Interactive comment on "Impact of spatial resolution on the modelling of the Greenland ice sheet surface mass balance between 1990–2010, using the regional climate model MAR" by B. Franco et al.

Anonymous Referee #2
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Dear Referee,
We want to thank you for the review and your comments. Please find below our response to your remarks.

This manuscript by Franco et al. assesses the influence of spatial resolution on simulating the SMB (and its different components) of the Greenland ice sheet using the regional climate model MAR. Doing so, the authors carried out important tests that are valuable in the process of coupling ice dynamical models with climate models. They also present a downscaling technique that can be used to improve the skill of lower resolution climate fields on a higher resolution (15 km), in addition to simple interpolation. This demonstrates how climate fields on a course resolution can be used on a higher resolution, such that they are suitable as a forcing field for ice dynamical models.

Sometimes the style of writing / choice of words is somewhat vague. For example, the section that describes the calculation of the model skill is too general, and cannot be understood on its own (see below for detailed comments).

We have reformulated the description of the skill score calculation.
"In order to add a statistical approach to our MAR simulations assessment, we also calculated an averaged error on the interpolated outputs (precipitation, run-off and SMB) averaged over the 1990–2010 period compared to the 15 km results, based on the skill score methodology of Connolley and Bracegirdle (2007). Firstly, we calculated the root mean square (RMS) deviation of the interpolated field (multi-annually averaged over the 1990-2010 period) to the multi-annual averaged outputs at 15 km resolution, normalized by the standard deviation of this 15km field to produce RMS_n. Afterwards, this normalized deviation was rescaled by a function into a weight between 0 and 1 to produce a measure of the model "skill". According to this statistical approach, the interpolated field that receives a skill score close to 1 can be considered highly reliable with respect to the outputs provided by the 15 km resolution run."
"The same methodology was additionally carried out for each annual 15 km outputs (precipitation, run-off, etc.): the RMS deviation of the multi-annual 1990-2010 averaged 15 km resolution run compared to each annual 15 km outputs was normalized by the multi-annual variability over the 1990-2010 period, and then rescaled between 0 and 1 to obtain multi-annual averaged 15 km skill scores (0.31 for precipitation, 0.70 for run-off, 0.73 for sublimation and evaporation, and 0.31 for SMB). These results allow a comparison with the skill scores calculated on the interpolated outputs: skill scores higher than these values are lower than the standard deviation of the 15 km run over 1990–2010."

The method used as 'intelligent' interpolation is presented as a valuable correction step within coupling of (regional) climate models and ice dynamical models. The only correction mentioned in the manuscript is topographic differences due to resolution changes. However, much larger topographic differences are to be expected when a coupled ice dynamical – climate model experiment is carried out, due to ice sheet retreat and/or expansion, in response to climate forcing. As such, can this technique also be used to correct the resulting climate fields for these topographic changes? This is relevant since it is even more computational expensive to run a regional climate model with and updated ice topography after each significant topographic change in the ice dynamical model.

This is a very interesting question. Indeed, the feedback of the topography of the GrIS is expected to be very important in long-term simulations. To answer this issue, we have performed three MAR simulations at 30 km resolution over the 1990-1999 period, differing from the original 30 km run by:

- an ice sheet topography uniformly raised by 100m (simulation defined as 30ra): Fig. A
- an ice sheet topography uniformly lowered by 100m (simulation defined as 30lo): Fig. B
- an ice sheet mask extended over the tundra for the entire Greenland (simulation defined as 30em), but keeping the original 30 km topography: Fig. C

in order to “simulate” large topographic differences and a large ice sheet expansion.

We have used our enhanced interpolation (for the run-off of meltwater and the sublimation and evaporation) to investigate whether this method is able to significantly reduce the biases induced by 30ra and 30lo compared to the 1990-1999 outputs produced by the original 30 km run (30rt). According to the figures (Fig. A,B) presented below, our enhanced interpolation technique allows to improve the comparison with the 30rt outputs and to reconstruct more reliable SMB results despite the topographic differences.

Finally, we have interpolated the original 30 km simulation (30rt) onto the 30 km extended ice sheet mask covering the entire Greenland, and assessed the anomalies to the 30 km run performed over this extended mask (30em). Fig. C suggests that a simple interpolation (without correction using vertical gradients because the same topography has been used here) onto a very extended ice sheet mask induces very high run-off biases, and thus large SMB discrepancies, compared to the simulation performed over this extended ice sheet mask. Moreover, our interpolation technique, applied here to correct the new ice sheet points outside the original 30rt mask according to the difference of elevation between these points and the closest original 30rt ice sheet points, does not allow to reduce these biases. Indeed, because the offset between the initial and the new ice sheet margin is too large, the behaviour of the original and the extended ice sheets is completely different for the pixels covered by both ice sheets. For example, in the western Greenland, as the neighbourhood tundra is now covered of ice in the 30em simulation, this induces lower temperatures than the original 30rt run (Fig. Ca), and hence lower run-off values where 30rt simulated an ablation zone with very high run-off (Fig. Cd). Consequently, it is impossible to interpolate reliable run-off from the original mask (30rt) onto the extended ice sheet mask (30em), and the vertical gradients cannot reduce the discrepancies because the new ice sheet points are lower and thus the run-off is still strengthened after the correction (Fig. Ce).
Nonetheless, it has been shown in the manuscript that the enhanced interpolation (using daily gradients) of the 25 km outputs onto the 15 km ice sheet mask gives reliable results, because the extent of the 15 km and 25 km ice sheet mask is more similar in this case.

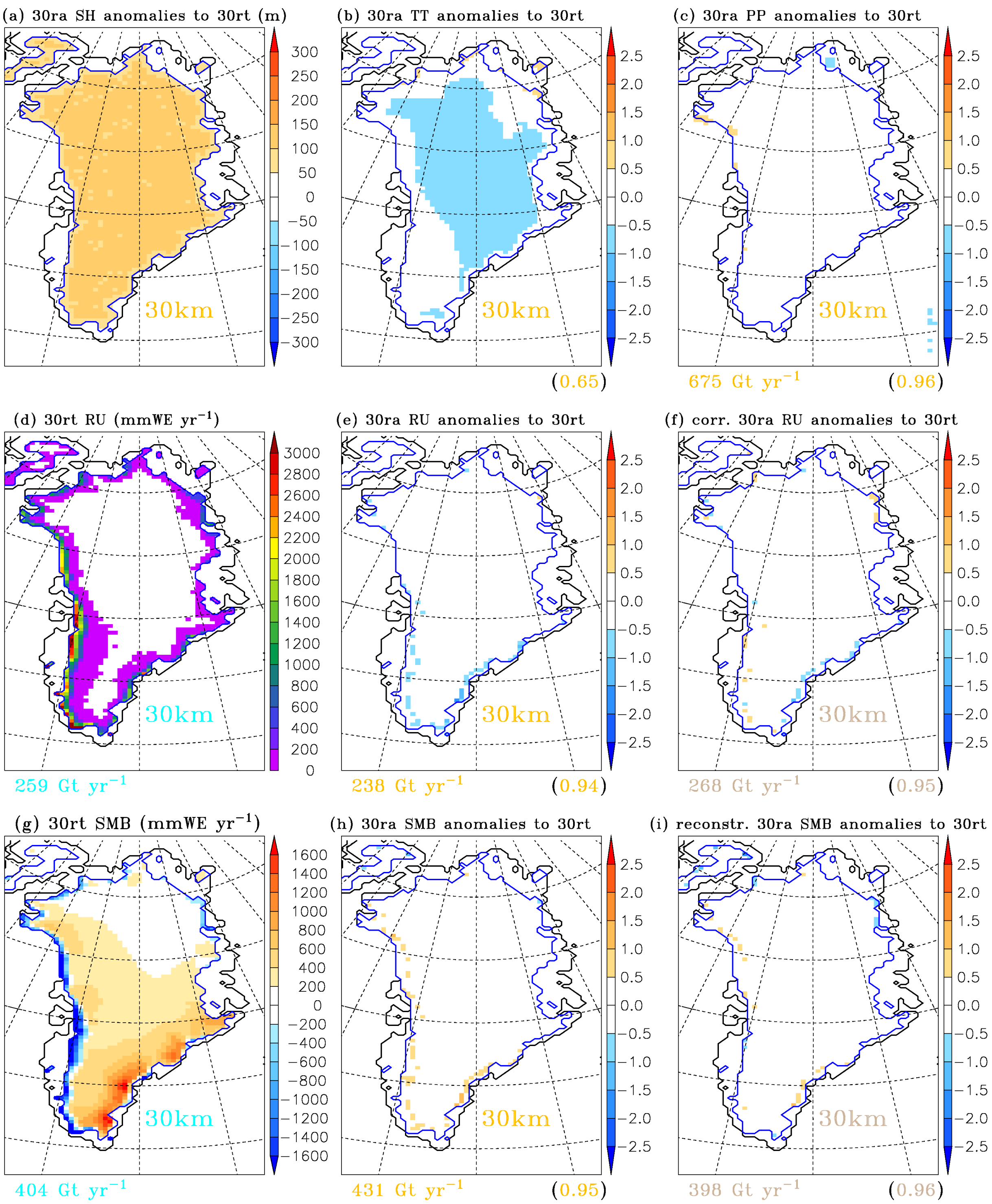


Fig. A.: **(a)** Surface height anomalies (m) of the 30 km resolution MAR topography raised by 100m (30ra), compared to the original 30 km topography (30rt). **(b)** Annual near-surface temperature anomalies (in standard deviation) of the 30ra outputs compared to the 30rt outputs, over 1990-2010. On the bottom right side of the view, in brackets, is the skill score of 30ra compared to 30rt. **(c)** The same as **(b)**, but for the annual precipitation anomalies (in standard deviation). On the bottom left side of the view is the annual amount of precipitation over the GrIS from 30ra. **(d)** Annual meltwater run-off (mmWE yr^{-1}) provided by 30rt over the 1990-2010 period. **(e)** Annual run-off anomalies (in standard deviation) of the 30ra outputs compared to **(d)**. On the bottom right side of the view, in brackets, is the skill score of the 30ra run-off compared to **(d)**. **(f)** The same as **(e)**, but for the 30ra run-off corrected by daily gradients. **(g-i)** The same as **(d-f)**, but for the annual SMB (mmWE yr^{-1}) simulated by the MAR model, and the reconstructed SMB from the corrected 30ra outputs.

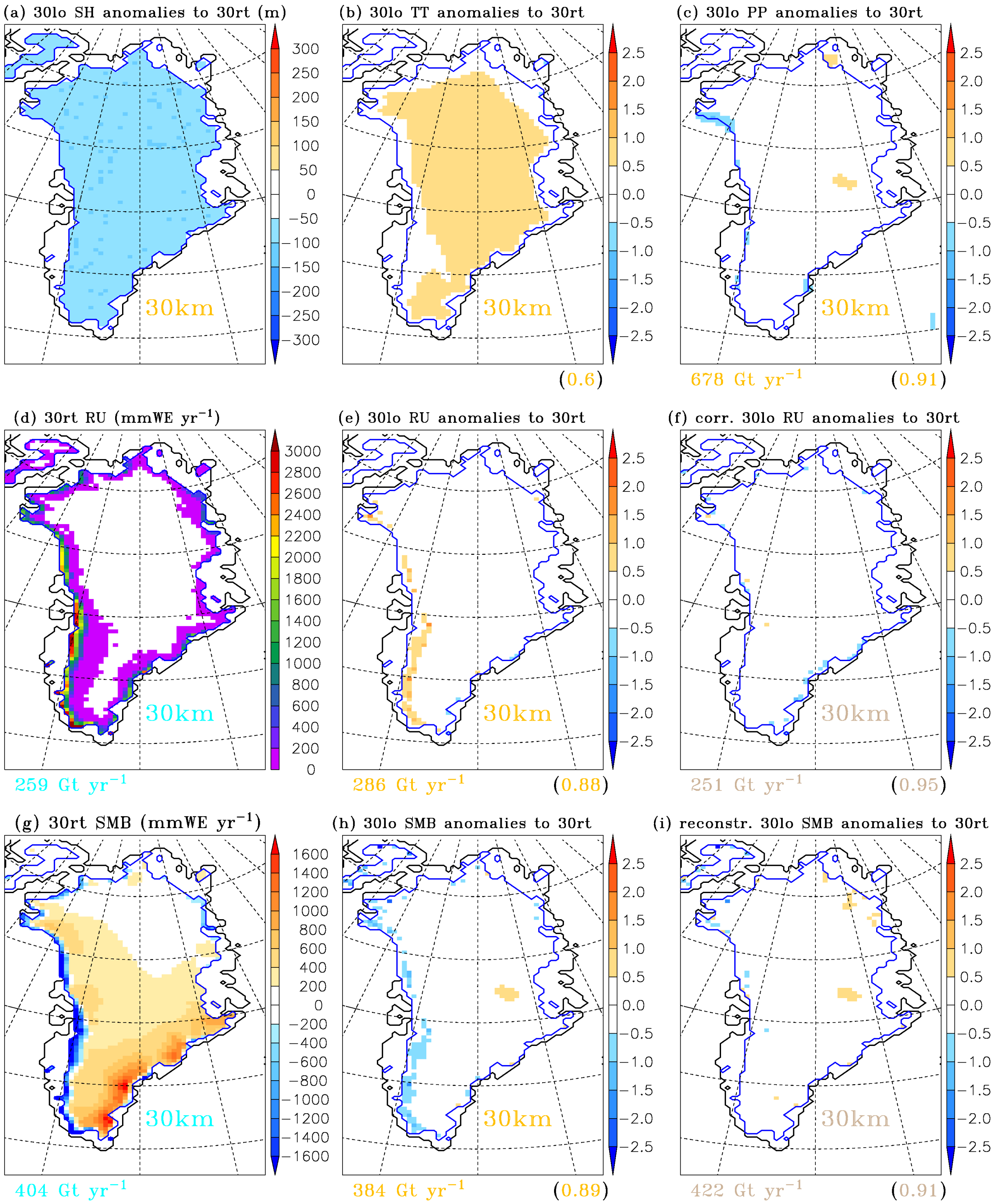


Fig. B.: The same as **Fig. A**, but for the 30 km MAR simulation with the lowered topography (30lo) compared to the original 30 km resolution MAR run (30rt).

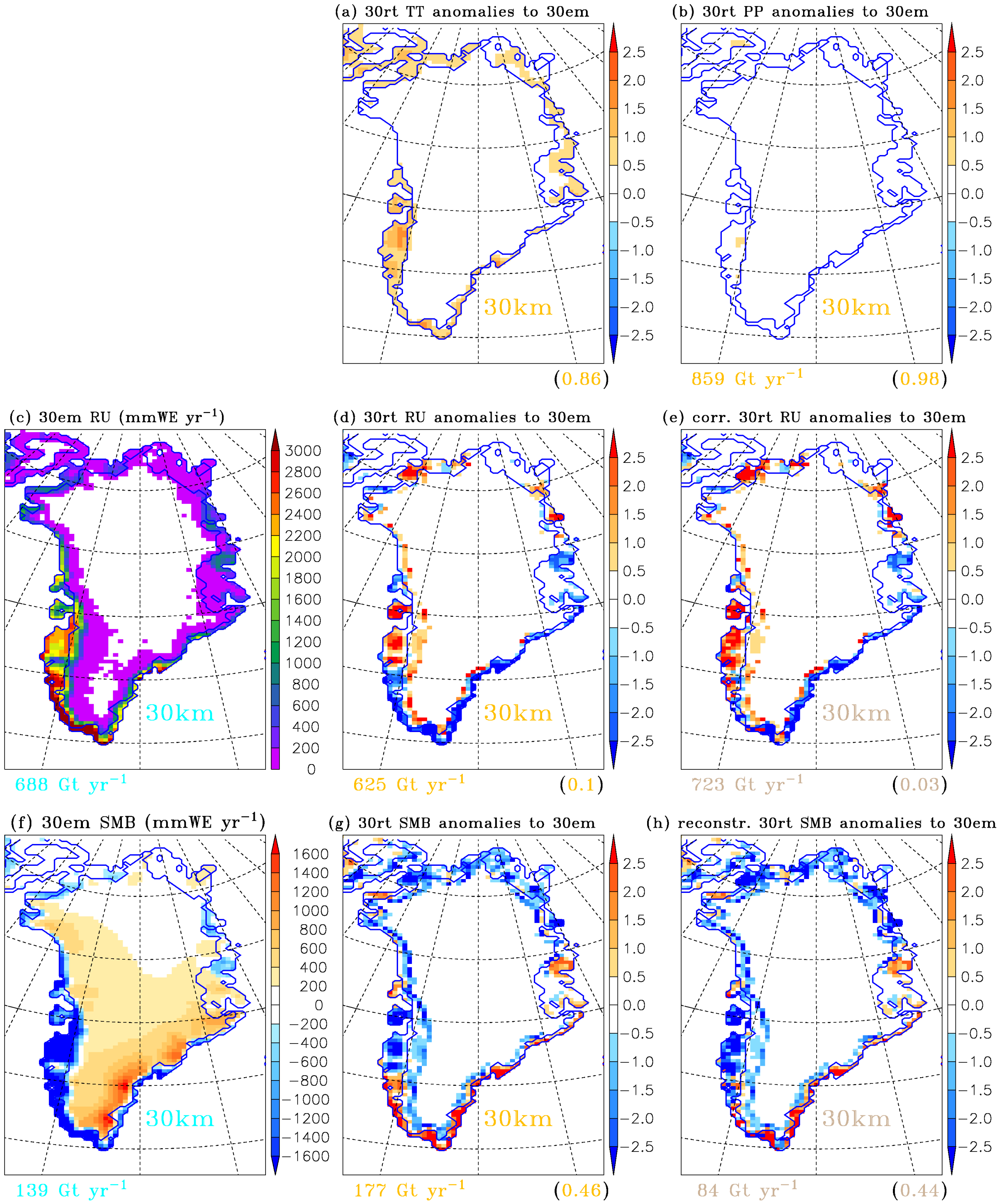


Fig. C.: **(a)** Annual near-surface temperature anomalies (in standard deviation) of the original 30 km run (30rt), compared to the 30 km simulation performed with an extended ice sheet mask (30em), over the 1990-2010 period. On the bottom right side of the view, in brackets, is the skill score of 30rt compared to 30em. **(b)** The same as **(a)**, but for the annual precipitation anomalies. On the bottom left side of the view is the annual amount of precipitation over the GrIS from 30rt. **(c)** Annual meltwater run-off (mmWE yr^{-1}) provided by 30em over the 1990-2010 period. **(d)** Annual run-off anomalies (in standard deviation) of the 30rt outputs interpolated onto the 30em ice sheet mask, compared to **(c)**. On the bottom right side of the view, in brackets, is the skill score of the 30rt run-off compared to **(c)**. **(e)** The same as **(d)**, but for the interpolated 30rt run-off, corrected by daily vertical gradients. **(f-h)** The same as **(c-e)**, but for the annual SMB (mmWE yr^{-1}) provided by 30em, and the interpolated and reconstructed 30rt SMB.

When these points, and the detailed comments below are carefully revised, I would recommend accepting this manuscript for publication.

Detailed comments

- Page 642, line 1-8: Inverse distance weighting is used to interpolate the coarser climate fields onto the 15 km grid. How are differences in marginal area treated between model resolutions? E.g. the 15 km ice mask contains ice over the Maniitsoq ice sheet, southwest Greenland, whereas the 50 km resolution lacks ice there. Figures of the difference of fields (e.g. Fig. 3i) do not show data here. Are these grid points not taken into account for when comparing results?

- For each simulation interpolated onto the 15 km MAR grid, a new ice sheet mask at 15 km resolution was created on which the investigated field from a coarser resolution is interpolated. Consequently, the ice sheet masks produced by the different "coarse" resolution simulations slightly differ between them, and are not so detailed than the original 15 km ice sheet mask. However, to allow a reliable comparison between the results produced by the different MAR simulations, it is better to compare these outputs on the 15 km ice sheet mask common to all the interpolated outputs, whatever the original resolution used by the MAR model to produce these outputs. Therefore, some marginal points of the original 15 km ice sheet mask are not included in the common mask, and thus not taken into account when we compare the results in the first part of this study.
- Nevertheless, we are aware that a detailed ice sheet mask is essential to produce reliable GrIS SMB results, especially at high resolution. Therefore, our interpolated method (presented in the second part of this study) was tested by interpolating the 25 km outputs onto the entire ice sheet mask from the original 15 km simulation, although some 15 km ice sheet pixels are located outside the 25 km ice sheet mask. However, our correction method based on vertical gradients of the field is also able to reduce the biases induced by an interpolation outside the coarser ice sheet mask.

- If values are calculated for grid points outside the coarser grid ice mask, problems may arise when using an interpolation technique such as inverse distance weighting. For example, run-off will generally increase towards the ice margin, hence the use of inverse distance interpolation may result in a slightly higher run off value of a target point that lies just outside the original coarse grid, compared to the nearest neighboring (coarse) grid point. Hence, an alternative extrapolation technique might be worth considering for these grid points.

- Please, see the response to the previous comment.
- In case of grid points located outside the ice sheet mask, we preferred an interpolation method enhanced by a vertical correction according to the topography instead of using a "pure" extrapolation technique based on a linear regression, in order to keep control on the interpolated values outside the original ice sheet. The biases induced by an extrapolation may be very large, very difficult to assess and then to correct. Conversely, the cross section along the K-transect investigated in this study showed that the low resolution MAR simulations reproduce quite well the run-off and SMB behaviour around the margin. Consequently, the local vertical gradients of the field calculated in the vicinity of the ice sheet margin, can be used with reliability to correct grid points just outside the ice sheet

mask. Moreover, such grid pixels are generally not very distant from the main ice sheet (where the local vertical gradients designed for the correction are calculated), hence the use of an extrapolation technique is not really justified in this case.

– Page 642, line 24: "multi-annual observed field" probably refers to the 15 km resolution modeled result. These are not observations.

– Indeed, we wanted to refer to the MAR outputs provided by the 15 km resolution run. This wrong sentence has been corrected in the manuscript.

– Page 642, line 24-25: "normalized it by a measure of the variability of this field" Vague wording. What kind of measure, presumably the standard deviation? Could you please specify this?

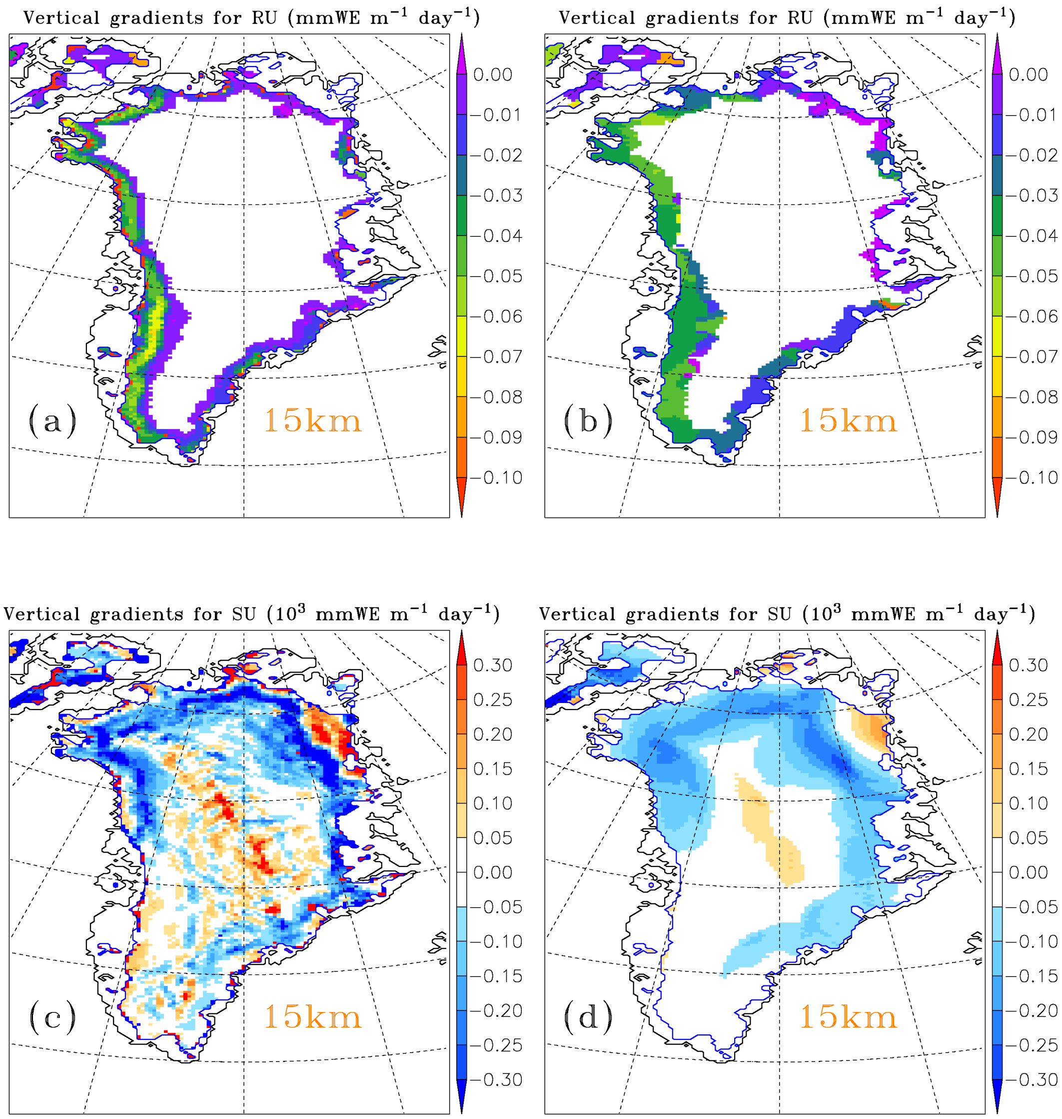
- Indeed, we normalized the RMS deviation by using the standard deviation of the field in each grid point. We have specified this in the manuscript (see the comment above, p.1).

– Sections 6 The method of 'intelligent interpolation' makes use of daily local vertical gradients within the particular climate fields. As such, is the correction then applied to the daily fields, or is a mean correction term computed over the entire period of simulation, and applied once?

- Daily local vertical gradients are calculated in each grid point within the ice sheet from the daily original fields (e.g. 25 km), and then applied to correct the daily fields interpolated onto the higher resolution grid (e.g. 15 km).

– It would be valuable to add a figure that illustrates the magnitude and spatial pattern of the gradients (for run-off, sublimation and evaporation).

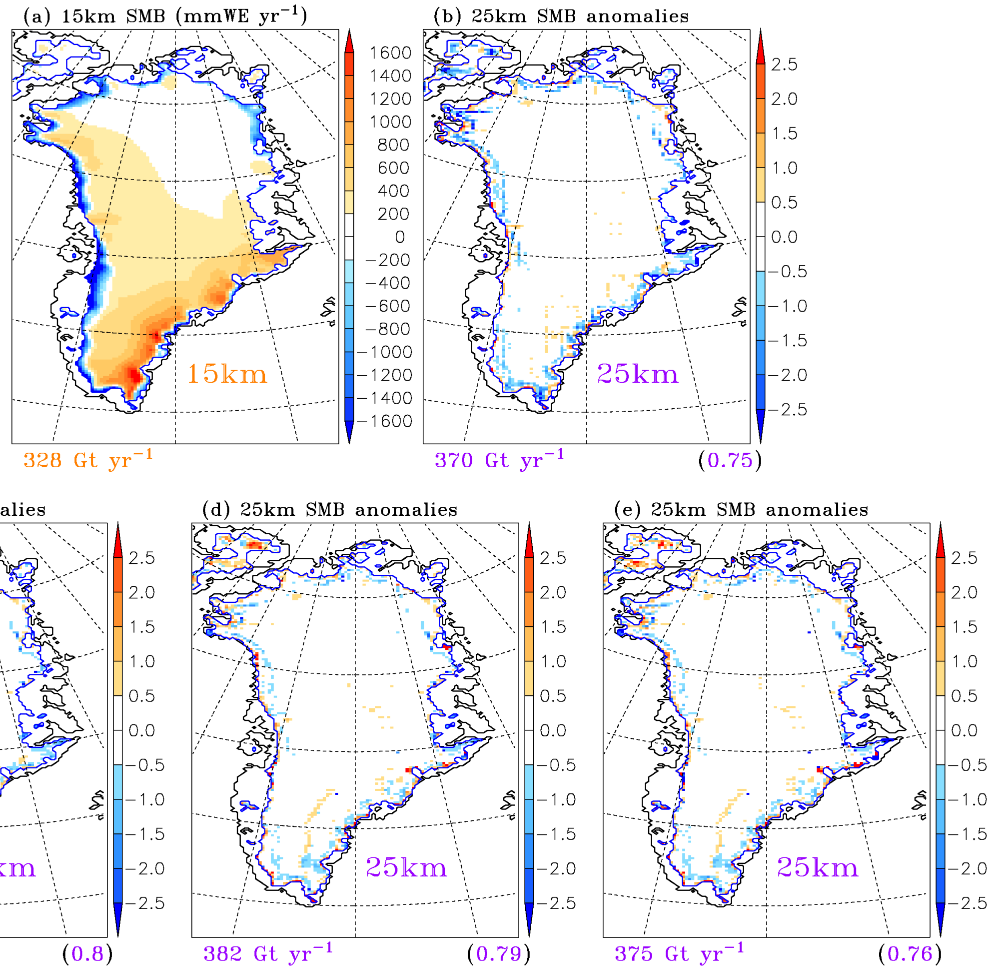
- The figure below shows an example of the spatial distribution of the daily vertical gradients (in this case, for July 1st 2010) implemented according to our method for the run-off **(a)** and the sublimation and evaporation **(c)**, when interpolating the 25 km MAR outputs onto the 15 km ice sheet mask. The same in **(b)** and **(d)**, but for daily vertical gradients produced by the method based on Helsen et al. (2012).



- Page 649, line 17: You refer to Helsen et al. (2012), who described a comparable method to take differences in topography into account in forcing an ice dynamical model with SMB from a regional climate model. Could you indicate how your gradients compare with theirs? Although they calculated gradients for SMB, your values for run off should be quite comparable in the ablation zone. Also for this purpose a figure showing spatial patterns of the gradients would be useful.

- Please, see the previous figure.
- The figure below compares the 25 km SMB outputs interpolated onto the 15 km ice sheet mask, and corrected according to different methods (the method based on Helsen et al. in b, and our method in c-e). **(a)** Annual 15 km SMB MAR outputs (in mmWE yr^{-1}) over the 1990-2010 period. On the bottom left side of the view is the total SMB (Gt yr^{-1}) from the GrIS, on the 15 km ice sheet mask. **(b)** SMB anomalies (in standard deviation) of the annual 25 km outputs interpolated onto the 15 km ice sheet mask and corrected with annual SMB gradients (according to the method based on Helsen et al., 2012), compared to **(a)**. On the bottom right side, in brackets, is the skill score of the interpolated field compared to the 15 km outputs. **(c)** The same as **(b)**, but for the reconstructed SMB from the 25 km MAR outputs (RU and SU) corrected with daily vertical gradients according to our method. **(d)**

The same as **(c)**, but for the daily 25 km SMB outputs interpolated onto the 15 km ice sheet mask and corrected with daily vertical SMB gradients according to our method. **(e)** The same as **(d)**, but for the annual 25 km SMB outputs interpolated onto the 15 km ice sheet mask and corrected with annual vertical SMB gradients according to our method.



– Page 649, line 14-15: What is meant with “common mask”?

- We referred to the ice sheet mask constructed at 15 km resolution, and common to all the 20, 30,... 50 km ice sheet mask interpolated onto the 15 km MAR grid.

Textual comments

– Page 636, Line 25: Consider “an increase in” before precipitation.

- This has been added to the manuscript.

– Page 637, line 2: Surface mass balance, instead of mass balance.

- Thank you for your correction.

– Page 640, line 4: typo: development

- Thanks

- Page 644, line 11: compared instead of applied?
- Indeed, this is a more adequate word.
- Page 647, line 7: enlarged instead of expanded
- This has been modified in the text.