide which 6 points to use.

Again, the original text was unclear. We use the maximum amount of points available to calculate a regression but at least 6 cells are required, i.e. the actual grid point and at least 5 adjacent pixels. These grid cells must 1) be adjacent to the current pixel, 2) be ice-covered, 3) have a non-zero value when downscaling melt and runoff. We apply condition 3) to preclude null or extreme runoff/melt regression slopes. If the current grid cell does not obey all these conditions, it is discarded until the extrapolation step. To make this clear, we reformulated as follow: "[...] ice-covered RACMO2.3 grid-point *using the maximum amount of points available, i.e. we use a total of six to nine ice-covered grid cells, being the current one and minimum five to maximum eight adjacent pixels.*"

Also, the wording through here can be confusing – e.g., in **L168**, does this refer to the 11km or the 1km data?

Here we refer to the 11-km grid, as was stated in the manuscript. At this stage, the downscaling algorithm extrapolates outwards - on the 11-km grid - the values obtained during the previous step of the regression slopes (b_{11km}) and intercepts (a_{11km}) to fully cover the 11-km domain and hence the entire ice mask at 1-km.

Specific comments:

L231-255.

1) This section needs more explanation and translation. The job of the authors is to make the readers job easy.

To stress the aim of the ice albedo correction, we included the following sentence: *"The bare ice albedo bias correction aims at minimizing the misfit between downscaled SMB v0.2 and in-situ measurements (Fig. 6b) by estimating the missing runoff in the low ablation zone in v0.2."*

2) I also thought that the f_{scale} value seems large. Could you add more comment on this? Speculation on how much this influences results?

To clarify the meaning and impact of f_{scale} , we added the following lines: *"This means that RU_{add} , i.e. accounting for elevation and bare ice albedo corrections, has yet to be increased by ~18% to optimise the agreement between downscaled and in-situ SMB (Fig. 6c)."*

In the manuscript, we explicitly stress that underestimated sensible heat fluxes (Fausto et al. [2016]) and underestimated cloud formation at the GrIS margins (Van Tricht et al. [2015]) are most likely responsible for the ~18% underestimation in ablation. However, the statistical downscaling approach is not designed to correct for these physical processes. We inserted the following sentence: *"However, as the statistical downscaling approach is not designed to correct for these physical processes, we adopted the empirical approach presented above."*

3) A reader is trying to assess how "true" the results from RACMO2.3 1km product are and some additional comment is needed here to make this clear.
See [Main Modifications](#) above and the additional Figure 13.

L206-207. Can you please provide a citation or additional information about why this is a reasonable assumption?

There is no physical basis for this assumption, which can be further refined in future versions of the downscaling procedure. The partitioning of diffuse and direct radiation is highly sensitive to weather conditions, i.e. clear or overcast sky, and can be highly variable within a single day (cloud formation or advection). Because RACMO2.3 output does not provide this partitioning on a daily basis, and to keep the approach straightforward, we decided to equally partition total radiation into direct and diffuse radiation. To clarify, we added the following sentence: *"This assumption is purely pragmatic; on the basis of data availability, it could be further refined in future versions of the downscaling procedure."*

L209.

1) Why is this correction only applied when there's both surface runoff and melt?

The reasoning here is that the ablation underestimation in Fig. 6b is mostly driven by overestimated ice albedo in the 11-km SMB product. Therefore, the correction is exclusively applied in the ablation zone ($SMB < 0$) characterized by non-zero melt and runoff in v0.2. We inserted the following sentence: *"Figs. 6b and 8 show that ablation underestimation in v0.2 is restricted to the low ablation zone ($SMB < -4$ mWE), where bare ice is exposed for long episodes in summer. Therefore, the following corrections are only applied to the ablation zone on days of melting bare ice when both surface runoff and melt are non-zero in the downscaled product v0.2."*

2) Shouldn't this be corrected for even when there's only melt because it may actually push the conditions at that pixel into a runoff regime instead of just refreezing or no runoff? Seems like this would influence the correct modeling of runoff extent.

The melt/runoff area is already corrected by applying the elevation dependence in v0.2 and further reconstructing melt and runoff using the estimated gradients and topography at 1-km. As a result, SMB v0.2 improves much the representation of the ablation zone although significant SMB biases remain and are corrected in v1.0.

L285. How are the climate conditions at Helheim "peculiar"? I'm not aware of any research that discusses conditions there being particularly different than many other outlet glaciers. This needs further explanation and/or citation.

The Helheim transect shows very small measured SMB gradients compared to other locations (see 'b' value in the plots), resulting in a quasi-constant ablation rate for all elevations (~ -1 mWE). The reason for this low SMB gradient is not clear at present although we noticed that each individual observation covers only 1 or 2 summer months. We reformulated as follow: *"The downscaled product fails at reproducing the quasi-constant ablation rate (~ -1 mWE) characterizing the Helheim transect. The reason for this low SMB gradient is not clear at present; it may be due to uncertainties in individual observation covering relatively short periods, i.e. 1 or 2 months, which are only limited to the melt season (July-August). Another possible explanation is that Helheim glacier experiences pronounced winter accumulation at low elevations, potentially caused by drifting snow transport, limiting summer ablation."*

L297+.

1) This is another area where more explanation would be helpful. Rather than just stating that the bias was removed, can you provide any explanation for the mechanisms possibly responsible for this bias?

In RACMO2.3, clouds formation occurs at too low elevations resulting in overestimated precipitation at the margins, e.g. southeast Greenland, while the ice sheet interior experiences too dry conditions. This bias is partly solved in RACMO2.3 by allowing ice cloud super-saturation, which delays precipitation formation to higher elevations (Noël et al., 2015). To overcome this bias, additional improvements have to be implemented in the cloud scheme. Eventually, repeating the downscaling procedure using forthcoming RACMO2.4 output would make the precipitation adjustment unnecessary. We inserted the following sentence: *"Despite significant improvements in the cloud scheme of RACMO2.3 (Noël et al., 2015), clouds become saturated and start to produce precipitation at too low elevations, resulting in overestimated precipitation at the margins, e.g. southeast Greenland, while the ice sheet interior experiences too dry conditions. This precipitation bias is currently being investigated, and we aim to resolve it in the upcoming version RACMO2.4."*

2) A justification for this adjustment beyond just making the data fit? This is an important opportunity to build confidence in the model and understanding of what the model does/does not do.

The justification is that RACMO3 systematically underestimated accumulation in the interior, because of the process described above. We added: *"To overcome the systematic negative SMB bias of RACMO2.3 in the GrIS accumulation zone (-37.5 mmWE/yr, Fig. 8), the daily total precipitation v0.2 is adjusted to correct for underestimation in the ice sheet accumulation zone (SMB > 0 mmWE/yr):"*

L325+. Add % in parentheses with all numbers since you started to do this in this section. Thank you for pointing that out.

L448. The end of the paper does not provide a useful summary conclusion. A useful conclusion would provide a final plain language assessment of the 1km product, the main focus of the paper.

We added the following paragraph at the end of the discussion section: *"We anticipate that the new, 1-km Greenland SMB product is especially useful for studies that address the mass balance of Greenland outlet glaciers that are too steep and/or narrow to be properly resolved at the typical horizontal resolution of regional climate models (~ 5-15 km). Future downscaled products can have even higher resolution (100m) and will be based on further improved RCM output fields of precipitation and melt."*

Figure 1. Recommend adding legend to figure for yellow and white points.

We included the suggested legend accordingly.

Figure 4. This figure is confusing. One simple improvement for a) would be changing the ends of the lines that the arrows are on – the arrow should point from the description to the item it's describing. Also, you should 8 sample points here even though the methods indicate 6 were used – the figure should be as close to the actual case as possible. The panel b was poorly referenced in the text and also confusing.

We decided to follow Referee#2 suggestions to improve Fig. 6a (see Referee#2 Figure 4a). We decided to keep Fig. 4b as is and now refer to it earlier in the text.

Figure 7.

1) I found it difficult to compare these plots because they all have different axes. How does the agreement look when all put on the same axes?

We decided not to modify the axes ranges. The axis range was chosen for each transect to optimize the readability and clarity of the figure. Using identical axes would prevent clear distinction between downscaled and in-situ SMB for many transects.

2) The location labeling in Figure 1 is poor – it's not entirely clear where these transects are and they should probably be represented by something other than overlapping yellow dots. Owing to the large number of measurements, the multiple case study regions and the transects' names, it would be somewhat difficult to improve the overall display of this figure. We deemed it important to show as many stations as possible even though they locally overlap. Letters are now closer to the associated transect to improve clarity.

3) 79N and Helheim have the same agreement problems near the terminus, but only 1 is mentioned in the text.

Thank you for pointing this out. We hypothesize that at 79N and Storstrømmen, SMB measurements lower than 200 m are located on floating glacier tongues with melt ponds, resulting in very low satellite albedo, while stake measurements are performed between ponds on brighter surfaces. As a result, the bare ice albedo correction could be overestimated. We now discuss this in more detail in the revised text: *"In addition, Nioghalvjerds-fjorden and Storstrømmen transects (Figs. 7a-b) also show significant remaining biases between in-situ and downscaled SMB at elevations lower than 200 m. We hypothesize that these SMB measurements are located on floating glacier tongues with melt ponds, resulting in very low satellite albedo, while stake measurements are performed between ponds on brighter surfaces. As a result, the bare ice albedo correction could be overestimated."*

Figure 8. How well-paired are these? Since it's the agreement between blue and red that is part of the main point, it's important to have a sense about the how well the points pair

with each other. The upper right points seem to suggest that it's quite close, is this similar for all points?

The aim of this figure is to show that the downscaled product v0.2 (blue dots) generally fits the observations better (dashed black line) than the original RACMO2.3 output (red dots). This is also supported by slightly reduced bias and RMSE in the downscaled product v0.2. Ultimately, the bias of course becomes zero in v1.0.

Figure 9. Panel labels should be added since these cover such a wide range of variables/values.

We modified the figure display accordingly (see Referee#2 Figures 9-12).

Referee#2: Anonymous

This manuscript presents a newly developed downscaled version of the RACMO regional climate/SMB model. The downscaling procedure applies a statistical elevation correction using the GIMP DEM, a correction leading to increased runoff via lower than-modeled and higher resolution MODIS albedo, and a bias correction to account for RACMO's apparent systematic underestimation of precipitation in the GrIS accumulation zone. The resulting 1-km downscaling of RACMO2.3 shows a notably improved agreement with in situ observations. In particular, the authors highlight better representation of marginal GrIS regions, where complex topography and steep elevation gradients result in large SMB gradients that are poorly resolved in the native 11-km RACMO. Given that RACMO is widely used in the glaciological community, the improved and higher resolution version presented in this paper will certainly be of wide interest.

General comments:

Below are comments that pertain mostly to the presentation of the material, as opposed to the downscaling methods employed. Overall, I believe the authors need to do a better job at describing the methods and presenting the results in their figures. Finally, I would suggest that the authors consider including more information (perhaps in a new section) on where the new dataset really shows promise for understanding the SMB variability and physical/climatic processes affecting the GrIS. Improved overall agreement with observations is shown (Fig 6), as well as improvements along some transects (Fig 7), and then the authors show some example regions while noting the effects of downscaling. However, the reader is largely left to decipher where the "old" RACMO still works, where the downscaling does a more realistic job, and areas where the SMB is still uncertain (and why). Given the wide use of RACMO, understanding a bit more where these uncertainties lie would be very helpful for the community, while also making for a much stronger manuscript. See [Main Modifications](#) above and the additional [Figure 13](#).

Specific comments:

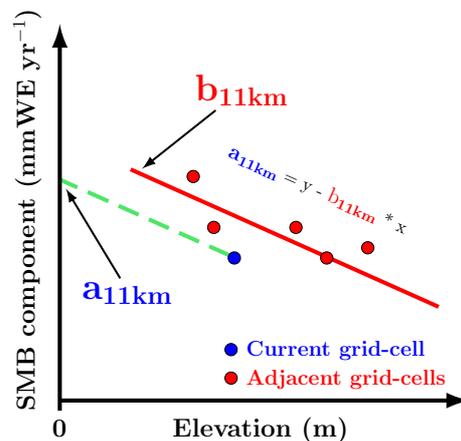
Abstract. You reference the elevation correction almost exclusively here (except for the last sentence), but the albedo correction in particular, and accumulation zone precipitation bias correction to a smaller degree, are also important to improving agreement with the observations. I would add reference to these other two important steps in the abstract.

We reformulated as: *"Applying corrections for elevation, bare ice albedo and accumulation bias, the high-resolution product is statistically [...] RACMO2.3 at 11-km."*

Figure 4a and L160+. The method for calculating the regression slope (b11km) using the

adjacent grid cells is clear: i.e., using a maximum of the 8 adjacent grid cells with different elevations and SMB components to generate a linear regression. This figure (and the text), however is somewhat confusing at first because it looks like a separate regression (the blue line, seemingly labeled a_{11km}) is being generated using only the single blue “current grid-cell” point. After studying this figure, my interpretation is that the blue line is simply applying the (red) regression slope (b_{11km} , red line) and the blue point’s x and y values to estimate the intercept, a_{11km} . At first glance, this is not apparent. I would suggest revising this figure to make it more clear. Perhaps you could make the blue line a different color (e.g., green), make it dotted, and only extending from the blue “current grid-cell” point to the y-axis, and have an arrow pointing toward this intercept point, labeled a_{11km} . This would make it look like less of a separate regression, and more clear that you’re just calculating the intercept using the local regression slope (b) and only the central grid cell elevation (x) and SMB component value (y). Perhaps you could also indicate this by showing the formula $a_{11km} = y - b_{11km} * x$ on the figure. I would also suggest including a legend to label the red points “adjacent grid cells” and blue point “current/central grid point”. Also, you should probably only show 6 adjacent grid cells, as this is what you end up using.

Thank you for these useful suggestions, we modified Fig. 4a accordingly (see updated figure below).



A perhaps bigger question I have about the method is why not just use the intercept value obtained from the first linear regression of the current grid cell and its adjacent cells?

Applying the regression directly would result in regionally smoothed a_{11km} and a_{1km} fields, negatively impacting the added value of the 1-km SMB components. To highlight this we inserted the following sentence: *“The regression is applied to the current grid cell to prevent local estimates of a_{11km} to significantly differ from the original RACMO2.3 value.”*

L165-168.

1) The method step here is unclear. Are you enlarging the native 11-km grid to match the larger spatial extent of the 1-km grid?

Indeed. To make this clear, we reformulated as: *“Next, valid estimates [...] on the 11-km grid to fully cover the more extensive 1-km ice mask.”*

2) Can you indicate how often this was used?

The extrapolation is also daily specific; we now mention it clearly in the manuscript. *“To that end daily regression parameters are extrapolated outwards [...]”*

3) Is this just at the lateral margins of the ice sheet?

The algorithm extrapolates a_{11km} and b_{11km} at the ice sheet margins as the relatively coarse

11-km RACMO2.3 ice mask is not able to resolve small Greenland peripheral ice caps and marginal GrIS glaciers for which estimates of $a_{1\text{km}}$ and $b_{1\text{km}}$ are crucial to reconstruct SMB at 1-km.

L207-210. Why not apply this correction to all grid cells? Certainly for some grid cells, this would provide enough additional energy to generate melt (i.e., in non-melt cells), and for other cells, sufficient additional melt to generate runoff in cells where melt doesn't already exceed refreezing. It seems to me that this extra SW absorption may be important not just for cells that already have runoff, but the whole GrIS SEB and snowpack temperatures as well through both increased SW absorption and latent heat release upon refreezing in areas that melt.

See response to Referee#1 at **L209 1-3**.

L248. Could it also be possible that this is due to only selectively applying the correction to cells already experiencing runoff?

The f_{scale} value is mostly driven by the missing ablation in low-lying areas where sensible heat flux may be underestimated in RACMO2.3 (Noël et al. (2015) and Fausto et al. (2016)). The ablation zone is well represented in the downscaled product owing to 1) the elevation correction of runoff (v0.2); 2) the bare ice albedo correction in ablation areas showing a surface albedo < 0.55 , i.e. bare ice exposure at the surface. See also reply to Referee#1 L209 (2) and L231-255 (2).

L273-274 and Figures 6a,b. A more minor point: I calculate a 16.25% decrease in the RMSE, not 18%. On **L279**, I calculate a 81.25% decrease in bias, not 88%.

Thank you for pointing this out. As explained in [Main Modifications](#), Fig. 6a-c still included small mistakes and had to be revised. We also corrected the associated numbers accordingly.

L291 and Figure 8. Text here refers to SMB v0.2, but figure states it shows SMB v1.0. Which is it?

It should be v0.2 instead of v1.0, thank you.

And you state you applied the bias correction to places where $\text{SMB}_{\text{v1.0}} > 0$ mmWE/yr, but to get $\text{SMB}_{\text{v1.0}}$, was it not necessary to first calculate $\text{PR}_{\text{v1.0}}$? This seems circular to me.

This was unclear in the original text. We reformulated as: *"To overcome the systematic negative SMB bias of RACMO2.3 in the GrIS accumulation zone (-37.5 mmWE/yr, Fig. 8), the daily total precipitation v0.2 is adjusted to correct for underestimation in the ice sheet accumulation zone ($\text{SMB} > 0$ mmWE/yr):"*

We also added the following sentence: *"The final $\text{SMB}_{\text{v1.0}}$ product is reconstructed as: $\text{SMB}_{\text{v1.0}} = \text{PR}_{\text{v1.0}} - \text{RU}_{\text{v1.0}} - \text{SU} - \text{ER}$ (12)"*

Figures 9-12. Can you add the names of these areas from table 1 in the respective figure captions? This would facilitate interpretation and cross reference between figure 1, table 1, sections 5.1-5.5, and these figures. Also, I found myself constantly needing to refer to the caption to interpret the panels. This became more problematic with figures 10-12 as I had to refer back to figure 9's caption. Please add some basic identifiers/titles to each panel.

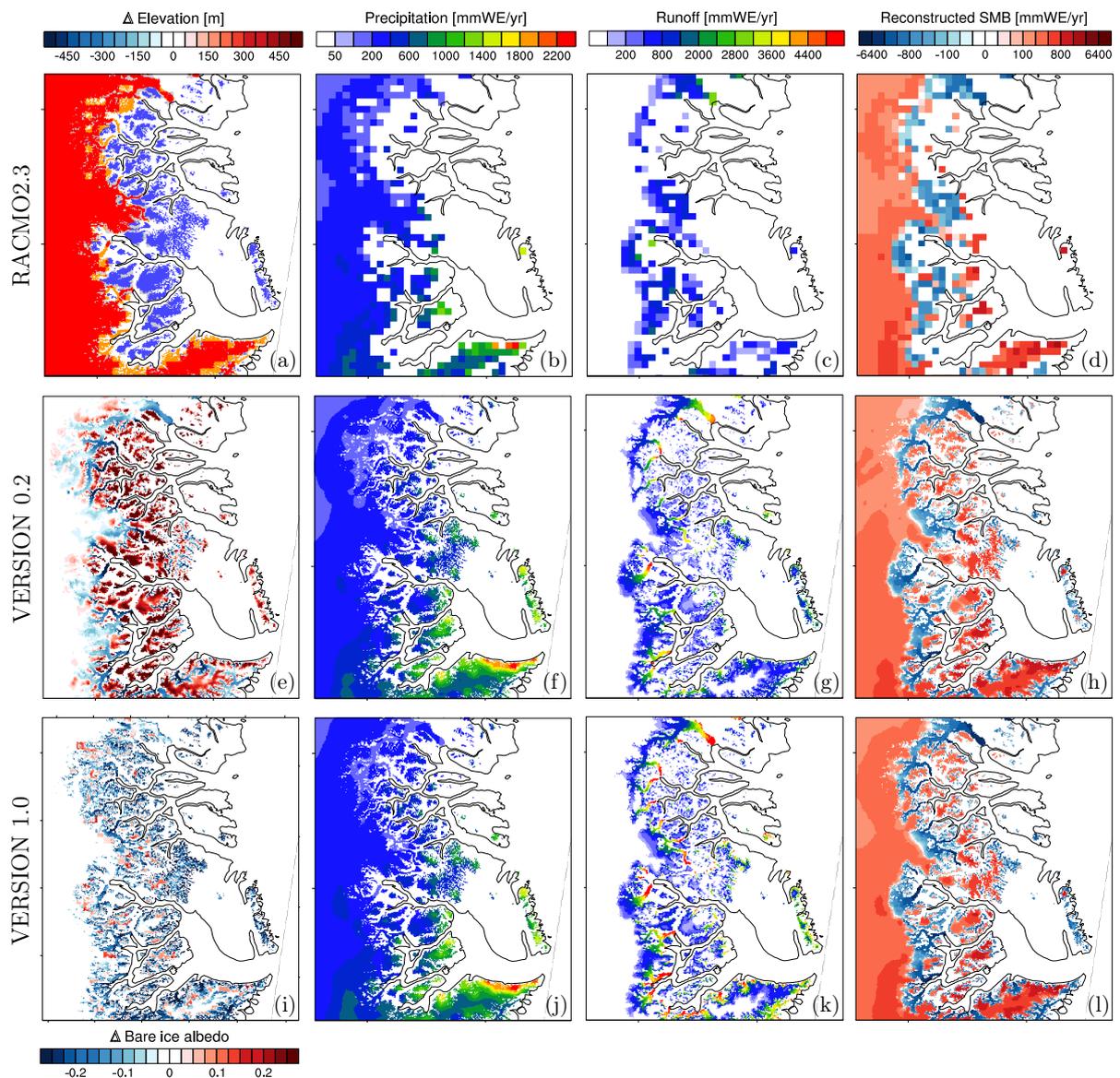
We updated Figs. 9-12 and captions accordingly (see updated Fig. 9 at **L334-335** below).

Panels k and l also incorporate the SMB bias correction, right? This is not clear from the caption, but it is suggested in the text (lines 330-331). Please also specify in the caption.

We updated the figures and modified the caption accordingly. “Centre east: a) Ice sheet mask in RACMO2.3 at 11-km (red) and in the down-sampled GIMP DEM at 1-km (orange) (blue box 1 in Fig. 1), and the mask of disconnected glaciers and ice caps at 1-km (blue); average (1958-2015) annual mean b) total precipitation, c) runoff and d) SMB (mmWE/yr) modelled by RACMO2.3 at 11km; e) elevation bias (m) between 1-km and 11-km resolutions. Figures f), g), h) represent annual mean total precipitation, runoff and SMB downscaled to 1-km using elevation dependence only (v0.2). Figure i) shows the bare ice albedo bias between MODIS measurements at 1-km (2000-2015) and RACMO2.3 at 11-km (2001- 2010). Figures j), k) and l) are similar to f), g) and h) but incorporate the bare ice albedo and precipitation corrections (v1.0).”

L334-335. A systematic overestimation of bare ice albedo is difficult to see here given the different grid sizes. Can you show a plot of the albedo bias as you’ve done for elevation in panel e of figure 9?

As suggested, we replaced Fig. 9-12 (i) by Δ BIA (bare ice albedo) and Fig.9-12 j by PRv1.0 (see example Figure below).



L351-352. Should these figure references to runoff be Fig 10 g and k (not h and l)?

Yes it should, thank you.

L360. Similar to above, should these references to increased melt refer to the runoff plots (g and k) rather than SMB (where differences are less perceptible)? Same for **L374**.

Thank you for pointing this out, we modified as suggested.

L414-416. This affects the entire GrIS, right? Perhaps change “high latitudes” to specify GrIS margins.

This issue mostly occurs at high latitudes where the satellite signal shows a slight tilt, potentially mixing radiances from neighboring tundra and ice scenes. It also affects the glacier floating tongues at the GrIS margins so we inserted the following sentence: *“Note that floating glacier tongues also show too low surface albedo, e.g. Petermann glacier (yellow dot in Fig. 12a), resulting from mixed signals from adjacent dark melt pond and brighter dry ice. The resulting albedo underestimation over low-lying floating tongues below 200 m leads to overestimated ablation (~ 0.2 mWE/yr; Figs. 7a and b); [...]”*.

L417-418.

1) I assume the underestimation of bare ice albedo prior to 2000 is because the MODIS time period used of 2000-2015 was one of very high melt, right? If so, you should explicitly state this.

We reformulated as: *“[...] underestimate the bare ice albedo prior to 2000 as the period 2000-2015 encompasses multiple record high melt years.”*.

2) This leads me to a second point on the use of the MCD43A3 dataset. It is known that the MODIS Terra sensor has degraded, giving too strong of an albedo decrease for Greenland. The MCD43A3 data are affected since they incorporate both Terra and Aqua observations (e.g., Polashenski et al., 2015, GRL, and others). I would suggest at least acknowledging this as a limitation in this section.

Thank you for this suggestion, we included this as an additional limitation. *“[...] d) the degradation of MODIS Terra sensors (Polashenski et al., 2015).”*

Technical corrections:

L9. “confined glaciated areas” is a bit unclear, could you reword this somehow?

We reworded as “isolated”.

L163. change erratic to erroneous. **OK.**

L179. remove comma. **OK.**

L181. Specifying that you are estimating b11km would be helpful here. **OK.**

L187. remove “are”. **OK.**

L191. specify “native resolution” or 11-km when referring to RACMO2.3 here. **OK.**

L281. specify Figure 11a for yellow dot. **OK.**

L288-290. Please add reference and better explain how this seasonality is different than that of other sites, e.g., Nordbogenscher, which is in a similar region that presumably experiences similar SMB seasonality. See response to Reviewer#1 **L285**.

Figure 7 caption. make reference to Figure 1 for locations. **OK.**

L356. remove “the” in “larger the glaciated”. **OK.**

L385. Fix reference to Figure 12 i and j. **OK.**

L386. Fix reference to Figure 12 h and l. **OK.**

A daily, 1-km resolution dataset of downscaled Greenland ice sheet surface mass balance (1958-2015)

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Abstract.

This study presents a dataset of daily, 1-km resolution Greenland ice sheet (GrIS) surface
mass balance (SMB) covering the period 1958-2015. **Applying corrections for elevation, bare
ice albedo and accumulation bias**, the high-resolution product is statistically downscaled
5 from the native daily output of the polar regional climate model RACMO2.3 at 11-km. The
dataset includes all individual SMB components projected to a down-sampled version of the
Greenland Ice Mapping Project (GIMP) digital elevation model and ice mask. The 1-km
mask better resolves narrow ablation zones, valley glaciers, fjords and disconnected ice caps.
Relative to the 11-km product, the more detailed representation of **isolated** glaciated areas
10 leads to increased precipitation over the southeastern GrIS. In addition, the downscaled
product shows a significant increase in runoff owing to better resolved low-lying marginal
glaciated regions. The combined corrections for elevation and bare ice albedo markedly
improve model agreement with a newly compiled dataset of ablation measurements.

1 Introduction

15 During the last two decades, the Greenland ice sheet (GrIS) experienced significant mass
loss as a result of increased meltwater runoff and sustained high solid ice discharge from
marine-terminating outlet glaciers (Van den Broeke et al., 2009; Rignot et al., 2008, 2011;
Sasgen et al., 2012; Shepherd et al., 2012; Enderlin et al., 2014). To fill spatial and temporal
gaps in the scarce in-situ observations, regional climate models (RCMs) are often used to
20 produce maps of the GrIS surface mass balance (SMB; Van Angelen et al. (2013); Burgess
et al. (2010); Ettema et al. (2010a,b); Fettweis (2007); Fettweis et al. (2005, 2011); Noël
et al. (2015); Lucas-Picher et al. (2012)). RCMs explicitly calculate the individual SMB
components (Lenaerts et al., 2012), i.e. precipitation, runoff and sublimation, over the en-
tire ice sheet (Fig. 1) at high spatial and temporal resolution and over extended periods.
25 However, the current spatial resolution of RCMs, typically 5 to 20 km, remains too coarse
to accurately resolve glaciated areas in topographically complex regions such as small iso-
lated ice caps and marginal outlet glaciers flowing into narrow fjords. In these regions, the
relatively coarse elevation and land ice masks used in RCMs might result in runoff underes-
timation (Franco et al., 2012; Noël et al., 2015), hampering realistic regional SMB estimates.
30 Performing higher-resolution simulations to address these issues would require a substantial
computational effort and is thus restricted to case studies of small regions and relatively
short time periods.

As an alternative, statistical downscaling can be applied to RCM output. Previously,
this method has been applied to the GrIS using global reanalysis and climate data (Hanna
35 et al., 2005, 2008, 2011). Machguth et al. (2013) downscaled near-surface temperature and
precipitation from 3 different RCMs (11-25 km spatial resolution) to force a glacier mass
balance model on a 250 m grid derived from the Greenland Ice Mapping Project (GIMP)
digital elevation model (DEM) (Howat et al., 2014), accurately resolving local glaciers and
ice caps of Greenland. Vertical gradients of climate parameters were iteratively calibrated to
40 enable the mass balance model to generate a realistic melt distribution for the period 1980-
2010, but the very high resolution restricted the analysis to a few regions. Franco et al.
(2012) statistically downscaled GrIS SMB by interpolating each component of the Modèle
Atmosphérique Régional (MAR) from the original 25 km grid to a 15 km resolution. This
method used local daily vertical gradients, except for precipitation, to correct for elevation
45 differences between MAR and a down-sampled version of the 5 km DEM from Bamber et al.
(2001). The elevation correction significantly reduced SMB biases. However, a resolution
of 15 km remains insufficient to resolve the rugged topography at the ice sheet margins; to
address this issue, near-km resolution is necessary.

Here, we present a new dataset of daily, 1-km resolution GrIS SMB components (pre-
50 cipitation, melt, runoff, refreezing, sublimation and snowdrift erosion) covering the period

1958-2015. The SMB product is statistically downscaled from data of the polar regional climate model RACMO2.3 at 11-km (Fig. 1), using an elevation dependent technique based on the elevation and ice mask from the GIMP DEM (Howat et al., 2014), down-sampled to 1-km. The following section briefly describes RACMO2.3, the GIMP DEM, observational datasets and MODIS bare ice albedo product used to evaluate and correct the downscaled dataset. The downscaling algorithm is explained in Section 3. Downscaled SMB is evaluated using ablation and accumulation measurements in Section 4. Section 5 discusses the downscaling results for four different regions and for the entire ice sheet. **The added value, limitations and uncertainties of the downscaling method are argued in Section 6, followed by conclusions in Section 7.**

2 Model and data

2.1 The regional climate model RACMO2

A detailed description of the Regional Atmospheric Climate Model (RACMO2) is presented in Van Meijgaard et al. (2008). RACMO2 incorporates the atmospheric dynamics and physics modules from the High Resolution Limited Area Model (HIRLAM) and the European Centre for Medium-range Weather Forecasts Integrated Forecast System (ECMWF-IFS, Undèn et al. (2002)). The polar version of RACMO2 is developed by the Institute for Marine and Atmospheric Research (IMAU), Utrecht University, and is especially adapted for use over ice sheets and other glaciated regions. Polar RACMO2 is interactively coupled to a multi-layer snow module, accounting for firn densification, meltwater percolation, refreezing and runoff (Ettema et al., 2010a); an albedo scheme with prognostic snow grain size (Kuipers Munneke et al., 2011) and a drifting snow module, simulating snow erosion and the drifting snow contribution to sublimation (Lenaerts et al., 2012). Recently, RACMO2.1 has been updated to RACMO2.3 as discussed in Van Wessem et al. (2014) and Noël et al. (2015). Model evaluation against SMB measurements, collected in the accumulation and ablation zones of the GrIS, showed generally improved agreement (Noël et al., 2015). The native 11-km climate run is forced at the lateral boundaries by ERA-40 (1958-1978, Uppala et al. (2005)) and ERA-Interim (1979-2015, Stark et al. (2007); Dee et al. (2011)) reanalyses and uses the 5 km DEM and ice mask from Bamber et al. (2001).

2.2 GIMP DEM

To downscale RACMO2.3 output, we use the ice mask and topography from the GIMP DEM, described in Howat et al. (2014), and currently considered to be one of the most complete ice masks for Greenland (Rastner et al., 2012). A 1-km ice mask and DEM are obtained by averaging the original 90 m GIMP grid-cells in each 1-km pixel covering Greenland. A

85 1-km resolution is deemed an acceptable trade-off between improved resolution, i.e. a 121
fold improvement compared to the 11-km grid, and manageable data handling given the
daily time resolution, time span (1958-2015) and the number of SMB components. As an
example, Figure 2a shows the topography and ice mask from RACMO2.3 at 11-km in central
east Greenland (blue box 1 in Fig. 1) and Figure 2b the GIMP DEM at 1-km. The latter
90 much better resolves small scale landforms such as narrow fjords and calving glacier tongues.
Integrated over the contiguous GrIS, the ice-covered area of $1.69 \cdot 10^6 \text{ km}^2$ for the 1-km grid
represents a 0.5% decrease relative to the 11-km mask. For our SMB calculations, we only
consider grounded ice, i.e. we discarded floating ice pixels using a 1-km version of the 90 m
grounded ice mask used in Enderlin and Howat (2013).

95 **2.3 Ablation and accumulation measurements**

To evaluate the daily downscaled SMB product, we use 1155 SMB measurements collected
in the GrIS ablation (1073) and accumulation (182) zones. The ablation dataset (Machguth
et al., 2016) was compiled as part of the Programme for Monitoring of the Greenland Ice
Sheet (PROMICE) (Van As et al., 2011) and includes stake and AWS measurements re-
100 trieved from 213 sites (yellow dots in Fig. 1). Accumulation observations were derived from
182 sites including snow pits and firn cores (Bales et al., 2001, 2009) as well as airborne
radar measurements (Overly et al., 2015) (white dots in Fig. 1). We exclusively selected
data having a temporal overlap with RACMO2.3 simulations (1958-2015). We rejected ob-
servations from sites with a $> 100 \text{ m}$ height bias relative to the representative elevation of
105 the 1-km GIMP topography.

To compare modelled and downscaled SMB with observations, different selection ap-
proaches were applied in the ablation and accumulation zones, as described in Noël et al.
(2015). In the accumulation zone, we select the closest grid-cell on the 11-km and 1-km grids
to represent modelled and downscaled SMB, respectively. In the ablation zone, an altitude
110 correction is applied by selecting the grid-cell with the smallest elevation bias among the
closest pixel and its eight adjacent neighbours.

2.4 MODIS bare ice albedo

A 1-km version of the 500 m MODerate-resolution Imaging Spectroradiometer (MODIS)
16-day Albedo product (MCD43A3) is used to retrieve estimates of bare ice albedo in the
115 GrIS ablation zone. Bare ice albedo is estimated as the average of the 5% lowest surface
albedo measurements for the period 2000-2015. A similar ice albedo product is used in
RACMO2.3 based on MODIS observations between 2001 and 2010 (Noël et al., 2015). In
RACMO2.3, bare ice albedo ranges from 0.3, i.e. dark bare ice exposed in the low ablation
zone, to 0.55 under persistent snow cover in the GrIS accumulation zone. Bare ice albedo

120 of glaciated pixels with no valid MODIS estimate are set to 0.47.

3 Methods

The daily, 1-km SMB product consists of statistically downscaled output from a previously conducted RACMO2.3 simulation at 11-km, covering the period 1958-2015. RACMO2.3 settings and lateral forcing are described in Noël et al. (2015). The downscaling algorithm
125 corrects the interpolated SMB components using their local regression to elevation. Figure 3 shows the spatial correlation of individual SMB components with elevation on the 11-km RACMO2.3 grid. The spatial correlation is calculated for each grid-box using 8 adjacent ice-covered pixels.

The elevation correction is exclusively applied to the SMB components which show a significant and spatially homogeneous correlation with elevation, i.e. melt, runoff and sublimation
130 (Fig. 3). These SMB components decrease with decreasing air temperature, represented by a negative correlation with elevation (Fig. 3b, d and e). Although precipitation negatively correlates with elevation over most of the ice sheet, the correlation remains small and highly heterogeneous at the margins (Fig. 3a). Snowdrift erosion exhibits a noisy correlation pattern. Therefore, daily precipitation and snowdrift erosion are bi-linearly interpolated to the
135 1-km ice mask without elevation corrections. Refreezing exhibits a marked bimodal correlation pattern (not shown), gradually increasing with height in the ablation zone, where pore space is more abundant, and decreasing towards the ice sheet interior due to limited meltwater supply. For this reason, and in order to have a consistent liquid water balance, daily refreezing is calculated as a residual:
140

$$RF = RA + ME - RU \quad (1)$$

where RF is the residual refreezing, RA is rainfall, ME is surface melt, and RU is melt-
145 water runoff.

Daily SMB values are obtained by summing the individually downscaled components:

$$SMB = P_{\text{tot}} - RU - SU - ER \quad (2)$$

150

where P_{tot} is total precipitation (liquid and solid), RU is meltwater runoff, SU is total sublimation (from surface and drifting snow) and ER is drifting snow erosion.

3.1 Elevation dependent downscaling

The downscaling algorithm interpolates daily SMB components to the 1-km topography and
155 ice mask in three successive steps (Fig. 4a).

First, the local dependence on elevation is calculated on the original RACMO2.3 11-km
grid. Regression parameters are computed on a daily basis and are, therefore, only valid
for that specific day. A local regression slope, $b_{11\text{km}}$ (mmWE per m, Fig. 4a), is calculated
for each ice-covered RACMO2.3 grid-point using the maximum amount of points available,
160 i.e. we use a total of six to nine ice-covered grid cells, being the current one and minimum
five to maximum eight adjacent pixels. This minimum number is chosen after testing the
downscaling sensitivity to the number of regression cells used, as discussed in Section 3.2. An
approximation of the SMB components at mean sea level, $a_{11\text{km}}$ (mmWE, Fig. 4a), is then
obtained using $b_{11\text{km}}$ and the current pixel. The regression is applied to the current grid cell
165 to prevent local estimates of $a_{11\text{km}}$ to significantly differ from the original RACMO2.3 value.
Local regression parameters for melt and runoff are only computed for pixels experiencing
ablation. Moreover, erroneous positive regression slopes, i.e. increasing melt rates with
altitude, are discarded until the following stage.

Next, valid estimates of $b_{11\text{km}}$ and $a_{11\text{km}}$ are extrapolated iteratively on the 11-km grid
170 to fully cover the more extensive 1-km ice mask. To that end, daily regression parameters are
extrapolated outwards of the 11-km ice mask by averaging $b_{11\text{km}}$ from at least 3 ice-covered
pixels from the eight cells surrounding the current one.

Finally, the extrapolated fields of $b_{11\text{km}}$ and $a_{11\text{km}}$ are bi-linearly interpolated to the
1-km ice mask, providing estimates of $b_{1\text{km}}$ and $a_{1\text{km}}$. The downscaled SMB components
175 ($X_{v0.2}$), i.e. runoff, melt and sublimation, are then computed as a linear function of the
high-resolution topography as:

$$X_{v0.2} = a_{1\text{km}} + b_{1\text{km}} \times \text{elevation}_{1\text{km}} \quad (3)$$

180 The downscaled dataset that is based on the above elevation dependent technique is
hereafter referred to as version v0.2.

3.2 Sensitivity experiment

Figure 5 shows the difference between 11-km and downscaled GrIS integrated daily runoff
in summer 2011. Each line represents a different minimum number of grid-cells, ranging
185 from 3 to 9, used to estimate the local regression of runoff with elevation ($b_{11\text{km}}$; Fig. 4a).
The results are moderately sensitive to the number of regression points used except for the
9 cells setting (current pixel and its 8 neighbours). The latter systematically underestimates

runoff at the beginning and the end of the melt season as it discards all low-lying glaciated pixels at the edge of the GrIS, which experience early melt and largest values of runoff. The standard deviation between the different settings (~ 0.2 Gt/day) is significantly smaller than the difference between 11-km and 1-km runoff (~ 0.6 Gt/day). The more regression points used, the smoother the runoff to elevation gradient field becomes, lowering the downscaled runoff and bringing it closer to the 11-km model output. Conversely, a small number of regression points can lead to spuriously large local gradients. To prevent the downscaling algorithm from substantially converging to, or diverging away from, 11-km RACMO2.3 output, we adopted a setting of **minimum** 6 regression points, which is closest to the average value of the different experiments (± 0.1 Gt/day).

3.3 Melt and runoff adjustments

RACMO2.3 uses a prescribed bare ice albedo field, typically ranging from 0.30 in the low ablation zone to 0.55 under persistent snow cover. It is based on the 5% lowest MODIS values of surface albedo averaged for the period 2001-2010 (Noël et al., 2015). A comparison with a similar 1-km MODIS product averaged for 2000-2015, ranging from 0.15 to 0.55, shows a systematic overestimation of ice albedo at 11-km, especially for low-lying marginal glacier tongues as shown in e.g. Fig. 12i. This causes melt energy to be underestimated during the melt season. To correct for this, downscaled melt and runoff are adjusted by estimating the missing amount of ice melt (ME_{add}) resulting from underestimated absorption of downward shortwave radiation (SW_d). In addition, as RACMO2.3 calculates radiative fluxes on a horizontal plane, the direct fraction of SW_d is corrected for the slope and orientation of each 1-km glaciated grid-cell, as described in Weiser et al. (2016). For simplicity, we assume SW_d to be equally partitioned between diffuse and direct radiation, and that the sun is exactly in the South at noon. **This assumption is purely pragmatic; on the basis of data availability, it could be further refined in future versions of the downscaling procedure. Figs. 6b and 8 show that ablation underestimation in v0.2 is restricted to the low ablation zone (SMB < -4 mWE), where bare ice is exposed for long episodes in summer. Therefore, the following corrections are only applied to the ablation zone on days of melting bare ice when both surface runoff and melt are non-zero in the downscaled product v0.2:**

$$ME_{\text{add}} = \Delta\alpha \times 0.5 \left(\frac{SW_{d \text{ 1-km}}}{L_f} + \xi \frac{SW_{d \text{ 1-km}}}{L_f} \right) \quad (4)$$

where ME_{add} (mmWE per day) is the additional amount of ice melt calculated at 1-km; $\Delta\alpha$ (-) is the difference between the averaged bare ice albedo retrieved from the set of regression cells used to downscale runoff at 11-km and the MODIS albedo product at 1-km; $SW_{d \text{ 1-km}}$ is the modelled daily cumulated downward shortwave radiation bi-linearly inter-

polated to 1-km; L_f is the latent heat of fusion ($3.337 \cdot 10^5$ J/kg) and ξ (-) is the correction
 225 factor for a tilted plane (Fig. 4b), applied to the direct component of downward shortwave
 radiation:

$$\xi = \frac{\cos(\zeta^*)}{\cos(\zeta)}$$

$$\begin{aligned} 230 \quad \zeta^* &= \sin(\zeta)\cos(a)\cos(\sigma)\cos(\Theta) + \sin(\zeta)\sin(\sigma)\sin(\Theta) \\ &+ \cos(\zeta)\cos(\sigma) \end{aligned}$$

$$\zeta = \text{acos}\left(\sin(\phi)\sin(\delta) + \cos(H)\cos(\phi)\cos(\delta)\right) \quad (5)$$

235

where ζ^* is the solar angle of incidence for a tilted plane, ζ is the solar zenith angle, a is
 the azimuth of the tilted plane, σ is the local surface slope, Θ is the orientation, ϕ is the
 latitude, δ is the solar declination and H is the hour angle set to 0 at noon (Fig. 4b). All
 angles are expressed in radians.

240

The bare ice albedo bias correction aims at minimizing the misfit between downscaled SMB
 v0.2 and in-situ measurements (Fig. 6b) by estimating the missing runoff in the low ab-
 lation zone. Additional runoff RU_{add} is calculated by applying a daily specific fraction Γ
 (-) to ME_{add} , estimating the melt contribution to surface runoff. Γ is defined as the ratio
 245 between daily downscaled runoff and melt in v0.2 estimated using elevation dependence only:

$$\text{RU}_{\text{add}} = \Gamma \times \text{ME}_{\text{add}} \quad (6)$$

Assuming that the residual misfit between reconstructed and observed SMB (ΔSMB , Fig. 6b)
 250 for the different ablation sites can be ascribed to underestimated runoff in the low ablation
 zone of the GrIS, RU_{add} is then scaled by a factor f_{scale} (-), obtained by computing a
 least-square fit minimising the difference between ΔSMB and RU_{add} using all ablation
 measurements:

$$255 \quad \Delta\text{SMB} = f_{\text{scale}} \times \text{RU}_{\text{add}}$$

$$f_{\text{scale}} = \frac{\sum \Delta\text{SMB} \times \text{RU}_{\text{add}}}{\sum (\text{RU}_{\text{add}})^2} \quad (7)$$

The least square fit yields a value of $f_{\text{scale}} = 1.176$ for the GrIS. This means that RU_{add} , i.e.
 260 accounting for elevation and bare ice albedo corrections, has yet to be increased by $\sim 18\%$

to optimise the agreement between downscaled and in-situ SMB (Fig. 6c). The fact that $f_{\text{scale}} > 1$ strongly suggests that additional processes might play a role in enhancing surface ablation, e.g. underestimation of modelled sensible heat flux from warm air advection along the GrIS periphery (Noël et al., 2015; Fausto et al., 2016) and uncertainties in cloud representation (Van Tricht et al., 2016). However, as the statistical downscaling approach is not designed to correct for these physical processes, we adopted the empirical approach presented above. The adjusted amount of runoff ($\text{RU}_{\text{v}1.0}$) is obtained by adding the missing runoff to the downscaled runoff ($\text{RU}_{\text{v}0.2}$).

$$\text{RU}_{\text{v}1.0} = \text{RU}_{\text{v}0.2} + f_{\text{scale}} \times \text{RU}_{\text{add}} \quad (8)$$

The corrected melt ($\text{ME}_{\text{v}1.0}$) is obtained in a similar fashion and refreezing ($\text{RF}_{\text{v}1.0}$) is estimated as a residual between adjusted melt, runoff and rainfall:

$$\text{ME}_{\text{v}1.0} = \text{ME}_{\text{v}0.2} + \text{ME}_{\text{add}} \quad (9)$$

$$\text{RF}_{\text{v}1.0} = \text{RA} + \text{ME}_{\text{v}1.0} - \text{RU}_{\text{v}1.0} \quad (10)$$

The downscaled SMB dataset resulting from the combined elevation correction and runoff adjustment is referred to as version v1.0 in the following sections.

4 Evaluation of daily downscaled SMB

Figure 6 evaluates the original RACMO2.3 SMB at 11-km (a), the 1-km raw downscaled SMB version v0.2 (b) and the 1-km corrected downscaled SMB version v1.0 (c) (mWE per year) with 1073 observations from 213 ablation sites (yellow dots in Fig. 1). The observational period was matched with the modelled and downscaled SMB using the exact number of days. Each blue star corresponds to the cumulative SMB for a duration ranging from 10 days to a full hydrological year. The downscaled SMB v0.2 agrees better with observations compared to the RACMO2.3 output at 11-km (Figs. 6a and b): we find a significant decrease of the RMSE (190 mmWE or -16%) and a smaller bias (100 mmWE or -21%). The deviation from unity of the regression slope decreases from 0.28 to 0.21 (-25%), and the variance explained increases from 47% to 61%. When applying the bare ice albedo and local orientation corrections, we find further significant improvements relative to version v0.2 (Fig. 6c), with now 78% of the variance explained and a significant decrease in RMSE (270 mmWE or -27%) and bias (310 mmWE or -84%). Red stars represent data from PROMICE station QAS_L (61.03°N, 46.85°W, 310 m.a.s.l; yellow dot in Fig. 11a) situated in an extremely

narrow ablation zone (~ 10 km) at the southwestern tip of Greenland. Here, modelled ablation gradients at 11-km are strongly underestimated in RACMO2.3 and are only marginally better resolved at 1-km. At this site, the additional corrections are especially important to obtain agreement with observations.

300 Figure 7 compares annual mean observed and downscaled SMB (v1.0) along 8 different SMB transects. There is good agreement for most transects, except for Helheim glacier (66.41N, -38.34W). The downscaled product fails at reproducing the quasi-constant ablation rate (~ -1 mWE) characterizing the Helheim transect. The reason for this low SMB gradient is not clear at present; it may be due to uncertainties in individual observation covering relatively short periods, i.e. 1 or 2 months, which are only limited to the melt season (July-August). Another possible explanation is that Helheim glacier experiences pronounced winter accumulation at low elevations, potentially caused by drifting snow transport, limiting summer ablation. In addition, Nioghalvjerds-fjorden and Storstrømmen transects (Figs. 7a-b) also show significant remaining biases between in-situ and downscaled SMB at elevations
 305 lower than 200 m. We hypothesize that these SMB measurements are located on floating glacier tongues with melt ponds, resulting in very low satellite albedo, while stake measurements are performed between ponds on brighter surfaces. As a result, the bare ice albedo correction could be overestimated.

In the accumulation zone, a small improvement is also found compared to v0.2 (Fig. 8),
 315 but accumulation remains underestimated. The SMB bias and RMSE are reduced by 0.7 (-2%) and 1.8 mmWE (-3%) whereas the regression slope and variance explained remain unchanged. In the accumulation zone, SMB is mostly driven by precipitation which is bi-linearly interpolated to 1-km without elevation correction. In addition, changes in sublimation are small due to the relatively homogeneous topography of the ice sheet interior,
 320 limiting SMB changes through downscaling. Despite significant improvements in the cloud scheme of RACMO2.3 (Noël et al., 2015), clouds become saturated and start to produce precipitation at too low elevations, resulting in overestimated precipitation at the margins, e.g. southeast Greenland, while the ice sheet interior experiences too dry conditions. This precipitation bias is currently being investigated, and we aim to resolve it in the upcoming version RACMO2.4. To overcome the systematic negative SMB bias of RACMO2.3 in the GrIS accumulation zone (-37.5 mmWE/yr, Fig. 8), the daily total precipitation v0.2 is adjusted to correct for underestimation in the ice sheet accumulation zone (SMB > 0 mmWE/yr):

$$330 \quad PR_{v1.0} = PR_{v0.2} + \frac{PR_{v0.2}}{PR_{v0.2}^2} \times \sigma_{SMB} \quad (11)$$

where $PR_{v1.0}$ is the daily adjusted total precipitation v1.0, $PR_{v0.2}$ is the daily bi-linearly

interpolated total precipitation v0.2, $PR_{v0.2}^a$ is the annual cumulative bi-linearly interpolated total precipitation v0.2 and σ_{SMB} is the accumulation zone SMB bias in the downscaled product v1.0.

The final $SMB_{v1.0}$ product is reconstructed as:

$$SMB_{v1.0} = PR_{v1.0} - RU_{v1.0} - SU - ER \quad (12)$$

340 5 High-resolution SMB patterns: case studies

Table 1 lists annual mean modelled and downscaled SMB components (Gt per year) integrated over four different regions (blue boxes in Fig. 1) as well as over the entire GrIS. These regions were selected for their specific climates, rough topography and narrow glaciated features which were not well resolved at 11-km. Figures 9, 10, 11 and 12 show the ice sheet mask for the selected regions at 11-km (red cells) and 1-km (orange cells) as well as peripheral glaciers and ice caps at 1-km (blue cells), the elevation bias between the 1-km and 11-km DEMs, and the bare ice albedo bias between the 1-km MODIS product and RACMO2.3 at 11-km; the latter figures moreover show the main SMB components at both resolutions for the two downscaled products (v0.2 and v1.0). In the following sections, we discuss the impact of downscaling on regional SMB. Here, SMB components are exclusively integrated over the contiguous GrIS; the SMB of detached ice caps will be discussed in a forthcoming paper.

5.1 Central east Greenland

Central east Greenland (blue box 1 in Fig. 1) is characterised by a large body of interconnected valley glaciers, mostly terminating in narrow glacial fjords. Figure 9a, e and i underline the inability of the 11-km mask to properly represent many glaciated areas, local topography or bare ice albedo. In the 1-km mask, the ice covered area increases ($\sim 2\%$) while the elevation bias can locally exceed 500 m over glacial valleys and small scale promontories (Tab. 1 and Fig. 9e); the average elevation bias is 80 m. These differences affect SMB in two ways. First, precipitation increases by 2.6 Gt/yr (12%) in v0.2 (Tab. 1 and Fig. 9b and f), exclusively caused by the expansion of glaciated area (no elevation correction is applied). Another 1.6 Gt/yr (6%) of precipitation is added in v1.0 (Fig. 9j) to compensate for the systematic negative SMB bias in the GrIS accumulation zone, as discussed in Section 4. For both downscaling versions, changes in runoff mirror the elevation change between the two resolutions (Fig. 9e), highlighting the high sensitivity of runoff to elevation. In version v0.2, integrated runoff increases by 7.7 Gt/yr (48%) (Fig. 9c and g). Furthermore, Fig. 9i reveals

a systematic overestimation of bare ice albedo at 11-km. Correcting for this further increases runoff over the glaciers tongues (Fig. 9k), accounting for ~ 13 Gt/yr (55%) of additional runoff with respect to v0.2 (Tab. 1). Negligible changes in sublimation and drifting snow are found (Tab. 1). As a consequence, integrated SMB on the 1-km mask decreases by 5.3 Gt/yr in version v0.2 (Fig. 9d and h) and by 16.6 Gt/yr in version v1.0 (Fig. 9l). This analysis for central east Greenland demonstrates the importance of accurately reproducing small scale topography and ice albedo to realistically capture local SMB variations.

5.2 Central west Greenland

The 11-km resolution DEM provides a reasonable representation of the wide, gently sloping western ablation zone of the GrIS, where most glaciers are land-terminating. The northern part of the selected area includes several marine-terminating glaciers which are better represented at 1-km (Fig. 10d and h).

Owing to negligible difference in glaciated area, precipitation remains almost unchanged for the two resolutions and versions (~ 15 Gt/yr). In both downscaled versions, enhanced runoff is mostly obtained over narrow, low-lying glaciers tongues and detached ice caps (Fig. 10c, g and k) where most of the elevation and ice albedo biases are found (Fig. 10e, i). On the ice sheet, the elevation correction increased runoff by about 1 Gt/yr (5%) (Fig. 10g) while an additional ~ 2 Gt/yr (10%) (Fig. 10k) can be ascribed to the ice albedo correction (Tab. 1).

5.3 South Greenland

Southeast Greenland (blue box 3 in Fig. 1) is a rugged region (Fig. 10e), characterized by multiple topographically-forced precipitation maxima (Fig. 11b and f) and narrow marginal ablation zones (Fig. 11c, g and k). Similar to central east Greenland, the larger glaciated area (+6.5%, Fig. 11a) at 1-km enhances integrated precipitation by ~ 6 Gt/yr (+7%) in v0.2 and 8.4 Gt/yr (+9%) in v1.0. Increased runoff (2.2 Gt/yr or 5% in version v0.2) at the southern margins can be ascribed to additional melt production over the better resolved narrow ablation zones (Fig. 11g and k) combined with a moderate mean elevation difference (~ 17 m) between both resolutions. In v0.2, the ice mask expansion explains most of the integrated SMB changes, leading to an overall mass gain of 3.3 Gt/yr.

Fig. 6b reveals considerable ablation underestimation in southern Greenland, expressed as a systematic SMB bias of 2 to 4 mWE relative to measurements collected at PROMICE station QAS_L (red dots in Fig. 6a). The main reason for this underestimation is that SMB at this location is characterized by a rare combination of high snowfall and strong summer melt.

The remaining ablation underestimation in v0.2 can be partly ascribed to an overestimated

bare ice albedo (0.47) prescribed in RACMO2.3 (Noël et al., 2015); observed albedo at QAS_L frequently falls to 0.2 during the melt season (Fausto et al., 2016). As a result, the additional bare ice albedo correction significantly improves runoff at station QAS_L
405 (Fig. 6c). Integrated over region 3, runoff increases by another ~ 13 Gt/yr (29%) relative to v0.2 (Fig. 11k). The increased marginal mass loss leads to the expansion of the southern ablation zone towards higher elevations (Fig. 11k and l), in line with local observations (Fig. 6c).

5.4 North Greenland

410 In north Greenland (blue box 4 in Fig. 1), the climate is dry, and most glaciers are marine-terminating. The ice sheet surface is relatively smooth and homogeneous. The wide ablation zone is reasonably well captured at 11-km, leading to a modest deviation in elevation (~ 43 m) (Fig. 12e). However, the ice-covered area decreases by $\sim 11\%$ between both resolutions as the 11-km grid contained erroneous floating glacier tongues (Fig. 12a). The ice area
415 reduction at 1-km affects precipitation (-0.8 Gt/yr or -12%) (Fig. 12b and f) and runoff (-3.1 Gt/yr or -35%) (Fig. 12c and g), resulting in a small SMB increase (2.3 Gt/yr) in version v0.2 (Fig. 12d and h). Large bare ice albedo discrepancies can be found on five major glaciers (Fig. 12i) where runoff increases substantially (~ 2 Gt/yr or 34%) in version v1.0, further decreasing the integrated SMB by 1.0 Gt/yr compared to v0.2 (Fig. 12h and
420 l).

5.5 Greenland ice sheet

Although similar in area, the 1-km ice sheet mask better resolves peripheral glaciers at the GrIS margins than RACMO2.3 at 11-km. GrIS integrated precipitation increases by 16.6 Gt/yr (+2%) in v0.2, most of which can be ascribed to ice area expansion in the
425 east (2.6 Gt/yr) and south of Greenland (5.8 Gt/yr), where precipitation is large. An additional 56.2 Gt/yr (+8%) is obtained in v1.0 when correcting for the accumulation zone SMB bias. The smooth topography of the ice sheet interior results in a small elevation difference of 4 m between both resolutions. Significant elevation biases are mostly restricted to peripheral glaciers and narrow ablation zones at the GrIS margins. As a result, runoff
430 increases by 13.6 Gt/yr (+5%) in version v0.2. Accounting for the bare ice albedo bias in RACMO2.3 further increases runoff by 69.3 Gt/yr in version v1.0, leading to a much improved agreement with ablation measurements. Of our selected areas, central east and south Greenland contribute 25% and 18% to the total runoff increase in the downscaled product v1.0 owing to the many low-lying glaciers tongues that can only be resolved at
435 1-km. Due to their smoother topography, north and centre west Greenland contribute much less to the runoff change ($\sim 3\%$ and 1% , respectively). Integrated over the contiguous ice

sheet, SMB is not significantly affected by the elevation dependence for which enhanced precipitation (16.6 Gt/yr) yearly balances the moderate increase in runoff (13.6 Gt/yr). In contrast, the bare ice albedo and precipitation corrections substantially increase marginal runoff (82.9 Gt/yr) and accumulation (72.8 Gt/yr), resulting in a decrease of SMB of -11.1 Gt/yr (-3%) relative to the 11-km product.

6 Added value, limitations and uncertainties

The downscaled SMB v1.0 is the first dataset to provide daily SMB estimates for all outlet glaciers of the GrIS at a 1-km resolution and for 58 years (1958-2015). Relative to the original RACMO2.3 output, this dataset improves local SMB values (Fig. 7) and produces more realistic SMB patterns over rugged glaciated areas along the GrIS margins (Figs. 9-12). Figs. 6 and 8 show that SMB v1.0 is an overall improvement on the original RACMO2.3. To further investigate this, Fig. 13 shows the annual mean SMB RMSE (model vs. observations) of the 11-km SMB field in RACMO2.3 (red), the downscaled product v0.2 (green) and v1.0 (blue) as a function of observed SMB, binned in 0.5 m w.e. intervals. In the ablation zone (SMB < 0), the SMB RMSE is reduced by 29-65% in v1.0 relative to the 11-km product, owing to the elevation correction in v0.2 (9-23%) and the additional albedo correction (20-42%). In the accumulation zone, the elevation dependence (9%) and the precipitation adjustment (19%) also contribute to reduce the SMB RMSE by 28% in v1.0. The largest RMSE reduction occurs in the lower GrIS ablation zone, where improvements in topography and bare ice albedo in v1.0 are greatest.

Although significantly improved, the downscaled SMB v1.0 is likely to be locally underestimated for four reasons: a) the bare ice albedo correction is evenly applied to both snow covered and bare ice regions experiencing surface melt and runoff, as no relevant proxy, reflecting day-to-day snow coverage, could be derived from RACMO2.3. However, this issue should have a limited effect on the magnitude of downscaled melt and runoff since the albedo correction is most efficient in summer, when the snow cover of low-lying glaciers has likely melted; b) the MODIS ice albedo product at 1-km becomes less accurate at high latitudes, likely suffering from bare soil contamination resulting from mixed reflectance signals recorded in both the tundra and ice covered regions. Note that floating glacier tongues also show too low surface albedo, e.g. Petermann glacier (yellow dot in Fig. 12a)), resulting from mixed signals from adjacent dark melt pond and brighter dry ice. The resulting albedo underestimation over low-lying floating tongues below 200 m leads to overestimated ablation (~ 0.2 mWE/yr; Figs. 7a and b); c) the average 1-km MODIS ice albedo product for 2000-2015 used in the melt correction remains constant in time and might underestimate the bare ice albedo prior to 2000 as the period 2000-2015 encompasses multiple record high

melt years; d) the degradation of MODIS Terra sensors (Polashenski et al., 2015). These limitations underline the high sensitivity of the downscaled product to the input fields used to initialize the downscaling procedure, i.e. RCM version used, the resulting modelled SMB components, bare ice albedo records, ablation measurements, topography and ice mask. The downscaled SMB v1.0 presents an estimated uncertainty of ~ 6 Gt/yr in the GrIS ablation zone, which was estimated by integrating the SMB bias in v1.0 (30 mmWE, Fig. 6c) over the ablation zone of the contiguous ice sheet (~ 202.000 km²).

We anticipate that the new, 1-km Greenland SMB product is especially useful for studies that address the mass balance of Greenland outlet glaciers that are too steep and/or narrow to be properly resolved at the typical horizontal resolution of regional climate models (~ 5 -15 km). Future downscaled products can have even higher resolution (100m) and will be based on further improved RCM output fields of precipitation and melt.

7 Conclusions

The relatively coarse spatial resolution currently used in RCMs remains insufficient to properly resolve small scale variations in elevation and ice cover at the ice sheet margins, significantly affecting the calculation of melt and runoff. In the present study, we statistically downscale individual SMB components from RACMO2.3 at 11-km to a 1-km ice mask and topography derived from the GIMP DEM, using a daily specific elevation dependence. Moreover, runoff and melt are corrected for biases in bare ice albedo in RACMO2.3. Precipitation and snowdrift erosion are bi-linearly interpolated without applying an elevation correction. Total precipitation is also adjusted to compensate for the dry accumulation bias of RACMO2.3 in the ice sheet interior. Downscaled daily SMB is then retrieved for the period 1958-2015 by summing daily downscaled precipitation, runoff, sublimation and drifting snow erosion. An evaluation of the downscaled SMB product against observations, collected both in the ablation and accumulation zones of the GrIS, shows improved agreement. In the ablation zone, the variance explained by the downscaled product v1.0 increased by 31% relative to the original RACMO2.3 11-km output, mainly through better resolved narrow outlet glaciers at the GrIS margins.

Integrated over the GrIS, precipitation increased by 16.6 Gt/yr due to the larger glaciated area in south and east Greenland at 1-km; an additional correction of 56.2 Gt/yr must account for the accumulation bias in the ice sheet interior in RACMO2.3. Likewise, a 13.6 Gt/yr increase in runoff is attributed to elevation corrections on the 1-km topography and another 69.3 Gt/yr extra runoff can be ascribed to underestimated bare ice albedo over narrow outlet glaciers at the GrIS margins. A small area in central east Greenland alone, characterized by multiple narrow glacier tongues poorly resolved at 11-km, accounts for \sim

25% of the total additional runoff.

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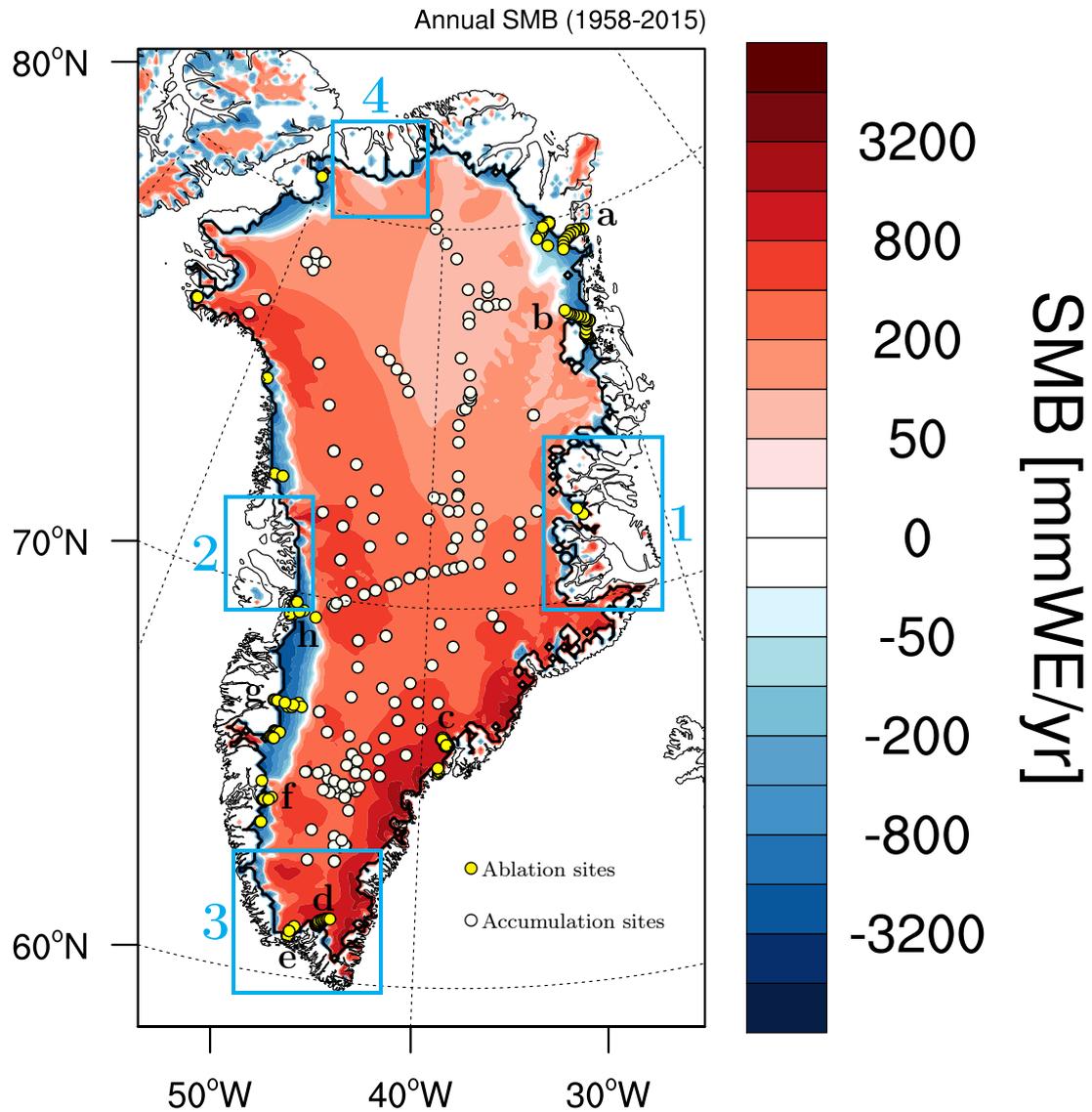


Fig. 1. Annual mean SMB modelled by RACMO2.3 at 11-km over the GrIS and surrounding ice caps for the period 1958-2015. This figure also depicts the location of 213 ablation measuring sites (yellow dots) and 182 accumulation sites (white dots) used for downscaled SMB evaluation as well as the four GrIS marginal regions (blue boxes), discussed in Section 5. Letters refer to the different transects shown in Fig.7.

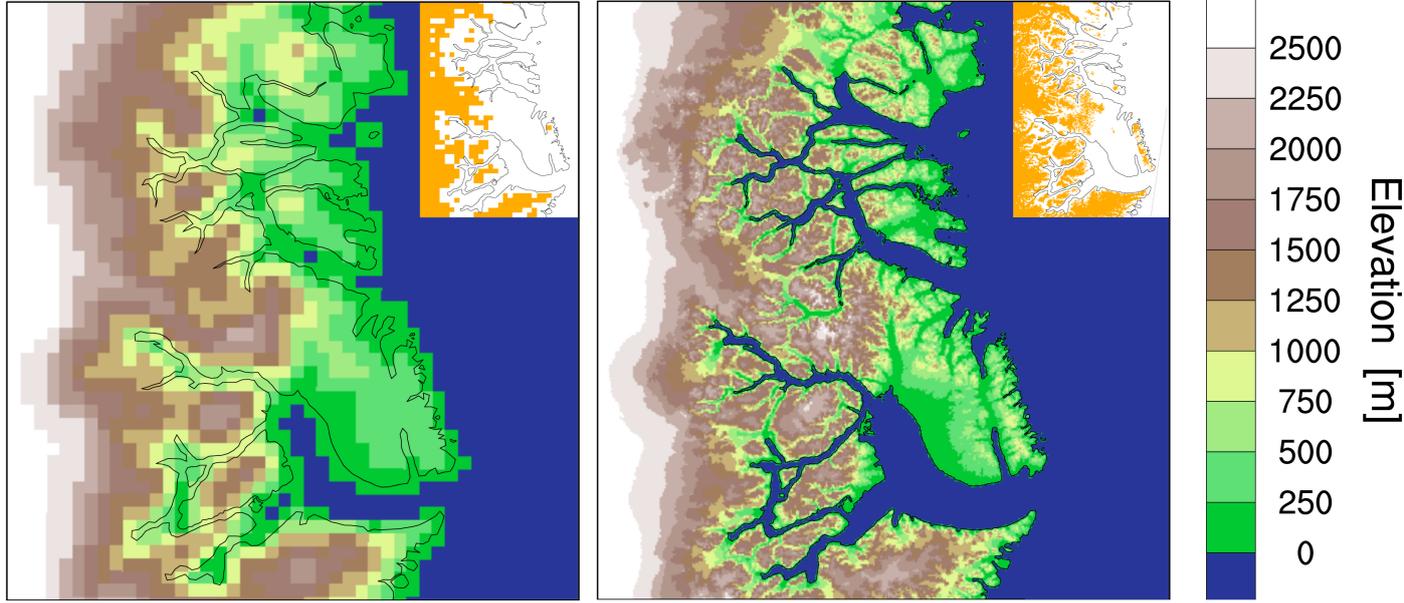
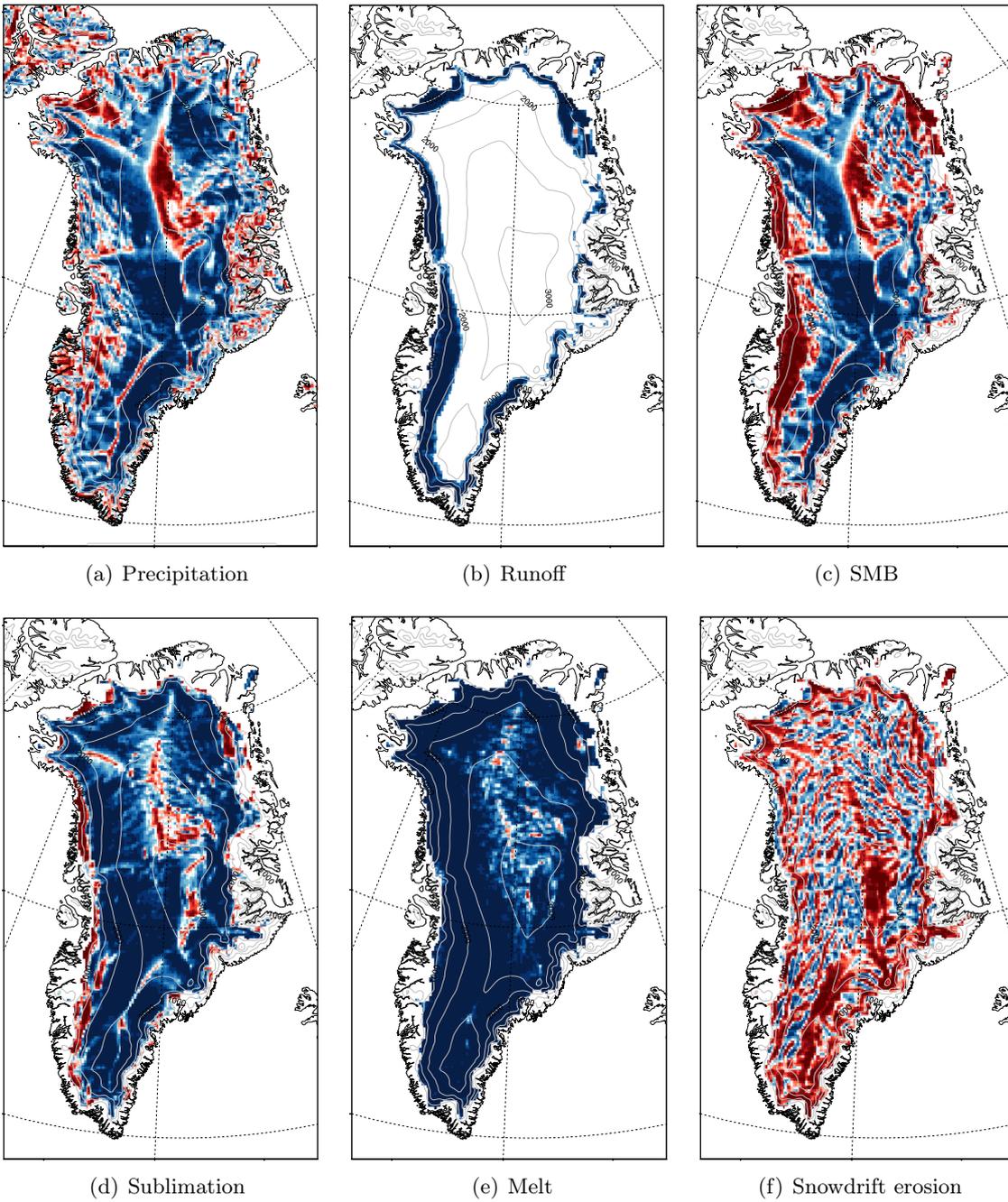


Fig. 2. Elevation and ice mask (yellow) as prescribed in RACMO2.3 at 11-km (left) and derived from the GIMP DEM down-sampled to 1-km (right) over central east Greenland (blue box 1 in Fig. 1).

1958-2015	Regions	Centre east			Centre west			South			North			GrIS		
Resolution	Unit	11km	1km	Δ	11km	1km	Δ	11km	1km	Δ	11km	1km	Δ	11km	1km	Δ
SMB $v_{0.2}$	<i>Gt/yr</i>	5.0	-0.3	-5.3	-4.6	-5.4	-0.8	44.3	47.6	3.3	-2.6	-0.3	2.3	349.3	351.3	2.0
Runoff $v_{0.2}$	<i>Gt/yr</i>	16.1	23.8	7.7	18.3	19.2	0.9	42.4	44.6	2.2	8.9	5.8	-3.1	284.1	297.7	13.6
Precip $v_{0.2}$	<i>Gt/yr</i>	22.6	25.2	2.6	15.0	15.2	0.2	91.4	97.2	5.8	6.9	6.1	-0.8	675.4	692.0	16.6
SMB $v_{1.0}$	<i>Gt/yr</i>	5.0	-11.6	-16.6	-4.6	-6.7	-2.1	44.3	37.3	-7.0	-2.6	-1.3	1.3	349.3	338.2	-11.1
Runoff $v_{1.0}$	<i>Gt/yr</i>	16.1	36.7	20.6	18.3	21.1	2.8	42.4	57.5	15.1	8.9	7.7	-1.2	284.1	367.0	82.9
Precip $v_{1.0}$	<i>Gt/yr</i>	22.6	26.8	4.2	15.0	15.8	0.8	91.4	99.8	8.4	6.9	7.0	0.1	675.4	748.2	72.8
Sublimation	<i>Gt/yr</i>	2.1	2.1	0.0	1.6	1.6	0.0	4.4	4.7	0.3	0.8	0.7	-0.1	41.3	41.9	0.6
Snow drift	<i>Gt/yr</i>	-0.5	-0.4	0.1	-0.3	-0.2	0.1	0.2	0.3	0.1	-0.1	-0.1	0.0	0.7	1.1	0.4
Ice area	10^4 km^2	5.9	6.0	0.1	2.7	2.7	-0.02	7.7	8.2	0.5	3.5	3.1	-0.4	170.3	169.4	-0.9

Table 1. Table listing (top) the annual mean integrated SMB components (Gt/year) covering the period 1958-2015 over four different regions, centre east ($69.6^\circ\text{N} - 74.3^\circ\text{N}$; $21^\circ\text{W} - 31^\circ\text{W}$; blue box 1 in Fig. 1), centre west ($69.3^\circ\text{N} - 72.5^\circ\text{N}$; $49^\circ\text{W} - 57^\circ\text{W}$; blue box 2), south ($59.5^\circ\text{N} - 63.3^\circ\text{N}$; $41^\circ\text{W} - 51^\circ\text{W}$; blue box 3) and north ($80.5^\circ\text{N} - 83^\circ\text{N}$; $42^\circ\text{W} - 62^\circ\text{W}$; blue box 4), and for the entire GrIS at both resolutions as well as the difference between 1-km and 11-km; (bottom) same for the ice-covered area (km^2).



Correlation to elevation [-]

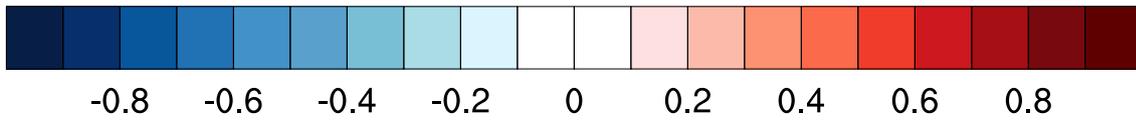


Fig. 3. Correlation to elevation of annual mean a) total precipitation (solid and liquid), b) runoff, c) SMB, d) sublimation, e) melt and f) drifting snow erosion modelled by RACMO2.3 and calculated on the 11-km grid for the period 1958-2015.

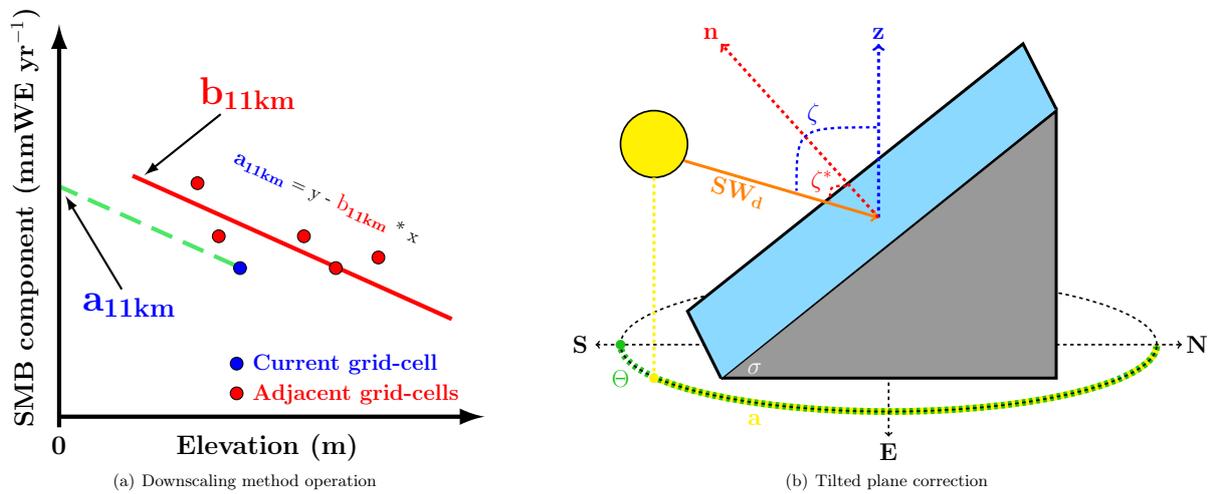


Fig. 4. (a) Elevation dependent downscaling procedure: local estimate of a daily SMB components regression to elevation on the RACMO2.3 grid at 11-km. (b) Scheme of a tilted plane as described in the GIMP DEM at 1-km.

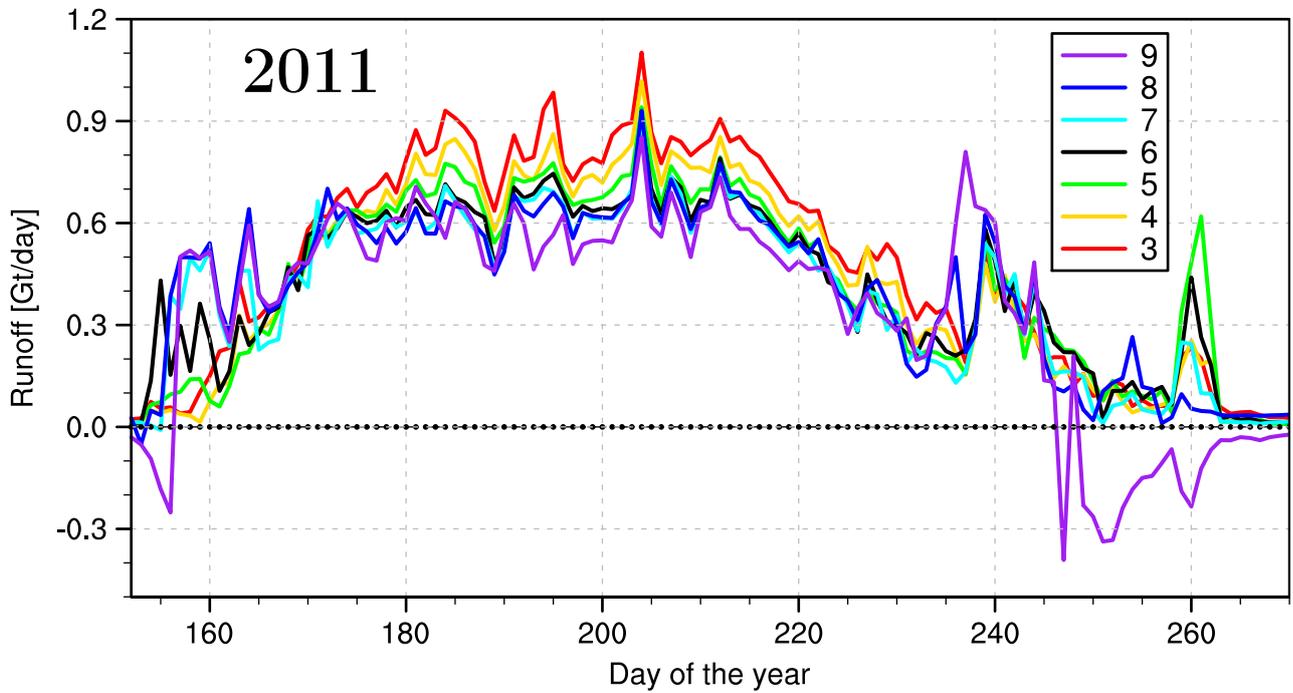
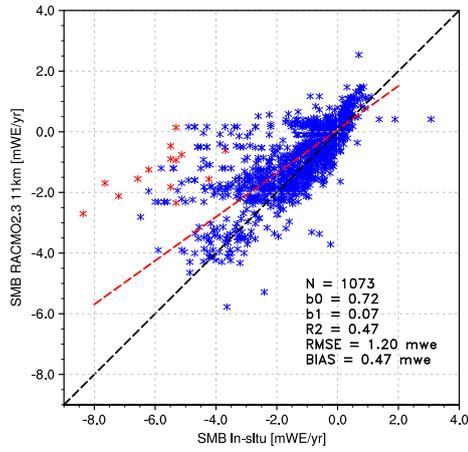
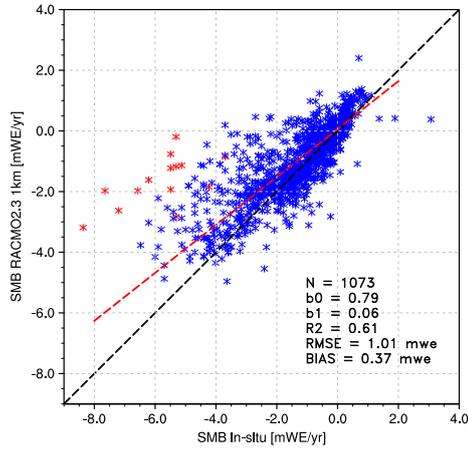


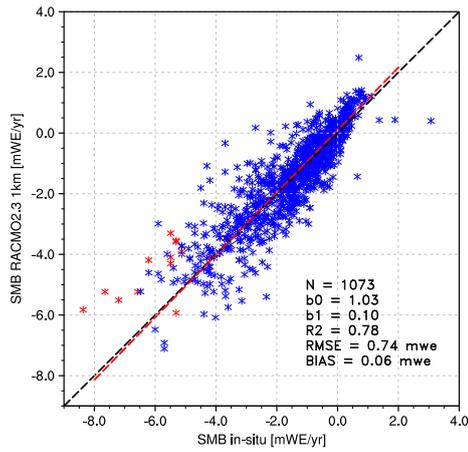
Fig. 5. Summer 2011 time series of daily, ice sheet integrated runoff difference (Gt/day) between the downscaled product at 1-km, using a minimum threshold of 3 to 9 regression points (legend), and the RACMO2.3 model at 11-km.



(a) Modelled SMB at 11 km



(b) Downscaled SMB at 1 km version v0.2



(c) Corrected SMB at 1 km version v1.0

Fig. 6. Comparison of SMB measurements collected at 213 sites with (a) modelled SMB from RACMO2.3 at 11-km; (b) downscaled SMB at 1-km (v0.2) and (c) corrected downscaled SMB at 1-km (v1.0). The red stars correspond to PROMICE station QAS_L located in southern Greenland (61.03°N, 46.85°W, 310 m.a.s.l). The red dashed line represents the regression including all measurements using a perpendicular fit.

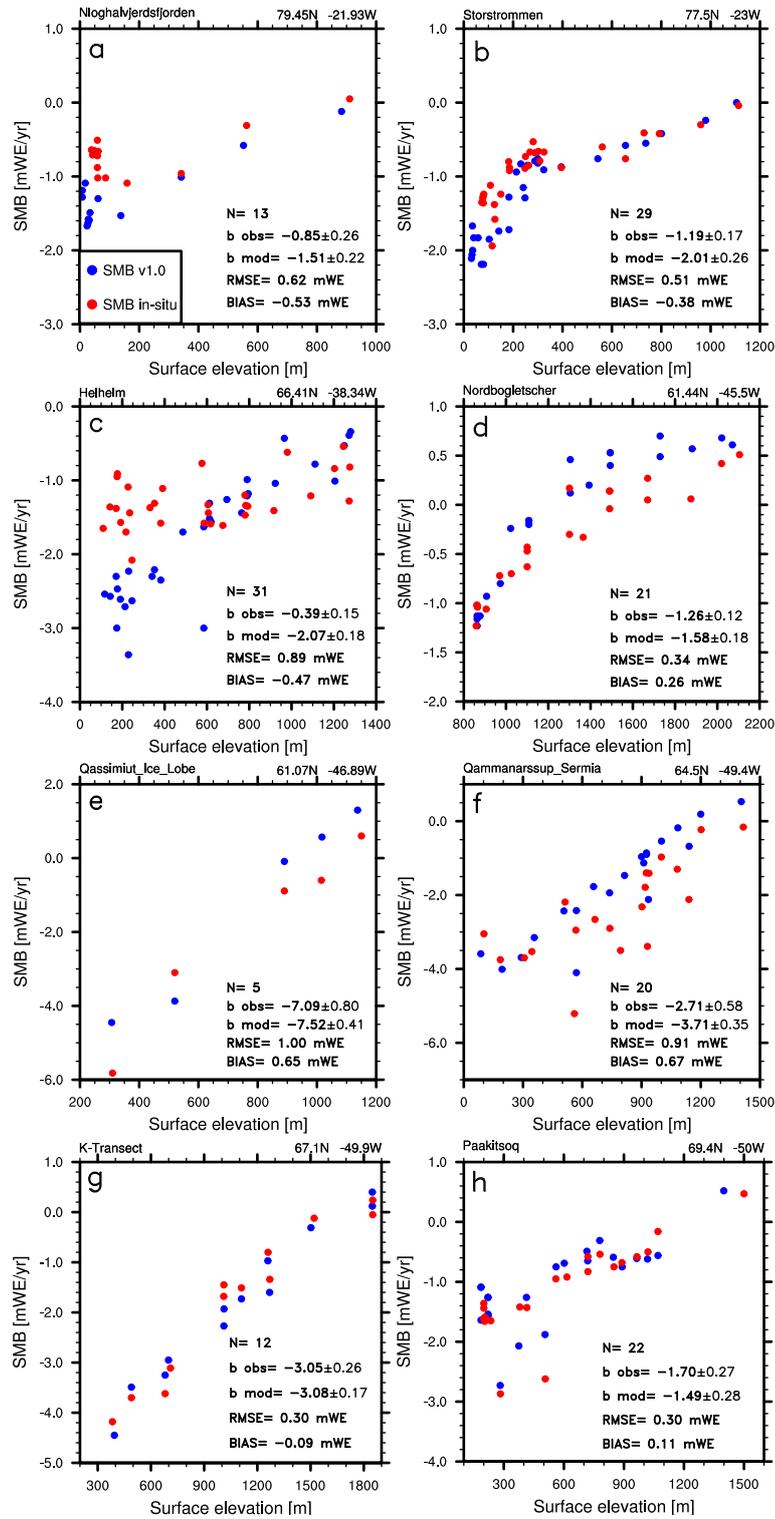


Fig. 7. Annual mean observed (red dots) and downscaled (blue dots, v1.0) SMB for 8 selected transects in the GrIS ablation zone (mWE/yr). Name and locations of these transects (Fig. 1) are listed at the top of each graph. Graphs also list the number of sites used for each transect, linear SMB-to-elevation regression retrieved from observations and downscaled (v1.0) data in mmWE/yr per m, RMSE and mean bias.

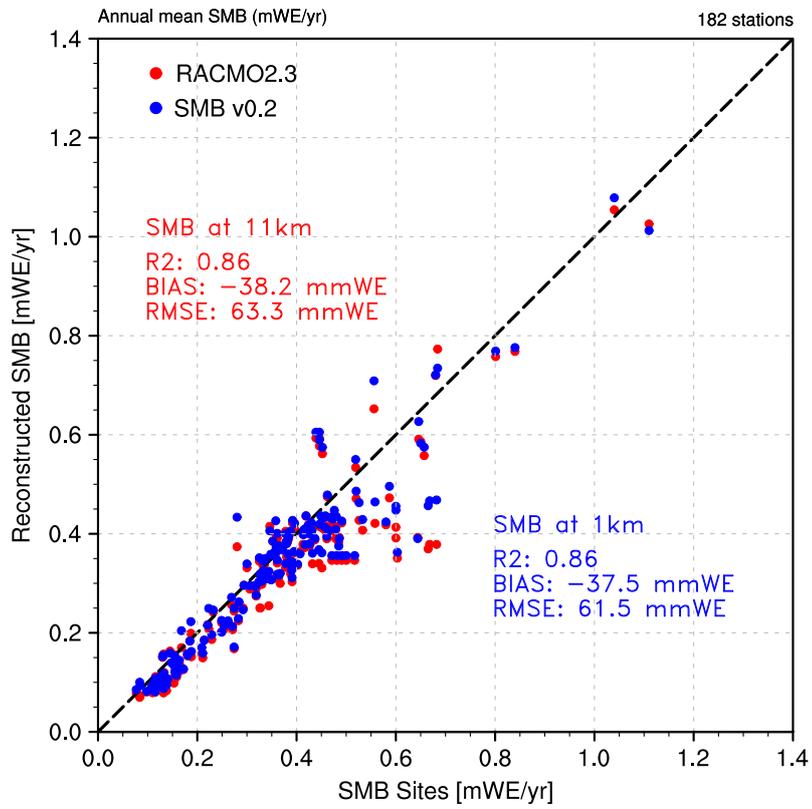


Fig. 8. Comparison of accumulation observations collected at 182 sites with modelled SMB from RACMO2.3 at 11-km (red) and downscaled SMB v0.2 at 1-km (blue) in mWE/yr. Note that bias correction has not yet been applied.

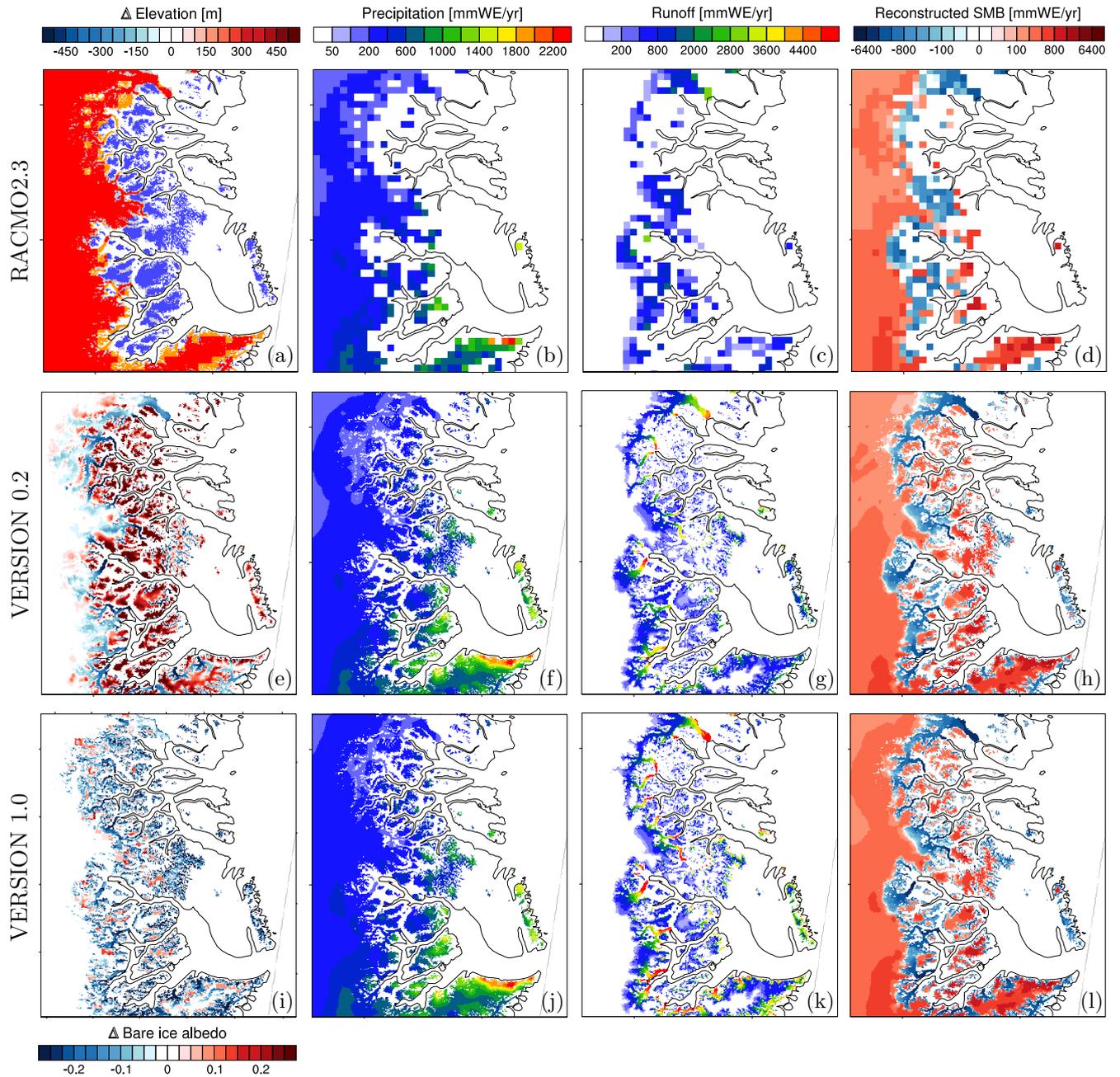


Fig. 9. Centre east: a) Ice sheet mask in RACMO2.3 at 11-km (red) and in the down-sampled GIMP DEM at 1-km (orange) (blue box 1 in Fig. 1), and the mask of disconnected glaciers and ice caps at 1-km (blue); average (1958-2015) annual mean b) total precipitation, c) runoff and d) SMB (mmWE/yr) modelled by RACMO2.3 at 11km; e) elevation bias (m) between 1-km and 11-km resolutions. Figures f), g), h) represent annual mean total precipitation, runoff and SMB downscaled to 1-km using elevation dependence only (v0.2). Figure i) shows the bare ice albedo bias between MODIS measurements at 1-km (2000-2015) and RACMO2.3 at 11-km (2001-2010). Figures j), k) and l) are similar to f), g) and h) but incorporate the bare ice albedo and precipitation corrections (v1.0).

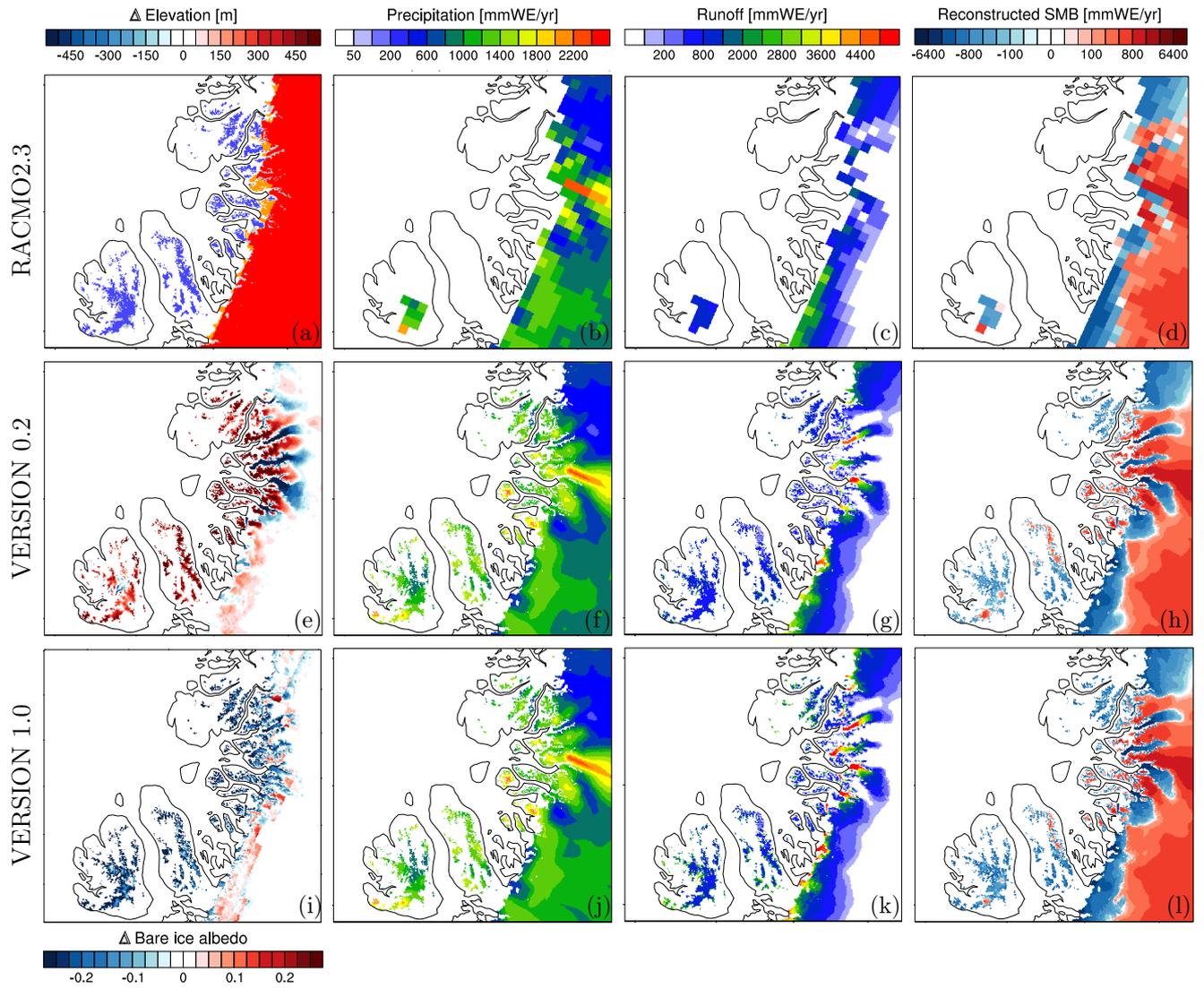


Fig. 10. Centre west: same as Fig. 9 but for central west Greenland (blue box 2 in Fig. 1).

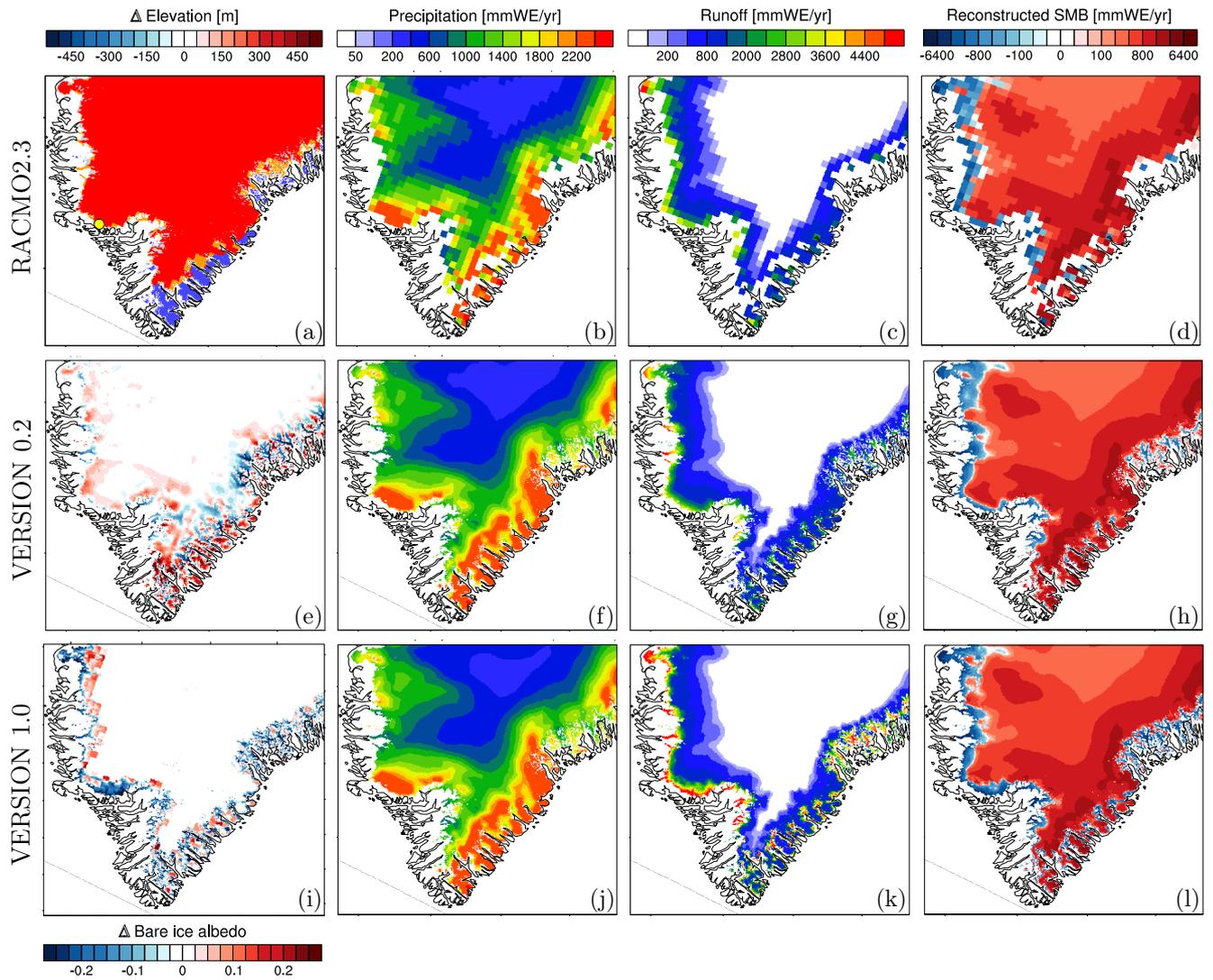


Fig. 11. South: same as Fig. 9 but for south Greenland (blue box 3 in Fig. 1). The yellow dot in a) locates station QAS_L.

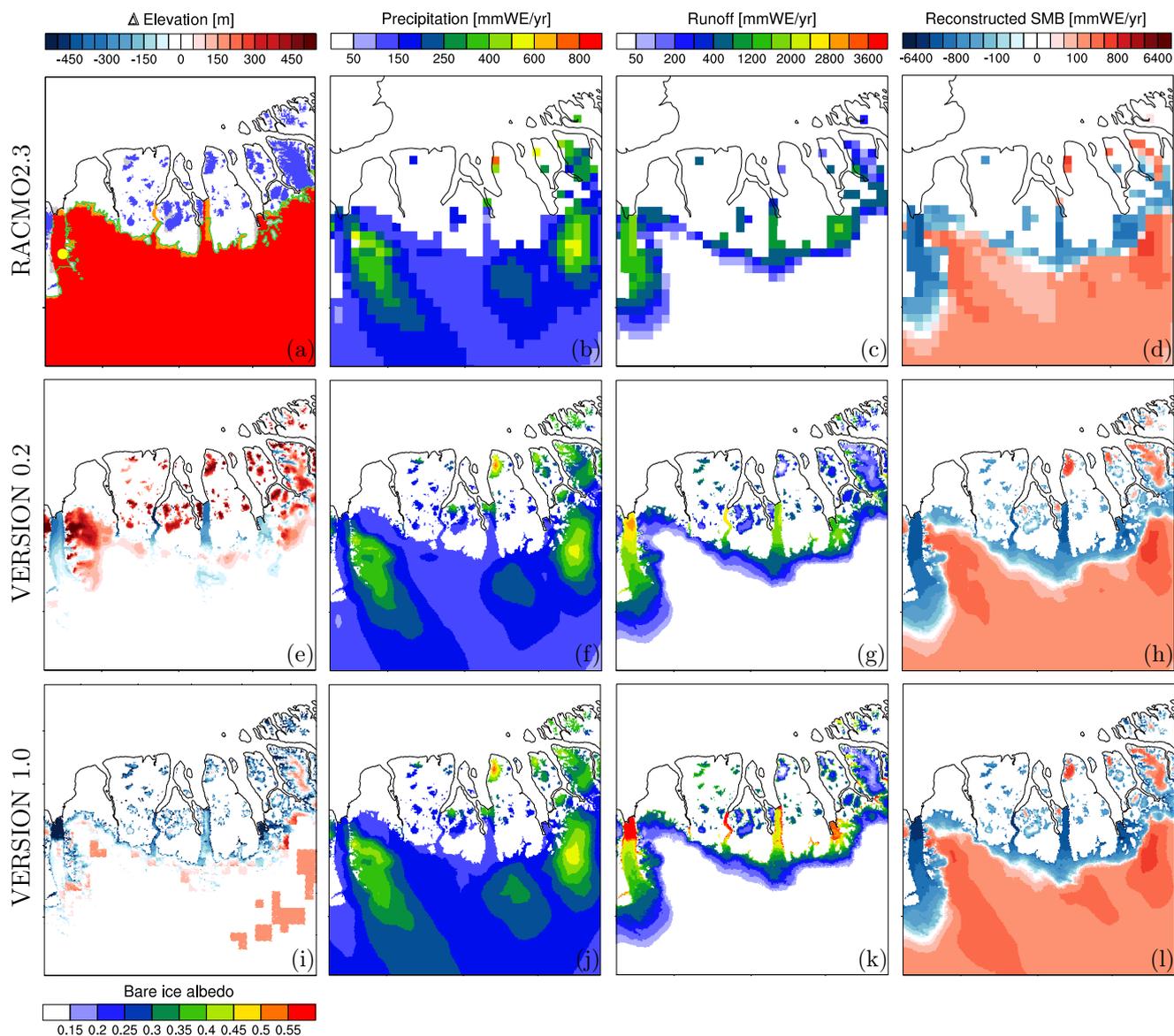


Fig. 12. North: same as Fig. 9 but for north Greenland (blue box 4 in Fig. 1). The green line in a) shows the grounded ice mask at 1-km. The yellow dot in a) locates the Petermann glacier site settled on a floating ice tongue.

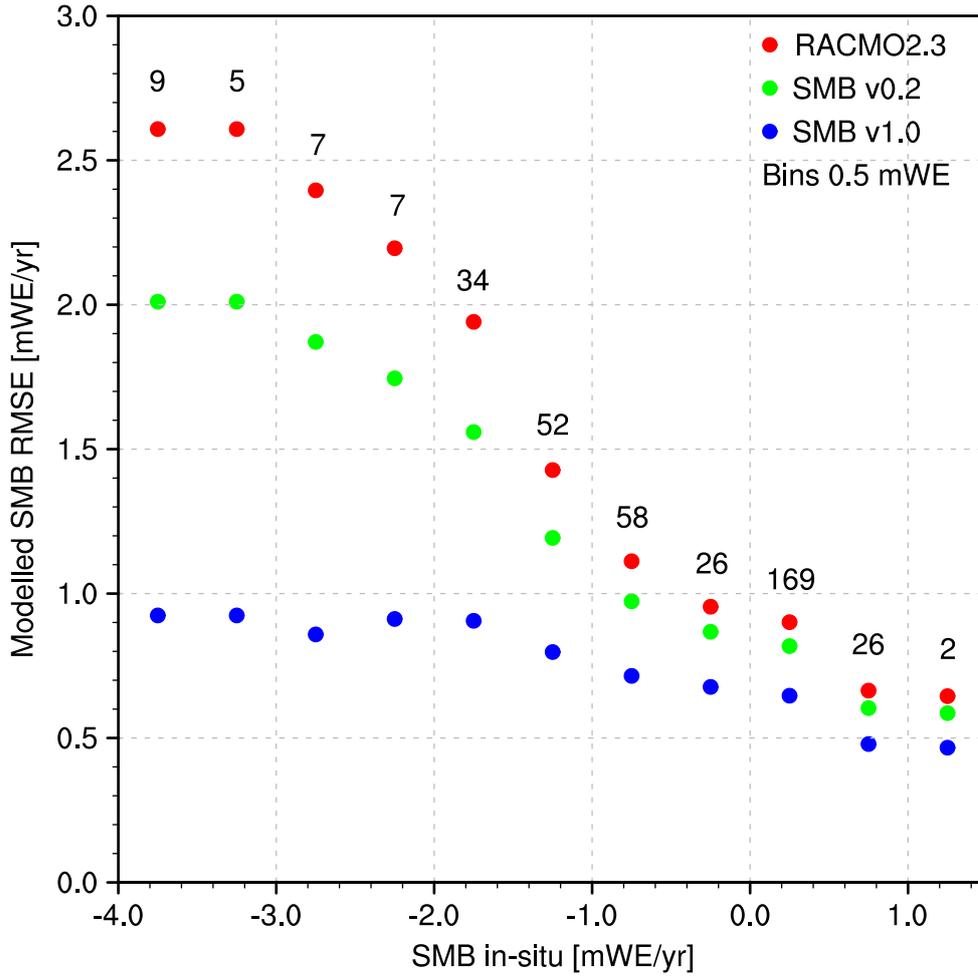


Fig. 13. Annual mean model SMB RMSE (model vs. observations) of the 11-km SMB field in RACMO2.3 (red dots), the downscaled SMB dataset v0.2 (green dots) and v1.0 (blue dots) as a function of observed SMB (395 observations). Modelled SMB is grouped in 0.5 mWE/yr bins except for the first bin, which ranges from -6.00 to -3.75 mWE/yr. Numbers indicate the amount of observations used in each bin.