Reply to reviews on "Towards direct coupling of regional climate models and ice sheet models by mass balance gradients: application to the Greenland Ice Sheet" by M.M. Helsen et al.

We would like to thank the two anonymous reviewers, who have commented on our manuscript and hereby helped us to include some critical changes that have certainly improved the manuscript. Below, we address each comment of the reviewers.

Reviewer #1

The method developed in this paper is useful while direct coupling between climate and ice sheet models is not yet practical due to the different time scales of the models, but the authors could, in my opinion, make more use of the large amount of model output from the climate model. For example, they only use the average Ts for the period 1958- 2007 rather than the time series from the model or (multi-)decadal averages to see how variable their results are over the period of the RCM run, and in their PDD calculation they assume a simple seasonal variation, rather than using the monthly or daily means that should be available from the RCM model. They also do not use the now available surface elevation and/or mass change observations from the Greenland Ice Sheet to validate their model results, but use only the total volume and simulated shape as has been done in ice sheet modeling studies for the last decades, so not much use of new observations or forcing is made in this paper, but rather standard model setup and validation is done. For this paper to present advancement in coupling regional climate and ice sheet models more use of the available RCM output should be made and hopefully it can be shown that using the SMB and SMB gradients from the RCM an improved present day ice sheet configuration can be achieved. The presentation of the results in the manuscript as it is now is not convincing the reader that improved present day ice sheet is simulated with this method.

> A general reaction: the principle goal of this paper is to present a new method that can be used in tandem with asynchronous coupling ice sheet - climate model runs. This does not necessarily lead to a closer agreement between simulated and observed ice sheet (this depends on the quality of the RCM, the ice sheet model, resolution, etc); it merely is a next step in an unambiguous treatment of the SMB forcing. Since SMB is the principle forcing parameter for an ice sheet model, it is vital to design a methodology that (1) enables to apply and reproduce such fields of SMB on a dynamic ice sheet topography, and (2) allows for an elevation – SMB adjustment while the ice sheet topography evolves. These intentions are now more clearly reflected in the introduction:
> *line 97: Here we introduce a novel approach to force an ice sheet model in which SMB fields of a regional climate model are used directly, which circumvents assumptions regarding the calculation of run-off. The method (Sect. 2) (1) enables to apply and reproduce fields of SMB to a dynamic ice sheet topography, and (2) allows for an elevation - SMB adjustment while the ice sheet topography evolves, the latter is the main novelty of this work. For this particular application, we use SMB fields from the regional climate model RACMO2/GR, a product that realistically simulates the SMB observations (Ettema et al., 2009). In principle, this method is designed for use in asynchronous coupled ice sheet - climate simulations, but here we apply it to a set of ice sheet model experiments using a single climatology (Sect. 3). In Sect. 4 we evaluate our method and conclusions are drawn in Sect. 5.*
>
> Regarding the request of making more use of the available RCM data: We have carried out several additional test, using (1) different episodes within the full 1958-2007 RCM period (see below), and (2) we have used different RCM results, calculated on two different topographies, keeping the other boundary conditions for the RCM fixed. In our view, this is the most rigorous test we could include to assess the performance of our SMB gradients method in reproducing the elevation – SMB feedback. At the time of initial submission of the discussion paper, we chose not to present RCM runs on

different topographies in this paper. However, we now think that the presentation of additional RCM runs, and a comparison with the SMB gradient method, provides firmer support for our methodology. Therefore, we included results that we obtained in a different study, which deals with the retreat of the Greenland ice sheet during the Eemian.

The first couple of paragraphs in the discussion now reflect this:

Line 607: The SMB gradient method is designed as a tool to improve asynchronous coupling between climate models and ice sheet models. As shown here, it can also be used as a stand-alone SMB forcing module. A rigorous test of the performance of the SMB gradient method would be to compare results against a regional climate run obtained on a different ice sheet topography. We do this for a model run on simulating Eemian climate conditions, since the GrIS was by then clearly out of balance. In this experiment, RACMO2/GR is forced at its lateral boundaries by the ECHO-G GCM, with greenhouse gas concentrations and orbital parameters of 125 ky BP (Van de Berg et al., 2011). RACMO2/GR was then asynchronously coupled with ANICE, using SMB gradients, to simulate GrIS retreat. A different resolution (18 × 18 km) was used for these RACMO2/GR simulations, which requires a reduction of the minimum number of Hs-SMB pairs to n = 37, to ensure an equal area-of-influence in comparison with the present-day fields. Here we show SMB calculations for two different time slices at 129 ky and 128 ky BP (Fig. 15a and b), to assess the performance of the SMB gradients method. The ice sheet extent through the Eemian is highly unknown; for 129 ky BP we chose an ice sheet configuration intermediate between estimates for glacial conditions and the present-day extent. The ice sheet for 128 ky BP is derived from a 1 ky simulation using the SMB approach described in this manuscript.

Between 129 and 128 ky BP (Fig. 15a, b and d), the decrease in ice sheet elevation is most pronounced along the southwestern margin, where the elevation difference reaches ~1000 m. The effect of this elevation change on SMB is well captured by the SMB gradient method, as calculated for 128 ky BP (Fig. 15c), based on the SMBracmo fields at 129 ky BP (Fig. 15a). The residual difference (SMBgradients- SMBracmo, Fig. 15f) is mainly positive, which points to a small underestimation of the decrease in SMB, hence SMB gradients were slightly too small in the RACMO2/GR simulation. However, most deviations can be explained by the changes in precipitation, which is a dynamic response on large-scale topographic changes. For example, the ablation area in south Greenland where ΔSMB is largest, experiences a significant reduction of precipitation because of the concave topography. Still, the correlation between the two SMB fields in Fig. 15b and c is very high (R^2=0.988) and the RMSD is only 91 kg m^{-2} yr^{-1}, in support of the SMB gradients method.

Regarding the request to make more use of time series from the RCM: We chose not to apply an alternative forcing using time series of e.g. SMB and/or temperature, since the type of ice sheet experiments we performed are insensitive to interannual variability, it is the climatology that matters in these type of model runs. We chose to use (as far as possible) the same forcing for the PDD model as for the SMB gradient model, since we wished to compare it as if the PDD model would be used as an intermediate model to transform an RCM climatology to useful SMB forcing field for an ice sheet model.

Using more of the available elevation change data is not as evident as it appears, since we do not claim that our model results contain any representation of the recently observed ice sheet changes. Our approach uses a climatology of multiple decades as forcing, which allows only comparison with mean states of the ice sheet (elevation, thickness), not with variability observed over a few years.

The abstract claims that a new parameterization of SMB is presented, which is not right, the authors are developing an elevation-SMB relationship based on the SMB output computed by a RCM. Also, on page 2125, line 17 the text indicates that a new method of SMB forcing is developed, again the paper describes method to compute elevation-SMB relationship from the SMB computed by the RCM. This is stated in the conclusion, the abstract and the beginning of section 2.4 should be rewritten to clearly state what is done in the paper.

> We agree with the reviewer that by making use of an existing SMB field from an RCM, we do not present a new SMB parameterization, we rather present a parameterization to account for the Hs-SMB feedback. We therefore removed the term 'SMB parameterization' throughout the text, and changed it with a more precise description: an adjustment of the SMB to account for the height – mass balance feedback in ice sheet model experiments.

Throughout the paper the SMB simulated by the RCM is stated to be data, which is not right, it is an output of a model that is used as input to another model, please rewrite on page 2119 line 25, page 2120 line 4, line 13, line 17, page 2121 line 7, line 10, line 16, page 2124 line 14 and maybe other places (please look carefully through the paper)

> In our interpretation of the word data, it can refer to either measurements or model generated data. However, to avoid any confusion, and to stress that we use a field of SMB that is generated by a model, we replaced the term "data" with more appropriate terms (SMB fields, Hs-SMB pairs, climate model results, variables, model data, or simply removed the term "data").

The assumptions made are not clearly stated, please formulate the description of your model setup such that the assumptions that are made are clear. For example the assumption that the simulated SMB from the RCM is assumed to be realistic (this is related to the comment above, the simulated SMB is NOT data).

> - We have now stressed our main objective of this approach more clearly in the introduction. Furthermore, we would like to point out that a thorough assessment of the quality of the RACMO2/GR SMB product has been carried out by Ettema et al (2009), to which we refer in this paragraph. Although this SMB field is not measured data, it compares very well with the available measurements:
>
> *Line 97: Here we introduce a novel approach to force an ice sheet model in which SMB fields of a regional climate model are used directly, which circumvents assumptions regarding the calculation of run-off. The method (Sect. 2) (1) enables to apply and reproduce fields of SMB to a dynamic ice sheet topography, and (2) allows for an elevation - SMB adjustment while the ice sheet topography evolves, the latter is the main novelty of this work. For this particular application, we use SMB fields from the regional climate model RACMO2/GR, a product that realistically simulates the SMB observations (Ettema et al., 2009). In principle, this method is designed for use in asynchronous coupled ice sheet - climate simulations, but here we apply it to a set of ice sheet model experiments using a single climatology (Sect. 3). In Sect. 4 we evaluate our method and conclusions are drawn in Sect. 5.*

Would the results be similar if the output of another RCM would be used? how general are the results?

> No, the results critically depend on the output of the RCM and the ice sheet model used. The novelty is in the method, which enables the application of any RCM SMB field as forcing for any ice sheet model.
> To illustrate the effect of the use of different SMB fields, we split the full RACMO2/GR simulation (1958-2007) into two periods: before and after 1990. From 1990 onward, a period of warming caused a negative SMB trend, so we would expect to see a smaller ice sheet as a result of using only the forcing of the this latter epoch. We

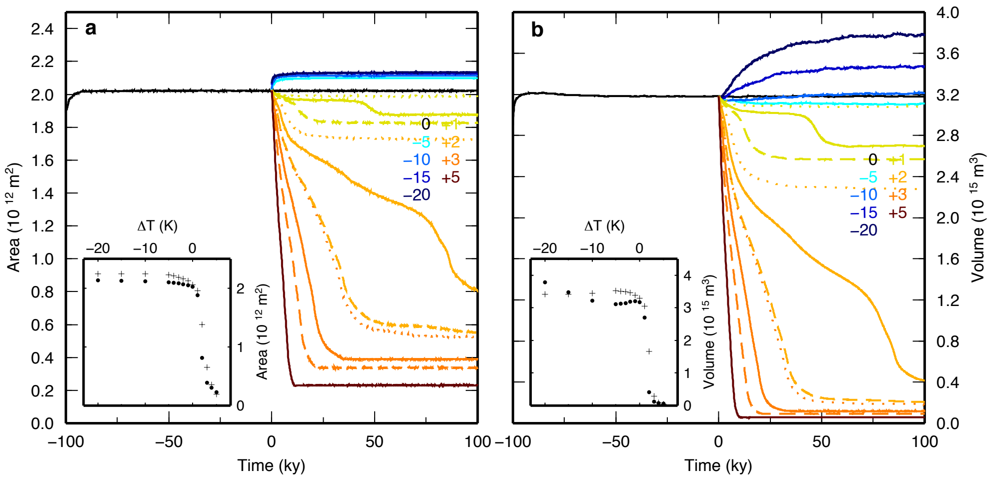
recalculated the SMB gradients for each period, and performed steady-state ice sheet simulations, like the reference experiment (Figure 9). As expected, using the post-1990 forcing results in a smaller steady-state ice sheet.
We added the following paragraph in the manuscript:

Line 428: To illustrate the effect of using a different climatology, we split the 1958-2007 RACMO2/GR SMB into two periods: before and after 1990. Since 1990, warming over Greenland has resulted in a significant negative trend in SMB (Ettema et al., 2009). Separate SMB gradients are calculated for each period and new steady-state runs were performed with the ice sheet model (red and blue lines in Figure 8a). The pre- 1990 SMB field results in only a small increased ice volume. However, the lower SMB of the post-1990 period results, as expected, in a smaller steady-state ice volume.

Also, I would suggest to make a sensitivity study of for example the very critical parameter γ_{atm} which controls the response of the ice sheet in the glacial cycle experiment, the constant 26.6 in equation (5) and the value 0.25 in equation (4) that seems to be somewhat arbitrarily chosen.

We followed these suggestions, and performed the following sensitivity experiments:

- For the parameter γ_{atm}, we used a range of values between -6 and -9 K km^{-1}, and performed runs with the ice sheet models for the glacial cycle experiment. Results are now shown in new Figure 12 It appears that especially ice volume in the Eemian interglacial is sensitive to this value, since in this epoch the largest positive temperature perturbation is applied. The final ice volume at t=0 varies only slightly as a function of γ_{atm}.
  We also performed sensitivity tests for the temperature perturbation experiments (sect. 3.2). Below, we plot results for the +1, +2 and +3 K experiments using γ_{atm}=-6 K km^{-1} (dashed lines), and γ_{atm}=-9 K km^{-1} (dotted lines) in the figure below.



  We did not include these results in the Figure in the paper, in order not to clutter it, but rather describe results in the text:
  Line 510: A large difference in ice sheet volume (89%) occurs between the +1 and +2 K experiments. These results are highly dependent on the value of γ_{atm} in Eq. (6). A sensitivity test using γ_{atm}=-6 K km^{-1} in the +2 K experiment has the same effect as a +3 K experiment using γ_{atm} =-9 K km^{-1}(not shown), which points out that care must be taken with the quantitative robustness of these results. However, it is expected that a threshold value exists for the SMB perturbation, above which the GrIS will eventually retreat to only a fraction of its current size. This is in agreement with e.g. Van de Wal (1999a), who performed a set of similar experiments using a different approach to estimate the SMB forcing.

- The value 0.25 in equation (4) is introduced to constrain the SMB value in the accumulation area, more specifically for areas with a decreasing SMB with altitude. This value is based on reconstructions of accumulation rate from ice core research, such as the GRIP accumulation record (Dahl-Jensen et al., 1993), which shows that the minimum accumulation during LGM attained a value of ~25% of the mean Holocene accumulation rate. This is now better justified in at line 215:

The minimum of 25% of the present-day value is based on reconstructions of accumulation rate from ice cores (e.g. Dahl-Jensen et al., 1993).

We performed two sensitivity runs using alternative values of 10% and 50%, and results of these runs are presented in new Figure 12, and discussed at line 558:

Figure 12 shows ice sheet volume through the glacial cycle. Since these results critically depend on the way Eq. 6 links a climatological temperature record to changes in SMB, we also show results obtained with different values of γ_{atm}, ranging from -6 to -9 K km^{-1}. Final ice volume does not vary strongly; the largest differences occur in the first part of the simulation (Eemian), because the positive temperature deviation is largest in this epoch. We do not show minimum Eemian ice volume here, given the strong dependence of the results on the value of γ_{atm}, the exact starting time of the simulation, and initial ice temperatures. Eemian ice volume will be estimated in a future study, using a coupled ice sheet - regional climate model simulation. Ice sheet growth during glacial conditions is largely controlled by the accumulation rate, which is constrained by the value of SMB_{min} in Eq. 4. If we change the value of this parameter to either 10% or 50% of the present-day value, ice volume in the glacial is directly affected, as illustrated by the blue lines in Figure 12.

- The constant 26.6 in equation (5) is based on the work by Reeh (1991), but they do not provide an uncertainty for this number. We performed two sensitivity tests, in- and decreasing the values by 20%, i.e. using values of 31.92 and 21.28 respectively. We show model results for the steady-state experiment without climate change perturbation, hence the results are included in Figure 9, and on line 421:

Neglecting the effect of refreezing (R) results in a 2% larger ice sheet (black dashed line in Fig. 8a), due to lower ice temperatures, that limit deformation rate and sliding. The dependency of Ts on the amount of refreezing is controlled by the constant in Eq. 5. In- or decreasing this value by 20% does not strongly influence the results, as illustrated by the red and orange curves in Fig. 8a.

The text is in many places unclear, the English could be improved considerably by proof reading the paper carefully before submission. A few places where the text could be improved are indicated below, but I am not native English speaker so my suggestion is good proof reading to polish the English before resubmission.

We did our best to improve the text.

Page 2118,lines 22-23 rewrite sentence, it is not clear what this sentence means

This sentence directly follows from the previous examples of difficulties with finding the right SMB forcing for ice sheet models. The sentence is rewritten, and added to the previous paragraph:

Line 94: All in all, simulations of ice sheet-climate interactions will strongly benefit from an unambiguous calculation of SMB in a coupled atmosphere-ice sheet model.

page 2128, lines 5-8, rewrite sentence to make it clearer

Sentence rewritten:

Line 445: The steady-state SMB equals 362 Gt yr^{-1}, and is in balance with the calving flux. This is 23 % lower than the integrated SMB value as calculated for the present-day ice sheet by RACMO2/GR (Ettema et al., 2009, Table 2). This difference can be explained by the expansion of the ablation area in the simulated ice sheet, reducing the SMB.

page 2129 Lines 9-10 rewrite, the English is strange here, do you mean that the sensitivity of the integrated SMB to changes in temperature is assessed?

Yes, that is what we did, so we changed this in the text accordingly:

Line 484: Table 2 shows the sensitivity of integrated SMB to temperature perturbations as calculated using the method in Sect. 2.4.

page 2131 lines 4-5 rewrite, this sentence is not clear

The minimum Eemian ice volume in this experiment is strongly influenced by the exact timing of the start of the simulation, the value of γ_{atm}, and the initial shape of the ice sheet at the start of the simulation. It therefore is too uncertain to include in the MS..

Line 565: We do not show minimum Eemian ice volume here, given the strong dependence of the results on the value of γ_{atm}, the exact starting time of the simulation, and initial ice temperatures. Eemian ice volume will be estimated in a future study, using a coupled ice sheet - regional climate model simulation.

page 2131 lines 12-13 rewrite, last glacier period. How can you be sure it occurred in reality?

We cite a review-paper here (Alley et al., 2010) that claims this is the case, but since we cannot be entirely sure, we added the word *probably* at line 592.

Page 2131 lines 23-25 rewrite, not well structured sentence

rewritten:

line 599: Two marginal areas in the southwest and northwest stand out (arrows in Fig. 14) because they have thinner ice than presently observed, and also contain wide ablation areas with more negative SMB values than in the RACMO2/GR reconstruction (Fig. 15). This highlights the sensitivity of these areas to surface melting.

page 2132 lines 5-9 rewrite, what is meant by “different fields of ice sheet elevation and extent” - changing geometry?

This sentence is now replaced by:

line 610: A rigorous test of the performance of the SMB gradient method would be to compare results against a regional climate model run obtained on a different ice sheet topography.

page 2132 line 10 rewrite, suggest “to assess the sensitivity of the ice sheet reconstruction to the SMB forcing

rewritten

page 2133 line 13-16 not clear sentences here (reconstruction of what?) page 2133 line 17-19 rewrite, English is poor here

rewritten as:

line 579: Not surprisingly, applying the PDD forcing results in yet another ice sheet volume history (grey line in Fig. 13).

line 657: The large differences with the PDD method illustrate the importance of SMB forcing on the outcome of GrIS model simulations.

page 2133 line 19-22 what do you mean by correct estimation? Do you know that frequent coupling will improve the results? How can you validate the results?

The idea behind the use of this SMB gradient method is that it enables a smooth transition of the SMB forcing in between ice sheet - climate model couplings. This ensures that the SMB field matches the next RCM product on a modified topography as well as possible. We now evaluated our results by including Figure 15, and the first two paragraphs in the discussion.

Page 2133 line 22-23 “in between these couplings” what is meant here? Please make this sentence clearer

Rewritten as:

line 666: As long as direct coupling is practically unfeasible, the best approach to correctly simulate changes in SMB as a result of changes in ice sheet topography is to frequently feed the new topography from the ice sheet model into the regional climate model. At these couplings, SMB from the climate model is accurately reproduced by the SMB gradient method, which is not the case using a PDD approach (Fig. A1). The SMB gradient method is designed to be used in between couplings, and assumes that the regional SMB - elevation dependence is persistent and a better predictor for SMB then an indirect correlation between temperature and SMB through elevation, as assumed in the PDD approach.

The naming of the method developed in this paper is not consistent throughout the paper, on page 2135 line 4 and Table 2 it is called SMB gradient method, in figure caption 9 and 10 it is called Hs-SMB gradient method, please be consistent throughout the paper.

We chose to use “SMB gradient method” throughout the paper.

The last part of the the conclusion is a direct repetition of the last part of the abstract, which I find a poor style, if nothing new is presented in the conclusion this section could be omitted, or the abstract could be rewritten as not to give away the conclusions of the paper.

We have rewritten the last part of the conclusion.

line 707: We applied the method to the GrIS, in two different experiments: (1) using steady-state forcing and (2) using more realistic glacial-interglacial forcing. These experiments result in ice sheet reconstructions and behavior that compare favorably with present-day observations. An evaluation experiment using two different GrIS topographies results in close agreement between the SMB gradient method and the regional climate model, which supports the SMB gradient method.

Specific comments

page 2116 line 7 replace “in” with “with” (or rewrite sentence to be clearer)

done

line 12 what does “dynamic SMB forcing” mean here? rewrite

rewritten:

line 13: The continuously adjusting SMB forcing is consistent with climate model forcing fields, also for initially non-glaciated areas in the peripheral areas of an ice sheet.

line 13 this method also uses a temperature lapse rate (equation (5)) to compute the elevation response, so that is not circumvented here either

This temperature lapse rate is only used when the model is forced with a climatic temperature record; the principle goal of this method is that it will be used in an asynchronous coupling setup between ice sheet model and regional climate model:

line 16: When applied to an asynchronous coupled ice sheet - climate model setup, this method circumvents traditional temperature lapse rate assumptions.

line 15 “more realistic” - how do you know it is more realistic?

We know that the climate has not been stable for the last 100.000 year, which is the unrealistic aspect of the steady-state experiment

Page 2117 line 8 add well after “reasonably”

done

page 2118 line 2 with assumption of (or rewrite, sentence is not very clear, suggest: Run-off is calculated by including an assumption of the amount of superimposed ice formation)

done

line 4 replace "non-stationarity" with spatial variability

changed to *spatial and temporal variability*

page 2119 line 1 suggest: by using the same spatial SMB gradients

done

line 21-22 here the assumption is that the RCM is producing realistic gradients, is that well validated?

The SMB gradient method is in principle designed to enable the use of any RCM products as forcing for any ice sheet model. Whether the RCM SMB field is a good or poor representation of reality (or for that matter, the ice sheet model) will then be reflected in the quality of the ice sheet reconstructions.

Line 26-27 same as above, the assumption is the the RCM is providing the "right" values

See previous comment

page 2120 line 1, what model results indicate that the gradients given by the RCM can be extrapolated outside the ice sheet mask?

SMB gradients are not extrapolated, they are calculated in the same way as for locations within the ice sheet mask. This is the best we can do to estimate SMB outside the present-day ice sheet mask.

Line 9, how accurate is the refreezing in the RCM? How well is it actually validated?

Again, it is not the scope of our study to assess the quality of the RCM or the ice sheet model used. We developed the SMB gradient method and applied it to the SMB field and ice sheet model we have available. Because our RCM calculated refreezing, we can make a correction for ice surface temperatures, and thereby apply the RCM data as consistent as possible to the ice sheet model.

Line 10 how realistic is the RCM output? Some indication could be given here.

We added a reference to Ettema et al (2009) who assessed the quality of the RCM SMB field.

Page 2121 line 3, how much is the intercept adjusted? How sensitive is the result to the selected intercept value?

There is not a single value for which the intercept is adjusted: it depends on how much the reference SMB value deviates from the regression line. We cannot assess the sensitivity of this aspect of the method, since this step allows us to reproduce the RCM SMB pattern to begin with.

Line 6, what do you mean here, if the fit becomes worse, why do you use that rather than the first?

As explained in the text: our method ensures a better spatial representation of the SMB gradients.

Line 13-14 how much too high? Please be concise in describing your choices and assumptions

We rewrote this sentence.

line 18 take "again" out

done

line 19 replace predicted with parameterized

done

line 22 "works well" what do you mean here? Does it give good ice sheet shape?

Yes, and an SMB pattern in good agreement with the RCM input. rewritten:

line 200: The resulting expressions work well for small SMB adjustments following small ice geometry changes.

Line 25 "vulnerable" what do you mean, sensitive? How sensitive, can you give us indication by doing a sensitivity test? What do you mean by large changes?

Changed this sentence into:

line 201: However, when temperature perturbations are imposed (see below), positive values of b_{acc} enforce a positive feedback between Hs and SMB. This becomes unrealistic with increasing Hs (Figs. 2c and 3a).

We now included results from sensitivity experiments that show how sensitive results are for the constraining values SMB_{min} and SMB_{max}.

Page 2122 line 5 "most suitable" what do you mean? What criteria do you use to select the "most suitable values?

A reference to Dahl-Jensen et al is added to justify the value of SMB_min. The value for SMB_max has been chosen based on several tests. An unrealistic SMB pattern would emerge for low temperatures when SMB_max is set higher.

Equations (3) and (4) explain the overlined values line 9 relationship

done

lines 10-18 how can you validate these results? Some kind of estimate of the robust- ness of these results should be given

The quality of these results is now assessed in the discussion, by comparing two SMB fields computer by RACMO2 on two different topographies.

line 19 the standard way of writing ice equivalent is m ice equiv. (see also page 2123 line 4, page 2125 lines 12 and 13)

Changed it to S.I. units: *2500 kg m^{-2} yr^{-1} km^{-1}*

line 21 how can you know that the established relationships are valid outside the glacier mask?

We can't be sure, but we do need some treatment for the SMB in case the simulated ice sheet expands over previously ice-free regions. In our opinion, this is the best treatment we can use for this, and in principle, the method is not so different compared to the area within the ice mask, the only difference is that the SMB value is not nudged towards its reference value, which is not available.

Page 2123 line 5, why 1m?
Lines 5-7, please explain better, what has been tested and how sensitive is the results to your choices/assumptions?

To account for an additional warming effect from the nearby tundra, we apply this lower SMB. We modified the following line:

line 249: Different values for this modification of SMB at the ice margin have been tested, and showed that the value chosen prevented an unrealistic expansion of the model ice sheet over the tundra under the present-day SMB forcing.

Line 14 rewrite, sentence is not clear "1-several km wide" what does that mean? Line 27, what do you mean by on-line?

changed into *a few km wide (line 259)*

Page 2124 line 3 model setup

done

line 7 relationship

done

line 15 relationship

changed into *functions*

line 19 “asynchronously” what do you mean, explain better, rewrite this sentence.

The concept of asynchronous couple ice sheet – climate model simulations is now described on line 319. This section is rewritten to:

The SMB gradient method is well suited to be used in asynchronously coupled ice sheet - climate model simulations: it is called in the ice sheet model each time step to account for SMB changes as a result of changes in ice sheet elevation changes and extent. After a certain integration time of the ice sheet model, the ice sheet topography and extent should be updated in the climate model, which can then generate a new SMB field, etc.

Page 2125 line 2 scales

done

line 11, why do you use this value for γatm, how sensitive is your results to this param- eter?

We based the value for γatm on a regression within the RACMO2/GR results. Sensitivity experiments have been carried out on the value of γatm, as described on line 559:

Since these results critically depend on the way Eq. 6 links a climatological temperature record to changes in SMB, we also show results obtained with different values of γ_{atm}, ranging from -6 to -9 K km^{-1}.

Line 25-26, rewrite, suggest “to take into account”

done

page 2127 line 12 a constant, take out “so no additional climate change forcing”

done

line 14 and 15 “quickly” and 10ka does not fit well together here, suggest to rewrite

quickly has been removed

line 18, how about glaciers and ice caps outside main ice sheet, on Greenland, do you include those in your summation?

Yes, these are included:

line 419: Only ice on the Greenland mainland has been taken into account.

Line 23 larger steady-state volume

done

line 24 after 100 ky simulation

done

line 25, the ice sheet advances, is it possible that the SMB is not negative enough? Can you give an indication for what the reason is, below there is discussion of the resolution, it can be also discussed here

We don’t think that the RCM SMB is too high, a comparison between measured SMB data along the K-transect and RACMO2/GR SMB (Ettema et al., 2007) shows that this is not the case.

page 2128 line 2, suggest to change SMBpos and SMBneg to SMBacc and SMBabl, also on Figure 8

done

line 7 by the expansion

done

line 20-22, can you give an indication of what the resolution of the model should be to include this effect properly? What is the difference between the results of 10 and 20km resolution simulations?

To resolve the influence of the rugged topography, the resolution should solve these fjords, which means much lower than 5 km. We suggest this by stating *outlet glaciers in these fjords have typical widths of less than 5 km*.

A difference between the 10 and 20km resolution was that the 10km run resulted in a slightly larger ice volume. The reason behind this is a complex interplay between thermodynamics, ice velocity, ice thickness, and thereby SMB feedbacks. We chose not to go into this in the paper, because the differences were only minor.

Line 24, what do you mean by typical phenomena, is there too little ablation in all the models, or is the resolution too low?

We mean the problem of accurately simulating the flow pattern in this rugged topography, as described in the previous paragraph. We rephrased it:

line 681: It seems a persisting feature in ice sheet models reconstructions (e.g. Greve, 2005; Graversen et al., 2010; Robinson et al., 2010).

Line 27-28 is it possible that the accumulation in the interior is too low? Can you validate the SMB in the RCM with observations?

The SMB in RACMO2/GR is validated with observations in Ettema et al (2009).

Page 2129 lines 1-7 can this indicate that the SMB field of the RCM is wrong? Is it possible that the ablation at the margins is too small?

No, the SMB field from the RCM is quite good, see above. It is possible that the ablation area at some places around the ice sheet is too small to be resolved, as we also note on line 256:

The area with low ELA in the southeast is caused by high accumulation, prohibiting the formation of an ablation zone on the 11 km ice sheet mask (in reality the ablation zone is only a few km wide).

We added the following line to also note that there is a difference in the ablation area, due to the advanced ice sheet:

line 449: This difference can be explained by the expansion of the ablation area in the simulated ice sheet, reducing SMB.

Line 10, it is obvious because eq (6) is setting this relationship. It must be very dependent on the value of γatm ? This experiment does not say anything about how the RCM responds to increased temperatures, is it possible that the accumulation in- creases more than the ablation increases?

True, this is mainly controlled by γatm. The experiment shows how our SMB forcing influences the ice sheet modeling results. It is not possible to do such an experiment with a RCM, in which temperatures are allowed to evolve freely. We rephrased this line:

line 484: Table 2 shows the sensitivity of integrated SMB to temperature perturbations as calculated using the method in Sect. 2.4.

Line 19 rewrite (take out (obviously), the sensitivity to changed T is set by equation (6), can you test the sensitivity of the results to this value

We did a set of sensitivity experiments for γ_{atm} for the glacial cycle run, and discuss results on line 559. We also performed sensitivity runs for the temperature perturbations in Figure 11. We describe the main outcome of these sensitivity tests in the text (line 511, see answer to one of the major comments, above)

line 21-22 How realistic is this? Do you think that negative bacc are realistic? Line 24 relationship

Yes, SMB decreases with elevation, also on glacial-interglacial timescales, due to less precipitable water which follows directly from the Clausius Clapeyron relation.

page 2130 line 3 "Huge difference" how large? You can add percentage change to give indication of how large the difference is.

The magnitude of the difference can be readily seen from Fig. 11. We added the

percentage:
line 510: A large difference in ice sheet volume (89%) occurs between the +1 and +2 K experiments.

Line 6, how can you validate this statement? What does "likely realistic" mean here?

We removed the word realistic here, since these steady state perturbations are anyhow not so realistic. But as these findings confirm earlier work (as stated later), we think that this is, qualitatively, a robust results.

Page 2131 line 3 response to line 5 on the initial conditions

We do not exactly understand this comment. What is meant in the text is that for a good reconstruction of Eemian minimum ice sheet extent, ice sheet shape and ice temperatures should be properly initialized by taking into account the glacial period preceding the Eemian. New text is:
line 558: Figure 12 shows ice sheet volume through the glacial cycle. Since these results critically depend on the way Eq. 6 links a climatological temperature record to changes in SMB, we also show results obtained with different values of γ_{atm}, ranging from -6 to -9 K km^{-1}. Final ice volume does not vary strongly; the largest differences occur in the first part of the simulation (Eemian), because the positive temperature deviation is largest in this epoch. We do not show minimum Eemian ice volume here, given the strong dependence of the results on the value of γ_{atm}, the exact starting time of the simulation, and initial ice temperatures. Eemian ice volume will be estimated in a future study, using a coupled ice sheet - regional climate model simulation.

line 20 take out "anymore" add "compared to observations"

done

line 23 with simulated SMB values lower than at present

changed into:
line 599: Two marginal areas in the southwest and northwest stand out (arrows in Fig. 13) because they have thinner ice than presently observed, and also exhibit large ablation areas with lower SMB values than in the RACMO2/GR reconstruction (Fig. 14).

line 24, what do you mean by wide ablation area? Along the margin, or to high elevation?

large ablation areas: in terms of distance from the margin to the ELA. Changed into *large.* see previous answer

Page 2132 line 2 the SMB gradient method (as in Table 2)

done

line 6, what do you mean by temporal gradients, doesn't the time series of the RCM run provide this? Can you do this test?

no, the time series do not contain differences in elevation. Therefore we now included the test with different topographies in RACMO.

Line 12 parameters

done

line 13 do you mean observations, or the RCM model output?

we meant the RCM output, text has been modified.:
line 266: with the present-day SMB field as reported by Ettema et al. (2009)

Line 15 show SMB – elevation relationship

done

line 16, what different values of T, explain (do you use the T from the RCM?) and rewrite to make sentence clearer

We used accumulation and temperature from the RCM, but to calculate different SMB values we perturbed the temperature. Then we calculated the associated elevation change for each temperature perturbation. The text is now changed into:
line 269: SMB_{PDD} is calculated using different values of mean annual temperature, but to facilitate comparison with the SMB gradient method, the results are plotted as a function of elevation, using γ_{atm} to translate ΔTs to Hs.

line 18, again here a sensitivity to the chosen value of γatm should be given

Indeed, γatm affects the SMB gradients here, since we use γatm to calculate a difference in Hs. We therefore changed these lines into:
line 273: This affects the SMB gradient: the general picture of steeper SMB gradients from the PDD method in the ablation regimes is less pronounced with a smaller value for γatm.

line 21 “currently found” do you mean modelled by the RCM?

yes, but these results compare well with observations. We changed this accordingly:
line 276: Fig. 2d also shows that the PDD method underestimates SMB values in the higher accumulation zone, due to a too strong decrease of accumulation with increasing elevation.

Line 25 “width of the ablation area” see above, do you mean width along the margin? (N-S extent or elevation extent?)

The elevation extent, changed accordingly (text now in appendix).

page 2133 line 2, if that is the case you would expect to see blue areas (negative difference) along the whole margin, which is not the case in figure 15b

Correct, this was not a valid statement in the text, and we removed it. The larger sensitivity to temperature perturbations however remains for the PDD method, as can be seen in table 2.

line 11 is that decrease in SMB realistic?

Yes, see above

Line 23-25 How can you conclude which is a “better predictor”? There is no model validation in the paper that supports this statement.

This line is replaced by:
line 673: The SMB gradient method is designed to be used in between couplings, and assumes that the regional SMB - elevation dependence is persistent and a better predictor for SMB than an indirect correlation between temperature and SMB through elevation, as assumed in the PDD approach.

Line 24 than

done

page 2134 line 4 large amounts

done

line 4-6 the resolution of the model should be discussed here as one reason for the

? The comment was not finished. We do mention the resolution issue at the end of this section.

line 6 direction to the coast

done

Conclusion is a direct repetition of the Abstract, please edit this section to avoid that

done.

page 2135 line 9 rewrite, suggestion: a number of parameters have to be chosen done

line 15 the time step for the numerical integral is one month

done

line 15, why do you not use the monthly output from the RCM, which should be more realistic than a sinusoidal curve?

We wish to use the same type of forcing fields for both models, and since monthly temperatures are no input for the SMB gradient method, we do not use them.

Line 20 in the forcing, we also use the... mean annual Ts (add this information to the main text)

done

line 26 mean annual fields? Why not mean monthly fields from RACMO?

As stated above: to avoid any differences in forcing we intent do use the same forcing fields

Figure caption Figure 3, line 4: to go through

done

line 5 and maximum

done

Figure 4 why is not the same colour scale used for these figures? (a and b, c and d)

The range of values of parameter a (panel a and c) is different than for b (panel b and d). To avoid the suggestion that the scales are equal, the color scales are different too.

rewrite figure captions for figs 5, 6, 9, 10, 13, 14 and 15, should be consistent with the others (starting with (a) then text)

done

Figure 7 what are the blue points along the coast in the south? (both SE and SW)

There must be a misunderstanding; we do not see any blue points along the coast in the south in Figure 7

Figure 8, change SMBneg and SMBpos to SMBabl and SMBacc

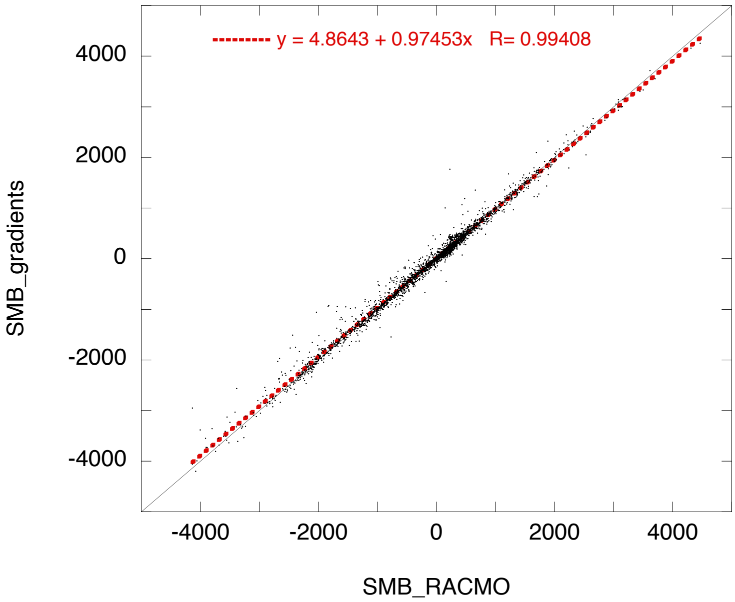
done

Reviewer #2

General comments
This article proposes a new approach toward coupling surface mass balance (SMB) results from climate models and ice sheet models. It focuses on the altitude dependency of the SMB. To do so, the authors develop a statistical scheme to calculate the vertical gradient of SMB, taking into account the fact that best regressions are different in the ablation zone and accumulation zone.
The method is well presented and I think it is a rather technical but useful paper. It could be improved by having more discussions on the general points below. And finally I still regret that the method has not been tested against RCM runs on a different topography. I know that the authors estimate that this is beyond the scope of the paper, but this would have been a real achievement.

We agree that additional RCM runs on a different topography, and a comparison with the SMB gradient method, would improve the paper. In the revised MS, we therefore included such a comparison using the modelled retreat of the Greenland ice sheet during the Eemian, using an asynchronous coupling approach between the ice sheet model (ANICE) and the RCM (RACMO2/GR). The first couple of paragraphs in the new discussion section now describe this:
line 607: The SMB gradient method is designed to improve asynchronous coupling between climate models and ice sheet models. As shown here, it can also be used as a stand-alone SMB forcing module. A rigorous test of the performance of the SMB gradient method would be to compare results against a regional climate model run obtained on a different ice sheet topography. We do this for a simulation of Eemian climate conditions, since the GrIS was by then clearly out of balance. In this experiment, RACMO2/GR is forced at its lateral boundaries by the ECHO-G GCM, with greenhouse gas concentrations and orbital parameters of 125 ky BP (Van de Berg et al., 2011). The SMB gradients computed from these Eemian climatologies are used to simulate GrIS retreat. A different resolution (18 × 18 km) was used for these RACMO2/GR simulations, which requires a reduction of the minimum number of Hs-SMB pairs to n = 37, to ensure an equal area-of-influence in comparison with the present-day fields. Here we show SMB calculations for two different time slices at 129 ky and 128 ky BP (Fig. 15a and b), to assess the performance of the SMB gradient method. The ice sheet extent through the Eemian is highly unknown; for 129 ky BP we chose an ice sheet configuration intermediate between estimates for glacial conditions and the present- day extent. The ice sheet for 128 ky BP is derived from a 1 ky simulation using the SMB approach described in this manuscript.
Between 129 and 128 ky BP (Fig. 15a, b and d), the decrease in ice sheet elevation and SMB is most pronounced along the southwestern margin, where the elevation difference reaches ~1000 m. The effect of this elevation change on SMB is well captured by the SMB gradient method, as calculated for 128 ky BP (Fig. 15c), based on the SMBracmo fields at 129 ky BP (Fig. 15a). The residual difference (SMBgradients - SMBracmo, Fig. 15f) is mainly positive, but not systematic. Most deviations can be explained by the changes in precipitation, which is a dynamic response on large-scale topographic changes. For example, the ablation area in south Greenland where ΔSMB is largest, experiences a significant reduction of precipitation because of the concave topography. Still, the correlation between the two SMB fields in Fig. 15b and c is very high (R2=0.988) and the RMSD is only 91 kg m−2 yr−1, in strong support of the SMB gradient method.

We did not include this scatterplot in the manuscript, but as a support for the given statistics in the text, we include it here:



1 I have difficulites to see in which framework this method will effectively been used.
- next centuries simulations: a full coupling should be possible which is better than using statistical parameterization of the SMB "lapse" rate. May be the method presented here could be useful for sensitivity studies to avoid running the RCM too often
- I am a bit sceptical about the use all along a glacial-interglacial cycle as it is given in the article. I aknowledge that the problem is strictly the same with a PDD method but for me it is just one more sensitivity study. I think the main difficulties are linked to changes in circulation and orographic precipitation.
- The use of this method in long term simulations with asynchronous coupling is more convincing and more detailled explanation should be given on how this could be done. How to decide the asynchrounous time step ? is is possible to derive a quality score of the method by using two successive topographies ? how the RCM will be given lateral boundary conditions ?

- We agree on the point that the method is particularly suited for asynchronous coupling experiments for long-term ice sheet – climate simulations. To underline this, we have rewritten the introduction:
line 97: Here we introduce a novel approach to force an ice sheet model in which SMB fields of a regional climate model are used directly, which circumvents assumptions regarding the calculation of run-off. The method (Sect. 2) (1) enables to apply and reproduce fields of SMB to a dynamic ice sheet topography, and (2) allows for an elevation - SMB adjustment while the ice sheet topography evolves, the latter is the main novelty of this work. For this particular application, we use SMB fields from the regional climate model RACMO2/GR, a product that realistically simulates the SMB observations (Ettema et al., 2009). In principle, this method is designed for use in asynchronous coupled ice sheet - climate simulations, but here we apply it to a set of ice sheet model experiments using a single climatology (Sect. 3). In Sect. 4 we evaluate our method and conclusions are drawn in Sect. 5.

- It is difficult to assess how large the asynchronous time step can be. We discuss this in the discussion:
line 649: When applying the SMB gradient method to asynchronous coupled ice sheet - climate simulations, the time step between the couplings must be chosen. This is not straightforward, as it depends on the rate of the climatic shifts, but also on the magnitude of the change in ice sheet topography. A 1000 yr interval for Eemian conditions is still acceptable, as shown in Figure 15, but it should be noted that the climate forcing is kept constant in this experiment.

- On the quality score of the method by using two successive topographies: we now included this, see above.

- For the RCM boundary conditions: this is a problem related to RCM simulations and not directly within the scope if this paper. We refer to the methodology presented by Van de Berg et al (2011).

2- I appreciate that the results are all along compared with the PDD method which was the standard method up to now, however, it would be better to explain early in the article (before the discussion) which variety of PDD was used. I am also a bit surprised that a significant advantage of this approach over the Pdd is not well highlighted: In this method, the day to day variability is implicitely taken into account because the climate model does it by cumulating SMB terms (precipitation, melting, ...) all over the year. It requires only the exchange of one field per year (or even several years) while with annual fields, the Pdd method has either to relies on assumptions such as periodic (sine) variation of temperature or exchange many more fields between climate model and ice sheet model.

- We restructured the text such that now the PDD model is already mentioned in the methods section, and various PDD results are no longer mentioned in the discussion but rather at the point were the respective figure are also discussed.
- We included a paragraph on the advantages of using the climatological net SMB product of an RCM over a PDD approach in the discussion:

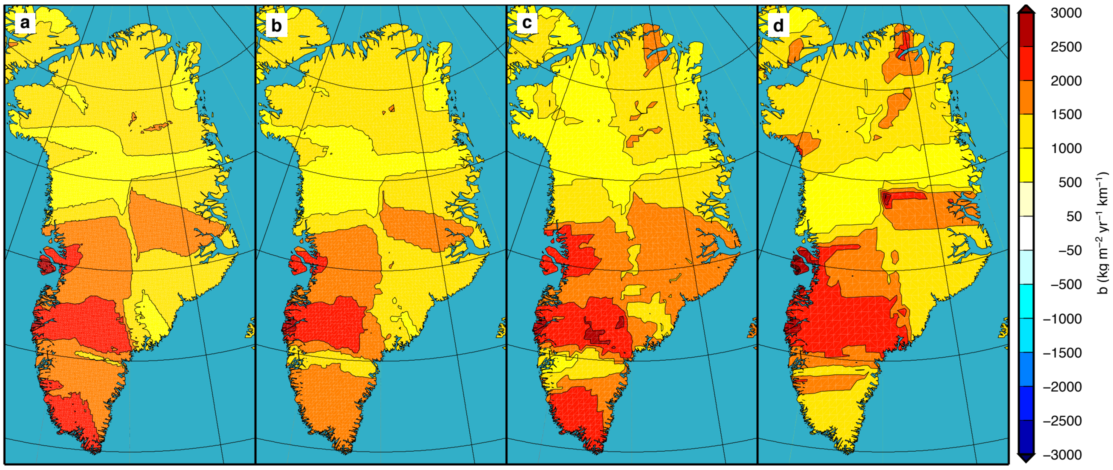
line 657: The large differences with the PDD method illustrate the importance of SMB forcing on the outcome of ice sheet model simulations. Advantages of using a climatological SMB from a regional climate model over a PDD based method are that day-to-day variability is implicitly taken into account. Moreover, a regional climate model captures more of the physics of processes important for SMB variability. Van de Berg et al. (2011) showed that a PDD approach can lead to erroneous SMB reconstructions in paleoclimate simulations. As long as direct coupling is practically unfeasible, the best approach to correctly simulate changes in SMB as a result of changes in ice sheet topography is to frequently feed the new topography from the ice sheet model into the regional climate model. At these couplings, SMB from the climate model is accurately reproduced by the SMB gradient method, which is not the case using a PDD approach (Fig. A1). The SMB gradient method is designed to be used in between couplings, and assumes that the regional SMB - elevation dependence is persistent and a better predictor for SMB then an indirect correlation between temperature and SMB through elevation, as assumed in the PDD approach.

3- The same philosophy as for SMB is applied to the refreezing and here I regret that the results have not been compared with the other refreezing schemes (Reeh and Janssens and Huybrechts for instance).

We would like to stress here that the refreezing scheme is included only because of its effect on the 'surface' ice temperature, due to latent heat release. Refreezing is part of the RCM output. While it is not within the scope of this study to assess RCM performance, the effect of refreezing on the elevation – SMB feedback is captured in our SMB gradients. Our main concern is the effect of refreezing on ice sheet temperature, and how this changes with a change in ice elevation.
Hence, we included a reference to the performance of the RACMO refreezing scheme with respect to different refreezing parameterizations:
line 315: Reijmer et al. (2011) compare R from RACMO2/GR with different parameterization schemes.

4-The method seems to require a lot of neighbouring points, ie. a climate model with a very fine grid (RCM as proposed in the article). I wonder wether this method is still robust with a GCM with a coarser grid. A test could consist in undersampling the RCM results and compare the reconstructions.

We performed such a test, by undersampling the 11km RACMO2/GR data to 22km, 33km and 44km resolution. This required adjustments on either the minimum amount of points to calculate the regressions, or on the search radius to find these points. We chose to reduce the minimum amounts of points (to 25, 12 and 6 respectively), such that the Hs-SMB pairs were approximately from the same area as in the 11km solution. From these Hs-SMB pairs we computed the SMB gradients, from which the parameter b_{abl} is shown in the Figure below for (a) 11 km, (b) 22 km, (c) 33 km, (d) 44 km. Decreasing the resolution even further would not yield in valid regressions, since the number of points (3) would then not allow a regression.



The general pattern is preserved in the coarser solutions, but there are changes. In particular the SMB gradients in the southern tip of Greenland become smaller with decreasing resolution, but locally SMB gradients also increase. Another aspect that can be recognized is that with decreasing resolution (and hence decreasing number of grid points in the regression) the patterns become more irregular, caused by the fact that in- or excluding certain grid points has more effect on the regressions. The main point is that the bigger picture remains the same, and that changes in SMB gradients are only weakly influenced by the chosen resolution:

line 230: We tested the sensitivity of the SMB gradients for changes in the resolution of the input data, by undersampling the 11km data from the regional climate model (not shown). These tests revealed that the patterns in Fig. 4 are robust, and that SMB gradients are only weakly dependent on resolution. However, to apply this method, it is critical that the narrow ablation zone is resolved by the regional climate model. This will generally not be the case in coarse-resolution GCMs.

Detailled comments.

p. 2121 top, Mb max should be explained at this level because there is a reference to figure 2 on which it appears and check the notation because it is SMBmax in equations and MBmax in figures.

The notation in the Figures has been adjusted;

SMBmax is explained in the caption of Figure 2. We prefer to keep the explanation of SMBmax in the text as it is, since otherwise it must be discussed before the part about the perpendicular linear regression.

p. 2122 equation (3) please define beter what are the various terms (SMBpos, SMBref)

done:

line 213: SMBpos refers to the mean positive SMB value within the search area. SMBref is the SMB value at the particular grid point. The minimum of 25% of the *present-day value is based on reconstructions of accumulation rate from ice cores (e.g. Dahl-Jensen et al., 1993).*

p. 2124 is the 26.6 simply related to the latent heat? It would be better to give the real equation.

This is the 'real' equation, as it is a parameterization as given by Reeh (1991), to account for the warming of the top firn layer related to latent heat release during refreezing.

p. 2124 line 16-17. Explain more physically why a diferent sign is demanded for the gradient on R depending on ablation/accumulation zone.

done:

line 309: As an additional constraint for the R_{Hs} relation, we impose a positive gradient in the ablation regime, and a negative gradient in the accumulation regime. These are the expected patterns, as R will increase with Hs in the ablation zone, since the water retention capacity will increase with the thickness of the snow layer. In the accumulation zone a reverse relation between R and Hs will occur, due to decreasing availability of meltwater.

p. 2127 line 20, experiment with no refreezing. Two variables are usually affected by the refreezing: the SMB itself and the ice temperature. Is it the case in this experiment and if yes, that means that the impact on temperature is more efficient than the one on SMB.

No, the SMB is not affected in this experiment, since the effect on refreezing is implicitly taken into account in the SMB value from the RCM. To stress that the experiment with no refreezing only discards the effect of R on ice temperature, these lines are rephrased as:

line 421: Neglecting the effect of refreezing (R) on ice temperature results in a 2% larger ice sheet (black dashed line in Fig. 8a), due to lower ice temperatures, that limit deformation rate and sliding. The dependency of Ts on the amount of refreezing is controlled by the constant in Eq. 5. In- or decreasing this value by 20% does not strongly influence the results, as illustrated by the red and orange curves in Fig. 8a.

p. 2131 line 16. The present topography at the end of any simulation is also dependent on the enhancement factor used in the ice sheet model. This parameter is usually introduced to calibrate the ice sheet model so the fact that the simulated surface elevation is in good agreement with the observed one is not that significant.

True, this is usually done in this type of experiments. Nonetheless we find this aspect worth mentioning, since the results of the glacial cycle experiment significantly improved the results, without tuning using any different enhancement factor.

figure 8. How is calculated the calving ?

The calculation of the calving is described on line 366:

Formation of ice shelves is not allowed; as soon as the ice thickness be- comes small enough that it will go afloat and ice is in contact with the ocean, the ice breaks off. As such, calving by means of a flotation criterion is included, but more detailed calving physics are not incorporated explicitly, since model resolution and dynamics are not suited for a more realistic treatment of calving of outlet glaciers.