We would like to thank the reviewers for their constructive comments that helped to improve the manuscript 'Remapping of Greenland ice sheet surface mass balance anomalies for large ensemble sea-level change projections'. We have revised the manuscript accordingly and would be happy to provide a new version.

Please find below the reviewer's comments in regular italic and a point-by-point response in bold font.

Referee 1 (Mario Krapp)

This paper presents a method to correct for unphysical biases in the representation of the surface mass balance (SMB) in ice sheet model. By defining a remapping function for SMB anomalies for different drainage basins and height ranges, mismatches between ice sheet model geometry and climate model topography can be accounted for and thus leading to meaningful smooth and continuous SMB anomaly fields for diffferent geometries across basin divides. As a result of this approach the authors show that the SMB bias is reduced compared to commonly procedure of applying SMB anomalies. The paper focuses on standalone simulations of the GrIS with no interactive ice sheet.

The paper is well written and has a clear message how to address the SMB biases for different ice sheet models, specificically for the Greenland ice sheet. The paper targets a specific audience (ISMIP6 modellers) but as part of a special issues that is understandable.

The paper in its present form has a few shortcomings which need to be addressed before I can recommend it for publication. Find my general comments (and a couple of technical ones) below:

Thank you very much for the positive evaluation.

General Comments

• This approach works for relatively high-resolution climate model output, i.e., MAR SMB data (an RCM), but what about coarse-resolution GCMs? What would you regard as (spatial resolution) limit to the approach? E.g., the minimum required number of drainage basins depends on how many samples per basin/height bin your SMB resolution would provide.

The spatial resolution of the climate model is not a limiting factor for this method. If needed, the output of a GCM could easily be interpolated or downscaled to a higher grid resolution. For our application we have used a downscaled version of the MAR output, originally run at 15 km, subsequently downscaled to 1 km resolution and interpolated to 5 km for our analysis. We have added this information in the text

and the advice that lower resolution model output should be interpolated to a higher resolution grid if needed. Whether the GCM provides a good enough representation of the SMB is a problem outside of the scope of our paper. For this it is important to remember that the remapping does not generate new information (except for regions outside the ice mask of the climate model). In terms of resolving the ice sheet SMB, the remapping can only be as good as the original SMB product. We have added a discussion point on that question in the manuscript

• Sensitivity on number of drainage basins:
What is the minimum number of drainage basins and/or height ranges that would give you an acceptable remapping? What is the overall sensititivy on resolution, i.e., number of basins? From figure 3, I can see that a at least a few different drainage basins could be grouped together, e.g., b3 & b4, b10-b13, b17 & 18, etc. I could see that fewer drainage basisn and fewer height ranges could give you similar I remapping error. To me, 25 drainage basins doesn't sound very "non-local" as is claimed in the abstract.

We would like to first clarify that our claim for the method to be 'non-local' refers to the remapping aspect of the procedure. What we mean is that the method can 'stretch' the original aSMB to the modelled geometry, as we have put it in the manuscript.
We have initially tested some examples of fewer than 25 basins, which led to unsatisfactory results, as the main climatological regions of the GrIS (dry SW/NE, wet SE/NW are not well captured. Notably, we have tested no separation (1 global lookup table) and 8 basins. In too large basins we typically find errors of opposite sign at opposite ends of the basin, suggesting that the height-aSMB relationship can be improved by further division. To formally explore sensitivity of the results to the number of drainage basins is difficult to achieve, because our initial delineation is handmade and a consistent variation of the number of basins is hard to do. Nevertheless, we have now added an evaluation of the number of basins in the supplement based on a schematic basin set that can more easily be extended. The limitation of this set is that it does not follow the observed basin divides, which is why we have maintained the original delineation in the main manuscript.
For the current delineation we have defined regions of roughly similar width around the ice sheet, as much as that was possible given the underlying drainage delineation (Mouginot et al. 2019). We believe re-combining basins for the sake of similarity would not make much sense, because it may limit robustness to other (untested) forcing fields and would only represent a very limited computational advantage.

• Uncertainty estimation:
The function aSMB=f(hc) isn't well constrained for a few drainage basins. b6, b13, or b25, for example, show substantial variations in each height bin. I don't think they can be resolved if more basins would be used (also because the mapping becomes more local, which is not the intention) and also not with fewer, unfortunately. So, I if those variations can't be resolved they then needed to be accounted for at least. In b25, the aSMB variations around the median amount to more than 2m/yr. That is substantial. I would like to see how this inherent uncertainty in the remapping function plays out for the future projections. You say on page 8 that these uncertainties are small compared to the uncertainties in the climate forcing. Could you give some figures how large thos uncertainties in the climate model forcing are (in SMB units) and then compare it to you errors due to the remapping? Furthermore, if the remapping errors are relatively small, this could warrant using even fewer drainage basins (as I have suggested before).

As mentioned in response to the last question, we have included an analysis of the number of drainages basins in the supplement. The results show that some improvement can indeed be achieved with refining the basins further.
The aSMB error integrated over all basins is 19 km^3 yr^{-1} or <1.7% for the end of the century SMB anomaly, as can now be read from figure 6 (see next point). This number compares to the CMIP5 ensemble range and standard deviation (6 models used in ISMIP6) of 650 km^3 yr^{-1} and 240 km^3 yr^{-1}, respectively. This information has been added to the manuscript.

• Could you also add the total integrated aSMB to Figure 6?

OK, we have added the totals in the legend and updated the caption accordingly. The totals are also mentioned in the text in comparison to typical climate model uncertainty and it shows that the uncertainty is much smaller than the structural uncertainty underlying the aSMB calculation itself.

• On page10 you say that the rempapping doesn't work well if the modelled surface elevation is too different from the observed. How "close" to observation does the ice modelled ice-sheet elevation need to be?

There is no limit on how close the modelled elevation has to be to observations. The biases (in the interior) are simply proportional to the height differences and the

SMB gradient in the forcing model. The point here is to clarify that the "feature of the remapping method […] can be interpreted both as an asset or as a shortcoming": the forcing is 'corrected' to the modelled surface elevation. We pick up on that point in the discussion.

• *Sect 4.1 (section naming)*
If the setup "should not be interpreted as a real projection" (p.13 l.3), then you should revise the section header, as "Future sea-level change projections" implies realistic projections.

OK, replaced 'real projection' by 'full ice sheet projection' at p13 L3. We just want to avoid that the SL numbers are taken as ice sheet contributions in global assessments, because we only integrate SMB anomalies and do not consider any ice sheet dynamics.

• *p.13 ll.12*
I don't think further refinement would help here. First of all, as you said, if it's a flowline feature than, of course it is a highly localised feature and depends on the representation of the ice sheet model. If you would increase the number of basins, your remapping becomes local, and you need to drop your claim about the key feature being its "non-locality" (see abstract)

There is a misunderstanding with the term 'non-local' here. See also comment above. What we assert with 'non-local' is the feature of the reconstruction part of the method to translate the SMB anomaly found for one place to another. This applies equally for a flowline that would be 'stretched' (or compressed) to fit the modelled topography. We maintain that the refinement would help to better resolve aSMB variations perpendicular to the flow-direction, most obvious for the basins 9, 15, 16 ,17, but also 2 and 3 (Fig. 5c). This discussion has been added in the manuscript.

• *Sect 4.2*
I'm slightly confused by what is presented here and I must admit that it is not easy to follow. A little more motivation at the beginning of the paragraph could help to clarify what the actual problem is.

We know from our own experience and discussion that the problem is involved and (we believe inherently) difficult to understand. We further clarified the description e.g. by adding a statement what to expect from this sub-section up front as suggested.

– I thought that the overall goal of the remapping is to provide a transfer function from (any) h to aSMB. To me this implies that the changing ice geometry h(t) is implicity accounted for, or am I missing something?

At the beginning of this work, we had the same understanding, but realised that this was not the case. The changing ice geometry h(t) is implicitly accounted for in its effect on *aSMB*, but not on the SMB itself. To clarify this distinction and include changes in SMB due to height changes is the point of this sub-section.

– Also, why is the reader presented with two methods, here?

We agree that presenting both methods was confusing, so we have moved the description of the second method to the appendix, following the advice of all three referees.

– Adding to my confusio, I don't understand what Figure 11 tells me.

The figure simply shows the additional effect we are including when adding the height-SMB feedback in addition to adding the dependence of aSMB on h(t).

– This section doesn't really "flow" with the rest of the manuscript and needs to be revised substantially

We have revised the text to make it more clear and accessible.

– The authors favour the "offline" version of the remapping. Wouldn't the interactive method make more sense as it would nudge the ice sheet towards realistic margins and elevation changes and thus reduce the mode bias on the go? I think that any model bias that is not corrected for (instantaneously) would lead to a model drift and thus ever-increasing errors. So, in my opinion, this method should be the recommended one.

The two methods are in theory identical, we have implemented both in one of the ice sheet models and find near identical results. As described, we favour the offline version for practical purposes.
Nudging an ice sheet model towards realistic margins would create a model drift during the projections, which is clearly not intended, so there may be a general misunderstanding about the role of the aSMB forcing.

• P15 l15 Which method is now the "proposed method"? Add the relevant reference to the Eq.

The whole section has been revised and the alternative method has been moved to the appendix. We have included reference to equation 10 as the proposed method.

• Same page, ll19 "(no ice sheet model is used)" Does this imply (as bofore in Sect. 4.1) that the sea level contributions aren't based on realistic projections? Pleas, clarify.

The SMB projections are real and represent a possible forcing for ice sheet model experiments. See response to comments (Sect. 4.1) before.

• Sect 5 Discussion and conclusions
– As far as I understand it, the remapping depends on the regional climate model used, i.e., MARv.9 forced by MIROC5. For the purpose of ISMIP6, different GCM will be selected for the future projections (https://www.the-cryosphere-discuss.net/tc-2019-191/). How sensible is the remapping approach to a different configuration of RCM forced by a GCM? While getting the correct figures is difficult, this needs to be discussed at least.

We have initially tested the remapping with an earlier MAR version forced by 4 different GCMs, and by now also successfully used the method with MARv.9 forced by 9 different CMIP GCMs. The basin delineation holds for these other forcing fields as well. We have added this information as a discussion point.

– How would the aSMB approach play out for "realistic" future projections.

The example we show is a realistic projection in terms of SMB. The reason we emphasize that it is not a sea-level projection is that we did not run an ice sheet model, so ice dynamics are not included. Once an aSMB forcing is remapped to the

specific ice sheet geometry, it produces results like any other aSMB forcing. By now, the remapping has also been successfully applied for the ISMIP6 projections.

– The paper is highly specific for a targeted audience, i.e., ISMIP6 modellers. I see that the remapping approach can reduce model biases and it is a quick method to run offline corrections after a standalon ice sheet model run. I can foresee that this method can also be used in a way as to quantify those "unphysical" model biases (by looking behind the reduction of the model bias we see in the integrated SMB responses of each ice sheet model in Figure 12), This is obviously beyond the scope of this paper but can be discussed.

Yes, agreed. The remapping may be used diagnostically and also in any other case where the ice sheet model geometry differs from the geometry of the climate model. We have added a discussion point along those lines.

• What can the reader expect for realistic large-ensemble sea-level change projections?

The reader can expect the addition of ocean forcing, ice dynamics responding to the forcing and a wide range of ice sheet models. The projection paper using the method has appeared in TC discussions. See also points before.

• I would highly recommend to make any scripts or tools that have been used for this paper publicly available.

Yes, we fully agree. The scripts are already available on github and will be archived as a zenodo archive upon publication.

• The available data are incomplete as are the data availability statements! Therefore, I couldn't review the associated data that have been produced along this paper. See the "data policy" section of TC (https://www.the-cryosphere.net/about/ data_policy.html), for details

Scripts and datasets are now available online and will be archived for publication. We have modified the availability statements accordingly.

Technical Comments
• P1 L27: It is not clear what "observed" is referring to?

OK, replaced 'observed geometry' by 'climate model geometry'. In our framework and aside from climate model resolution they are identical.

• I wouldn't use colors for the bar chart in Figure 12, as they don't add any information.

The colour scheme has been chosen to be in line with figures in the initMIP paper and facilitate direct comparison. Not changed.

Thanks again for reviewing this paper.

<u>Referee 2</u>

General comments

This paper describes a method for adjusting a surface mass balance (SMB) anomaly field that has been calculated with reference to a specific ice sheet topography, such that it may be applied to an ice sheet model with a different topography, minimising un-physical impacts in the target model that may arise purely from this difference in initial height. In other words, it aims to estimate, from a single base field, the SMB anomaly that would be physically consistent with any given surface, without explicitly recalculating the climate and SMB anomalies on that surface. Such a method is desirable in a multi-model ice sheet comparison project such as ISMIP6, where a single future scenario forcing needs to be applied consistently across a spectrum of ice sheet models that have significantly different representations of the present day ice sheet state.
Evidence from preliminary work in ISMIP (initMIP) shows that such a method will make comparing the ISMIP6 experiments across the different participating models very much more robust, so this is in principle a worthwhile contribution to the field, and may well prove useful beyond the immediate scope of the ISMIP6 experiments themselves. The method described is sensible and the paper is written carefully, and addresses the main questions that arise regarding its application and the degree to which it may inherently distort the input fields.

Thank you very much for the positive evaluation.

This is a methods paper, describing a method that I believe has already been used by a number of groups conducting the ISMIP6 experiments, so there's no real scientific *interpretation to quibble over and the main goal of the paper is to document what was done, say why certain decisions were made how they were and enable others to reproduce the method. The only real fault I find with the current state of this paper then is the derivation of the time and height dependent remapping procedure, section 4.2. There's clearly some subtlety in how to remap the real changes in SMB that come from a changing climate (simulated in the RCM) at the same time as estimating what would be expected to physically occur as the ice sheet height evolves (not simulated in the RCM) along with applying the numerical dSMB/dz remapping to account for the initial state mismatch, but I found 4.2 a very confusing way of trying to explain this. This is perhaps due to the notation used - for me the summary in words at the end was much clearer than the form of the equations used to derive it. This section, alone, doesn't do a great job of allowing others to understand and reproduce the method for themselves.*

We have reworked section 4.2 by starting with a clear motivation and by moving the alternative formulation to the appendix. See also response to several comments raised by reviewer 1.

Further, given that the method may have use beyond the current ISMIP6 effort, it might be useful to future readers to highlight things that could have been done better in hindsight, or that could be applied if a reader's individual use case isn't subject to some of the (wide-ranging) restrictions implied by the ISMIP ensemble. So, whilst it is stated (pg5, line 13) that other choices of hc and R might be appropriate for a non-MAR forcing product, it might guide future applications for the authors to note some more detail as to why they decided their choice was "sufficient". In this vein, whilst there is attention on the needs of different ice sheet models as targets for the method, perhaps the authors could speculate on issues that might arise from using a different source climate model - eg a GCM with a lower horizontal resolution than MAR.

We have clarified in the text the main factors influencing the parameter choices and why we have considered them to be 'sufficient'. We have also added a discussion item to address other use cases, e.g. when applying a different climate model. See also response to comment from Reviewer 1.

Lastly, playing devil's advocate (and supporting writing for maximum clarity, and defensively) readers not familiar with ISM modelling might question whether what's being done here is a fudge of the "right" boundary condition purely for the sake of convenience for modellers who haven't initialised their ice correctly and don't want it *forced into correctness by these "right" boundary conditions. I would thus recommend being careful in outlining the motivation and the scientific intent of the adjustment. As an example, pg 2, l28: "appropriate" carries an ambiguous meaning here. I think there are a couple of other places terms like this are used too. For me it would be better to be very explicit and stress that the method is intended to transform the climate forcing so that it has more physical consistency with the ice sheet state it will be used with. So, in section 2 "this effect we are trying to capture" could be made more explicit along the lines of: here is a physical relationship between ice geometry and boundary conditions we need to be able to honour in each model that uses our forcing set, because the two things are not independent and blindly applying the same set of absolute boundary values to every ISM would impose an artificial inconsistency.*

Good point. We have revisited the text to work it towards more careful formulations. We have replaced 'appropriate' by 'physically consistent' on page 2 and revised the description in section 2 as suggested.

Detail comments
page 4, line1: "fixed function of observed surface elevation" could add "sampled across the entire ice sheet"

Thanks, added as suggested.

pg4, l5: "apply the remapping" could add "separately"

OK, added.

pg4, l13: it's not obvious to me why the median is used, rather than any other average

We tried the average and found the median to be more robust against eventual outliers. This has been added in the text.

pg4, l16: is there any possibility at this point to recalculate/merge the drainage basins for ISMs that might have very different/coarse geometries? Who does each part here? Do ISM groups remap themselves based on the lookup table?

The drainage basin delineation should not change between analysis and reconstruction to avoid distortion of the aSMB field. We at least do not see a

meaningful way to merge different basins. The remapping could in principle be done by each individual modeller. In practice, we have provided remapped SMB based on individual initial ice sheet geometries. This is described in more detail in section 4.2.

pg4, l33: What were the MAR boundary conditions - ERA?

MAR was forced by MIROC5. We have added 'forced by MIROC5 (Watanabe et al. 2010)'.

pg5, fig 2: The choice of colours is a bit random, some are indistinguishable from each other - does this invite unnecessary use of printer ink!?

OK, we have updated the figure as a grey scale image instead.

pg5, l12: "judged sufficient" is not very precise - if you're going to say other intervals might be appropriate for other products, could you give some kind of guidance as to why you felt this choice was appropriate for this product?

OK. We have expanded on this point to clarify why we judge the parameter choice as sufficient. This is related to the spatial variability and smoothness of the original aSMB product.

pg9: might be a good place to note the effect of the remapping on (integrated) SMB conservation? One would not expect it to conserve, of course - and probably you actively don't want it to, again within a framework of transforming the SMB forcing so it gains physical consistency with the state you're applying it to rather than preserving numerical neatness for its own sake.

OK, added a sentence clarifying this relation:
'This also illustrates why the method is not designed to conserve mass when remapping to a different geometry: it demands a different SMB forcing.'

pg13, l12: notes "where the relationship between surface elevation and aSMB breaks down". I think this could ideally be expanded and come much earlier in the paper, as a general caveat to the applicability of the whole approach.

Agreed. We have now added comments about this limitations already on page 9 where results presented in Figure 5 are discussed.

Could you add an estimation of where/how badly this affects things, or how far the target topography can be from the original before this sort of method is not worth applying?

The discussion in this point deals with errors when remapping to the same geometry, not to a different geometry. We have an extended discussion point on the limitations for different geometries. See also comments to reviewer 1.

pg 14: whilst I got the principle fine, I found the derivation of the form of the time- and height-dependent anomaly on page 14 (ultimately, eqs (10) or (12)) to be very confusing. Not sure how best to suggest clarifying, but some points to consider:

This sub-section was also criticised by the other reviewers and we have reworked it accordingly. With some comments overlapping, please also see responses to the other reviewers.

Line 10, I didn't find the omission of hˆbar from the R(...) operator and elsewhere helpful for clarity, I ended up writing it back in everywhere it was not explicit to remind myself that these terms originated at hˆbar rather than any other h. For consistency throughout the uses of h, would hˆbar be more clear as h_RCM, h_0 as h_ISM(t=0), and h(t) as h_ISM(t)?

We feel the h^bar in R(…) is redundant, because any remapping operation is always from h^bar to another h. There is a balance between adding more information to the symbols and keeping the formulation compact, the latter of which we have emphasized by choosing single letter symbols where possible. We are confident that other changes to this part have made the sub-section much clearer. Though, we've learned by own experience that this part of the remapping is very difficult to understand.

*Lines 13-17 seem to be there primarily to illustrate what *not* to do, as a misleading false start. Is this part really needed at all?*
Line 18, and eqs (9) and (10) are the fairly straightforward aim of it all - could all of lines 10-17 actually be left out, and the two terms on the RHS of (10) just be explained as

representing the explicit climate change dependence and the height-dependence of the SMB respectively (if that's what they are)?

We feel it is important to lay out the whole complexity of the problem to make readers understand this is a non-trivial issue. We have tried to improve clarity by revising the description.

The alternative form in eqs (11) and (12) is not uninteresting, but since it's ultimately not used I'm afraid it contributed more to my initial sense of confusion than my education. Could make it a footnote?

Agreed. We have moved this part to the Appendix for interested readers.

Line 6: I additionally wasn't clear how the various d(SMB)/dz terms were in practice derived for the ISMIP forcing product - via a local spatial SMB gradient from MAR, from the basin-scale SMB vs height lookup tables described in section 2.1 or one of the other methods noted in the references on lines 7 and 8?

We use the Franco method based on MAR output. This has been clarified in the text.

pg16, l5: wasn't clear to me how the physical and unphysical biases in the sea-level contributions were being discriminated between, unless it's simply that the remapping is a good thing, so the biases left after applying it must be physical, and the difference between that and what was there before are unphysical?

The physical and unphysical biases can indeed not formally be discriminated. Though the idea of the argument is to contrast biases that can be (physically) expected for an ice sheet of different shape and the (unphysical) biases of an aSMB derived for one geometry directly applied to another.

pg17, l31: Are the scripts to do the remapping also going to be made available (with long-term storage) somewhere - perhaps as part of the TC submission?

Yes, they will be made publicly available through links in the availability section.

Thanks again for a constructive review of our manuscript.

Referee 3

As part of ice sheet model intercomparison efforts, participating modeling groups utilize forcing fields such as anomalies of the surface mass balance (aSMB). These anomaly fields are constructed under the assumption that the ice sheet geometries (extent and surface height distribution) between the model and the reference are identical. If the geometries differ substantially, some remapping of the forcing fields is necessary to minimize unrealistic forcing. The authors present a compact and new procedure to remap atmospheric forcing fields, and they apply it to the Greenlandic ice sheet exemplarily.

The ice sheet is divided into sectors, which resemble here drainage basins of the ice sheet. For each sector, they construct a lookup table of the actual aSMB and the (ice) surface elevation for defined elevation intervals from bottom to the top. The final lookup table contains the elevation-aSMB relationship for each basin. During the remapping, the applied relationships of the actual and neighboring basins are weighted according to their distance to the point of interest. The actual ice sheet elevation defines for each grid point the remapped forcing field. If this remapping is performed for all time steps, also transient aSMB fields could be remapped.

The authors show that the procedure works reasonably well for the trivial case, where the forcing field is remapped to the original reference topography. They also derive the influence of a temporarily evolving ice sheet elevation on the applied aSMB. Ultimately, they apply the procedure to model results of the initMIP exercise (Goelzer et al., 2018), where they analyze the formerly strongly diverging sea-level contributions of different models. These sea levels come closer together because the influence of the partly substantial different horizontal extent of the simulated ice sheets is corrected.

The manuscript is well-structured and written. I consider the reporting of scientific/technical procedures as important because they will help us to enhance the re-producibility of results and allows us to compare and understand diverging results. I recommend accepting this manuscript after minor revision.

Thanks for the positive comments.

1 General comments

The manuscript is well written and leaves only room for very few suggestions. The main assumption is the already mentioned strong dependence of the surface mass balance (SMB) with elevation. For the ablation part of the SMB, this is clear considering the strong relation between elevation and the near-surface air-temperature, where the latter could be understood as a proxy for melt potential. However, the same does not *necessarily apply for the accumulation as part of the SMB. Could this difference disturb your procedure? If yes, under which circumstances does it occur?*

The remapping is most important for the margins of the ice sheet, where ablation is typically the dominant term to the SMB and aSMB. In the accumulation area in the interior of the GrIS, the elevation dependence of aSMB decreases, but aSMB is anyway close to zero, which mitigates this effect.
Note also that we operate with a lookup table that is *mapped* as a function of elevation, not with a regression. This implies that the method can also deal with the situation where aSMB decreases with decreasing elevation and then increases again (e.g. basin 2 in Fig. 3), which is not the case e.g. in the method of Helsen et al. (2013).

In some basins, you detect a substantial spread in the constructed primary lookup table (mid-east, south, north-west). Does a larger spread indicate that a further division of this section should be performed? Can you provide a criterion, that helps to weight the benefits of smaller basins and potentially smaller spread versus larger basins and larger spread?

Indeed, further refinement of the basins can improve the representation. We have included an analysis of the number of basins in the supplement with an alternative schematic basin delineation. The main problem to move to a larger number of basins is the difficulty to define a meaningful basin set. This is now discussed in the manuscript. See also responses to reviewer 1.

You checked the sensitivity of dsnorm for values between 50 km and 125 km and haven't found a strong dependence. What happens if dsnorm reaches the grid resolution of the ice sheet model (dxism): dsnorm −→ dxism?

The grid resolution of the aSMB product in use is 5 km, quite far outside of the interesting range for dsnorm. Nevertheless, as pointed out in response to questions by reviewer 1, the aSMB product could simply be interpolated or downscaled to a higher resolution to avoid technical issues if *dsnorm* −→ *dxism*. See also response to reviewer 1 on this question.

Do you detect beside discontinuities at the boundaries of the basins any other problem?

For some basins the tables would not have entries at high elevation due to limited coverage of the elevation range. This is already mentioned in the text.

What happens when the generally coarse grid of a driving global atmosphere model (resolution: dxatm) is used, where we easily reach: dsnorm −→ dxism?
This analysis may help to explain what happens if we drive the ice sheet directly with the output of global atmosphere models.

The grid resolution itself is not a limiting factor, as the data can be interpolated to sufficient resolution to fulfil technical requirements for the remapping. Instead, the real limitation is in the quality of the original aSMB product. We have added a discussion item on that question.

In the derivation of the SMB-height feedback, I have found the part (page 14) between lines 19 and 22 (incl.) confusing. May you move it into the supplement and refer to it for the interested reader, while the following "alternative" method becomes the main method.

Line 19-22 describes the preferred method that has actually been used, so we want to keep that in the main text. We have moved the alternative method (line 23-) to the appendix to make the section clearer.

The results of section 4.3 ("Application to a large ice sheet model ensemble") suggest that the correction (Figure 12c) is larger for models with a bigger initial sea-level contribution and ice-sheet extent. Have you tried to analyze the relation between (A−Aref)/Aref and Δzsl, where Aref and A are the reference and actual ice-covered area in each model, respectively, and Δzsl is the sea-level difference (Figure 12c)? Please, at least add this figure to the supplements?

Indeed, there is a clear tendency for models with a larger area to exhibit larger corrections in Figure 12c. A scatter plot of this relationship is given below. However, while this tendency is mentioned in the manuscript, we found the figure does not add important information and have not included it.

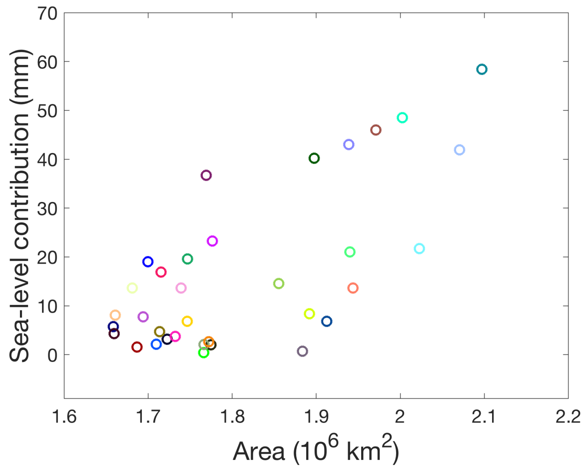

Figure 1 Initial ice sheet area of initMIP-Greenland models (Goelzer et al., 2018) and difference of sea-level contribution when remapping is applied (Fig 12c).

2 Specific comments

2.1 Text

Page 3, Line 10 What does "similar" actually mean? Please, clarify.

OK, Replaced 'similar' by 'close'

Page 4, Line 13 What happens if you use the mean instead of the median?

The median is chosen because it is more robust against outliers. This has been added in the text.

Page 4, Line 23 You may want to be more generic by replacing the "climate model's surface elevation" with the "reference field's elevation"?

OK, replaced as suggested.

Page 6, Line 1 I guess I understand you, but the sentence is not entirely clear. Please rephrase.

OK, reformulated.

Page 8, Line 8-9 Here you state that the basins 7–9 have the largest mismatch. What is the reason behind?

We have added following description to the text: ‘These three basins all exhibit detailed and varied topography at the margins, which may contribute to the errors. The largest signed errors are found in basin 7 with compensating biases of opposite sign.’

Page 9, Line 15 Do you mean "where the modeled ice sheet is smaller (e.g. Basin 16, Figure 7d)"?

Yes, thanks for the suggestion.

Page 16, Line 1 Please provide a citation for ocean area of 3.618 ·14 m2?

OK, added a reference.

Page 17, Line 12 The relationship is nearly uniform in each sector’s center. You may clarify this if you think it’s necessary.

Not necessary as it does not contradict the linearity mentioned here.

2.2 Figure
The figures show in general the main features. However, some lines are hard to recognize, because they are too thin. Please check the figures.

OK, we have checked all figures and redrawn and removed in some cases the contour lines. See details below.

Figures 5, 7, 10, and 11: In some of these figures, small deviations are hard to notice because the color around small deviations is white or gently yellow or light-blue. Would it be possible to use a colorbar, where either the deviation around zero is not white or, alternatively, mark the ocean with a light-gray color, for instance? If the ocean would be gray, you do not need to add a contour line to represent to coast.

OK, we have marked the ocean in gray colour and kept the present-day coastline only in some cases where that information seems useful.

Figures 5 and 7: The red contour lines are barely seen. Please thick the lines and mention its purpose in the related figure captions.

OK, we have removed the contour lines in Fig 5, where they did not add more information. For Fig 7 we have made the lines thicker and grey to better match with the background colour and avoid a colour that is in one of the colourbars.

Figure 3: Please mention the meaning of the lower-right labels (basin number as de- fined in figure 2) in the figure caption.

OK. added description in the caption.

Figure 8, Subplot b: It's hard to see if "extended-original" is as large as "remapped-extended?" Please replace "remapped-extended" with "extended-remapped."

OK. adapted as suggested.

Figure 9: Mention that each subfigure's title indicates the basins as defined in figure 2.

OK, this information is added in the caption.

The lower right subfigure is smaller due to the color-bar. Could you improve it? For example, by moving the color-bar to the right or below the group of sub- figures.

OK, we have updated the figure accordingly.

Figure 10, Subfigure a) and b): Since the interior of Greenland shows only pale colors, you may add the zero contour line to guide the reader. If so, please mention the zero-contour line in the figure caption.

OK, updated as suggested.

Figure 11: Since the interior of Greenland shows only pale colors, you may just add the zero contour line to guide the reader.

OK, we have added a contour line in panel a. We have tried the same for panel b and c but found it decreased readability of the figures. So we keep it only in panel a.

Thank you very much for the review.

Remapping of Greenland ice sheet surface mass balance anomalies for large ensemble sea-level change projections

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Abstract

Future sea-level change projections with process-based standalone ice sheet models are typically driven with surface mass balance (SMB) forcing derived from climate models. In this work we address the problems arising from a mismatch of the modelled ice sheet geometry with the one used by the climate model. We present a method to apply SMB forcing from climate models to a wide range of Greenland ice sheet models with varying and temporally evolving geometries. In order to achieve that, we translate a given SMB anomaly field as a function of absolute location, to a function of surface elevation for 25 regional drainage basins, which can then be applied to different modelled ice sheet geometries. The key feature of the approach is the non-locality of this remapping process. The method reproduces the original forcing data closely when remapped to the original geometry. When remapped to different modelled geometries it produces a physically meaningful forcing with smooth and continuous SMB anomalies across basin divides. The method considerably reduces non-physical biases that would arise by applying the SMB anomaly derived for the climate model geometry directly to a large range of modelled ice sheet model geometries.

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1 Introduction

Process-based ice sheet model projections are an important tool to estimate future sea-level change in the context of the Intergovernmental Panel on Climate Change assessment cycle (IPCC, 2013). For the first time, in the upcoming IPCC assessment report (AR6), ice sheet model projections are formally embedded in the Coupled Model Intercomparison Project (CMIP, Eyring et al., 2016) in the form of the CMIP-endorsed Ice Sheet Model Intercomparison Project ISMIP6 (Nowicki et al., 2016; 2020). ISMIP6 aims at providing estimates of the future sea-level contribution from the Greenland and Antarctic ice sheets based on standalone ice sheet model (ISM) simulations, forced by output from CMIP atmosphere-ocean global climate models (GCMs) and fully-coupled ISM-GCMs. This paper focuses on standalone simulations of the Greenland ice sheet (GrIS).

The first ISMIP6 activities focused mainly on the problem of ice sheet model initialisation (Goelzer et al., 2018a; Seroussi et al., 2019), but also identified issues that may be encountered when a large range of ice sheet models is forced with climate model output. The most important forcing derived from climate models in the context of future sea-level change projections for the GrIS is the surface mass balance (SMB) describing the rate at which mass is added or removed at the ice sheet surface. For the ISMIP6 projections it was decided to apply the SMB forcing as an anomaly, i.e. as the change in SMB relative to a given reference period. This approach has the important advantage that it allows for participating ice sheet modellers to use their own SMB product during initialisation and simply add provided SMB anomalies in a projection experiment.

However, problems were identified when a given surface mass balance anomaly (aSMB) was applied to the wide range of Greenland ice sheet models used in the community (Goelzer et al., 2018a). The key issue is a mismatch between modelled initial and observed ice sheet geometries, the latter of which underlies the SMB field. These differences are related to uncertainties in forcing, physical parameters, and the underlying ice sheet model physics. For instance, a geometrical mismatch generally means that the modelled ablation zone and the prescribed anomalous ablation are not co-located, leading to an incorrect mass balance forcing.

With the original intention to apply identical forcing to all participating models, a forcing data set was prepared for initMIP-Greenland (Goelzer et al., 2018a) that consisted of an SMB anomaly based on the present-day observed geometry. The SMB anomaly was extended outside the observed ice sheet mask following a simple parameterization to accommodate larger than observed ice sheet model extents. In practice, however, ice sheet models with larger-than-observed initial areas exhibit larger melting under such forcing, simply because their ablation areas are extended outwards.

To address this problem, we present here a method to remap the SMB anomaly as a function of surface elevation, and thereby produce physically consistent forcing for different ice sheet model geometries. The proposed method was developed for future sea-level change projections made with a large ensemble of ice sheet models (with possibly widely different initial geometries) forced by output of different climate models and scenarios. However, other applications can be envisioned, for example any

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other case where the climate model forcing is generated for an ice sheet geometry differing from that of the ice sheet model itself. Asynchronously-coupled climate-ice sheet simulations and experiments with accelerated climatic boundary conditions may also be improved with the presented method.

In the following we describe our approach and method (Sec 2), the resulting forcing (Sec 3), and time dependent applications (Sec 4), and finally discuss the results (Sec 5).

2 Approach and method

Our approach aims to generate a SMB forcing (at a yearly time scale) applicable to an ensemble of Greenland ice sheet models that exhibit a wide range of initial present-day ice sheet geometries. The forcing is based on an existing aSMB product that is generated at a fixed present-day surface elevation. This aSMB product will typically be the output of a regional climate model, but could come from any SMB model or GCM. While the forcing will have to be adapted for the individual model geometries, it should remain as close as possible to the original product when applied to the observed present-day geometry.

The proposed method is based on the strong elevation dependence of SMB and aSMB and is illustrated for a schematic flowline of a land-terminating ice sheet margin (Figure 1). For a larger ice sheet geometry (red, dashed), the horizontal equilibrium line position lies farther from the ice divide than for a smaller ice sheet (black). It is this effect that we are trying to capture with our method: a different ice sheet geometry requires a different forcing to honour physical consistency. Remapping the SMB anomaly as a function of surface elevation, as we propose, allows for a "stretching" of the SMB product to match the larger ice sheet extent, while maintaining its overall shape.

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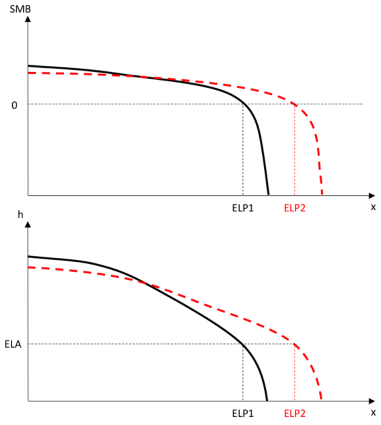

Figure 1 Schematic cross section for two different ice sheet geometries (bottom) and associated surface mass balance (top). The two geometries share the same equilibrium line altitude (ELA), but exhibit different horizontal equilibrium line positions (ELP1, ELP2).

For initMIP-Greenland, the SMB anomaly was parameterised as a fixed function of observed surface elevation and latitude sampled across the entire ice sheet (Goelzer et al., 2018a), which was subsequently used to define a forcing product everywhere on the grid. In principle, we could use the same global approach to generate SMB forcing for a range of different initial ice sheet geometries. However, regional differences in the height-aSMB relationship can be large and justify a spatially better resolved approach.

To capture regional differences, we therefore apply the remapping separately for a set of drainage basins (Shepherd et al., 2012; Zwally et al., 2012; Mouginot et al. 2019). In practice, the following steps are executed to (1) derive and (2) apply the height-aSMB relationship to different geometries.

(1) Defining an elevation-aSMB lookup table:

- Divide the ice sheet into drainage basins
- For each individual drainage basin do:
    - For each elevation band with central height h_c and range R of heights do:
        - find aSMB values for all heights in R
        - calculate the median aSMB of these
        - Save result to lookup table aSMB=f(h_c)

(2) Remap aSMB to a new geometry:

- Use the drainage basins separation in (1)
- For each individual drainage basin do:

- For each ISM grid point do:
  - interpolate aSMB linearly as a function of height using a combination of lookup tables (1) for this and neighbouring basins (see Sec 2.2)

2.1 Defining an elevation-aSMB lookup table

The first step (defining an elevation-aSMB lookup table) is independent of the ice sheet model characteristics and relies only on the initial aSMB product, the reference field's elevation, and a meaningful basin selection. Ideally, the basin division should separate regions with largely different SMB characteristics, e.g. wet and dry regions. At the same time, our method requires that each basin contains a wide elevation range so that the lookup tables can be completely filled. For this study we created 25 basins by combining several smaller basins from a recent drainage delineation (Mouginot et al. 2019). The basins may consist only of single outlet glaciers or even flowlines, as long as they cover a sufficiently large elevation range. The basin delineation is extended outside the observed ice sheet mask to accommodate different (i.e. larger) ice sheet geometries than observed (Figure 2). This was done once manually using observed topography of ice-free regions and bathymetry as guidance. In order to test the robustness of the method to the number of basins, we have constructed an alternative basin set that can be subdivided semi-automatically, albeit not following observed drainage divides (Figure S1, supplementary material).

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While the method can be applied to any aSMB product, here we use model output from the regional climate model MAR (Fettweis et al., 2013) forced by MIROC5 (Watanabe et al. 2010), as it has been run for the RCP8.5 scenario and was chosen for ISMIP6. We use output of MAR version 3.9 run at a horizontal resolution of 15 km that has been downscaled to 1 km (Delhasse et al., 2019) and subsequently interpolated to 5 km resolution for our analysis. If needed e.g. for a coarser resolution climate model output, the aSMB could be interpolated to a high enough target resolution to guarantee that sufficient samples are present in each basin and elevation band. We demonstrate the method here with aSMB at the end of the century relative to the 1960-1989 reference period, calculated as the time mean change:

$$aSMB = \overline{SMB}^{2091-2100} - \overline{SMB}^{1960-1989}. \quad (1)$$

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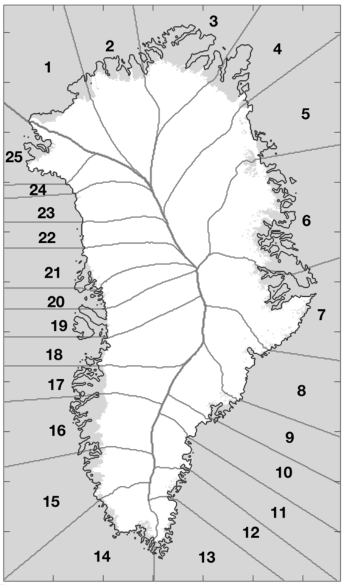

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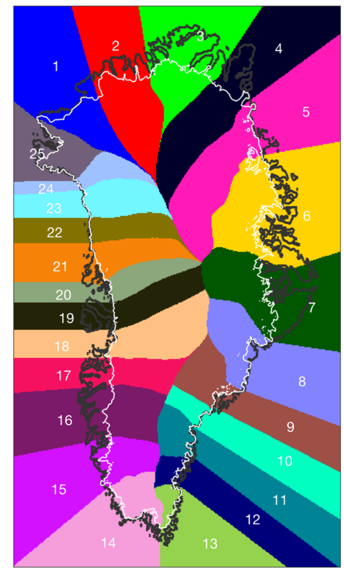

Figure 2 Basin separation. The basin delineation is based on Mouginot et al. (2019), combined into a set of 25 regional basins and extended to the grid margin.

For each drainage basin we define an elevation-aSMB lookup table based on the MAR SMB data in that basin. We define elevation bands with centre h_c and range R, find all grid points with matching elevation, and register the associated aSMB values. We calculate the median aSMB value of all available points for each elevation band (Figure 3), resulting in a lookup table aSMB=f(hc). The median is chosen rather than the mean for its robustness to outliers. The step size dh=100 m between subsequent elevations h_c and the value for the range of R=100 m was chosen after some initial testing, but was not formally optimised. The main factors influencing this parameter choice are spatial variability and smoothness of the original aSMB product, which also depends on the original resolution of the SMB model (in this case: 15 km). Given the relatively smooth aSMB field, the chosen parameters were judged sufficient to describe the variation in the elevation-aSMB relationships for each basin (Figure 3). Other interval sizes may be more appropriate for other climate forcing products.

For all table entries at 0 m elevation, we have copied the more robust table entry at 100 m, rather than using the 0-50 m height interval with sparser data. For basins with missing values for high elevations, we repeated the highest-elevation aSMB value until 3500 m (circles in Figure 3).

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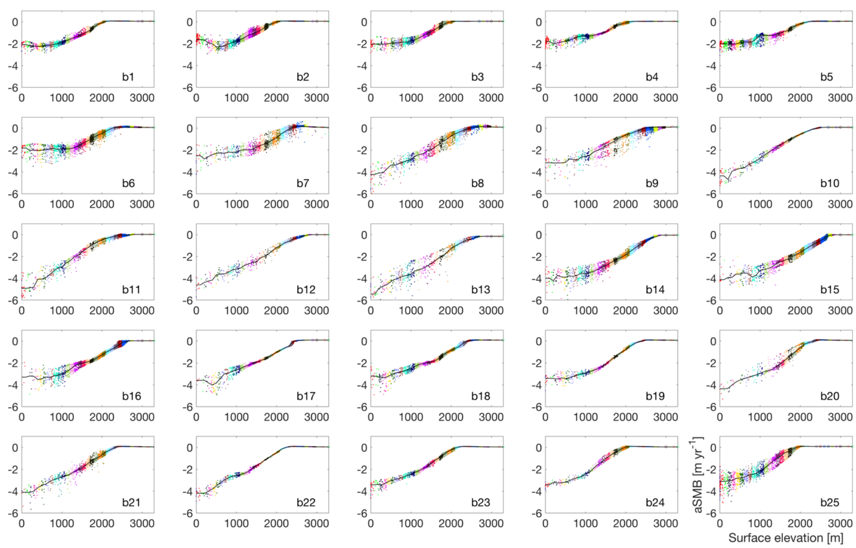

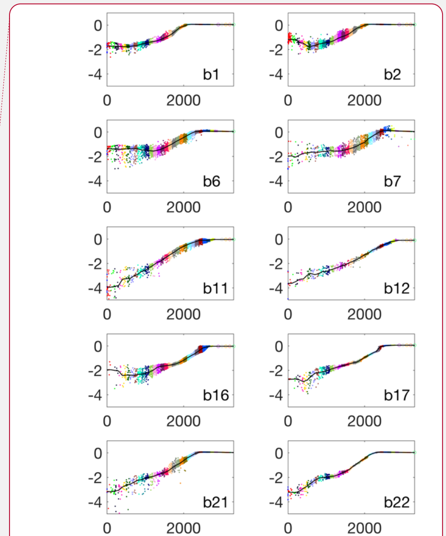

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Figure 3 SMB anomaly (m ice equivalent per year) from the RCM MAR (scatter) and with the elevation interval medians (used for the mapping) shown with a black line. Different colours indicate the elevation ranges considered for the elevation-aSMB lookup table. **The subfigure labels indicate the basin identifiers as defined in Figure 2**

2.2 Remap aSMB to a new geometry

For the reconstruction of SMB on an ice sheet model geometry, we define the aSMB for each grid point using a combination of lookup tables from the local and neighbouring basins. We weight the aSMB values of the surrounding neighbour basins by proximity, which results in a gradual decrease of influence of the next neighbouring basin away from the divides (Figure 4). The aSMB for each point in a specific basin b_0 is calculated as

$$aSMB_{b0}(x,y) = \mathrm{aSMB}_{b0}(h) * w_0(x,y) + \mathrm{aSMB}_{b1}(h) * w_1(x,y) + \ldots \mathrm{aSMB}_{bn}(h) * w_n(x,y), \quad (2)$$

where $\mathrm{aSMB}_{bi}(h)$ is the aSMB value found by interpolating the lookup table for basin b_i at the elevation h(x,y).

The weights of the gradients in the current basin b_0, are calculated as

$$w_0 = 1 - \frac{p_1 + p_2 + \cdots + p_n}{p_0 + p_1 + p_2 + \cdots + p_n}, \quad (3)$$

which is the residual of the sum of the weights for neighbouring basins b_1 through b_n defined as

$$w_1 = \frac{p_1}{p_0 + p_1 + p_2 + \cdots + p_n} \tag{4}$$

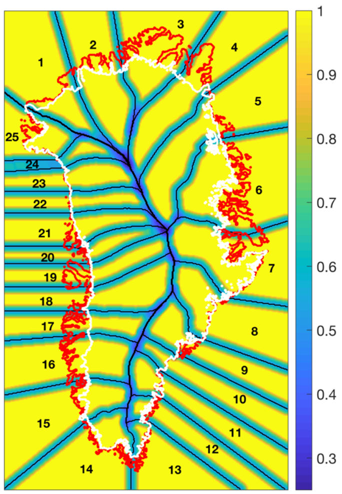
$$\ldots$$

$$w_n = \frac{p_n}{p_0 + p_1 + p_2 + \cdots + p_n}.$$

Here p_0=1 and p_1, p_2, … p_n are proximities of a given point to the neighbouring basins b_1- b_n which are limited to the interval [0, 1]:

$$p_i = 1 - \min\left(\frac{ds_i}{ds_{norm}}, 1\right), \tag{5}$$

where ds_i is the distance from a given point in b_0 to the nearest point in neighbouring basin b_i, which is normalized by a prescribed distance $ds_{norm} = 50\ km$. This value of ds_{norm} was chosen to minimize the mismatch between original and reconstructed aSMB (other tested values were 75, 100 and 125 km), though variations in ds_{norm} have limited influence on the results. As an example, near divides with only one neighbouring basin in proximity, the local weighting factor w_0 increases from 0.5 at the divide to 1.0 at the centre of the basin (Figure 4).



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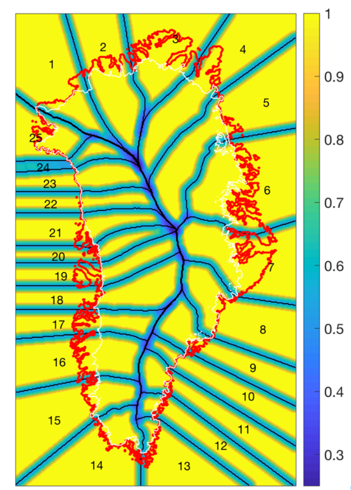


Figure 4 Weighting factor of the local basin for remapping. The local weighting factor increases from the basin divides (black lines) to 1.0 in the centre over a specified distance (here 50 km), while the factor for the neighbouring basin decreases proportionally (not shown). The white contour outlines the ice sheet margin and the red line the Greenland coast.

3 Results

Figure 5 shows results for aSMB at the end of the MAR RCP8.5 simulation (Eq. 1). The original MAR aSMB (Fig. 5a) has been used to remap aSMB at the same surface elevation (Fig. 5b).

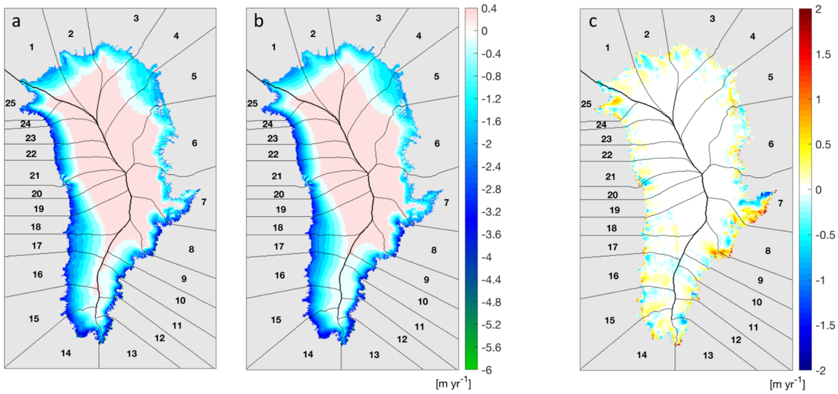
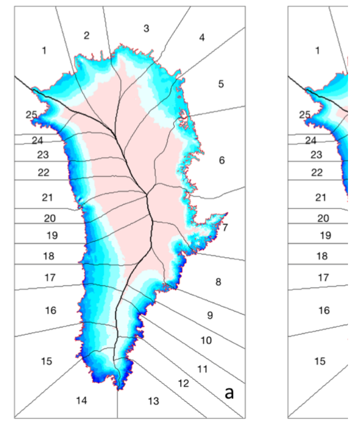


Figure 5 SMB anomaly from the RCM MAR for the observed geometry (a), remapped to the same observed geometry (b) and differences (b)-(a) in (c).

The reconstructed aSMB is very similar to the original, reproducing the overall pattern. Some smaller-scale features are lost, however, by averaging laterally across the basin and over elevation bands. The difference map (Fig. 5c) reveals some along-flow features at the margins (e.g. in basins 2, 3, 9, 15, 16 and 17), suggesting that the local median value is not a good representation and that refinement of those basins could further improve the remapping. The absolute error in spatially integrated aSMB per region in this case is on average 2.3% with extremes of 4%, 6% and 16% in basins 5, 8 and 9, respectively (Figure 6). These three basins all exhibit detailed and varied topography at the margins, which may contribute to the errors. The largest signed errors are found in basin 7 with compensating biases of opposite sign. We consider these errors acceptable given typical uncertainties in climate model forcing (e.g. van den Broeke et al., 2017) and our specific interest in large scale, ice-sheet-wide results to be used in ISMIP6. Specifically, the aSMB error integrated over all basins is 18 km^3 yr^{-1} (Figure 6) compared to an ensemble range (650 km^3 yr^{-1}) and ensemble standard deviation (240 km^3 yr^{-1}) for the 6 CMIP5 models used in ISMIP6 (Goelzer et al., 2020). The robustness of the method to changes in the number of basins has been evaluated with a schematic basin set that can be subdivided semi-automatically (Supplementary material). Within the range of tested basin numbers (20-100) the remapping error is the lowest for the largest number of basins (100), but varies non-steadily and by only up to 15 % across the tested range (Figure S2).



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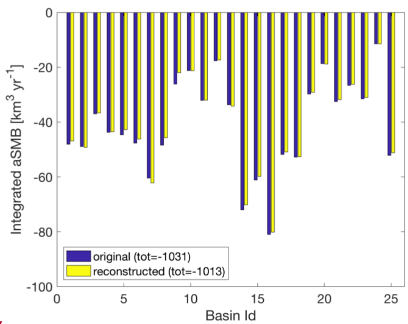

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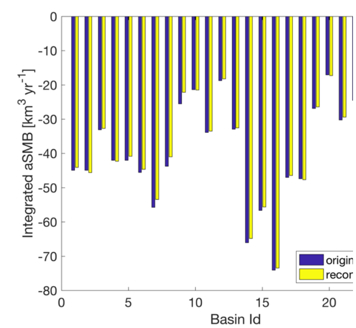

Figure 6 Integrated aSMB per basin from original MAR model output (blue) and for reconstruction on the same geometry (yellow). Greenland-wide total values are given in the legend.

The remapped aSMB for an example modelled geometry with large differences relative to the observed is shown in Figure 7c for one member of the initMIP ensemble (VUB_GISM). The remapped aSMB shows a pattern similar to the original (Figure 7a) with smooth and continuous aSMB across basin divides. Where the ice sheet extends well beyond the observed ice mask (grey contour lines) the aSMB is naturally extended following the modelled surface elevation, as is best visible in sector 3. Results from a standard method of extending the SMB outside the observed ice sheet mask at the observed surface elevation (Franco et al., 2012) are shown in Figure 7b for the footprint of the modelled ice sheet. This method uses the 4 closest, distance-weighted SMB values inside the MAR ice mask, and applies a correction based on the elevation difference between the interpolated elevation of the 4 SMB pixels and the local elevation by using the local vertical SMB gradient computed in this area. Due to low elevation of the tundra surrounding the ice sheet, the extension provides generally low aSMB for regions outside the observed ice sheet mask, which is illustrated in Figure 7d, showing the difference between the original (Figure 7a) and extended (Figure 7b) aSMB. By definition, the original and extended aSMB are identical over the common ice mask, but positive differences can be seen in regions where the modelled ice sheet is smaller (e.g. basin 16, Figure 7d). The remapping method notably prevents the occurrence of large-amplitude negative aSMB outside of the observed ice sheet mask, illustrated by the difference between the two approaches (Figure 7e).

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We quantify the differences between the three aSMB products again by integrating them over the drainage basins (Figure 8a). The largest differences between the original and extended aSMB are found in basins where the modelled ice sheet extends far beyond the observed ice sheet mask (basins 3, 4 ,6 and 7), or where the aSMB has large negative amplitude (basin 12, 14 and 15). In all these cases, the remapping reduces the bias (in most cases considerably), which is visualised by showing basin integrals of differences between original and extended (blue) and between remapped and extended aSMB (yellow) in Figure

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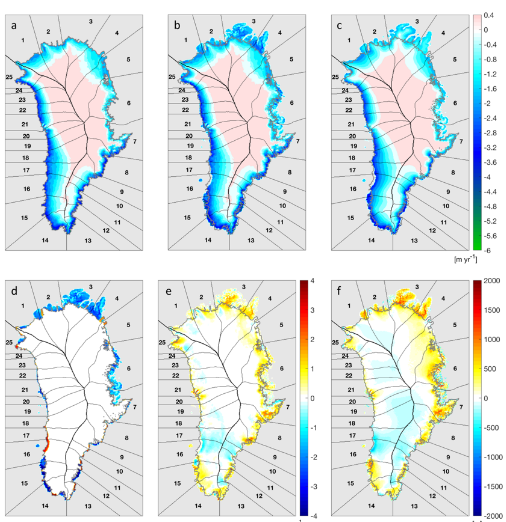
8b. In most cases, biases in the extended aSMB (blue) are reduced by the remapping, illustrated by bars of the same sign (yellow).

The biases are reduced but are not expected/supposed to be entirely removed by the remapping, because a physically larger ice sheet should have a larger accumulation and/or ablation areas. This also illustrates why the method is not designed to conserve mass when remapping to a different geometry: it demands a different SMB forcing. The improvement of the aSMB forcing by the remapping is mainly found in regions where the modelled ice sheet extends beyond the observed mask and where the remapped aSMB is predominantly higher than the extended aSMB (Figure 7e). Differences between original and remapped aSMB in the interior of the ice sheet (Figure 7e) indicate averaging in the remapping process as discussed before, but more importantly are due to differences in the modelled surface elevation compared to the observed. This illustrates a feature of the remapping method that can be interpreted both as an asset or as a shortcoming, namely that biases in surface elevation (Figure 7f) are propagated to the aSMB forcing.

For ice sheet models with initial states close to observations, the reconstructed aSMB looks very similar to the original, while for models with largely different geometry, the overall structure of decreasing aSMB towards lower elevation is well captured. A similar comparison as in Figure 7c and Figure 8a, for three other modelled geometries from the initMIP-Greenland ensemble is given in the supplement (Figure S3 and Figure S4).



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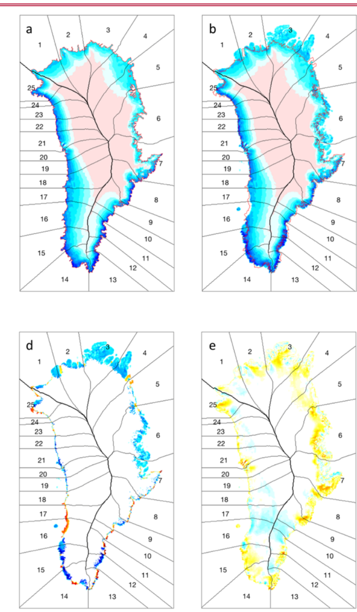

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Figure 7 (a) SMB anomaly from the RCM MAR (same as Figure 5a), (b) extended to the VUB_GISM initial geometry using the method of Franco at al. (2012), (c) remapped with weighting between neighbouring basins for the same geometry, (d) difference b-a, (e) difference (c)-(b) and (f) model bias in surface elevation. The grey lines mark the observed ice sheet margin.

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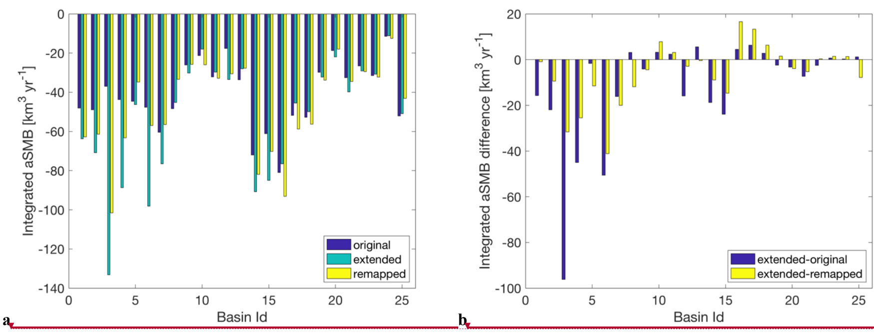

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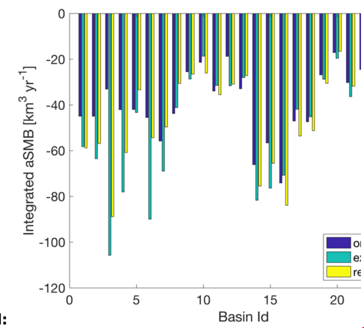

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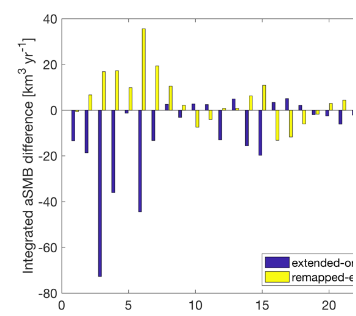

Figure 8 Remapping results for a model state far from the observed geometry. (a) Integrated aSMB per basin from MAR model output on the observed ice mask (blue), for extension of the VUB_GISM model ice mask (green) and remapped to the VUB_GISM model geometry (yellow). (b) Differences between extended and original aSMB (blue) and between extended and remapped aSMB (yellow).

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4 Time dependent forcing

The same method can be used to define elevation-aSMB lookup tables and calculate remapped aSMB for climate change scenarios, generating a time-dependent forcing. We have done this as a pilot application for MARv3.9 forced by MIROC5 (Watanabe et al. 2010) under scenario RCP8.5 (Figure 9) with available SMB data from 1950-2100 (Fettweis et al., 2013; Delhasse et al., 2019) computed for ISMIP6. We have calculated aSMB for the period 2015-2100 against a reference SMB as an average of the period 1960-1989. The resulting lookup tables (Figure 9) show the decrease in aSMB for the lower parts of each basin as expected.

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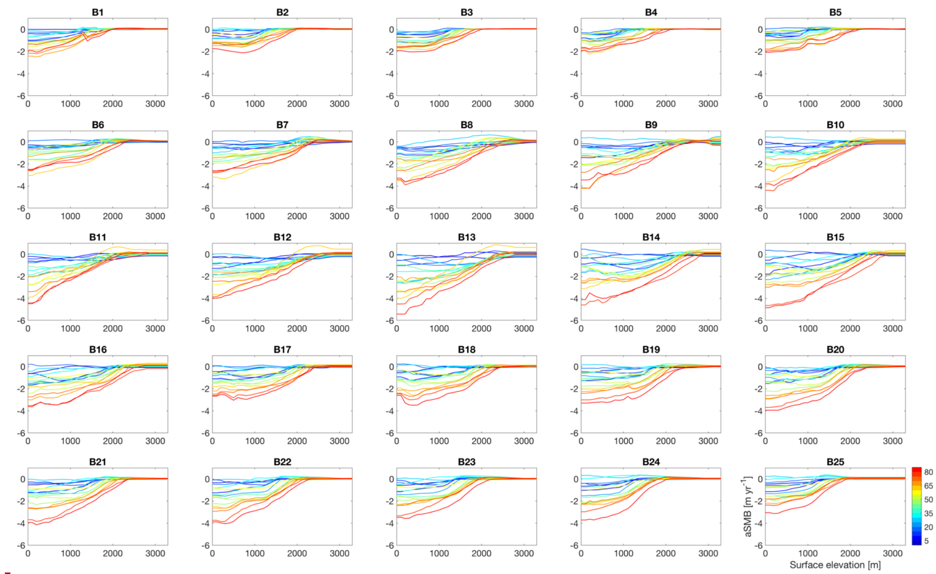
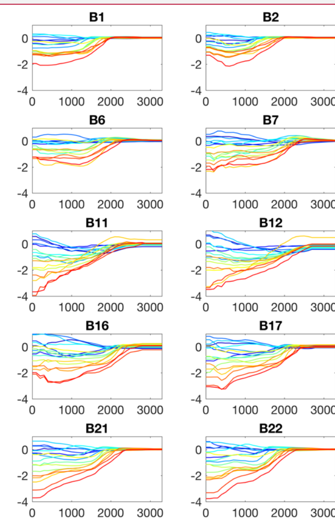


Figure 9 Elevation-aSMB lookup tables for climate change scenario MAR MIROC5 RCP8.5. Time is colour coded to indicate years since 2015 with lines given every 5 years until year 2100. The subfigure titles indicate the basins as defined in Figure 2.



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4.1 Future sea-level change projections

The initial goal of the proposed method was to apply it to future sea-level change projections with a large ensemble of ice sheet models (with possibly widely different initial geometries) and forced by output of different climate models and scenarios, e.g. in the framework of the ice sheet model intercomparison project ISMIP6 (Nowicki et al., 2016; 2020; Goelzer et al., 2020). For such applications, the basin separation can be defined and the lookup tables can be calculated for specific climate models and scenarios ahead of time. Basin separation and weighting functions can be calculated for each specific ice sheet grid in advance. To apply a specific forcing scenario, the information transmitted to an individual ice sheet modeller consists of aSMB values for L elevation bands for M basins at N time steps. When the initial ice sheet geometries are known in advance, the remapping can also be done offline and aSMB(x,y,t) can be distributed directly, avoiding the need to implement the remapping in each individual ice sheet model (see section 2.2).

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To test the feasibility of our method, we have applied it to a projection using only modelled and remapped aSMB to infer changes in ice sheet geometry. By ignoring any ice dynamic adjustment (i.e. no ice sheet model is used) and assuming the ice sheet to be in steady state with an unknown reference SMB, the time evolution of the ice sheet is fully determined by the initial geometry (surface elevation and mask) and the given aSMB. This setup does not consider any ice dynamic effects, such as the adjustment of ice flow to the SMB change itself and variations in marine terminating outlet glaciers. We emphasize that this experimental setup serves to illustrate the use of the remapping method and should not be interpreted as a full ice sheet projection including the dynamic response.

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We first compare two different representations of the cumulative (time-integrated) SMB anomaly as a measure of the spatially resolved ice thickness change at the end of the scenario.

1. The time-integrated original aSMB of the climate model, by definition at fixed surface elevation (MOD).
2. The time-integrated aSMB calculated by remapping to the same fixed surface elevation (MAP).

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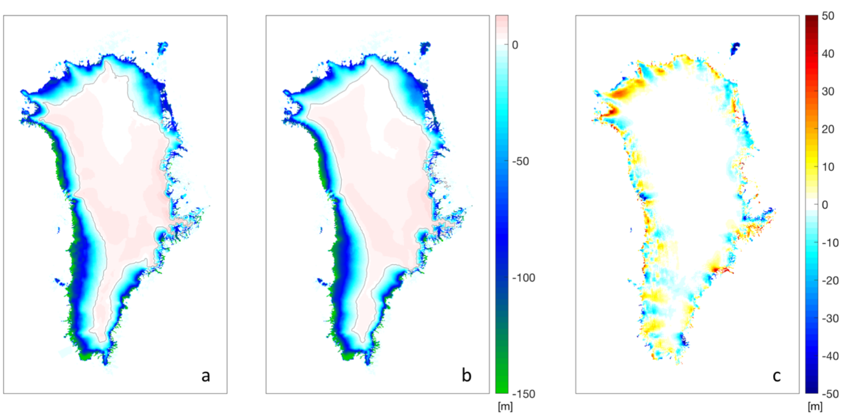
In both cases, the resulting thickness change for aSMB<0 is limited by the available ice thickness at each grid point.

The two cases MOD and MAP show similar results (Figure 10a,b), indicating that the remapping performs well to capture the general pattern of SMB change also in this time-dependent application. Direct comparison between MOD and MAP (Figure 10c) reveal limitations in the remapping, mainly arising from localised melt and precipitation anomalies that are not resolved with 25 basins or where the relationship between surface elevation and aSMB breaks down (see also Figure 5c). The difference map (Figure 10c) shows some along-flow features on a larger spatial scale, suggesting that further refinement of the regions could improve the representation.



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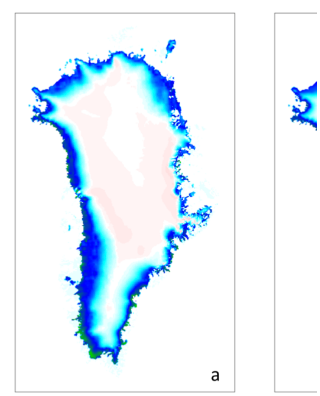

Figure 10 Time-integrated aSMB for MOD (a), MAP (b) and differences MAP-MOD (c), representing the error of the remapping. The zero line is given in (a) and (b) as a grey contour.

4.2 SMB-height feedback

In general the SMB anomaly that should be applied at any point on the evolving ice-sheet surface h depends both explicitly on time t, because the climate is changing, and implicitly on time, because the ice-sheet surface h(t) is changing. The aim of this sub-section is to derive a method, including both effects, for estimating the SMB anomaly from RCM output, and to determine how this method can be applied in an ensemble of ice sheet models. In all other parts of this paper we have used "aSMB" for the SMB anomaly both in the RCM and as applied to the ice-sheet model. In this section (and Appendix A) alone, where the distinction is crucial, we reserve "SMB" and "aSMB" for quantities on the RCM grid, while by "ASMB" we mean the SMB anomaly to be applied to the ice-sheet on its own surface h(t).

We denote the height by three symbols for different circumstances: $\overline{\mathrm{h}}$ for the SMB anomaly and other quantities calculated from the RCM output at a fixed surface elevation, $h_0 = \mathrm{h}(0)$ when remapping to the initial surface elevation that the ice-sheet has at $\mathrm{t} = 0$, and $\mathrm{h} = \mathrm{h}(\mathrm{t})$ when remapping to a time evolving geometry. The SMB anomaly in the RCM (at fixed surface elevation $\overline{\mathrm{h}}$) can then be expressed as $\mathrm{aSMB}(\mathrm{t}) = \mathrm{SMB}(\mathrm{t}) - \mathrm{SMB}(0)$.

In order to perform the remapping, we first need to estimate a 3D field (including height-dependence) from the 2D field (at $\overline{\mathrm{h}}$) given by the RCM. To do this, we need to estimate the local variation of SMB and aSMB with surface elevation i.e. $\mathrm{d(SMB(t))/dz}$ and $\mathrm{d(aSMB(t))/dz}$, respectively. The latter can be written as

$$\mathrm{d(aSMB(t))/dz} = \mathrm{d(SMB(t))/dz} - \mathrm{d(SMB(0))/dz}, \qquad (6)$$

where the term d(SMB)/dz(t) can be approximated from the RCM output, typically by analysing spatial SMB gradients in close proximity of the point of interest (Franco et al., 2012; Noël et al., 2016; Le clec'h et al., 2019), or by parameterising the effect (e.g. Edwards et al., 2014a,b; Goelzer et al, 2013). Here, we derive d(SMB)/dz(t) using MAR output (Franco et al., 2012).

The remapping of a time-dependent quantity X from the fixed RCM grid and fixed surface elevation $\overline{\mathrm{h}}$ to some other ice-sheet surface Z may be formally written as an operator $\mathrm{R}(\mathrm{X}(\mathrm{t}, \overline{\mathrm{h}}), \mathrm{Z})$. Since the RCM surface $\overline{\mathrm{h}}$, is fixed we will write the operator more simply as $\mathrm{R}(\mathrm{X}(\mathrm{t}), \mathrm{Z})$ in the following. With this notation, the quantity used in the test procedure of Section 4.1 is $\mathrm{R}(\mathrm{aSMB}(\mathrm{t}), \mathrm{h}_0)$, the time-evolving aSMB(t) remapped from the fixed RCM topography to the initial ice-sheet topography. This is *not* the SMB anomaly which should be applied to the time-evolving ice-sheet, because it includes only the climate-dependence of aSMB (its explicit dependence on time), and omits the effect of changing surface elevation (the implicit dependence on time via h(t)).

At first sight it may be surprising that the elevation effect is still *not* properly taken into account by the time-evolving aSMB(t) remapped to the evolving h(t), $\mathrm{R}(\mathrm{aSMB}(\mathrm{t}), \mathrm{h}(\mathrm{t}))$. This quantity involves a dependence on the modelled elevation change $\mathrm{dh}(\mathrm{t}) = \mathrm{h}(\mathrm{t}) - h_0$, and can be approximated as

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$$R(\mathrm{aSMB}(t), h) \approx R(\mathrm{aSMB}(t), h_0) + R(d(\mathrm{aSMB}(t))/dz, h_0) * dh(t). \quad (7)$$

By using (6), we get

$$R(\mathrm{aSMB}(t), h) \approx R(\mathrm{aSMB}(t), h_0) + [R(d(\mathrm{SMB}(t))/dz, h_0) - R(d(\mathrm{SMB}(0))/dz, h_0)] * dh(t) \quad (8)$$

(shown in **Figure 11**c). This quantity however includes only the elevation-dependence of the time-dependence of aSMB, which is a second-order effect, and it omits the first-order effect of the height feedback on SMB.

To preserve the full effect of elevation change on SMB, the quantity ASMB(h,t) that we need is the anomaly in remapped SMB, rather than the remapped SMB anomaly $R(\mathrm{aSMB}(t), h(t))$. The desired quantity is:

$$\mathrm{ASMB}(t, h) \equiv R(\mathrm{SMB}(t), h) - R(\mathrm{SMB}(0), h_0) \quad (9)$$

$$\approx R(\mathrm{SMB}(t), h_0) - R(\mathrm{SMB}(0), h_0) + R(\mathrm{SMB}(t), h) - R(\mathrm{SMB}(t), h_0)$$

$$\mathrm{ASMB}(t, h) \approx R(\mathrm{aSMB}(t), h_0) + R(d(\mathrm{SMB}(t))/dz, h_0) * dh(t). \quad (10)$$

Comparing (8) and (10), we can appreciate that (8) is incomplete because the first term in square brackets, which also appears in (10), is mostly cancelled by the second term in square brackets; indeed, if the vertical gradient of SMB is the same in the two climates, there is no effect of elevation change in (8).

To enable the calculation of (10) in ISMIP6, we remap the time-dependent $\mathrm{aSMB}(t, \bar{h})$ and $d(\mathrm{SMB}(t, \bar{h}))/dz$ to the initial ice-sheet topography h_0.

We have chosen this approach because the remapping can be done offline for a given initial ice sheet geometry. The format of data to be exchanged for an ensemble projection is then the same with and without remapping: the modeller receives time-dependent R(aSMB(x,y,t),h_0) and R(d(SMB)/dz(x,y,t),h_0) and has to implement a mechanism to calculate the additional term due to elevation change from the latter. An alternative online formulation, where the remapping would have to be implemented in each ice sheet model is given in Appendix A.

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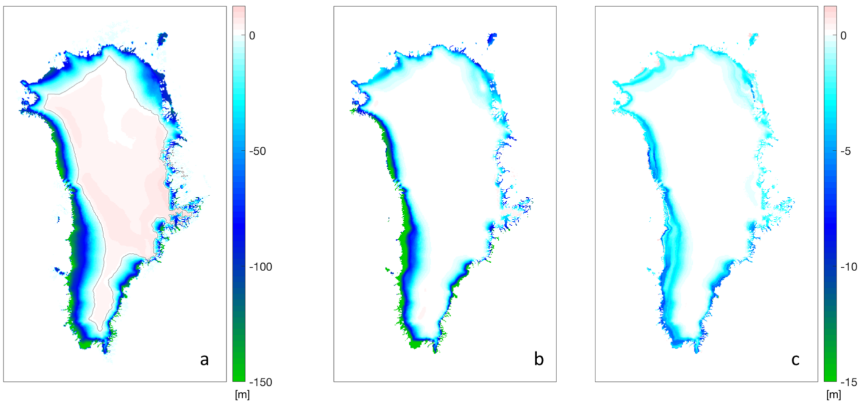

Figure 11 Total elevation change 2015-2100 due to local time-integration of aSMB with remapping to the evolving geometry (a), elevation change due to d(SMB)/dz(t) (b) and due to remapping only (c). The zero line in a is given as grey contour. Note the different colour scale in (b) and (c) compared to (a).

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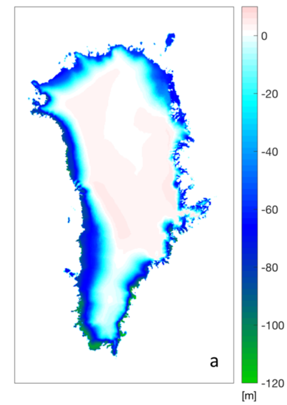


4.3 Application to a large ice sheet model ensemble

To illustrate the use of the proposed method (Eq. 10) for a larger group of models, we have applied the transient aSMB calculation for the modelled initial states of the initMIP-Greenland ensemble (Goelzer et al., 2018a). We use the publicly available output of the initial model states, which are provided on a common diagnostic grid (Goelzer et al., 2018b). The time-dependent aSMB of MIROC5-forced MAR (RCP8.5) is remapped to the surface elevation of the initial state of each model. The geometry is then propagated (similar to section 4.1) over the period 2015-2100 as a function of the applied SMB anomaly (no ice sheet model is used), taking the height-SMB feedback into account as described in the last section. The resulting sea-level contribution (Figure 12a) is calculated by time-integration of the aSMB assuming an ocean surface area of 361.8×10^6 km^2 (Charette and Smith, 2010) and an ice density of 917 kg m^{-3}. Differences between models are due to differences in (initial) ice sheet extent and surface elevation. We compare this result to a control experiment, with surface elevation changes considered as above, but here the original MAR aSMB is applied without remapping (Figure 12b).

Comparison between the two cases shows that (unphysical) biases in the estimated sea-level contribution are considerably reduced, especially for the models that show a too large initial ice sheet extent and consequently a too large sea-level contribution. However, some (physical) biases remain as expected, e.g. because a larger ice sheet has a larger ablation area.

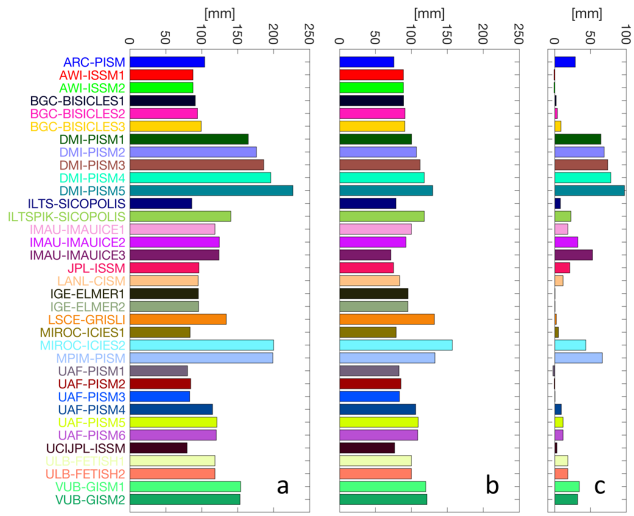
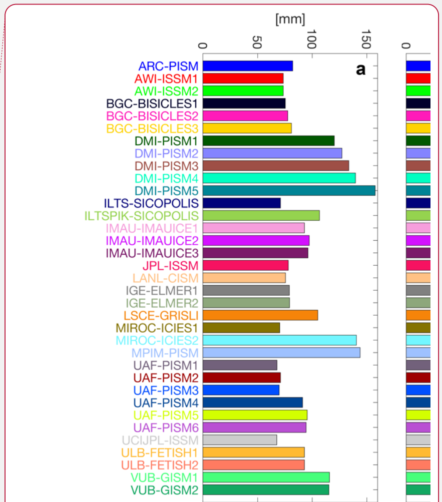


Figure 12 Sea-level contribution in 2100 derived by integrating a transient aSMB over the initial ice mask of each initMIP-Greenland model, (a) without remapping, but extension to the modelled ice sheet extent, (b) with remapping to the initial surface elevation of each individual model and (c) difference (a)–(b).



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5 Discussion and conclusions

The described method allows application of SMB anomaly forcing for a large range of different ice sheet models and addresses problems arising from differences in initial ice sheet geometry. Remapping to the same geometry closely reproduces the original aSMB, while remapping to other, modelled geometries shows patterns similar to the original, with smooth and continuous aSMB across basin divides. This shows that the method is indeed suited to record and remap the aSMB for a wide range of ice sheet geometries, while retaining the physical patterns originally represented by the data.

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Because the method produces a physically motivated aSMB forcing for a given ice sheet geometry, it also propagates biases in surface elevation to the SMB. This implies that for a given ice sheet geometry, biases due to a different ice sheet mask or due to elevation differences have to be accepted. In cases where the ice sheet mask is quite well matched, it may be preferred to apply aSMB without remapping to prevent propagation of small biases in surface elevation to the SMB forcing. In the initMIP-Greenland ensemble as a whole, biases due to differences in ice sheet mask were dominant, but this is not necessarily the case for each individual model. Therefore, we propose to evaluate the magnitude of the implied aSMB biases in offline calculations to decide whether remapping should be applied or not. This 'diagnostic mode' of the method can also be

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envisioned for other applications, such as quantifying unphysical model biases for coupled and standalone ice sheet simulations.

The main difference between our method and existing approaches of transforming the SMB to a different geometry (Franco et al., 2012; Helsen et al., 2013) is the non-locality of the remapping process, which may be described as its key feature. Like Helsen et al., (2013) and Franco et al., (2012), we assume a linear relationship between elevation and SMB for a given time and location, but that relationship is not geographically uniform or constant in time. This means, however, that the original aSMB field is not exactly reproduced when the remapping is applied to an ice sheet with identical surface elevation, at least not for the basin delineation currently used. However, in the limit of reducing the width of the basins to individual flowlines, the reproduction of the aSMB at the original geometry should converge to the original field. Using a basin separation based on flow-lines is preferable, because they mostly follow the surface elevation gradient so the aSMB can be sampled in a continuous method that largely maintains the spatial structure. While this would increase the number of parameters that have to be fitted for each individual model geometry, it would also allow further improvement of the aSMB representation. We have based our delineation on an existing basin separation, but considerable handwork is required as long as automatic methods to generate meaningful basin separations of chosen detail for a complex geometry and flow like the GrIS are unavailable. We have tested the performance of the method for a schematic set of basins that can be more easily extended, albeit not following observed basin divides.

The ice sheet integrated mass anomaly is not conserved when remapping to a different geometry, given that a different geometry demands a different SMB forcing. It would in principle be possible to impose mass conservation on the ice sheet or even on the basin scale by comparing spatial averages of the original and remapped forcing and subtracting the difference. This would lead, however, to a spatial shift of regions where positive and negative anomalies are applied and, in the latter case, to discontinuities between neighbouring basins. Similar problems would arise for rescaling of aSMB.

We have shown how to apply the method for different ice sheet geometries, but so far have circumvented the problem of different model grids. While for ISMIP6 we have chosen to interpolate the already remapped aSMB to the native ice sheet model grids, the method could also be applied directly after interpolating the basin division and weighting to the individual ice sheet model grid. If the remapping were to be implemented in the ice sheet model itself, it could even be applied for adaptive grids that change over time.

On the input side, aSMB is provided in the present application at 5 km resolution, which was statistically downscaled from the regional climate model MAR run at 15 km. A similar grid resolution of the input data set should be envisioned when the aSMB comes instead from a coarse resolution GCM, because sufficient grid resolution is required to derive the lookup table for a chosen number of elevation bands. However, since remapping with a lookup table locally acts as a spatial linear

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interpolator over the observed ice sheet, it propagates shortcomings of the input data set. The limiting factor for applying remapping to aSMB derived from GCMs or other coarse resolution models lies therefore in the quality of the original aSMB itself, rather than in technical aspects of the remapping.

The remapping is illustrated here with MAR v3.9 forced by MIROC5 as one of the data sets used in ISMIP6 projections (Goelzer et al., 2020). We have successfully applied the remapping also to output of the same MAR model forced by 5 other CMIP5 GCMs and 4 CMIP6 GCMs, and to output from an older MAR model version forced by 4 different GCMs. We therefore consider the remapping to be robust for a number of different forcing products.

6 Appendix A: Alternative formulation for the SMB-height feedback

An alternative method of calculating the dependence of ASMB on surface elevation (section 4.2) is described in the following. We can replace equations 9 and 10 by writing

$$\mathrm{ASMB}(t,h) \equiv \mathrm{R}(\mathrm{SMB}(t),h) - \mathrm{R}(\mathrm{SMB}(0),h_0) \qquad (11)$$

$$= \mathrm{R}(\mathrm{SMB}(t),h) - \mathrm{R}(\mathrm{SMB}(0),h) + \mathrm{R}(\mathrm{SMB}(0),h) - \mathrm{R}(\mathrm{SMB}(0),h_0)$$

$$\mathrm{ASMB}(t,h) \approx \mathrm{R}(\mathrm{aSMB}(t),h) + \mathrm{R}(d(\mathrm{SMB}(0))/dz, h_0) * dh(t). \qquad (12)$$

To calculate (12), we would have to remap the time-dependent $\mathrm{aSMB}(t,\bar{h})$ and the initial $d(\mathrm{SMB}(0))/dz$ to the time-evolving ice-sheet topography h. This implies that the remapping has to be implemented in the ice sheet model so that the lookup tables for both quantities can be applied online, in function of the changing geometry. From a practical point of view, the option described in the main text (remap to a fixed initial elevation and apply d(SMB)/dz(t), Eq.(10)) is much easier to achieve and has been chosen for the ISMIP6 projections (Nowicki et al., 2016; 2020; Goelzer et al., 2020). We have implemented and compared both methods in one ice sheet model and find nearly identical results for both of them.

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Code availability. The scripts used for remapping, analysis and plotting are available at https://github.com/hgoelzer/aSMB-remapping and will be saved in a publicly available archive on zenodo upon publication.

Data availability. The basin delineation and data sets used in this study are available during production at https://surfdrive.surf.nl/files/index.php/s/8nD5b2mMvG93sj1 and will be made publicly available on zenodo upon publication. The MAR based outputs for ISMIP6 are available at ftp://climato.be/fettweis/MARv3.9/ISMIP6. The initMIP ice sheet geometries are available at https://doi.org/10.5281/zenodo.1173088.

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Author contribution. HG conceived the study and developed the remapping method in discussion with the other authors. HG wrote the manuscript with assistance of the other authors.

Competing interests. Xavier Fettweis is a member of the editorial board of the journal.

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