

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 #1

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Dear Referee,

We want to thank you for the review and your constructive suggestions. Please find below the response to your comments.

General comments

This paper analyses the effect of model resolution on the surface mass balance estimates of the regional climate model MAR, specifically for Greenland. Simulations on different resolutions were done (15 to 50 km). Analyzed is the effect of model resolution and the relative contribution caused by smoothed topography. Furthermore, the methods do downscale model results are analyzed.

In general this manuscript is well written, the research consistently performed, analyzed and discussed. Some paragraphs needs to be rewritten because they aren't clear now, see specific comments below. From that point of view, I have no major comments.

However, my concern is that this paper, in its present form and focus, will have little impact. It shows that high resolution (< 25 km) is not always needed for a good estimation of the Greenland SMB, and that clever interpolation can reproduce high-resolution fields from lower resolution output rather well. But points are not worked out to their fundamental question and solution: a) which model resolution is needed to resolve an ice sheet (section) with a typical topographic length scale X ?

We agree that we have to answer this question. We are currently working on this issue and the response will follow in a few days.

b) What is the best method to get the most out of a low-resolution regional climate model simulation?

Indeed, which maximal YY km resolution is required to obtain reliable SMB outputs at a higher XX km resolution? Therefore we have used our method to interpolate the different spatial resolutions used in this study onto different higher-resolution MAR grids. These results are summarized in a new table (see below Table A) that will be added and discussed in the manuscript. This table shows that a maximal resolution (YY km $< 2 \times XX$ km) of less than twice the desired spatial resolution (XX km) is needed to obtain reliable interpolated SMB results at XX km resolution, otherwise the skill scores are decreasing rapidly and the interpolated outputs are becoming less reliable.

Table A. Summary of SMB skill scores and annual SMB results for the GrIS (in brackets) of MAR simulations interpolated onto MAR grid and corrected with daily vertical gradients, for the 1990-2010 period.

MAR grid	SMB skill scores (and annual SMB results for the GrIS) of MAR simulations interpolated and corrected onto MAR grid				
	20RT	25RT	30RT	40ED	50ED
15 km	0.90 (343 Gt yr ⁻¹)	0.80 (341 Gt yr ⁻¹)	0.67 (357 Gt yr ⁻¹)	0.46 (377 Gt yr ⁻¹)	0.31 (392 Gt yr ⁻¹)
20 km	/	0.88 (321 Gt yr ⁻¹)	0.80 (335 Gt yr ⁻¹)	0.53 (358 Gt yr ⁻¹)	0.38 (372 Gt yr ⁻¹)
25 km	/	/	0.88 (362 Gt yr ⁻¹)	0.67 (382 Gt yr ⁻¹)	0.43 (390 Gt yr ⁻¹)
30 km	/	/	/	0.72 (352 Gt yr ⁻¹)	0.53 (368 Gt yr ⁻¹)
40 km	/	/	/	/	0.68 (416 Gt yr ⁻¹)

a) Add an analysis of the local typical length scale of the topography of Greenland and relate this to the local quality of the RCM on different resolutions. From this, estimate the resolution needed to resolve the SMB of the Greenland ice sheet – and other glaciated areas on the world.

(See response to the point a) above).

b) Somehow I got the impression that the authors still work on the optimal interpolation method (p. 657, l. 12). In that case, I suggest to remove the analysis of this preliminary method from this manuscript and focus entirely on question a) and the resolution effects. Why present something, which you will improve very soon? If this (a paper on the best method to interpolate low resolution fields) is not planned, then improve this method to a final product and show the results here, or leave out the suggestion that the method must be developed further.

Currently, we no longer work on specific interpolation methods. This study, conducted in the framework of a PhD research, aims to investigate the effect of model resolution, and to present an interpolation method producing reliable SMB results on a higher-resolution ice sheet mask, from lower-resolution RCM outputs. In the conclusion, the suggestion that the “only first step ... must be developed further” is an “unfortunate” sentence: what we wanted to express is that the issue of SMB interpolation has not been much discussed until now (except by Helsen et al.) and that we propose here an efficient method. However, we recognize that our method has its limitations, which were presented in the conclusion. As the SMB interpolation is currently a very interesting issue (for forcing ice dynamical models, etc.), we meant that it would be very useful to develop new efficient methods not affected by these limitations. We agree that the suggestion (in its present form) in the conclusion must be left out, and that the last part of Discussion and Conclusion needs to be refocused on what our method brings to the issue of the SMB interpolation.

These concerns are not severe enough to inhibit publication, but I strongly advise the authors to take this additional step and improve the manuscript.

Comments

- The English is ok, but consider rewording ‘diminishing resolution’, ‘depleting skill scores’,

‘debased topography’. For me it sounds like that the resolution is gone soon, the model runs out of skill score and the topography became morally wrong. So check if these words are indeed ‘the right words’.

Thanks. We have reworded these words more adequately in the manuscript by using now 'low resolution', 'decreasing skill scores' and 'smooth topography'.

- Is it possible to number the figures in the supplementary material (S1 to Sxxx) and use this numbering when referring to it in the manuscript?

Indeed, this will make references to the supplementary figures easier.

- I know that I’m a (too big) fan of abbreviations, but is it an idea to define abbreviations for the different simulations, and make a table with the different simulations? For example, define 25ST for the 25 km simulation with smoothed (=50km) topography simulation. Now I get lost somewhere in section 7, due to the numerous simulations and their comparisons.

This is a very good idea: this should help the reader to distinguish the different simulations investigated in this study and make the figures easier to be read. Please find below the different abbreviations we propose to use (Table B). This table will be included in the manuscript. Nevertheless, we limit the use of abbreviations to the MAR simulations performed in the framework of this study strictly (and we don't include e.g. YY km simulation interpolated onto the XX km MAR grid) in order not to force the reader to “decode” these too many abbreviations.

Table B. Definition of the different MAR simulations performed in the framework of this study, and the related abbreviation.

Abbreviation	Definition
15rt	15 km simulation on Real 15 km Topography
20rt	20 km simulation on Real 20 km Topography
25rt	25 km simulation on Real 25 km Topography
25st	25 km simulation on Smooth 50 km Topography
30rt	30 km simulation on Real 30 km Topography
40ed	40 km simulation on real 40 km topography over Extended Domain
50ed	50 km simulation on real 50 km topography over Extended Domain
40od	40 km simulation on real 40 km topography over Original Domain
50od	50 km simulation on real 50 km topography over Original Domain

- p. 640 l. 14-19: The K-transect ends on Russell glacier, an ice sheet promontory. Therefore, it requires a very high (< 2 km) model resolution to resemble the glacier outline on this area. My point is, hence, ‘distance to the ice sheet margin’ is not a good tuning parameters for matching model data with K-transect data. It is better to use the elevation of S9 and S10 to match the relative grid point locations. Elevation is more important on the SMB than distance to the margin.

We agree that elevation is a more important parameter. Please find below, after the comments, the new related figure (Fig. A). Nevertheless, most of these cross-sections have been shifted towards the centre of the ice sheet, consequently we are now underestimating the elevation of S6, S7 and S8, and most importantly this does not allow a good comparison

between the modelled/observed SMB. Therefore we propose to add this new figure to the supplementary material but keep unchanged our Fig. 1.

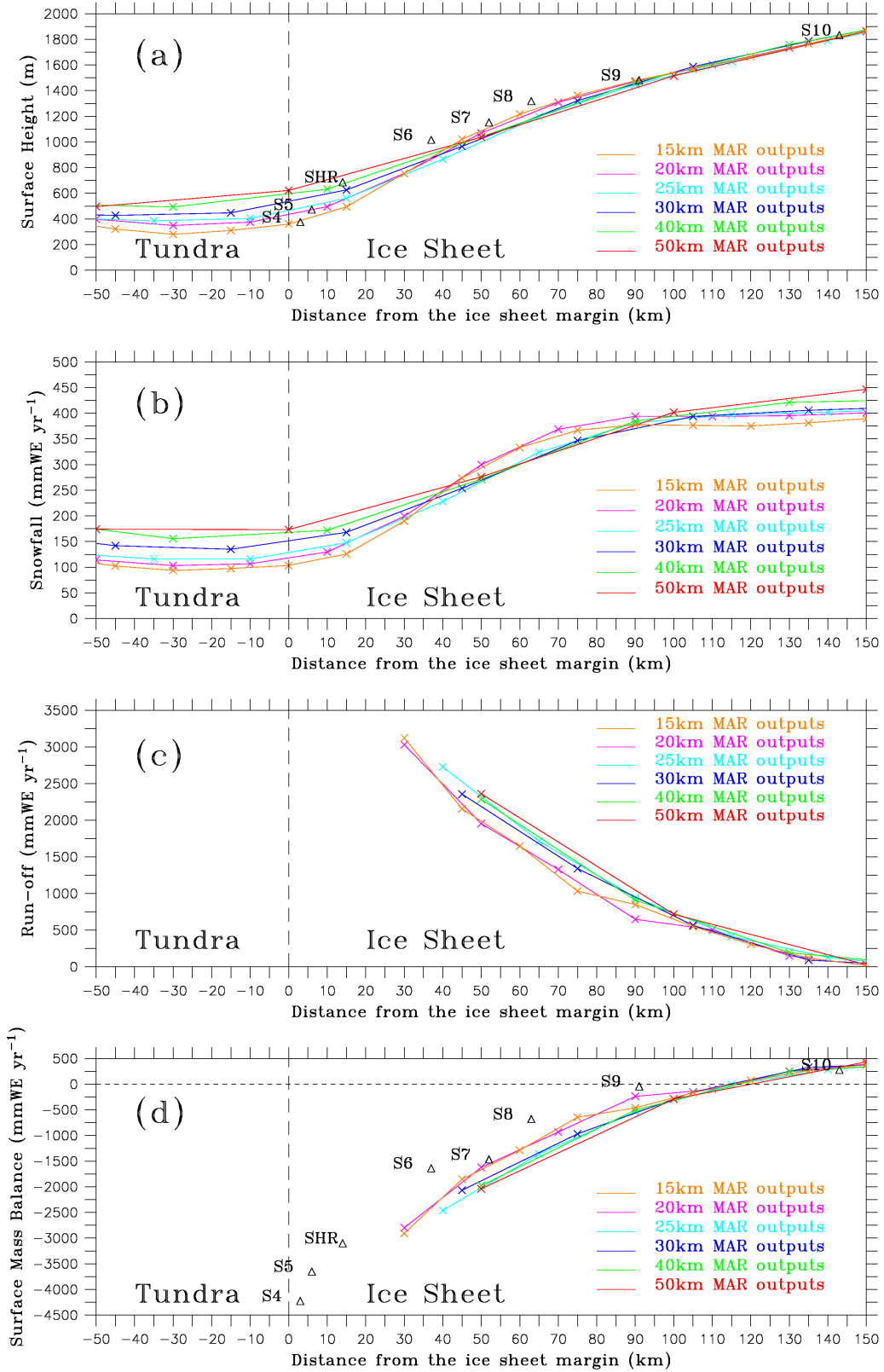


Fig. A. (a) Cross section of surface height (m) through the GrIS along the K-transect (67°N, west Greenland) for the 15–50 km resolution MAR runs, with station data drawn in black symbols. (b) The same as (a), but for annual snowfall (mmWE yr⁻¹) over the 1990–2010 period. (c) The same as (b), for the annual run-off of meltwater (mmWE yr⁻¹). (d) The same as (b), but for the annual SMB (mmWE yr⁻¹).

- p. 641 & 666: Add to figure 1 a comparison of model/observed SMB as function of elevation.

Please find below this comparison in a scatterplot (Fig. B). We propose to add this plot to the supplementary material.

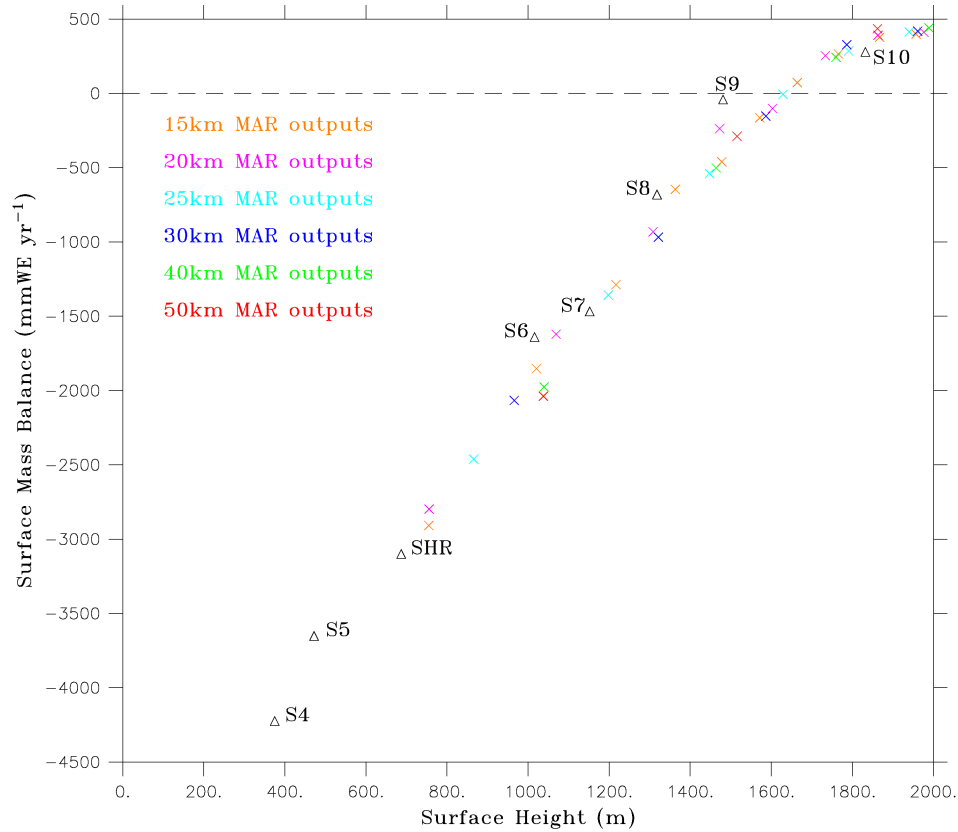


Fig. B. Scatter plot of the annual surface mass balance (mmWE yr⁻¹) along the K-transect (67°N, west Greenland) according to the surface height (m) for the 15-50 km MAR runs, with station data drawn in black symbols.

- p. 641 l. 19-28: I don't get the point of this paragraph. For example, which computation time is saved by the interpolation? Likely the authors refer to the calculation time of high resolution run, but that is what I conclude after reading the whole manuscript. Please rephrase.

Indeed we refer to the important calculation time (CPU time) of high-resolution run. For example, according to Table 1 in the manuscript, interpolating the 25 km resolution results onto the 20 km grid, instead of using outputs provided by the 20 km resolution run, allows to save 150% of the relative computing time of the 20 km simulation. This paragraph has been rephrased.

“As suggested by Table 1, increasing the spatial resolution of MAR requires a large additional computation time (CPU time) to perform the simulation; e.g. running the MAR model at 15 km resolution takes five times longer than the 25 km simulation. To reduce the additional computing time needed by the very high resolution MAR simulations, we interpolated the outputs produced by the MAR model running at a lower resolution (20–50 km) onto a higher-resolution grid (here 15 km). The intention behind this was to obtain outputs at higher spatial resolution, reliable enough to be used as forcing fields and requiring

acceptable computing time to be produced. However, we first had to gauge the lack of information of the interpolated data compared to the results directly provided by the simulations at this higher spatial resolution.”

- From p642 onwards: Use Gt yr^{-1} , that’s the common used dimension. Moreover, $\text{km}^3 \text{ yr}^{-1}$ is unclear, is it ice, snow or water equivalents?

It is water equivalents. We will use Gt yr^{-1} .

- p. 643 l. 4-9: I only understood this paragraph after several times rereading, please rephrase. It’s in my view not really a control reference, these tests give an idea how good or bad a certain skill score is.

Indeed, these tests are primarily a comparison, hence this paragraph has been rephrased.

“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.”

- p. 648 l. 6-16: Indeed the 25-20 km resolution captures most of the SMB (components) variability since for most of Greenland the typical topographic length scale is larger than 25 km. For the rugged parts of Greenland (deep south and southeast) 15 to 25 km is still too coarse to capture the SMB correctly. This connection of model skill and topographic length scale is essential and should be added here.

We have added this remark to the paragraph.

“Section 4 highlighted some biases within the fields of precipitation, run-off and SMB coming from the different spatial resolutions investigated in this study. However, while these biases gradually increase with reducing spatial resolution, the 20–25 km resolution runs provided quite reliable results compared to the 15 km outputs. Moreover, as the 20–25 km simulations require a reasonable computing time, their outputs interpolated at a higher spatial resolution can be considered a suitable alternative to the very high-resolution results required to act as forcing fields of an ice dynamical model. We therefore sought to dampen the anomalies of the SMB components we have highlighted between the 20–50 km results and the 15 km MAR outputs, in order to produce SMB fields more reliable as potential forcing fields for higher-resolution simulations. Nonetheless, since most of the SMB components can be captured by the 15-25 km resolution runs, the rugged parts of the GrIS in the closest vicinity of the margin require a higher resolution to be resolved (Fig. 1).”

- Section 6.1: The method remains vague to me. It’s not 3D interpolation; it’s not 2D x-y or xy-z interpolation. Please make it more specific and add an explaining figure in the supplementary materials. In the end, this method supports one of the main conclusions of this paper, i.e., high resolution is not always needed.

We have rephrased the description of the method, and added an explaining figure to the supplementary material (see below Fig. C).

“This section details the correction of the 25 km outputs interpolated onto the 15 km ice sheet mask to reduce the anomalies with respect to the 15 km MAR fields by applying a correctional factor to each interpolated point (taking into account the differences between the 15 km and the 15 km interpolated 25 km topographies): an explaining figure is presented in Supplementary Material. For each point of the 15 km grid, we identified the eight ice sheet points from the 25 km grid the closest to this 15 km grid point. For each couple from these eight points, a daily local gradient of the field was calculated according to the difference in surface height on the 25 km resolution grid. Then these local gradients were weighted by the total difference in elevation between the eight 25 km points to produce a daily vertical gradient of the field, specific to the 15 km grid point. Finally, as correction factor, this daily vertical gradient was applied to correct the 25 km field interpolated onto the 15 km grid, according to the difference between the interpolated 25 km surface height and the original 15 km topography on this point. The use of vertical weighting (instead of a simple average) in the gradient computation aimed to dampen the influence of “extreme” local gradients; i.e. a strong variation of the field between two 25 km points located almost at the same surface height generates a very large gradient. Finally, if the 15 km point lies beneath all the eight closest 25 km points (e.g. along the ice sheet margin), only the maximum local gradient was taken into account in order to strengthen the correction.”

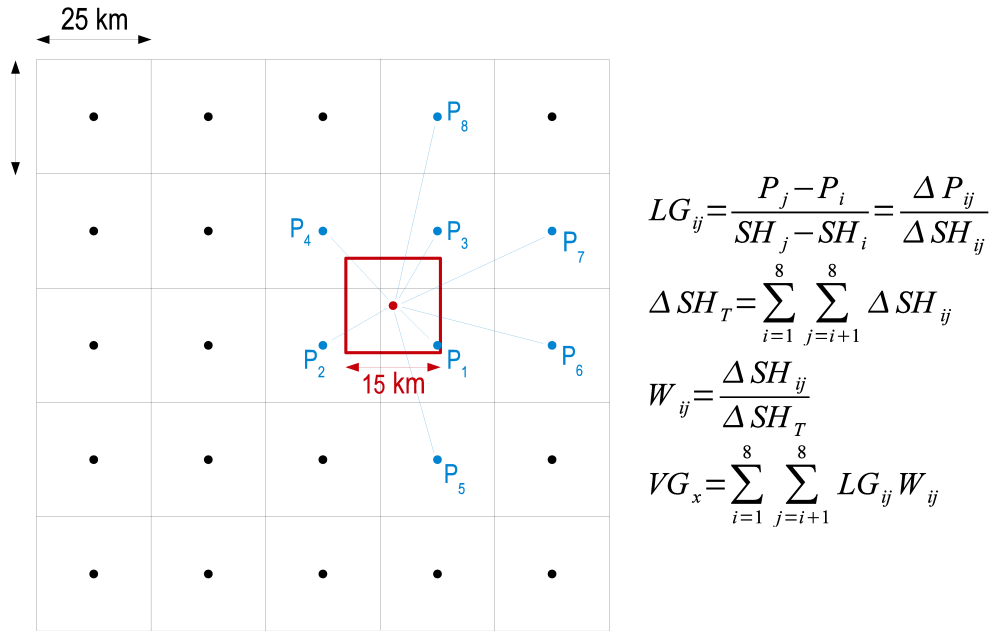
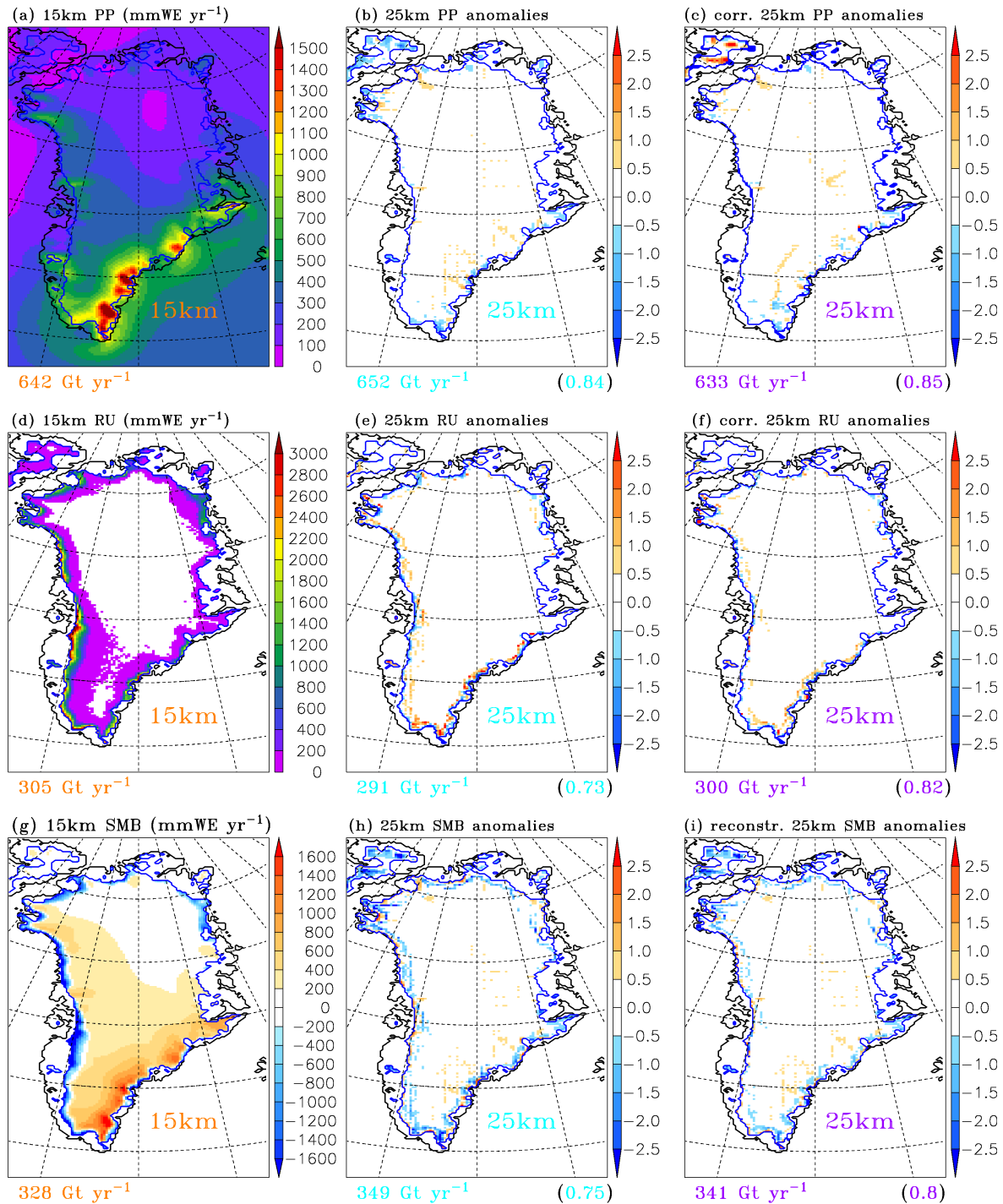


Fig. C: Explaining figure of the method of correction used in this study: e.g. for an interpolated 15 km point x , corrected from the eight closest 25 km points. P_i = value of the field in the 25 km point i . SH_i = surface height of the 25 km point i . LG_{ij} = local gradient of the field calculated between the 25 km points i and j . W_{ij} = weight of the local gradient between i and j . VG_x = vertical gradient of the field for the interpolated 15 km point x , used to correct this point x according to the difference of elevation between the real 15 km topography and the surface height at this point x .

- Section 6.4: Since one of the main conclusions is that precipitation can’t be improved by clever interpolation, this should be supported by Figures. Probably there was not much to show, but still. Space permitting, add it to Figure 6, otherwise to Figure 16.

The figures related to the interpolation and correction of precipitation have been added to Fig. 6. Please find below this new figure (Fig. D).



- p. 654: I don't get entirely clear what is shown in Figure 7f and 7i. Is it the 'smooth surface 25km simulation' corrected to the 'real surface at 25km' or the 50km simulation cleverly interpolated to the 25km grid?

This is the smooth surface 25 km simulation (25ST) corrected to the real surface at 25 km (25RT). The use of abbreviations will make these figures easier to be read.

- p. 656, l. 15: '... harshly challenge. . . ' I would say that the differences in precipitation estimates by the different models are more a problem than their different responses to grid resolution.

This paragraph has been changed.

“The conflicting behaviours of the RCMs concerning the simulated precipitation and their responses to grid resolution are still unexplained. Because snowfall and rainfall represent the main input to the GrIS SMB, further investigations are required to develop a full understanding of what causes heavier precipitation in each RCM. For instance, a detailed comparison between the specific physics of each model should reveal more information about this issue”.

- The conclusions, i.e., the last part of Discussion and conclusion, can be a bit more focused to the research questions. The conclusions are now clouded by possible improvements and unresolved problems.

We agree. See our comments above about this point.

Minor comments

- p. 637 l. 15: Add a reference to the aims and goals of ICE2SEA.

We have added a reference.

- p. 640 l. 6: Benefited? Where is the profit? I would use ‘. . . which needed an enlarged domain . . .’

Indeed, this word is not really appropriate and has been modified.

- p. 641 l. 3: It is not too cold for significant snow fall, there is still 300 mm yr⁻¹. What is actually meant? In fact the surface slopes are similar for all resolutions, so snowfall differences should also disappear.

This sentence has been modified.

“Further inland, the precipitation rates stop increasing because the surface slopes are more gentle and temperatures become too cold to add significant snowfall.”

Indeed, snowfall differences should disappear, but this study has shown different responses of MAR to the spatial resolution concerning the simulated precipitation over the ice sheet.

- p. 641 l. 15-17: Can you give, using the topography, an estimate of the resolution required to resemble S4 and S5? < 2, 5 or 10 km?

A resolution < 5 km is required. This has been added to the manuscript.

- p. 646 l. 7: include the word ‘annual’ or include the dimension yr⁻¹ to the number.

Thanks for the correction.

- p. 646 l. 9: Consider expressing the trend as 10 Gt yr⁻² (values is my guess).

Indeed, it will be more appropriate.

- p. 647 l. 5: To my memory, the increase of RACMO precipitation for smaller resolution is

due to enhanced orographic precipitation in SE Greenland. Orographic precipitation is much more vigorous in RACMO than in MAR. For even higher resolutions, this increase in RACMO stops since more high accumulation points fall outside the ice sheet mask. MAR instead excludes the coast of southeast Greenland from the ice sheet. So, I don't see this results as un-explainable.

Thanks for the information. It will be mentioned in the manuscript.

- p. 648 l. 22: Why 8 points, not 9 (a 3x3 square)?

We have chosen not to use a 3x3 (or 5x5) square because, for ice sheet points located in the vicinity of the margin, a 3x3 square of lower-resolution points is not entirely included in the ice sheet mask (sometimes 1 or 2 points only). By choosing the 8 closest points included in the ice sheet mask, we can ensure a sufficient number of points to calculate reliable gradients. However, we have shown in this paper that this method is still efficient with 4 or 12 closest points.

- p. 649 l. 17: Interesting to see that this method works better than Helsen et al (2011). Does this method allow estimating SMB components out of the elevation window of the 8 points?

Yes, it does, because it is only based on local vertical gradients of the field correcting the interpolated field, whatever the difference of elevation between the interpolated topography and the real surface. This is what happens for 15 km points just along the ice margin: such a 15 km point is often located below all the eight 25 km points we take into account to correct it.

- p. 650 l. 10-17: Make more clear when is referred to the interpolation to 15 km and when to the original 15 km simulation.

We have modified the paragraph.

“Therefore, despite the use of the maximum local gradients, the run-off gradients of the interpolated 15 km points located in close proximity to the GrIS margin could be slightly underestimated, making the correction factor insufficient to significantly reduce the negative anomalies along the border of the ice sheet. In addition, at the beginning of the melt season bare ice appears earlier over the original 15 km pixel (inducing high run-off rates) while the closest 25 km pixels, higher in altitude, are still covered by melting snow, retaining a large part of the meltwater. Consequently, the local gradients derived from these 25 km pixels are not fully reliable when used in place of an interpolated 15 km pixel.”

- p. 652 l. 21-22: Consider rephrasing to something like: ‘In this section, the effect of coarse resolution topography is investigated by analyzing high resolution (X-Y km) simulations which use coarse resolution (50 km) topography.’ It now takes very carefully reading to grasp the intention.

Thanks for this good suggestion.

- Table 1: Provide actual relative computing times or add ‘estimated’ to column caption.

“Estimated” has been added to column caption.

- Figure 5: The caption is not very clear. Clearly state that a positive value implies a decrease (?) compared to the original grid. Consider removing the comments on interpolation. Add ‘original grid’ and ‘extended grid’ to the pink/red/green texts below the figures. Furthermore, expand the figure domain so that the expanded and original extend of the domains can be plotted.

The figure and its caption have been modified (see below Fig. E).

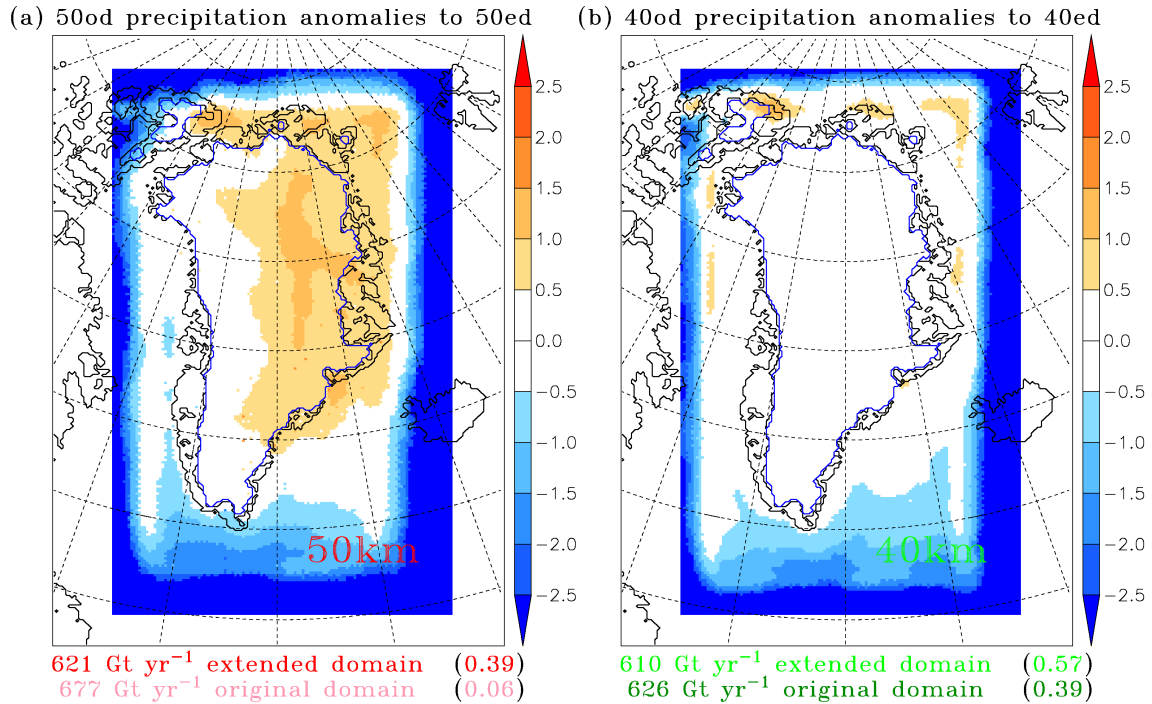


Fig. E: (a) Annual precipitation anomalies (in standard deviation) of 50od (original domain) from the MAR model to 50ed (extended domain), over the 1990-2010 period. Positive (negative) values mean higher (lower) precipitation simulated by 50od than 50ed. On the bottom left side of the view is the annual amount of precipitation (Gt yr⁻¹) from 50ed (in red) and 50od (in pink). On the bottom right side of the view, in brackets, is the skill score of 50ed (in red) and 50od (in pink) compared to 15rt. (b) The same as (a), but for the 40ed (in clear green) and 40od (in dark green).

- Figure 7: I assume that this figure will be larger in the final version. I think individual subfigures should not be smaller than 3 cm wide otherwise readers need a microscope. In the current version, Figure 7 has subfigures of almost 2 cm wide.

Indeed, these subfigures will be very larger (more than 3 cm wide) on the A4 format of the final version.