Dear Editor, dear Reviewers,

the authors wish to thank both reviewers for the detailed review containing many helpful remarks and constructive criticism! We do appreciate very much the time spent on getting down to the study. Before answering the points raised by both reviewers, we want to inform that we have detected an application error when calculating the SMB with SEMIC. This has a significant effect on the results, for instance the SLE contribution (Figure 1).



Figure 1: Sea level equivalent until the year 2100 (left panel) and 2300 (right panel) for all GCMs. Additionally, the control run and the mean of all GCMs are shown. The right panel shows additionally the mean and standard deviation at the year 2100 and 2300 by Fürst et al. (2015).

Beside the updated results (which are now fit better to observations and previous studies) and the corresponding changes to the text, we have performed the following major changes - that are all also documented below in detail:

- As both reviewers suggested re-structuring the manuscript, the material in the revised manuscript is presented as follows:
 - 1. Introduction
 - 2. Model description
 - 2.1 SEMIC
 - 2.2 Ice flow model
 - 3. Results
 - 3.1 Forcing fields
 - 3.2 Present day state
 - 3.3 Projections
 - 4. Discussion
 - 5. Conclusion
- We have improved the control run (see Figure 1).
- SEMIC and the calculation of the SMB are explained in more detail and became more prominent in the manuscript.
- Although the point was not raised by the reviewers, we will focus more on "The effect of overshooting 1.5°C" as mentioned in the title

Technicalities: below we answer each point raised by the reviewers and mark our answer in blue color. Point raised by both reviewers are answered at one location and referenced at the second one. 'Done.' denotes that this point would be solved in the revised version of the manuscript. This could be that it will be either done directly, or that due to other changes the point does not arise any more, or that the point has been answered at another place in this text already.

Reviewer #1

- Summary -

The response of the Greenland ice sheet (GrIS) to a RCP2.6 global warming scenario is studied with an ice sheet model forced by a combination of climate models. The output from existing Global Coupled Climate Model (GCM) simulations is further processed with a surface energy balance model of intermediate complexity to generate surface mass balance and temperature forcing for the ice sheet model. While a feasible two-way coupling strategy between GCMs and ice sheet models remains unavailable, this study applies anomaly forcing and a number of corrections to estimate the future sea-level contribution from the GrIS. The full potential of the high-resolution, higher-order ice sheet model is not realised due to a lack of important forcing mechanisms (ocean) and a rather crude climate forcing. This leaves the application of the surface energy balance model of intermediate complexity as the main novelty compared to state of the art projections. Nevertheless, this component has not been treated with sufficient detail and its output requires more analysis and a better comparison with observations. The description of the experimental setup and processing of the forcing data is not always easy to follow and also needs more precision. I therefore suggest major revisions along the lines of my comments given below.

- General comments -

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The SMB forcing is clearly the most important ingredient for this type of projection, in particular since the study does not consider any oceanic forcing. Consequently, more effort has to go into understanding and discussing the SMB product resulting from a chain of different models and processes. What is missing entirely is a (spatially resolved) validation of the used SMB forcing compared to observations and other modelling results.

Yes, indeed this is an important point and we followed the reviewers suggestion. With using the parameters of Krapp et al. (2017) the direct output of the SMB from SEMIC has a misfit of about ~2m/a and a correlation of ~ r^2 =0.5 by comparing SMB_RACMO_1960-1990 and SMB_SEMIC_1960-1990 (almost similar for all GCMs used). However, recalling Equation 3 and 4 from the manuscript,

$$SMB(x, y, t) = \overline{SMB}_{RACMO}^{(1900-1990)}(x, y) + \Delta SMB(x, y, t) + SMB_{corr}(x, y, t),$$
(3)

(4)

$$\Delta \text{SMB}(x, y, t) = \text{SMB}_{\text{SEMIC}}(x, y, t) - \overline{\text{SMB}}_{\text{SEMIC}}^{(1960-1990)}(x, y),$$

we do not use the direct output of SEMIC, but apply anomalies computed using SEMIC. The benefit of our approach is, that only the GCM trends of SMB changes are added to the RACMO SMB reference field, which represents the real SMB distribution very well. If we compare the computed SMB to RACMO (according to Eq. 3 and 4 without the synthetic SMB_{corr}), for instance for the HadGEM2-ES year 1990, it shows a very good agreement (Figure 2). See also answer to specific comment "p10 I2" below. In the revised manuscript we dedicate an own section to this issue.



Figure 2: (left panel) surface mass balance of RACMO2.3 (Noel et al., 2016) for the year 1990; (middle panel) surface mass balance for HadGEM2-ES for the year 1990 according to Eq. 3 and 4 in the manuscript (without SMB_{corr}); (right panel) scatter plot of both fields.

The modelling approach of using the intermediate complexity model SEMIC to calculate SMB based on GCM input for projections of the GrIS sea-level contribution is one of the new and interesting aspects of this study and should receive much more attention. SEMIC is treated in the description and analysis practically as a black-box element, but should instead have a much more prominent place. The key question this study should be in the position to answer is if and why SEMIC is an improvement to, or similarly suited as other methods that are used to produce SMB forcing based on GCM output. The current alternatives include e.g. regional climate models (which are hardly mentioned in the manuscript) and models based on the positive-degree-day method.

We expand the section about the SEMIC model in order to give the reader a better understanding of the model. In the new version of the manuscript we also review in the introduction section briefly the already existing alternatives used and relate the discussion section accordingly. The reason we have not included too much detail on that issue previously is, that we basically apply SEMIC and that the model in itself and all the parameter tuning is work done by Krapp et al., 2017. The advantage of using a semi-complexity model is indeed its simplicity and cost efficiency, which would allow ice sheet modellers to also run computation up to time scales of thousands of years (e.g. until 5000) studying long-term commitment of various emission scenarios and hence not be limited by the availability of regional climate model output. However, regional climate models having the clear benefit for representing snow and firn layers with all melt and refreezing processes by far more realistic than any semi-complexity model will ever do. For the future, we plan a study on comparing the difference in ice sheet model response to three different types of forcings, PDD, SEMIC and a regional climate model forcing.

The authors rely on the parameter settings of the SEMIC model, which have been optimised for a different climate model input (Krapp et al., 2017). The Krapp et al. study shows that the SEMIC model can well approximate the MAR SMB results given MAR climate input. It must however be expected that the parameters that were chosen for a completely different climate input (different model, RCM vs GCM) are not optimal. Unless evidence can be provided that the applied parameters are indeed suited for the GCM forcing used in the present study, the model parameters should be optimised. Discussion on differences to other results (e.g. as done compared to Fürst et al., 2015) hinges on the implied sensitivity of the SMB model, which is currently not possible to be judged.

We haven chosen the same parameters of SEMIC as Krapp et al., 2017, due to the following reason: the parameter tuning procedure performed by Krapp et al., 2017 aimed to find a parameter set which gives a best fit between SMB and skin temperature T_s of SEMIC with only a limited number of processes and simpler parameterisations than a regional climate model with full complexity would derive. As a regional climate model is typically validated against reanalysis data and observations, the best match between SMB and T_s of SEMIC and regional climate model (in that case MAR) is the best way to represent the processes and their parameters in SEMIC. We see it thus as a tuning of the parameterisation of the processes. Once the process description in SEMIC is optimised, any type of input, either GCM or reanalysis data fields, will lead to the best possible SMB and T_s fields that SEMIC can produce. Still, the GCM will lack the best atmospheric fields over the ice sheet, as it is limited in resolution compared to a regional climate model. Given experiences we made from these three GCMs used in this study, which are all have different drawbacks, which would mean to have a tuning for each of them and this tuning would then make the whole benefit of having a semi-complexity model with low costs meaningless. Furthermore, it would basically mean to compensate far too low near surface temperatures with SEMIC parameters, which would offset the whole comparison of GCM forcing. Therefore, we have chosen a different approach: we compensate for this by using the SEMIC output only as an anomaly.

Modelling decisions, in particular those concerning the chain of processing used to arrive at the SMB and temperature forcing have to be better explained and motivated. In the current manuscript, some of the modelling choices appear arbitrary and it is not clear if they are optimal, possible to improve or just used in absence of better options.

We can understand this and follow the reviewer's recommendation and try to describe the processing of SMB and Temperature product better in the revised manuscript.

The organisation of the material in the manuscript is not optimal and could profit from a reorganisation. To name just a few examples, some aspects belonging to model setup and initialisation appear too late in the text, while some results first appear in the conclusions after they have already been discussed. The ice sheet model is introduced first (2.1), while it is the much less important component for the projection compared to the SMB forcing. See also specific comments below.

We do not agree that an ice model is much less important for the projection compared to the SMB forcing. In order do estimate the SL contribution from the ice sheets an appropriate ice flow model (resolution, ice dynamics (and response), grounding line migration, etc.) is necessary. The main novelty in this study is from our point of view, the derivation of an appropriate initial state, which is also stressed in Goelzer et al. (2018) and given that our way to derive an initial state became a recommendation from a community benchmark experiment, this is indeed clearly the benefit of the study presented here. However, as about 50% of the current mass loss of Greenland is due to changes in SMB and, as the reviewer claims that the SEMIC is the main novelty of this study, we will follow the recommendation and first introduce the SMB forcing and describe the ice flow model afterwards. We agree that some information was not placed optimal in the manuscript and we will follow the concerning specific points raised by the reviewer below. We will also provide a separate discussion section on this issue in the revised manuscript.

There may be a problem with the thermodynamic model used to spin up the temperature as presented in Table 2. I suggest to thoroughly check and verify that aspect of the modelling. We can proof that the thermodynamic model is correct as the numerical code is verified against analytical solution (Kleiner et al., 2015). Furthermore, the application to Jakobshavn Isbræ gives reasonable results for the thermodynamic model (Bondzio et al., 2017). There, the simulated temperatures show a good match to measured temperature profiles at the fast flowing area of the ice stream.

From our point of view the selected scenario (p-cl, Gr) as initial state for the projections from our sensitivity study shows a reasonable match to the observations, given the lack of knowledge of the geothermal heat flux, which affects any type of ice sheet modelling of Greenland independent of atmospheric forcing. At least the GRIP location with T_{sim} of -18°C is too cold (T_{obs} =-8°C). Due to the fact, that the applied inversion technique for the friction coefficient allows sliding everywhere, the portion of deformational shearing may be under estimated, which cannot be proven without any observations of basal velocities that are unfortunately not existing at all. However, for our projections on centennial timescales this is a negligible effect.

The manuscript is so far rather short and could easily accommodate additional material that would be required to respond to the issues raised above and below. We agree and provide additional material.

- Specific comments -

p1 I6 Not clear why a threshold of 1.5C is relevant when calculated regionally for Greenland. To start with, the global threshold of 1.5 is a political target and is not directly related to a real threshold in the climate system. Locally, a 1.5 degree warming has no specific meaning at all. Instead of referencing the years when 1.5 warming is reached in the GCMs, we refer to the different warming trends in the GCMs.

Over which area is the Greenland wide average calculated?

We have used the ice sheet mask provided by the BedMachine dataset (Morlighem et al., 2014).

p1 I8 How is plausibility of the future forcing assessed? This has to be made clearer and the wording should be changed accordingly.

You are right. Our "plausibility-check" is very subjective. In the section "Forcing fields" lines 1-15 we discuss the forcing fields, in particular, the temperature distribution and its change over time. From our point of view the temperature field should reveal a higher warming in the North (polar/arctic amplification) and overshoot the mean global warming value. Both aspects are only fulfilled for HadGEM2-ES. The plausible DSMB pattern (p9 l28) is a consequence from the temperature. We take care of this in the new version of the manuscript.

p1 114 It is not well documented what the reason for the loss of floating ice tongues really is. In the absence of ocean forcing this should be explained by interaction with the SMB. Or are part these changes related to the unforced response of the ice sheet model? In the new simulations not all floating tongues are lost. We will explore this in more detail.

p1 I14 What values? Greenland sea-level contribution? Elevation changes? Clarify See next comment.

p1 114 A lower bound of what? The actual future sea-level contribution of Greenland? The contribution under forcing scenario RCP2.6? I think you cannot make a meaningful statement about a lower bound based on the results of this study. There is a combination of missing important processes (ocean forcing) and uncertainties about the climate forcing (intrinsic and not properly studied) that make a quantitive statement very hard to justify.

The sentence is rewritten to: "The sea-level contribution estimated in this study may serve as a lower bound for RCP2.6 scenario, as processes proven to play a major role in GrIS mass loss are not yet represented by the model."

Regarding the missing processes: It has been shown by the SeaRISE effort (Bindschadler et al., 2013) that increased oceanic melting and increased sliding will lead to a further mass loss of the GrIS. Both aspects are very likely within a warming climate. Therefore, we assume that our values are a lower bound.

About the uncertainties in climate forcing, we hope to convince the reviewer with the new version of the manuscript that contains additional material.

p1 I19 Repeated "past decade". Compare also "past decades" in I21. More precision needed. Done.

p1 I22 Remove "Obviously" Done.

p2 I2 To asses *all* "the impacts of global warming of 1.5C ..." is a huge aim. Be more specific about the aims of this study in particular. We delete "aim of this study here" and moved it to the end of the section "introduction".

p2 I3 RCPs were not designed for a specific warming level. Reformulate. Done.

p2 I5 "are not passing the limit". Which limit, be more precise. Done. "Limit of $1.5^{\circ}C$ or $2^{\circ}C$ " is added.

p2 I6 Remove "potential". If the effect is return to below the threshold, it is an actual overshoot.

Done.

p2 l9 Repeated "response" Done, first appearance is deleted.

p2 I9 Maybe "GCM" is better than "atmospheric model" here. Yes, you are right. Atmospheric model is replaced with GCM.

P2 I10 Maybe "surface mass balance changes". Done.

P2 I12 Replace "uncoupled" by "one-way coupled". Done.

p2 I13 The causality in this sentence is not clear. What does higher-order physics have to do with corrections of atmospheric forcing? Done. The sentence is partly removed.

p2 I16 "the low computation cost" Done.

p2 I17 Why is high resolution a requirement for higher-order physics?

Compared to Shallow Ice Approximation the higher-order physics include transversal and longitudinal stress gradients. If the resolution is low, the gradients in the geometry are decreasing and therefore the influence of these stress gradients. In order to resolve the geometry and the stress gradients a high resolution is needed.

We have not discussed that in the text so far, as this is well known in ice modelling, however, we can include a paragraph on that on editor request.

Also, for this study, representing the SMB forcing accurately should be the most important aspect where computational resources should be directed to. Done.

p2 I19 "anomalies *of*" Done.

p2 l21 More precision needed to replace "obtain these anomalies from the GCM" Done. We have rewritten the "Aim of the study" at the end of the Introduction (see also comment to p2 l2).

p2 l24 Consider describing the ice sheet model later since it is the least important component in this study. See comment to major point above.

p2 l25 I suggest a less technical description here, e.g. "Ice flow and thermodynamic evolution of the GrIS are approximated" Done.

p2 l28 It is not the elements themselves (as in finite elements) that have these characteristics (SIA to FS). Reformulate. Which approximation is finally used? The sentence is rewritten and we give a reference to the Blatter-Pattyn approximation.

p3 I1 The reader does not necessarily know what "the balance equations" refers to. We drop "balance equations" here.

p3 I5 Better to describe how basal melt rates are calculated before saying that they are held constant during the experiment. Done.

p3 I7 "Under grounded ice" Done.

p3 I7 Melting is not *due to* frictional heating. Frictional heating and geothermal heat flux warm the ice that may eventually melt. More precision needed.

Only geothermal heating and internal deformation warms the ice. Once the ice temperature at the base reaches the pressure melting point sliding occurs and with that melting takes place. The boundary condition is switched from a Neumann-type to Dirichlet-type condition and all excessive energy is used for melting. According to Aschwanden et al. (2013) melting a_b is defined as:

 $a_b = F_b - (q - q_{geo}) n_b / (L^* rho_i),$

where F_b is the frictional heating, q the heat flux into the ice and q_{geo} the geothermal flux entering the ice at the base (n_b is normal vector, L is latent heat and rho_i the density of ice). Once the pressure melting point is reached frictional heating and geothermal flux is only used for melting. However, we rewrite the sentence to: "Once the pressure melting point at the grounded ice is reached melting is calculated from basal frictional heating and the difference in heat flux at the ice/bed interface."

p3 23 "shearing" Done.

p3 26 Remove "fields". Done.

p4 I1 Replace "or" by "and". Done.

p4 I1 "All methods are suitable ...". I don't think this represents the conclusions of the study very well. There are clearly methods that are more suitable than others and a combination between different methods may be needed, is how I would put it. We replace "suitable" with "required".

p4 I5 What exactly is initialized over 50 years? Is the geometry relaxed? What constant temperature is used? Be more precise in your description. The aim should be to make the model setup reproducible for other modellers.

Yes, "initialized" should be replaced by "relaxed". We update the description of the initial state by giving more details.

p4 I7 Why is the spinup done to 1960, and the reference period 1960-1990. Motivation needed.

The spin-up is done to 1960 in order to start the projections before the tipping point of GrIS mass balance (Noel et al., 2017). The reference period 1960-1990 is chosen as we assume the ice sheet close to steady state in this period.

p4 I7 "basal-friction inversion" requires some additional description and references to place what is meant here in the context of state of the art techniques. What is inverted for and by optimisation of what precisely?

We add: "The inversion approach infers the basal friction coefficient k^2 in Eq. 1 by minimizing a cost function that measures the misfit between observed and modelled horizontal velocities (Morlighem et al., 2010)."

p4 I9 "mesh refinements are made at certain points during the initialization ..." Done.

p4 I10 Explain better the sequence of runs. Is the forcing over 125 kyr repeated several times? The number of years add up to 290 kyr, but the forcing is supposedly only for 125 kyr. We rewrite this paragraph to better explain our spin-up strategy. To make it clear the spin-up is only run over 125kyr before present. The mesh sequences just repeat a certain period of the spin-up by subsequently refining the mesh.

p4 I20 What precisely is taken, thickness and bedrock data? Bedrock and thickness is taken from BedMachine Greenland. We added that to the text.

Removes "bed from". Add "data set" after "BedMachine Greenland" Done.

p4 I21 This belongs to the description of basal-friction inversion that should be added in the section before.

Done.

p4 I23 Add "spatially constant" before "surface temperature anomaly". Describe better what "based on" means. Supposedly the present day RACMO temperature is offset by a spatially constant temperature anomaly? Done.

p5 I4-7 Reformulate this sentence, too long. Done.

p5 I10 Motivate the choice of models. Why these three GCMs?

We add a motivation for the selection of the three GCMs: "We have selected GCMs which covering the CMIP5 historical scenario, the RCP2.6 scenario until 2300 and reveal an overshoot in annual global mean near-surface temperature change relative to pre-industrial levels (1661-1860)."

p5 I14 Specify the reference period against which the change is calculated. We add that the reference period is the pre-industrial level from 1661–1860.

p5 I19 Could give a more specific reference here, i.e. a specific IPCC chapter. Done.

p6 I2 Why would polar amplification only have consequences in extreme years? Or does it have an impact on the amount of extreme years? Clarify.

We rephrased this, as we did not intend to make any statement on the amount of extreme years, nor on the amplification having only consequences in extreme years. We intended to say that the interannual variability is larger if looking at temperature time series over Greenland compared to global average.

p6 I2 Add reference to figure 2 at end of sentence. Done.

p6 I3 Add "amplification" after similar. Done.

p6 I4 Polar amplification is not the same as Greenland amplification. Consider and discuss the difference and similarities if any.

We switched the wording to the terminology Arctic amplification.

p6 I7 "A striking feature" in which model? All models show the higher variability. Compare Figure 1a and b in the manuscript.

p6 I9 "lower bound" and "upper bound" is the wrong wording for this case. Use "the highest" and "the lowest forcing" or similar. Done.

p6 I11 "might be different across the GrIS". Why "might", you have the data to check that and make an informed statement. Done.

p6 I13 How does a model "best" represent overshooting. Either temperature overshoots or it doesn't. Reformulate. Done.

p6 I15 Specify what you mean by "ice sheet specific quantities". Done.

p6 115 It would be useful to describe the SEMIC model in coarse lines here, since it is an important ingredient to the simulations. In my opinion it represents one of the interesting new aspects in the presented simulations. Based on this description you should judge the advantages and shortcomings of this approach and compare it to other used methods like positive-degree-day models, RCMs and other intermediate complexity models (e.g. REMBO, Robinson et al., 2010).

See answer to major points above.

p6 118 As mentioned before, SEMIC has been tuned to reproduce MAR SMB given MAR climate forcing. It cannot be expected that the model tuning translates to another model like the GCMs used here. The ultimate test is if the SMB produced for the recent past compares well against observations. This should be shown for the three GCM models and eventually it requires returning of SEMIC for that purpose. See answer to major points above.

See answer to major points above.

p6 118 Not clear what the shortcomings of the Krapp method to treat albedo were and neither how this has been improved for the present study. This requires some additional description. Extending on the last comment, changes to the albedo scheme likely also have an impact on the SMB and would lead to different tuning even for the same climate model input.

We agree with the reviewer. We expand the section about the SEMIC model. In order to be consistent with parameters provided by Krapp et al. (2017) we switched back to the albedo scheme used by Krapp et al. (2017) for the new simulations.

p6 I24 Motivate why this two-step procedure is necessary.

Usually this two-step procedure is not necessary. One would interpolate the GCM data from the original 1° grid directly to finite element grid of ISSM. Without going into the details, it is technically the easiest way. However, for future applications we are aim to avoid the intermediate interpolation. We add a sentence to the revised version of the manuscript.

p6 I28 Add "(.)" after "quantities". Done.

p6 I30 In my understanding hs^ISSM-pd should be replaced by hs^SEMIC-pd. Or are they both considered the same? Please clarify.

In general hs^ISSM-pd and hs^SEMIC-pd at the initial state are the same. However, to be more precise we change hs^ISSM to hs^SEMIC.

p6 I31 What (and when) exactly is the present-day surface elevation referred to here? In the revised version of the manuscript we make a clear distinction between initial state (1960; end of spin-up) and present day (~2000).

p7 l4 The following three paragraphs are only remotely related to the atmospheric forcing and would fit much better with 2.2 about the initial state of the ice sheet model. Done. As mentioned above, we restructure the revised manuscript.

p7 I5 This is confusing. Before ISSM is run forward in time, wouldn't it have exactly the geometry that you have prescribed? A good match with the observed geometry is therefore not a result. Reformulate?

Yes, you are right. Our initial state is exactly the geometry that we prescribed from observations. We rephrase this paragraph.

p7 I7 Remove "perfect" before equilibrium. Done.

p7 I10 Not clear why the models have to be "run on the same ice sheet mask". Clarify. As RACMO and our model are run on the same ice sheet mask and geometry the forcing fields of RACMO could be used. A model that was run with evolving geometry and calving front during a paleo spin-up and ends with a significant different ice sheet mask and geometry at present day could not easy utilize the RACMO data. We add a sentence to clarify this.

As RACMO and our model are run on the same ice sheet mask and geometry the p7 I15 Replace "ice sheet models" by "initial states". Done.

p7 I16 Shouldn't the imbalance be subtracted to counteract it? See also equation (3), which should have a minus sign before SMB corr.

Yes, you are right. "Add" is replaced with "subtracted".

P7 I17 The SMB correction method has been used by other modellers before (nevertheless, it is not unproblematic), which calls for adding some references (e.g. Price et al. 2011, Goelzer et al., 2013). The magnitude of the required correction should be quantified (see references above for comparison) and the shortcomings of the method should be discussed. We agree - in the new version we add a figure and give numbers of the applied SMB correction. The method will also be discussed but very briefly. Our SMB correction is in the interior of the ice sheet close to zero but dominant at fast flowing outlet glaciers.

P7 I17 It is not clear to me why SMB corr is time dependent here. In my understanding, the most effective method should be to subtract the imbalance diagnosed for t=1 for each year of the forward experiments (unless an iterative procedure is used). What SMB_corr is used after the end of the relaxation run from 2060 onwards? Please explain this better.

This was indeed not explained in sufficient detail. However, for the revised version of the manuscript we have re-run the simulations by using the imbalance at t=1a from the relaxation run. The time-varying SMB correction is dropped for the new version of the manuscript. With the new SMB correction, the model drift (i.e. SLE; see Figure 1) is close to zero. We will introduce a paragraph to the SMB_{corr} (see comment to P7 I17).

p8 I3 "GCM" does not appear in the formula. Done.

p8 l4 I thought RCP2.6 was only defined until 2100. Describe how it has been prolonged if that is what has been done here.

We did not prolong RCP2.6 ourselves but there are official extended RCP2.6 scenarios, see e.g. Meinshausen et al. (2011), based on which climate modelling centers carried out extended future climate projections within CMIP5, bias-corrected versions of which were used here.

p8 I5 Maybe "albeit without a correction term"? Done.

p8 I9 What does "bias corrected onto the [..] grid" mean exactly?

Thank you for pointing out this imprecise wording. In the revised manuscript version we will write "The ISIMIP2b atmospheric forcing data are CMIP5 climate model output data that have been spatially interpolated to a regular 0.5° x 0.5° latitude-longitude grid and bias-corrected using the observational dataset EWEMBI (Frieler et al., 2017; Lange, 2017)."

p8 I14 "respectively". Done.

P8 I16 In my understanding h_fix should be the modelled present-day surface elevation, not the observed. This would result in corrections for the actually occurring elevation changes. Or are they (modelled and observed) identical?

This was not well explained in the manuscript. The terms of present-day and initial state were mixed up and not properly defined. In our case h_{fix} is identical to the surface elevation used in SEMIC and to the surface to the end of the spin-up.

p9 I25 These gradients were found as best fit to SMB simulated by a specific RCM (MAR) at different elevations. Applying these in your setup may be better than nothing, but for a consistent picture, these should ideally be recalculated based on your own model setup (SEMIC). Maybe, if you can run SEMIC at different elevation, you could get a feeling for the implied differences. At the very least this inconsistency should be recognised and discussed as a shortcoming.

This would be an interesting study. But for our application we follow the same argumentation above to the major point "parameter tuning". The parameters found by Edwards et al. (2014) are the most physical reliable and additionally we don't want to have different parameters between the three GCMs.

p9 I6 replace "reveals" by "shows" or "exhibits" Done.

p9 I12 What criteria are used to judge plausibility of the warming patterns? See comment to p1 I8.

p9 I15 Same problem here. What criteria are used to judge implausibility of the warming patterns?

See comment to p1 l8.

p9 I16 Add "as Figure 3" after "in a similar fashion". Done.

p9 I16 Remove "as" before "as" or "as" after "as". Done.

p9 l22 Reformulate "extreme pattern". Done.

p9 I33 Validation of the SMB for the present day has to come much earlier to give confidence in SEMIC and should include analysis of the 2D pattern, not only total numbers.

We will introduce a new section on this issue. See answer and Figure 2 to major point above.

p10 I2 All of this suggests that the confidence in the derived SMB forcing (and consequently the resulting SL numbers) is rather low, something that should be discussed in the end of the paper. However, ultimately you are using anomalies with respect to 1960-1990, so maybe that looks better. To be shown.

Due to the error we made when running SEMIC (see preamble of this document), the time series improves very much. Annual variations of the calculated SMB are now in the order of the DMI/polarportal and RACMO2.3 data.



Figure 3: Time series of SMB according to Eq. 3 for all three GCMs under RCP2.6 forcing scenario (thick line is a 50-year running mean applied to the GCM data). In grey colour and black line the range and mean of SMB between 1981–2010 from DMI/Polarportal is marked (polarportal.dk). The dashed line shows the SMB time series of RACMO2.3 (Noël et al, 2016) from 1958-2016.

p10 l11 ls it important which model is used? If not, make that clear. The behaviour is for all models similar. We wrote that now explicitly.

p10 I15 These results are difficult to see in Figure 6. It could help to plot velocity differences or ratios instead. Zooming in on some important regions could also give the interpretations more substance.

In the new version of the manuscript we will provide a scatter plot of observed and simulated velocities.

p10 I19 This paragraph should start with a motivation before going into technicalities on how things are calculated.

We rephrased this section.

p10 I24 It seems like a strange choice to not correct the reported SL changes for the model drift. I interpret all the corrections that go into the method as an attempt to produce a steady state at 1960. Or are you suggesting that the model drift should represent some natural background evolution? In my understanding the (negative) SL response in an unforced forward experiment is purely an artefact of the initialisation method and should be corrected. Another motivation would be to be transparent about the remaining model drift, which I could appreciate. However, in this case the results of a full control experiment should be presented alongside with the SL numbers of the forced experiments so that the actual magnitude of the projection can be easily judged by the reader.

This point is solved. The new control run shows almost no SL contribution (see Figure 1).

p10 I25 As mentioned in the general comments, I am not convinced that the timing when Greenland mean temperature changes cross 1.5 degree is a very meaningful diagnostic, in the light of spatially divergent warming trajectories. What interpretation are you hoping to derive from this analysis?

The story line of the project started with global overshooting scenarios, so scenarios which fulfil the Paris agreement, but are overshooting the 1.5° before 2100 and cool down to 1.5° globally by 2100. The science question arising from this was for us, if the society chooses this pathway to 1.5°, how does Greenland mass loss develop? So, indeed the timing of Greenland crossing 1.5° is not that meaningful, we just used this as a kind of further proxy to assess the

GCMs. A GCM that crosses 1.5° late is suspect to underrepresent the overshooting effect on Greenland.

p11 I4 "This is potentially an effect of ice dynamics"? You are running an ice sheet model, which should put you in the place to make an informed statement about what is going on here.

The paragraph will be rewritten due to the updated results.

p11 l9 Reformulate "false trend". Done.

p11 I18 What are these "errors in vertical ice velocities"? If this is a shortcoming of your ice sheet model, that should be discussed at some place in the model description. Does the same problem occur in the unforced control experiment? Again, being in full control of the ice sheet model in use here, you should be able to diagnose exactly what the problem is. As the high elevation decline does not appear anymore in the new simulations, this sentence is dropped.

p11 I27 Why is this section called "Acceleration" when some of the glaciers see deceleration? I suggest rewording to "Dynamic response" or similar. Done.

p11 I32 I am wondering in how far a detailed analysis of individual glaciers is justified given that an important aspect of the forcing in form of interaction with the ocean and sub-glacial hydrology is missing. The comparison suggests that we could hope to get the behaviour of individual glaciers in line with observations, which I consider very unlikely given the steady-state initialisation, coarse GCM-based forcing and lack of important forcing mechanisms.

This is indeed a good point raised. It is certainly true, that important forcing mechanisms like the oceanic forcing and subglacial hydrology are missing in this study, however, representing the dynamics of a glacier in the narrow fjords of Greenland well or representing the large NEGIS well, is only achieved with sufficient grid resolution and physics in the model, which our model both fulfils. This is indeed assessed by comparing individual glacier drainage basins with observation, like the surface velocity field. We are concerned about the statement 'given the steady-state initialisation' – we do not perform a steady-state initialisation at all, in contrast, we perform a complex initialisation procedure with mixture between inversion and paleo-spin ups. This procedure has been the top procedure in an international benchmark assessing the ability of models to achieve a good initial state (Goelzer et al., 2018). The reviewer seems to have overlooked this substantial part of this study. The coarse GCM-based forcing is subsequently processed in SEMIC is improving the resolution and the anomaly forcing is making sure, that the SMB in individual glacier basins is in high resolution – so the glacier basins are forced on high resolution.

p12 l2 You could speculate that you could maybe reproduce observed acceleration of Jacobshavn Isbrae if calving rates are forced like in Bondzio et al (2017). If this is really the case in your model is not clear until you have tried it. Reformulate.

We reformulated this sentence. It is obvious, why we did not try it: there are no *observations* of calving rates in the time period 2018-2300 available in 2017.

p12 I7 What is generally the magnitude and pattern of the SMB correction, average, largest magnitude, overall positive or negative? Where is it particularly prominent? What does that mean for ice dynamics and SMB, which fail to generate or export enough ice from a given region?

See Answer to comment P7 I17 above.

p12 I7 Replace "undermining" by "underlining" Done.

p12 I10 What does "geometric settings at their base" refer to? Clarify

With geometric setting we refer to bed topography.

p12 I10 Why does alternation between acceleration and deceleration mean the model is able to "resolve glacier valleys well"? What does it mean to resolve glacier valleys well? The geometry, the velocity structure within the valleys?

To resolve glacier valleys well means that the velocity field within a glacier valley is reasonably well representing the observed velocities. If a glacier is narrow, e.g. 3km wide, a coarse resolution ice model, e.g. running on 5km, will never be able to represent this glaciers dynamics or contribution to mass loss, as both velocity field and elevation change will lack sufficient resolution. If your grid resolution is too coarse, a narrow glacier would entirely accelerate or decelerate, as you would not have enough elements within such a narrow valley. This is what we had in mind when we formulated this sentence, but we rephrased it to avoid any confusion.

p12 I14 Sea-level contribution is in mm not mm a-1 Done.

p12 I31 These numbers should be given before, when the results are being discussed, and as mentioned earlier, together with the model drift of an unforced control experiment. Done.

p13 I2 This paper requires a dedicated discussion section before the conclusions that serves to discuss the advantages and shortcomings of the models and processing steps needed to arrive at the final numbers.

Please see also comments above.

p13 I4 "switching between spin-up and RCP forcings" A correctly applied anomaly method should not lead to any additional model drift, other than the imbalance resulting from imperfection of the data assimilation process. Possibly the SMB implied during initialisation differs from the one used further on? Often modellers use a (short) relaxation run as part of the initialisation to avoid too large model drift in the forward experiments, possibly combined with a correction method as applied here. At any rate, the uncorrected model drift of as much as 50 % of the signal by 2100 (MIROC) and the corrected model drift of still 30 % of the signal seems pretty large given the low magnitude RCP2.6 forcing applied here. This should be discussed in the paper at some point.

Due to the improved SMB_{corr} for the new version of this manuscript, this point is dropped.

Table 1 Not clear which actual years are covered by these spin-up runs. Clarify. See answer to specific comment p4 I10 above.

Table 2 - What does it mean when a temperature of 0.00 is indicated as modelling results? The -2.4 at NGRIP means that the temperature is at the pressure melting point (PMP). Is that the case for the simulated temperatures for p-cl,Gr and pd-cl,Gr?

We do apologize - the observed values are PMP. Ours were provided pressure corrected. This will be corrected in the new manuscript version.

- Basal temperatures of ~ -20 seem to be extremely low compared to the observed ice core temperatures (nowhere below -14) and are at odds with my own experience in thermodynamic modelling of the GrIS. The results should raise some doubts about the correctness of the applied thermodynamic model.

See answer to major point above.

- Typically, one would expect the pd spinup to result in generally warmer basal temperatures throughout, because of the lack of glacial signatures in the evolution. This is not confirmed in some cases. Why is that?

See answer to major point 5 of Reviewer 2.

- Could add the NEEEM ice core to the list of constraints Done.

Figure 1 Add what area is used to calculate GrIS warming. All land area, observed ice sheet mask? b) Include GrIS in y-label.

We have used the ice sheet mask provided by the BedMachine dataset (Morlighem et al., 2014). b) Done.

Figure 2 Caption: "The grey line depicts the identity" Done. Also describe here which range of years are plotted Done.

and from what product

It remains unclear what the reviewer means with product/grid? This is just a plot of the global data versus a sub-dataset over Greenland of the GCMs with different GCMs denoted in color. Add what area is used to calculate GrIS warming. Done.

Figure 3 Colour bar labels are not well readable at this size. Could remove identical colour bars per row of figures and have one big one.

We apologize the bad quality of the figures. Figure will be updated as suggested.

Figure 4 Colour bar labels are not well readable at this size. Could remove identical colour bars per row of figures and have one big one.

We apologize the bad quality of the figures. Figure will be updated as suggested.

Figure 5 The forcing that the ice sheet model actually sees and that goes into the SL projections is based on anomalies of the SMB with respect to 1960-1990. How does figure 5 look like and how does the constructed SMB compare to observations when this anomaly calculation is applied?

This must be a misunderstanding. Figure 5 is exactly the figure that you want to see. As stated in the caption the plotted SMB is according to our SMB anomaly equation (Eq. 3) which is imposed on the ice surface.

Caption: Is there a paper reference available for the SMB observation product?

The webpage give in the text (p9 I34) is added here, but to our knowledge there is no paper reference available. The new figure also provides the RACMO time series and reference (Figure 3).

Figure 6 Figure colour bar labels are not well readable at this size. Could remove one of the identical colour bars per row of figures.

Should add contour lines in panel c and d. Caption: (a) simulated horizontal velocity magnitude, (b) observed horizontal velocity magnitude (Rignot and Mouginot, 2012), ... Done.

Figure 7 Figure labels are not well readable at this size. Labels should be increased to be readable in the final two-column layout. Done.

Caption: Add what area is used to calculate GrIS warming. Done.

You should note here that the relaxation run differs in setup from the other experiments In the new figure the relaxation run is not shown, as it was only run for 1 year.

Reviewer #2

General comments:

This manuscript presents future volume evolution scenarios of the Greenland Ice Sheet under three different surface mass balance forcings. Atmospheric forcing is provided by three global climate models and the surface mass balance is computed with a relatively simple surface energy balance model. The ice-sheet model employed, is the state-of-the art ISSM model with higher order ice physics. The sea-level rise projections from surface mass balance perturbation alone are between 46-71 mm by 2100 and 114-189 mm by 2300.

The topic of the manuscript is of interest to ice-sheet modellers as well as the wider cryospheric community. The overall structure of the paper is logical but some sections would benefit from a tidy-up and the language is hard to follow in some places. While the results are certainly not groundbreaking and omit any contributions from ice dynamics, I think the manuscript presents enough novelty and hence merits publication subject to consideration of my comments listed below.

We are concerned about the statement that we omit any contributions from ice dynamics. The study presented is solving the higher order approximation of the momentum balance of ice sheets, which is not standard for all ice models performing projections, as quite many of them are relying on shallow ice / shellfish stream approximation. Not only do we solve the higher order momentum balance, but we do so in high resolution, hence the benefit of this level of approximation is not suppressed by coarse grid resolution.

Specific comments

The study's strong point from an ice-sheet modelling perspective is the model initialisation which combines the two commonly employed spin-up and data assimilation techniques. The main focus is, however, on the surface mass balance forcing with the SEMIC model. In the light of this and the importance of the surface mass balance forcing, for someone that is not familiar with the SEMIC model, I am missing a succinct description of the model fundamentals and the configuration used in this manuscript. Furthermore, the entire manuscript would benefit from some reordering and substantial improvements to certain sections and improvements in readability of some figures (detailed below). My main concern is with the calculation of the surface mass balance anomaly for the projections. Please find below my main concerns, followed by specific comments.

Main concerns:

My main concern is the calculation of the surface mass balance anomalies. First of all, I understand that you account for the model drift by adding a synthetic SMB correction term (SMB_{corr} in Equation 3). But what dh/dt is applied – an average of your unforced relaxation run from 1960-2060 or the last or first time step of this relaxation simulation? How can this term be time-varying in your projections? On page 9 line 20 this time-varying SMB_{corr} term is used as an explanation for spatial differences in the SMB pattern. Maybe I missed it, but it would help if you clarified this.

The SMB correction was probably not explained with sufficient detail – as also mentioned by Reviewer #1. The relaxation run for measuring the SMB correction was run from 1960 to 2060 exactly on the same time steps as the subsequent climate forcing runs. From the relaxation run we have taken the dh/dt values from every time step $t_1, t_2, t_3..., t_{end}$ and prescribed these as a SMB correction (after 2060 the SMB correction is held constant). The dh/dt values during the first time steps are rather large compared to the later ones as the ice sheet approaches equilibrium. Therefore, the SMB correction in the year is 2000 much larger as in 2100 or 2300. These you can see in Fig. 4. However, in the new version of the manuscript the time varying SMB correction will no longer appear as we have modified the SMB correction towards an time independent correction in our new simulations. The SMB correction is taken from the first year and held constant in time (see answer to Reviewer #1, comment to P7 I17).

2. The more critical point is how you compute your SMB in Equation 3. The way I understand it and please correct me if I am wrong, Equation 3 states that SMB_RACMO plus your correction for the model drift should give you an SMB that keeps your ice sheet close to steady state (or at least present geometry).

It is actually not about keeping it close to steady state, it is keeping the SMB distribution as close to the realistic one, which we assume RACMO – or any other validated regional climate model – to be.

The applied perturbations are however calculated with respect to the SEMIC model baseline. If you use your RACMO_SMB to keep your ice sheet in steady state, you should also calculate your anomalies with respect to your SMB_RACMO field. If not, your perturbations to the surface mass balance appear a bit arbitrary. Would it not be more consistent to use the SEMIC output? The argument that your model drift gets larger is rather weak, considering that you would just get a larger SMB_{corr} term from the unforced relaxation simulation.

We are confident that the computation of the SMB is correct and consistent – the anomaly approach is widely used in ice flow modeling (e.g. Goelzer et al., 2013, 2018). If we assume the ideal case in Eq. 3 and 4 the reference terms $+SMB_RACMO_{1960-1990}$ and $-SMB_SEMIC_{1960-1990}$ will cancel out and the climatic forcings from the SMB_SEMIC(t) remain. This is certainly not the case and the equation must be interpreted as having the RACMO reference field – with a good spatial distribution – as a background field where the trends from SEMIC are added.

For the relaxation and control run we have used a simplified form of Equation 3 and 4 by neglecting the input from SMB_SEMIC. Of course, we could use a GCM forcing for the relax/control run from the so-called pre-industrial run from the ISIMIP2b project, but the results are unlikely affected by it. The temperature changes in the pre-industrial run are so small, that a Δ SMB_SEMIC_{pre-industrial} according to Eq. 4 will be negligible.

You are right, one could drop both reference terms and put all the model drift in the SMB correction term and use the SEMIC output directly. In this case we would lose information on climatic forcing versus synthetic forcing, which are an additional quality measures. The Total SMB for SMB_RACMO₁₉₆₀₋₁₉₉₀ is ~ 400 Gt/a, for SMB_SEMIC₁₉₆₀₋₁₉₉₀ ~ 500 Gt/a (dependent on GCM input) while the SMB_{corr} is ~ 100 Gt/a.

In the new version of the manuscript we give a better motivation for the choice of our SMB calculation and the assumptions we made for the relaxation and control run.

3. I think the section "Input data" should be removed as this mostly repeats earlier statements (e.g. Greve 2005 dataset). The basal drag inversion should be moved to the "Initial state" section as this is where it is most appropriate.

I would introduce a section "Results" which would start with the subheading "Forcing fields" and continue with "Present day elevation and velocities". The heading "Projections" followed by "Present day ..." was confusing. I would suggest to add "projections" where appropriate e.g. Mass loss projections, Speed up projections etc.

We have restructured the manuscript accordingly. As mentioned in the preamble of this document, we have introduced a separate results and discussion section.

4. Please provide a more complete description of the SEMIC model than the few lines provided on P6 L15-22. You also claim to have improved the albedo parameterisation, but to me it is not clear how or to what extent. Please expand on this. We agree with the reviewer. We expand the section about the SEMIC model. In order to be consistent with parameters provided by Krapp et al. (2017) we switched back to the albedo scheme used by Krapp et al. (2017) for the new simulations. As also replied to Reviewer #1, we also introduce a validation of the applied SMB fields (see first major points of Reviewer #1).

5. I am certainly not an expert on ice temperature, but to me the following questions came up when looking at Table 2. Are there no temperatures from observations for EastGRIP? At EastGRIP there is not temperature available yet. But we expect to get a temperature profile in the near future as the coring project is currently ongoing (http://eastgrip.org). Why are there such large differences in basal temperatures between the Greve (2005) and Shapiro and Ritzwoller (2004) maps at the selected locations? Does this mean that temperature in these regions is dominated by the geothermal heat flux and that this heat flux is that different at these locations? Why do the simulated temperatures do not agree with GRIP temperature observations?

The large differences between the four set-ups arise from the different geothermal flux maps used and from the imposed surface temperature forcing. The Greve (2005) geothermal flux is generally larger, particularly in the northeast and at the Dye3 location (South Dome), than the Shapiro & Ritzwoller (2004) fluxes. Generally, the Greve (2005) geothermal flux leads to a warmer ice base compared to Shapiro & Ritzwoller (2004).

The present-day climate forcing would generally lead to a warmer ice, as the history from the paleo conditions are missing. Consequently, the different combinations lead different thermal states. In the new version of the manuscript we have dropped these sensitivity study, as it is not relevant for the paper, and describe only the setting that we have used.

Technical corrections Abstract

L2 "...sea-level change under different atmospheric forcing scenarios from ..." Done.

L11 Sentence starting with "Simulated an observed sea-level rise..." That makes no sense to me. Is it simulated or observed? I believe you are trying to say that your simulated sea-level rise for the period 2002-2014 matches sea-level rise from observations in magnitude? Please clarify.

There was a typo: "An" changed to "and".

P1L19 delete second "past decade" Done.

P1L22 Delete "Obviously, ..." Done.

P2L1 "engaged"? Do you mean encouraged? Indeed, we mean encouraged.

P2L20 "...provided by ..." Done.

P2L27 replace "." with "," Done.

P2L27 Sentence starting with "ISSM is designed to ... " Is this really important for the paper? Also while I welcome the fact that the authors kept the details of the ice-sheet model brief, I would appreciate if you could add what higher-order physics you used (Blatter-Pattyn, Stokes or SSA)? Please add to ice-flow model section. Also, can elements be either Stokes or SIA? Do you mean that for each element you can choose what force balance is solved? The sentence "ISSM is designed to ..." is shortened. We give a citation to Blatter-Pattyn. The paragraph is slightly rewritten.

P3L2 "...surface mass balance and climate forcing" The sentence is rewritten to: "The upper boundary incorporates the climatic forcing (i.e. the surface mass balance and ice surface temperature)." P3L19 "compensates" Done.

P3L20-21 "...according to a sub-grid paramterization scheme,..." Done.

P3L24 "... towards the base where vertical shearing becomes more important." Done.

P4L4 Delete sentence starting with "Furthermore, the themo-mechanically ..." I think it is obvious that if you simulate ice temperatures that your simulations are sensitive to temperatures.

Done.

P4 L5-13 and Table 1 I do not completely understand when you start your mesh refinements? The way I understand your initialisation method is that you run your temperature spin-up with mesh sequence 1, then you do an inversion for basal friction parameters and run your temperature spin-up again with a refined mesh before you do another inversion on the refined mesh? Please describe this more clearly.

As also the other reviewer suggests giving more details, we have rewritten this paragraph (see answer to Reviewer #1, his comment p4 l10).

P5L4-7 Please reformulate this sentence. It is too long. Also please delete "aim" as this implies that you are not sure it is going to work. Your results show that it clearly does work. Done.

P5L10 Could you explain why the three GCMs were selected as forcing? So far this choice appears a bit random.

See answer to Reviewer #1; his comment p5 l10.

P5L20 This sentence is unclear. It reads like Greenland warms above 1.5°C but you are talking about T I believe. Also, could you state more clearly that you are comparing it to the global temperature increase in the GCMs. We rephrased this sentence.

P6L3 Sentence starting with "While HadGEM2 ... " makes no sense to me. Leading to similar factors? What factors?

The warming of IPSL-CM5A-LR and HadGEM2 is of the same magnitude. We rephrased this sentence.

P6L8 "reaches" Done.

P6L8-9 This sentence has to come earlier as it is indeed very striking, but also expected. Done.

P6L9 Please delete "Summarizing" Done.

P6L17 Please delete "Due to the fact that Krapp et al. (2017) performed calibration over GrIS" Done.

P6L28 "We follow ..." Done.

P7L4 Here and throughout "the ISSM"="ISSM" Done.

P7L5 very well = well Done.

P7L14-16 This statement needs a citation. Is this true for Greenland? I doubt that every data assimilation initialization leads to a 3% ice volume gain. We removed this statement.

P8L5 By doing so = This ensures that Done.

P8L14-15 espectively=respectively Done.

P9L4 "leads to an increase in temperatures ..." Done.

P9L5 "exceed 2°C of warming" Done.

P9L6 and P9L8 Be more specific. By how much? Numbers please! We give numbers in the new version of the manuscript.

P9L13-15 Please explain this. Why is this the most plausible? It is not apparent to me. See answer to Reviewer #1, his comment p9 I12.

P9L16 delete first "as" Done.

P9L19 here and throughout vallies=valleys Done.

P9L20-21 See main comment above. How can this be time-varying? See answer to major point 1 above.

P9L27 "The magnitude of SMB is far less in the period 2300-2000..." Done.

P9L31 which pattern? Spatial or temporal or both?

We are interested in the spatial distribution of the SMB and its change over time. However, in order to illustrate what the ice sheet's total surface gains and losses have been over the year from SMB we show the integrated SMB in the time series. We rephrased this sentence.

P11L14 Again why is this the most plausible pattern? Please elaborate. See comment to p1 l8.

P11L33 "... experience acceleration across all simulations." Done.

P12L8 levelled out = balanced Done.

P12L17 "...ice sheet loses contact with the ocean." Done.

P12L17 resolution = grid resolution Done.

P12L28 "considerably large". What does this mean? Be more specific!

Done. We add "... their temperature variation is considerably large".

Figures:

We apologize the bad quality of the figures. After a major storm in northern Germany two days prior to submission our computing cluster had power failure due to fire and we were unable to update the figures at the time of submission.

Figure 1: Can you make the line for 1.5°C bold to aid visibility when the models pass this threshold?

We added a dashed bold line.

Figure 3: Question mark before "C" symbol in Figure. Colour bar is too small. As it is the same magnitude for all panels one big colour bar should suffice. Figure will be updated as suggested.

Figure 4: See comments for Figure 3 Figure will be updated as suggested.

Figure 6: Again, use one colour bar per panel. Also, please have colour bar labels on the same side of the colour bar and avoid overlap of axes labels with main Figure. Please align top and bottom panels properly. Figure will be updated as suggested.

Figure 7: Again bigger axes labels and legends. Figure will be updated as suggested.

Figures 8 and 10: See comments for Figure 3 Figure will be updated as suggested.

References (only new ones compared to the manuscript)

Lange, S.: Bias correction of surface downwelling longwave and shortwave radiation for the EWEMBI dataset, Earth Syst. Dynam. Discuss., https://doi.org/10.5194/esd-2017-81, in review, 2017.

Meinshausen, M.; Smith, S. J.; Calvin, K.; Daniel, J. S.; Kainuma, M. L. T.; Lamarque, J.-F.; Matsumoto, K.; Montzka, S. A.; Raper, S. C. B.; Riahi, K.; Thomson, A.; Velders, G. J. M. & van Vuuren, D. P., The RCP greenhouse gas concentrations and their extensions from 1765 to 2300, *Climatic Change*, **2011**, *109*, 213

The effect of overshooting 1.5°C global warming on the mass loss of the Greenland Ice Sheet

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Abstract. Sea level rise associated with changing climate is expected to pose a major challenge for societies. Here, we estimate Based on the efforts of COP21 to limit global warming to 2.0°C or even 1.5°C by the end of 21th century (Paris Agreement), we simulate the future contribution of the Greenland ice sheet (GrIS) to sea level change in terms of different ice sheet atmospheric forcings arising from three general circulation models (GCMs), HadGEM2-ES, IPSL-CM5A-LR and MIROC5,

- 5 for RCP2.6. We run the under the low emission representative concentration pathway (RCP) 2.6 scenario. The ice sheet model ISSM with higher order approximation and use a is used and initialized with a hybrid approach between spin-up /inversion scheme to estimate the present day state. The and data assimilation. For three general circulation models (HadGEM2-ES, IPSL-CM5A-LR, MIROC5) the projections are conducted up to 2300 with forcing fields for surface mass balance (SMB) and ice surface temperature (T_s) are computed by the SEMIC model (Krapp et al., 2017)and applied as anomalies to RACMO2.3
- 10 fields... The projected sea level rise ranges between 21–38 mm by 2100 and 36–85 mm by 2300. According to the three GCMs used, warming of 1.5°C has been reached at GrIS by 2005 (HadGEM2-ES, MIROC5) or as early as 1995 (IPSL-CM5A-LR). Forcing fields suffer from underestimation of polar amplification (MIROC5) and implausible distribution of changes in T_s (IPSL-CM5A-LR). HadGEM2-ES is the most plausible forcing, with globally a exceeded early in the 21th century. The RCP2.6 peak and decline behaviour leading to overshooting of scenario is therefore in a another set of experiments manually adjusted
- 15 to suppress the 1.5°C and over GrIS a slight C-overshooting effect. These scenarios show a sea level contribution that is on average about 38% and 31% less by 2100 and 2300, respectively. The rate of mass loss in 23rd century is for some scenarios not excluding a stable ice sheet. This is most likely due to an integrated SMB that never fall below zero, or even a recovery of SMB towards values of about half the present daySMB. We find sea level to rise for HadGEM2-ES by 71 mm by 2100 and 189 mm by 2300. Simulated an observed sea level rise 2002–2014 is of the same magnitude, but with a temporal lag to
- 20 be at least five years (HadGEM2-ES). By end of 22nd century sea level contribution is still 0.46 mm slightly below present day. Although the mean SMB is reduced in the warmer climate, a ⁻¹ for HadGEM2-ES. Hence, even a future steady-state ice sheet with lower surface elevation and hence volume might be possible. Our results indicate, that uncertainties stem from the underlying climate model to calculate the surface mass balance. However, the RCP2.6 peak and decline scenario will lead to significant changes of GrIS including elevation changes up to 100 mand loss of floating tongues. The values of . The sea level
- 25 contribution estimated in this study may serve as a lower bound , as processes for RCP2.6 scenario, as the current observed

observed sea level rise is in none of the experiments reached; this is attributed to processes not yet represented by the model but proven to play a major role in GrIS mass lossare not yet represented by the model, but are considerably larger than other studies.

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1 Introduction

Within the past decade the Greenland ice sheet (GrIS) has contributed in the past decade by about 20% to sea level rise (Rietbroek et al., 2016) and global sea level rise has just recently shown to accelerate (Nerem et al., 2018). The mass loss of GrIS comprises two main contributions: acceleration of outlet glaciers and changes in the surface mass balance. In the past

10 decades these changes in surface mass balance contributed to about 60%, whereas 40% is attributed to increasing discharge (van den Broeke et al., 2016). Obviously the The question arises which impact the GrIS will have on global and regional sea level change in the next decades and centuries. The Paris Agreement

Negotiated during COP21, engaged scientists to assess 'the impacts of global warming of 1.5the Paris Agreement's aim is to keep a global temperature rise in this century well below 2°C above pre-industrial levels and related global greenhouse gas

- 15 emission pathway', which is the aim of this study. While the different to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius (UNFCCC, 2015). However, the statement holding global temperature below 2°C implies keeping global warming below the 2°C limit over the full course of the century and afterwards while efforts to limit the temperature increase to 1.5°C is often interpreted as allowing for a potential overshoot before returning to below 1.5°C (Rogelj et al., 2015). Here we selected the Representative Concentration Pathways (RCP, Moss et al., 2010) are leading to 2.6, being the lowest
- 20 emission scenario considered within CMIP5 and in line with a 1.5°C or 2.02°C global warming at 2100, the global limit of global warming. Depending on the global circulation models (GCM) considered the global temperature change over time varies considerably between different global circulation models (GCM), although the political target is met at 2100. Whereas some models in RCP2.6 are not passing the limit of 1.5°C or 2.0°C global warming before 2100, other scenarios cross this limit and exhibit subsequent cooling (?). This effect of returning to below (Frieler et al., 2017).
- 25 While global temperature rise may be limited to 1.5°C was termed as an potential overshoot (Rogelj et al., 2015). This overshooting could have a or 2°C by 2100, warming over Greenland is enhanced due to the Arctic amplification (Pithan and Mauritsen, 2014) and may exceed 4°C by that time and has exceeded 1.5°C (relative to 1951–1980) already in the past decade (GISTEMP Team, 2018). Given that this is about more than 2°C above the warming by 2000 this could have an considerable impact on ice sheet mass loss and over Greenland. This implies an enlargement of the ablation zone and goes along with a decline in SMB. However, it
- 30 is currently unclear, how fast GrIS could react to cooling . In order to study this response, we perform simulations in which an and recovery of SMB, as ice sheets are also reacting dynamically to atmospheric forcing.

Recent large-scale ice sheet modelling attempts for projecting the contribution of the GrIS under RCP2.6 warming scenarios are very scarce. Fürst et al. (2015) conducted a very extensive study to simulate future ice volume changes driven by both atmospheric and oceanic temperature changes for all four representative concentration pathway scenarios. For the RCP2.6 scenario they estimate an abated sea level contribution of 42.3±18.0 mm by 2100 and 88.2±44.8 mm by 2300. The value by

5 2100 is in line with estimates given by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5, IPCC (2013)). The AR5 range for RCP2.6 is between 10-100 mm by 2100 (the value is dependent whether ice-dynamical feedbacks are considered or not).

The GrIS response to projections of future climate change are usually studied with a numerical ice sheet model is used to simulate the change in ice sheet volume and ice velocities, as response to (ISM) forced with climate data. ISM response

- 10 is subject to the dynamical part and the surface mass balance (SMB). In the past, ISMs often used the rather simple and empirical based positive degree day (PDD) scheme, in which the PDD index is used to compute melt, run-off and ice surface temperature from atmospheric temperature and precipitation (Huybrechts et al., 1991). One disadvantage of the PDD method is, that the involved PDD parameters are tuned to correctly represent present-day melting rates but may fail to represent past or future climates (Bougamont et al., 2007; Bauer and Ganopolski, 2017). On one far end of model complexity, a regional
- 15 climate model (RCM) resolves most processes at the ice-atmosphere interface and in the upper firn layers, such as RACMO (Noël et al., 2018) or MAR (Fettweis et al., 2017) with higher spatial and temporal resolution than GCMs. RCMs have been shown to be quite successful in reproducing the current SMB of the GrIS. However, as they are computationally expensive, an intermediate way would be most suitable, balancing computational costs and parameterisation of processes, such as the energy balance model of intermediate complexity, like SEMIC (Krapp et al., 2017).
- 20 Here we target in particular RCP2.6 peak and decline scenarios in order to study the GrIS response on overshooting by means with an numerical ISM. The projections are driven with climate data output from the CMIP5 RCP2.6 scenario provided by the ISIMIP2b project for different GCMs (Frieler et al., 2017). To obtain ice surface temperature and surface mass balance . As these two forcing fields are not a direct output of an atmospheric model we use a from the atmospheric fields, the surface energy balance model SEMIC (Krapp et al., 2017) is applied. The SEMIC model (Sect. 2.1) is driven offline to the ISM and
- 25 therefore the climate forcing is one-way coupled and applied as anomalies to the ISM. The advantage of this one-way coupling is the lower computational costs, allowing for reasonably high spatial and temporal resolution of the ISM. In order to study the effect of overshooting, we design a RCP2.6-like scenario without an overshoot by manually stabilizing the forcing at 1.5°C. For modelling the flow dynamics and future evolution of the GrIS under RCP2.6 scenarios, the thermo-mechanical coupled Ice Sheet System Model (ISSM, Larour et al., 2012) with a Blatter-Pattyn type higher order momentum balance (BP; Blatter, 1995; Pattyn, 1995; P
- 30 is applied (Sect. 2.2). A crucial prerequisite for projections is a reasonable initial state of the ice sheet in terms of ice volume, ice extent and ice surface velocities. Beside starting projections with the most realistic setting, the prevention of a model shock after switching from the initialization procedure to projections, is very important. Both has been a major issue in the past, which gave rise to an international benchmark experiment initMIP Greenland (Goelzer et al., 2018) for finding optimal strategies to derive initial states for the ice velocity and temperature fields. Using a hybrid approach of a thermal paleo-spin up and data
- 35 assimilation has been shown to be a good way and is applied here.

Before driving the projections, the SMB forcing is validated thoroughly against RACMO. Then we explore the response of the GrIS and its contribution to sea-level rise under RCP2.6 scenario with overshoot and an modified RCP2.6 scenario without overshoot.

2 Model description

20

5 2.1 Energy Balance Model

Numerical ISMs need the annual mean surface temperatures and annual mean surface mass balance of ice as boundary conditions at the surface. To derive these ice sheet specific quantities, we use the surface energy balance model of intermediate complexity to obtain (SEMIC, Krapp et al., 2017). Although we only apply SEMIC and do neither adjust parameters of SEMIC, SEMIC is described very briefly. SEMIC computes the mass and energy balance of snow and/or ice surface. In

10 order to tune parameters for a number of processes, (Krapp et al., 2017) performed an optimisation based on reconstruction and regional climate model data. These parameters have been used in our study, too. The energy balance equation reads as

$$c_{\text{eff}} \frac{dT_{\text{s}}}{dt} = (1 - \alpha) \cdot \text{SW}^{\downarrow} - \text{LW}^{\uparrow} + \text{LW}^{\downarrow} - H_{\text{S}} - H_{\text{L}} - Q_{\text{M/R}},$$
(1)

where α is the surface albedo that is parameterized with the snow height (Oerlemans and Knap, 1998). The downwelling shortwave SW⁴ and downwelling longwave radiation LW⁴ at the surface are provided as atmospheric forcing (sect. 2.2). The

15 upwelling longwave radiation LW^{\uparrow} is described by the Stefan-Boltzmann law. The latent H_L and sensible H_S heat fluxes are estimated by the respective bulk approach (e.g. Gill, 1982). The residual heat flux $Q_{M/R}$ is calculated from the difference of melting M and refreezing R and keeps track of any heat flux surplus or deficit in order to keep the ice surface temperature and T_s below or equal to 0°C over snow and ice.

The surface mass balance - The disadvantage of this type of uncoupled or time slice simulations is the missing response of the atmospheric forcing to ice sheet elevation change, which we aim to overcome by applying corrections to both temperature SMB in SEMIC is considered as follows

$$SMB = P_s - SU - M - R,$$
⁽²⁾

where P_s is the rate of snowfall and SU the sublimation rate, which is directly related to the latent heat flux. The melt rate is dependent on the snow height, if all snow is melted down the excess energy is used to melt the underlying ice. Refreezing

25 is calculated differently for available melt water or rainfall. Moreover, the porous snowpack could retain a limited amount of meltwater while over ice surfaces refreezing is neglected and all melted ice is treated as run-off. In SEMIC, the total melt rate M and refreezing rate R are calculated from available energy during the course of one day. As the set of equations are solved using an explicit time-step scheme with a time step of one day, a parametrization for the diurnal cycle (a cosine function) account for thawing and freezing over a day. This reduced complexity, one-layer snowpack model saves computation time and allows for integrations on multi-millennial timescales compared to more sophisticated multilayer snowpack models. Further details are given by Krapp et al. (2017).

2.2 Atmospheric forcing

Here we targeted in particular peak and decline scenarios, temporarily exceeding a given temperature limit of global warming

- 5 to 2.0°C or even 1.5°C by the end of 2100. From the official extended RCP2.6 scenarios (Meinshausen et al., 2011), we have selected GCMs which covering the CMIP5 historical scenario, the RCP2.6 scenario until 2299 and reveal an overshoot in annual global mean near-surface temperature change relative to pre-industrial levels (1661–1860). Three different GCMs were used in our study: IPSL-CM5A-LR (L'Institut Pierre-Simon Laplace Coupled Model, version 5 (low resolution)), MIROC5 (Model for Interdisciplinary Research on Climate, version 5) and HadGEM2-ES (Hadley Centre Global Environmental Model
- 10 2, Earth System). The GCM output was provided and prepared by the ISIMIP2b project following a strict simulation protocol (Frieler et al., 2017). Figure 1a displays the temporal evolution of the annual global mean near-surface air temperature T_a for those GCMs for the historical simulation up to 2005 continued with the RCP2.6 simulation up to 2299. Global-mean-temperature projections from IPSL-CM5A-LR and HadGEM2-ES under RCP2.6 exceed 1.5°C relative to pre-industrial levels in the second half of the 21st century. While global-mean-temperature change returns to 1.5°C or even slightly lower by 2299 in
- 15 HadGEM2-ES, it only reaches about 2°C in IPSL-CM5A-LR by 2299. For MIROC5, it stabilizes at about 1.5°C during the second half of the 21st century. In order to determine the onset of overshoot we scan the historical and RCP2.6 scenarios of the individual GCMs identifying the time, when the global warming reaches 1.5°C in a 11-year moving window above pre-industrial levels. The characteristic dates of overshooting 1.5°C for HadGEM2-ES is by 2021; MIROC5 reaches this level by 2041, while IPSL-CM5A-LR by 2009 (coloured dots in Fig. 1).
- The phenomenon, that tends to produce a larger change in temperature near the poles was termed polar amplification. Particularly, it enhances the increase in global mean air temperature over arctic areas (referred here as arctic amplification). Generally, the the CMIP5 models show an annual average warming factor over the Arctic between 2.2 and 2.4 times the global average warming (IPCC, 2013, Tab. 12.2). As mechanisms creating the arctic amplification may be represented to different extents in the GCMs, the level of future amplification is different across the GrIS. The three GCMs used in this study represent
- 25 this trend to differing extents over GrIS¹ (Fig. 1 and 2). For HadGEM2-ES and IPSL-CM5A-LR the arctic compared to the global warming is amplified relatively similar (warming approx. 4°C relative to 1661–1860). In contrast, MIROC5 reveals a considerably lower arctic amplification (warming approx. 3°C relative to 1661–1860). A striking feature among all models is the higher variability over GrIS compared to the global mean values. In terms of global and arctic future annual mean near-surface temperatures MIROC5 is the lowest and IPSL-CM5A-LR the highest forcing.
- 30 The ISIMIP2b atmospheric forcing data are CMIP5 climate model output data that have been spatially interpolated to a regular $0.5^{\circ} \times 0.5^{\circ}$ latitude-longitude grid and bias-corrected using the observational dataset EWEMBI (Frieler et al., 2017; Lange, 2017). To drive the SEMIC model to obtain the ice surface temperature $T_{\rm s}$ of the ice sheet and the surface mass balance SMB we need to provide the atmospheric forcing (consisting of incoming shortwave radiation SW^{\downarrow} , longwave radiation LW^{\downarrow} , near-surface air temperature $T_{\rm a}$, surface wind speed $u_{\rm s}$, near-surface specific humidity $q_{\rm a}$, surface air pressure $p_{\rm s}$, snowfall rate $P_{\rm s}$, and

Table 1. Lapse rates and height-desertification relationship for initial corrections of GCM output fields near-surface air temperature T_a , precipitation of snow P_s , precipitation of rain P_r , and downwelling longwave radiation LW^{\downarrow} used as input for SEMIC. Here, $h^{\text{ref}} = 2000 \text{ m}$ and $\gamma_R = -0.6931 \text{ km}^{-1}$ is the desertification coefficient.

variable	lapse rate γ and desertification relationship	reference
$T_{a\sim}$	<u>0.74 K/100 m</u>	Erokhina et al. (2017)
$\underbrace{LW^{\downarrow}}_{\longleftarrow}$	$2.9 \mathrm{W}\mathrm{m}^{-2}$	Vizcaíno et al. (2010)
Ps. Pr.	$\underbrace{\exp(\gamma_p[\max(h_s^{\text{ISSM-pd}}, h^{\text{ref}}) - h^{\text{ref}}])}_{\$} \forall h_s^{\text{GCM}} \leq h^{\text{ref}}$	Vizcaíno et al. (2010)
P_s, P_r	$\underbrace{\exp(\gamma_p[\max(h_s^{\text{ISSM-pd}}, h^{\text{ref}}) - h_s^{\text{GCM}}])}_{s} \forall h_s^{\text{GCM}} \geq h^{\text{ref}}$	Vizcaíno et al. (2010)

rainfall rate P_r). These fields are available from the three GCMs model output data. SEMIC is driven by the daily input of the GCMs while the output is a cumulative surface mass balance . Aiming at covering higher-order physics within the ice sheet model, high spatial resolution in the area of outlet glaciers is required and hence we run and a mean surface temperature over each year.

- 5 Given the differences in resolution between the GCMs and ISSM, a vertical downscaling procedure is applied to the atmospheric forcing fields. First the atmospheric fields are conservatively interpolated from the GCM grid onto a regular high resolution 0.05° grid. The output fields of SEMIC are subsequently conservatively interpolated on the unstructured ISSM grid. This two-step procedure is not necessary but currently it is technical the easiest way. For future applications we will avoid the intermediate interpolation and run SEMIC directly on the target unstructured ISSM grid.
- 10 To account for the difference in ice sheet surface topography between GCMs and ISSM corrections for several quantities (\cdot) denoted by (\cdot)^{cor} are initially performed. We follow the corrections proposed by Vizcaíno et al. (2010)

$$\underbrace{(\cdot)^{\text{cor}} = (h_s^{\text{SEMIC}} - h_s^{\text{GCM}})\gamma_{(\cdot)},}_{(\cdot)}$$

with the lapse rates $\gamma_{(.)}$ shown in Table 1 and h_s^{SEMIC} is equal the ISSM ice surface elevation at the initial state. Subsequently, SEMIC computes the ice-surface temperature T_s and the surface mass balance SMB based on these corrected input values.

15 SEMIC is applied as developed by Krapp et al. (2017). These authors perform a particle-swarm optimization to calibrate model parameters for the GrIS and validate them against the RCM MAR. We adopt their derived parameters here. The parameter tuning aimed to find a parameter set which gives a best fit between SMB and ice temperature T_s of SEMIC with only a limited number of processes and simpler parameterisations compared to a more complex RCM. A RCM is typically validated against reanalysis data and observations, therefore, we assume the tuned parameters are most reliable to represent

20 the processes and parametrizations within SEMIC. In terms of process description the optimized SEMIC configuration leads to the best possible SMB and T_s fields. However, although the coarse GCM-based forcing has underwent a downscaling of particular fields and is processed in SEMIC with a higher resolution the atmospheric fields over the ice sheet still lacks details and quality compared to a RCM. Given the experiences we made with GCMs used in this study (e.g. the timing of maximum warming, the ice sheet model here stand-alone and apply corrections of the atmospheric forcing fields according to the simulated elevation change. The advantage of this approach, is the computational costs, allowing for reasonably high spatial and temporal resolution of the ice sheet model, required for higher-order physics and length of an overshoot) would require a separate tuning for each GCM. This basically means to compensate, for capturing the dynamic response of the ice sheet. e.g. too low near surface temperatures, with SEMIC parameters, which would offset the whole comparison of GCM

5 forcing. Furthermore, this additional tuning steps would make the benefit of having a semi-complexity model with low costs meaningless.

For modelling the flow dynamics and future evolution of the GrIS, we apply the thermo-mechanical coupled Ice Sheet System Model (ISSM, Larour et al., 2012). The model is forced with anomalies for temperature and Because the details of the GrIS surface climate are not well captured on the GCM coarse grid, the absolute SEMIC output fields (SMB and T_s) are not

- 10 directly used to force the numerical ice flow model ISSM. The climatic boundary conditions applied here consist of a reference field onto which climate change anomalies from SEMIC are superimposed. The initialization of the ice flow model based on data assimilation makes it possible to use forcing data from high resolution RCMs that were run on the same ice sheet mask and ice surface topography. As the reference SMB field we choose the downscaled RACMO2.3 product (Noël et al., 2018) whereby a model output was averaged for the time period 1960–1990, denoted SMB(1960–1990)_{RACMO}. The reference
- 15 period 1960–1990 is chosen ice sheet is assumed close to steady state in this period (e.g. Ettema et al., 2009). The climatic SMB that is used as future climate forcing read as

$$\operatorname{SMB}_{\operatorname{clim}}(x, y, t) = \overline{\operatorname{SMB}}_{\operatorname{RACMO}}^{(1960-1990)}(x, y) + \Delta \operatorname{SMB}(x, y, t),$$
(4)

with the anomaly defined as

$$\Delta \text{SMB}(x, y, t) = \text{SMB}_{\text{SEMIC}}(x, y, t) - \overline{\text{SMB}}_{\text{SEMIC}}^{(1960-1990)}(x, y),$$
(5)

- 20 where $t = \{1960, 1961, ..., 2299\}$. Note that the historical scenario is run from 1960-2005 and followed by the RCP2.6 scenario from 2006-2299. In an ideal case, both reference terms $\overline{\text{SMB}}(1960 1990)_{\text{BACMO}}$ and $\overline{\text{SMB}}(1960 1990)_{\text{SEMIC}}$ will cancel out and the absolute climatic forcing $\text{SMB}_{\text{SEMIC}}(x, y, t)$ would remain. This is certainly not the case and the equation must be interpreted as having the RACMO reference field (with a good spatial distribution) as a background field with the trends from SEMIC superimposed.
- 25 The same equations hold for the temperature imposed on the ice-surface. This ensures that the unforced control experiment produces identical behaviour for each GCM. Results for future projections depend only on the atmospheric GCM input, or similarly SEMIC output, and therefore the results can be compared quantitatively.

In the presented study, the ice flow model is forced with the offline processed SEMIC output. This one-way coupling strategy is computational cheaper and the technically challenging online coupling is avoided. However, as the ice sheet evolves

30 in response to climate change, local climate feedback processes are not captured. Most importantly the interaction of the ice surface between air temperature and precipitation, which in turn affects the surface mass balance. The SMB-feedack process is considered with a dynamic correction to the SMB_{clim} (see sect. 2.4 below). This correction is applied within ISSM and to the surface mass balance derived from different GCM data from the CMIP5 term only.

2.3 Validation of SMB forcing

In order to validate the obtained climatic SMB_{clim} (Eq. 4), the resulting SMB patterns and time series are compared with other available data-sets. Beside the spatial pattern of the surface mass balance, the time series of the integrated SMB over Greenland illustrate what the ice sheet's total surface gains and losses have been over the year from SMB (Fig. 3). The grey shaded box

- 5 and black line depicts the range and the mean SMB between 1981–2010 from Polarportal (polarportal.dk) derived from a combination of observations and a weather model for Greenland (Hirlam-Newsnow). The dashed black line shows the results from the RACMO2.3 product. The integrated SMB magnitude of each GCM is consistent with RACMO2.3 and polarportal data. The drop in SMB after 2000 is present in all three GCMs and RACMO. The decline of SMB roughly corresponds with MAR results forced with the GCM NorESM1-M under RCP2.6 scenario provided from (Fettweis et al., 2013, last column in Tab. 2)
- , although it is not strictly comparable because they use a different GCM climate data. They estimated a loss of -124±100 Gt a⁻¹
 in 2080–2099 relative to 1980–1999.

For HadGEM2-ES the integrated SMB remains around 200 Gt a^{-1} after 2050. The SMB for IPSL-CM5A-LR recovers from 2050 onwards and shows an increase from around 200 Gt a^{-1} to around 350 Gt a^{-1} by 2300. MIROC5 reveals the lowest SMB change over time and recovers after 2050 from 250 Gt a^{-1} to 300–350 Gt a^{-1} by 2300. The SMB of IPSL-CM5A-LR and

15 MIROC5 is by 2300 almost of similar magnitude as present-day.

For the available RACMO2.3 time series we have computed the coefficient of determination r^2 and the mean signed difference (MSD) for surface mass balance, accumulation and melt (Fig.4). The interannual SMB variability agrees well and the MSD oscillates around zero and with values up to $\pm 0.5 \text{ m a}^{-1}$ (Fig.4a). For the time period 1960–2016 the overall surface mass balance difference over the ice sheet between SEMIC and RACMO is almost zero with -0.007 m a⁻¹, 0.016 m a⁻¹ and

- 20 0.0200 m a⁻¹ for HadGEM2-ES, IPSL-CM5A-LR and MIROC5, respectively. These numbers are in the ISIMIP2b project (?). The surface energy balance model SEMIC (Krapp et al., 2017) is applied in order to obtain these anomalies from the GCM data, same range as given by Krapp et al. (2017) for the comparison between SEMIC and MAR. Nonetheless, averaging the MSD over the whole time period the surface accumulation agrees better compared to surface melt (surface accumulation: -0.034 m a⁻¹, -0.031 m a⁻¹, -0.023 m a⁻¹; surface melt: 0.048 m a⁻¹, 0.066 m a⁻¹, 0.061 m a⁻¹). The coefficient of determination
- 25 is larger than 0.8 for all components except with some outliers.

3 Model setup

2.1 Ice flow model

Three-dimensional dynamic variables (velocity, pressure, enthalpy)of Table 2 shows annual mean integrated SMB over the entire GrIS for various periods. Averaged over most of the periods the annual mean integrated SMB is among the model rather

30 similar. Most obvious are the GrIS are approximated using the differences between the GCMs for the period 1997–2016. The year 1997 was identified as the critical time of Greenland's peripheral glaciers and ice caps mass balance decrease **Table 2.** Annual mean integrated SMB (Gt yr⁻¹) covering various periods. Time series of SMB_{clim} for the GCMs are calculated by Eq. 4 for RCP2.6 scenario with overshoot. The column '1.5°C reached' gives an 11-year mean at the characteristic time of overshooting 1.5° C. Anomaly in SMB (Δ SMB) is in 2080–2099 with respect to 1980–1999.

Model	1960–1990	1960–1997	1997-2016	1981-2010	1960-2016	<u>1.5°C reached</u>	ΔSMB
RACMO2.3	402.8	403.4	279.1	363.1	364.8	~	÷.
polarportal	≂	≂	≂	<u>370</u>	≂	~	
$\operatorname{MAR}^{a}_{a}$.≂	.≂	.≂	.≂	.≂	-	-124 ± 100
HadGEM2-ES	400.0	<u>391.2</u>	277.0	358.1	355.2	170.0	-179.2
IPSL-CM5A-LR	408.9	412.5	332.8	403.7	382.2	363.9	-170.4
MIROC5	395.0	398.5	341.2	341.8	380.0	288.4	-80.9

^a MAR forced with GCM NorESM1-M under RCP2.6 scenario (Fettweis et al., 2013)

(Noël et al., 2017). For this period of declining SMB the HadGEM2-ES agrees well to the RACMO2.3 product. In general the compared values over all time periods agree fairly well.

The validation include an analysis of the spatial pattern of SMB. Here we compare exemplary the spatial pattern of RACMO2.3 for the year 1990 against the SMB derived from HadGEM2-ES for the year 1990 (Fig. 5). The maps show, that

5 accumulation and ablation patterns agree reasonably well. The SMB patterns for other GCMs or time slices are qualitatively similar but deviate in absolute values as the annual variability is not coherent among all models.

2.1 Modified RCP2.6 scenario without overshoot

The global climate warming of the selected GCMs exceeds the political target of 1.5°C during the 20th century although the RCP2.6 is the strongest mitigation scenario focussing on negative emissions (Moss et al., 2010). In order to estimate the
overshooting effect on the projected sea level contribution from the GrIS we manually construct a RCP2.6-like scenario without an overshoot assuming an immediate climate stabilisation at that time when 1.5°C is reached. As mentioned before, we identify the time when the global warming reaches 1.5°C in a 11-year moving window above pre-industrial levels. The characteristic times of overshooting 1.5°C for HadGEM2-ES is by 2021; MIROC5 reaches this level by 2041, while IPSL-CM5A-LR by 2009. Before reaching these threshold the unaltered historical and RCP2.6 forcing is applied. The extension of the forcing from

- 15 these characteristic times is of crucial importance. Since the forcing is constructed by using the GCM trends instead of absolute values an arbitrary time period can be used. In order to account for decadal variability and assuming a stabilized climate we reuse the climatic forcing fields from 2250–2280 until the end of the simulation (light grey shaded areas in Fig. 1 and 3). At the characteristic times the three GCMs reveal a SMB that differs up to 200 Gt yr⁻¹ (Column '1.5°C reached' in Tab. 2). While HadGEM2-ES has declined to 170 Gt yr⁻¹, IPSL-CM5A-LR remains with 363.9 Gt yr⁻¹ relatively close to present-day. In the
- 20 following, the modified RCP2.6-like scenario without overshoot is termed as RCP2.6 without overshoot.

2.2 Ice flow model

Ice flow and thermodynamic evolution of the GrIS are approximated using the finite-element Ice Sheet System Model. ISSM uses an incompressible non-Newtonian constitutive relation with viscosity dependent on temperature, microscopic-water content and strain rate, while neglecting the softening effect of damage or impurities. ISSM is designed to use variable elements

- 5 ranging from shallow ice approximation to full-Stokes and has also the capability to perform inverse modelling for inferring basal sliding parameters. ISSM. The model has been applied successfully to both large ice sheets in the past (Bindschadler et al., 2013; Nowicki et al., 2013; Goelzer et al., 2018) and is also used for studies of individual drainage basins of Greenland, e.g. the North East Greenland Ice Stream (Schlegel et al., 2013) (Choi et al.), Jakobshavn Isbræ (Bondzio et al., 2016, 2017) and Store Glacier (Morlighem et al., 2016). Here, we use an incompressible non-Newtonian constitutive relation with viscosity dependent
- 10 on temperature, microscopic-water content and strain rate, while neglecting the softening effect of damage or impurities. The BP approximation to the Stokes momentum balance equation is employed in order to account for longitudinal and transverse stress gradients.

Beside the balance equations, ISSM is specified with kinematic boundary conditions at the upper and lower boundary of the ice sheet. The upper boundary incorporates the climatic forcing, i.e. the surface mass balance and with that the climatic

- 15 forcingice surface temperature, while the base of the ice is specified as both impenetrable with the bedrock and in balance with the rate of melting. Within this study the basal melt rate is not a focus and hence we neither perform sensitivity tests to sliding nor change the basal melt underneath floating tongues or vertical calving fronts of tidewater glaciers. The basal melt rate below ice shelves is parameterised with a Beckmann-Goosse relationship (Beckmann and Goosse, 2003). The unknow-melt-factor is roughly tuned adjusted such that melting rates corresponds to literature values (e.g. Wilson et al., 2017). At the grounded ice
- 20 melting occurs due to Within this study the basal melt rate is not a focus and hence the basal melt underneath floating tongues or vertical calving fronts of tidewater glaciers are not changed. Once the pressure melting point at the grounded ice is reached melting is calculated from basal frictional heating and the difference in heat flux heat flux difference at the ice/bed interface -

At the ice base sliding is allowed everywhere and the basal drag, τ_b , is written using Coulomb friction:

$$\boldsymbol{\tau}_b = -k^2 N \boldsymbol{v}_b,\tag{6}$$

- 25 where v_b is the basal velocity vector tangential to the glacier base and k^2 a constant. The effective pressure is defined as $N = \rho_i g H + \rho_w g h_b$, where H is the ice thickness, h_b the glacier base and $\rho_i = 910 \text{ kg m}^{-3}$, $\rho_w = 1028 \text{ kg m}^{-3}$ the densities for ice and sea water, respectively. We apply water pressure at marine terminating glaciers and observed surface velocities (Rignot and Mouginot, 2012) at land terminating glaciers. A stress-free-traction-free boundary condition is imposed at the ice/air interface.
- 30 Geothermal heat flows into the ice in contact with bedrock (Greve, 2005, scenario hf_pmod2) and adjust dynamically to the thermal state of the base (Aschwanden et al., 2012; Kleiner et al., 2015). The spatial pattern of the geothermal flux is taken from Greve (2005, scenario hf_pmod2). The ice surface temperature includes Dirichlet conditions from the atmospheric forcing explained belowabove.

For all simulations, the ice front is fixed in time, and a minimum ice thickness of 10 m is applied. This implies that calving exactly compensate compensates the outflow through the margins and initially glaciated points are not allowed to become ice-free. However, regions that reach this minimum thickness are assumed to retreat. The grounding line is allowed to evolve freely according to the a sub-grid parameterization scheme, which tracks the grounding line position within the element (Seroussi et al., 2014).

Model calculations are performed on a horizontally unstructured grid with a higher resolution, $l_{\min}l_{\min} = 1 \text{ km}$, in fast flow regions and coarser resolution, $l_{\max} = 20 \text{ km}$, in the interior. The vertical discretisation comprises 15 layers refined to-wards the base where sharing is dominat. See Table 3 for statistics of the different meshes used. Note that mesh sequence 1-3 are only used during initialization while mesh sequence 4 is used for both initialization and the projections presented belowvertical

- 10 shearing becomes more important. The complete mesh comprises 574 056 elements. Velocity, enthalpy and (i.e. temperature and microscopic water content) and geometry fields are computed on each vertex of the mesh using piecewise-linear finite elements. The Courant-Friedrichs-Lewy condition (Courant et al., 1928) dictates a time step of 0.025 yearsfor mesh sequence 4. Using the AWI cluster Cray-CS 400 computer, a simulation with an integration time of 340 years requires ≈ 8 hours on 16 nodes comprised of 36 CPUs.
- 15 Mesh Statistics. mesh l_{\min} l_{\max} number of integration time in sequence (km) (km) elements thermal spin-up (kyr) 1-15-50 117 586 125 2 5 50 192 220 125 3 2.5 35 272 650 25 4 1 20 574 056 15-

2.3 Initial state

5

Future projections of ice sheet evolution first require the determination of the initial state. Different methods are currently used to initialize ice sheets and it has been shown, that the initial state is crucial for projections of ice dynamics (Bindschadler et al.,

- 20 2013; Nowicki et al., 2013; Goelzer et al., 2018). The recent initMIP-GrIS intercomparison effort (Goelzer et al., 2018) focusses on the different initialization techniques applied in the ice flow modelling community and found none of them is the method of choice in terms of a good match to observations or and a long term continuity. All methods are suitable required for modelling the projections of the GrIS planned within CMIP6 (Nowicki et al., 2016) phase phase (Nowicki et al., 2016) on time scales up to a few hundred years. However, while inverse modelling is well established for estimating basal properties, the temperature
- 25 field is difficult to constrain without performing an interglacial thermal spin-up. Furthermore, the thermo-mechanically coupled problem is sensitive to temperature.

In our initialization approach the Here, we setup a hybrid approach between spin-up and inversion scheme to estimate the initial state. The ice sheet geometry is initialized (bed, ice thickness and ice sheet mask) is taken from the mass-conserving BedMachine Greenland data set (Morlighem et al., 2014). The geometric input for thickness and ice sheet mask are masked to

30 exclude glaciers and ice caps surrounding the ice sheet proper. An initial relaxation run over 50 years using zero assuming no sliding and constant temperature ice temperature of -20°C is performed to avoid spurious noise. The A temperature spin-up is then performed using this time-invariant geometryforced with paleo elimatic conditions. As the computational expensive BP approximation is employed, mesh refinements are made at certain points during the whole initialization procedure (see Table 3). The first mesh sequence is starting 125 kyr before present and 1990 and run up to the year 1960. During the 1960

and assumes a spatially constant friction coefficient $k^2 = 50 \text{ sm}^{-1}$ and forced with paleo-climatic conditions. The imposed paleo-climatic conditions is a multi-year mean from the years 1960 to 1990 of the RACMO2 product (Ettema et al., 2009) and offset by a spatially constant surface temperature anomaly for the last 125 kyr based on the GRIP surface temperature history derived from the $\Delta^{18}O$ record (Dansgaard et al., 1993). The initial ice temperature at 125 kyr before 1990 is a steady-state

5 temperature distribution taken from a spin-up with time independent climatic conditions from the reference period 1960–90. The spin-up is done to 1960 in order to start the projections before the critical time of Greenland's peripheral glaciers mass balance decrease (Noël et al., 2017) with an additional buffer of approx. 30 years.

In the subsequent basal-friction inversion, the ice rheology is kept constant using the enthalpy field from the end of the temperature spin-up. As the computational expensive higer-order approximation to Stokes flow is employed, mesh refinements

- 10 are made during the whole initialization procedure (see Table 3). Each mesh sequence The inversion approach infers the basal friction coefficient k^2 in Eq. 6 by minimizing a cost function that measures the misfit between observed and modelled horizontal velocities (Morlighem et al., 2010). Observed horizontal surface velocities are taken from (Rignot and Mouginot, 2012). The procedure of temperature spin-up is run for \approx and inversion is repeated on the subsequent three mesh sequences. The repeated temperature spin-ups starting 125 kyr, 125 kyr and 15 kyr, respectively, and updated with the before 1990 and again
- 15 run up to the year 1960. The initial values for the temperature field at these times are taken from the respective times from the previous mesh sequence; the basal-friction coefficient from the is updated from the inversion on the previous mesh sequence. The mesh sequencing reduces the expense of initialization and produces a sufficiently consistent result in terms of velocity and enthalpy. The final solution on Note that mesh sequence 1-3 are only used during initialization while the final solution of mesh sequence 4 at year 1960 of this procedure is used as initial state for all projections presented below.
- 20 For the hybrid initialization we make the three basic assumptions: (1) The currently observed present-day elevation is valid for the entire glacial cycle: changes in elevation and spatial extent of the GrIS are ignored, (2) the basal friction coefficient obtained from the inversion is valid for the past glacial cycle, and (3) the GRIP record can be applied to the whole ice sheet without spatial variations.

Please note, that similar results from this procedure have been submitted to the ISMIP6 initMIP-Greenland effort (Goelzer et al., 2018), but the simulations were run with the geothermal flux distribution by Shapiro and Ritzwoller (2004) and additionally with a time independent climate forcing representing present-day conditions. However, by using the modified heat-flux

distribution by Greve (2005) Greve (2005, scenario hf_pmod2) we found a generally better agreement to measured basal temperatures at ice core locations(Table ??).

2.4 Input data

30 The present-day ice sheet geometry is taken from the mass-conserving bed from BedMachine Greenland (Morlighem et al., 2014) . Observed horizontal surface velocities (Rignot and Mouginot, 2012) are assimilated to infer the basal friction coefficient. While the geothermal flux distribution is taken from Greve (2005, scenario hf_pmod2),. Basically, the comparison of simulated to observed temperatures at the ice base shows too low temperatures for some locations. Due to the fact, that the applied inversion technique for the friction coefficient allows sliding everywhere, the present day surface temperature based on the

Table 3. Simulated (T_{sim}) and observed basal temperatures (T_{obs}) at ice-core locations GRIP, NorthGRIP, Camp Century, Dye3 and EastGRIPMesh Statistics. Climate forcing: pd-cl = present day climate, p-cl = paleo climate. Geothermal flux: Gr = Greve (2005), SR = Shapiro and Ritzwoller (2004).

mesh sequence	T _{obs} (°C)-l _{min} (km)∼	T _{sim} (°C) ℓ _{max} pd-cl, SR (km)	T _{sim} (°C) number of pd-cl, Gr elements	Tsim (°C) Tsim (°C) integration time in p-cl, SR p-cl, Gr thermal spin-up (kyr)
Camp Century ^a _1	-13.00-15	-12.55_50	-11.79_ 117_586	-14.11 -13.34_125
$\frac{\text{NGRIP}^{b}}{2}$	-2.40 5	-16.76_50	0.00 - <u>192 220</u>	-22.29 0.00 125
GRIP ^c _3	-8.56 -2.5	-20.92_35_	-18.91 _272_650	-21.29 -18.39 25
$\frac{Dye3^d}{4}$	-13.22- 1	0.00-20	-8.41- <u>574.056</u>	0.00 -8.49 15

EeastGRIP ? -2.34 0.00 -14.15 0.00

RACMO2 product (Ettema et al., 2009) and the surface temperature anomaly for the last 125 kyr is based on the GRIP surface temperature, T_s , history derived from the $\Delta^{18}O$ record (Dansgaard et al., 1993). Present day surface temperature and paleo surface temperature anomaly are taken from the SeaRISE webpage². Input data for the surface mass balance is described in the next section portion of deformational shearing may be underestimated, which cannot be proven without any observations

- 5 of basal velocities that are unfortunately not existing at all. However, for our projections on centennial timescales this is a negligible effect (Seroussi et al., 2013).
 - 2.4 Atmospheric forcingAs described above, we aim at using respective output fields (consisting of incoming shortwave radiation SW[↓], longwave radiation LW[↓], near-surface air temperature T_a, surface wind speed u_s, near-surface specific humidity q_a, surface air pressure p_s, snowfall rate P_s, and rainfall rate P_r) of different
- 10 GCMs to derive from global models the respective surface temperature T_s, of the ice sheet and the surface mass balance SMB, as GCMs typically do not provide these ice sheet specific quantities. The GCM output was provided and prepared by the ISIMIP2b project following a strict simulation protocol. Here we targeted in particular peak and decline scenarios, temporarily exceeding a given temperature limit of global warming to 2.0°C or even 1.5°C by the end of 2100 (?). Three different GCMs were used in our study: IPSL-CM5A-LR,
 15 MIROC5-Synthetic and HadGEM2-ES. Figure 1a displays the temporal evolution of the annual global mean
 - near-surface temperature T_a , for those GCMs for the historical simulation up to 2005 continued with dynamic surface mass balance parameterization

As we perform a one-way coupling of the RCP2.6 simulation up to 2300. In order to determine the beginning of overshoot and the onset of cooling we extract characteristic dates in global warming and warming above GrIS. HadGEM2-ES produces

a global temperature rise of more than 1.5°C by 2021; MIROC5 reaches this level by 2028, while IPSL-CM5A-LR by 2009.
 IPSL-CM5A-LR is the only GCM that represents any cooling below that limit by 2300, while MIROC5 oscillates around the

2

limit from the 2090s onward. HadGEM2-ES is approaching 1.5°C towards 2170, while remaining slightly above the limit until 2300.

The enhanced increase in global mean air temperature over polar areas has been termed polar amplification. The factor between temperature increase over Greenland compared to the global temperature increase might be as high as 1.8 to 3.3

- 5 (IPCC, 2013). Temperatures are rising in Greenland above 1.5°C earlier and exceeding a much higher warming value, representing the effect of the polar amplification (Fig. 1b and 2). Tedesco et al. (2016) demonstrated that this may have consequences on surface melt and run-off in extreme melt years. The three GCMs used in this study represent this trend to differing extents. While HadGEM2-ES-climatic forcing the SMB-elevation feedback needs to be considered. Here we rely on the dynamic SMB parameterization developed by Edwards et al. (2014a, b) and previously applied by Goelzer et al. (2013). This
- 10 parameterization assumes that the effect of SMB trends follow a linear relationship

$$SMB_{dyn}(x, y, t) = SMB_{clim}(x, y, t) + b_i(h_s(x, y, t) - h_{fix}(x, y)),$$
(7)

where $SMB_{dyp}(x, y, t)$ and $SMB_{fix}(x, y, t)$ are the SMB values with and IPSL-CM5A-LR are leading by relatively similar factors (warming up to 5°C relative to 1661–1860), MIROC5 reveals a considerably lower polar amplification (up to 3°C relative to 1661–1860). HadGEM2-ES and MIROC5 exhibit a warming of 1.5°C by 2005, while IPSL-CM5A-LR is also

15 crossing the limit as early as 1995. Both HadGEM2-ES and IPSL-CM5A-LR show no decades until 2300 when the annual mean near-surface air temperature of GrIS is falling below 1.5°C warming relative to 1661–1860, whereas MIROC5 is reaching this value by 2110. A striking feature is the higher variability compared to the global mean values.
Summarizing, in terms of global annual mean near-surface temperature evolution MIROC5 represents the lower bound of

our global forcings and IPSL-CM5A-LR represents the upper bound. As the mechanisms creating the polar amplification may be represented to different levels in the GCMs, this trend might be different across the GrIS. While MIROC5 is also across the GrIS the lower bound, highest near-surface temperatures are found for HadGEM2-ES. In terms of overshooting scenarios, HadGEM2-ES represents this behaviour best for overshooting 1.5°C, while IPSL-CM5A-LR rather represents an overshooting

of 2°C for about 160 years from 2040 onwards.

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To derive ice sheet specific quantities, we use the Surface Energy balance Model of Intermediate Complexity (SEMIC) as

- 25 developed and applied to the GrIS by Krapp et al. (2017). These authors perform a particle-swarm optimization to calibrate model parameters and validate them against the regional climate model MAR. Due to the fact that Krapp et al. (2017) performed calibration over the GrIS, we adopt the parameters presented in their analysis here. However, we choose a more sophisticated albedo parameterization than was described by Krapp et al. (2017) that is dependent on the actual melt rate (Denby and Greuell, 2000) . This reflects the alteration of snow-surface properties by metamorphosis of the snow as function of air temperature. SEMIC
- 30 is driven by the daily input of the GCMs while the output is a cumulative surface mass balance and a mean surface temperature over each year.

Since the GCM and the ISSM are run on a different resolution, without taking height changes into account, respectively. The surface elevation changes are taken from ISSM elevation $h_s(x, y, t)$ while running the simulation and a reference elevation $h_{\text{fix}}(x, y)$. In our setup the reference elevation correspond to the ISSM ice surface elevation at the initial state. In this parameterization the SMB gradient b_i is dependent of both location and sign. It can take four values and a downscaling procedure is applied to the atmospheric forcing fields. First the atmospheric fields are conservatively interpolated from the GCM grid onto a regular high resolution 0.05separation is made on the location relative to 77° grid. We run the SEMIC model on a regular high resolution 0.05° grid, but the output fields are subsequently conservatively interpolated on the unstructured ISSM grid.

To account for the difference in ice sheet surface topography between GCMs and ISSM, we initially perform corrections for several quantities denoted by $(\cdot)^{cor}$, while the variables are named according to the SEMIC convention. We basically following the suggested corrections by Vizcaíno et al. (2010)-

$(\cdot)^{\rm cor} = (h_s^{\rm ISSM-pd} - h_s^{\rm GCM}) \gamma_{(\cdot)},$

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- 10 with the lapse rates $\gamma_{(\cdot)}$ shown in Table 1 and $h_s^{\text{ISSM-pd}}$ N and on the sign of the present-day surface elevation. The surface pressure is not corrected. Subsequently, SEMIC computes the ice-surface temperature T_s and the surface mass balance SMB based on these corrected input values. Furthermore, we apply a dynamic correction to the SMB (SMB_{dyn}) in which we account for the effect of the elevation change during the simulations (see below). This correction is applied within ISSM and to the surface mass balance term only. Lapse rates and height-desertification relationship for initial corrections of GCM output fields
- 15 near-surface air temperature T_a , precipitation of snow P_s , precipitation of rain P_r , and downward longwave radiation LW^{\downarrow} used as input for SEMIC. Here, $h^{\text{ref}} = 2000 \text{ m}$ and $\gamma_p = -0.6931 \text{ km}^{-1}$ is the desertification coefficient. variable lapse rate γ and desertification relationship reference $T_a 0.74 \text{K}/100 \text{ m}$ Erokhina et al. (2017) $LW^{\downarrow} 2.9 \text{W} \text{ m}^{-2}$ Vizcaíno et al. (2010) P_s , P_r $\exp(\gamma_p[\max(h_s^{\text{ISSM-pd}}, h^{\text{ref}}) - h^{\text{ref}}]) \quad \forall -h_s^{\text{GCM}} \leq h^{\text{ref}}$ Vizcaíno et al. (2010) P_s , $P_r \exp(\gamma_p[\max(h_s^{\text{ISSM-pd}}, h^{\text{ref}}) - h_s^{\text{GCM}}]) \quad \forall -h_s^{\text{GCM}} \leq h^{\text{ref}}$ Vizcaíno et al. (2010) P_s , $P_r \exp(\gamma_p[\max(h_s^{\text{ISSM-pd}}, h^{\text{ref}}) - h_s^{\text{GCM}}]) \quad \forall -h_s^{\text{GCM}} \leq h^{\text{ref}}$ Vizcaíno et al. (2010) P_s , $P_r \exp(\gamma_p[\max(h_s^{\text{ISSM-pd}}, h^{\text{ref}}) - h_s^{\text{GCM}}]) \quad \forall -h_s^{\text{GCM}} \leq h^{\text{ref}}$ Vizcaíno et al. (2010) P_s , $P_r \exp(\gamma_p[\max(h_s^{\text{ISSM-pd}}, h^{\text{ref}}) - h_s^{\text{GCM}}]) \quad \forall -h_s^{\text{GCM}} \leq h^{\text{ref}}$ Vizcaíno et al. (2010) P_s , $P_r \exp(\gamma_p[\max(h_s^{\text{ISSM-pd}}, h^{\text{ref}}) - h_s^{\text{GCM}}]) \quad \forall -h_s^{\text{GCM}} \leq h^{\text{ref}}$ Vizcaíno et al. (2010) P_s , $P_r \exp(\gamma_p[\max(h_s^{\text{ISSM-pd}}, h^{\text{ref}}) - h_s^{\text{GCM}}]) \quad \forall -h_s^{\text{GCM}} \leq h^{\text{ref}}$ Vizcaíno et al. (2010) P_s

20 2.4.1 Atmospheric forcing of future scenarios

The output fields (SMB-SMB. This separates regions of largely different sensitivity, namely the ablation zone with a larger gradient compared to the accumulation zone, and T_s) from the SEMIC model are not directly used to force the ISSM. Although the initial state of the ISSM matches the current observations (both ice sheet geometry and surface velocities) very well and the unknown parameters are well constrained due to the data assimilation, a more sensitive ablation zone in the South compared to the North. While a complete uncertainty analysis is given by Edwards et al. (2014a), only the maximum likelihood gradient

set, $\boldsymbol{b} = (b_{\boldsymbol{p}}^N, b_{\boldsymbol{p}}^N, b_{\boldsymbol{p}}^S, b_{\boldsymbol{p}}^S)$, is used here:

 $b_p^N = 0.085 \text{ kg m}^{-3} \text{ a}^{-1},$ $b_n^N = 0.543 \text{ kg m}^{-3} \text{ a}^{-1},$ $b_p^S = 0.063 \text{ kg m}^{-3} \text{ a}^{-1},$ $b_p^S = 1.890 \text{ kg m}^{-3} \text{ a}^{-1},$ 30 $b_n^S = 1.890 \text{ kg m}^{-3} \text{ a}^{-1},$ where the subscripts (p,n) and the superscripts (N,S) indicate the evaluation of the SMB sign and the region separation, respectively.

A shortcoming of the performed hybrid initialization is, that usually a fixed initial ice sheet causes a model drift when imposing the ice thickness equation. This is a result from using an ice sheet that is not in perfect equilibrium with the applied

5 SMB and ice flux divergence.

The fixed ice sheet approach during the initialization makes it possible to use forcing data from high resolution climate models that were run on the same ice sheet mask. As a reference SMB field we relied on the downscaled RACMO2.3 product (Noël et al., 2016) whereby a model output was averaged for the time period 1960–1990, denoted $\overline{\text{SMB}}(1960 - 1990)_{\text{RACMO}}$. When using the SMB fields from SEMIC directly, the model drift is much larger compared to using RACMO2.3 SMB (not

10 shown here).

An initial unforced relaxation run from 1960 to 2060 demonstrate the effect of model drift (black line in Fig. 9). Once the We utilize the local ice thickness imbalance once the ice sheet is released from its fixed topography , it gains of about 3% of its initial volume, which is typical for ice sheet models that are based on data assimilation. We utilize the local ice thickness imbalance from the relaxation runand add the from an one year unforced relaxation run, i.e. $\Delta SMB(x, y, t) = 0$ in Eq. 5. The

- 15 resulting $\partial H/\partial t$ is subtracted as a surface mass balance correction, $SMB_{corr}(x, y, t)SMB_{corr}(x, y)$, for the further runs . In doing so, the subsequently performed control run with the imposed correction shows, that the model drift could be reduced by (similar as in Price et al. (2011); Goelzer et al. (2018)). However, instead of assuming an zero SMB anomaly one could calculate the anomaly with a GCM input from the CMIP5 pre-industrial scenario. But given the small temperature changes the SMB anomaly will be close to zero and the calculated ice thickness imbalance is unlikely affected by it. However, the final
- 20 <u>SMB correction is on average 0.01 m a⁻¹, with 5% of the total ice-sheet area having a correction of >25 m afactor about 0.6 at 2060 (grey line in $^{-1}$, predominantly at marine-terminated ice margins and ice streams (Fig. 9).</u>

In order to account for the future climate forcing we calculate anomalies from the SEMIC output that were added on the reference SMB field and SMB correction field. The SMB that is used as future climate forcing read as 6). For these locations the synthetic SMB correction can be considered as an additional ice thinning or thickening from dynamic discharge that is not

25 intrinsically simulated. A performed control run with the imposed SMB correction exhibits a negligible model drift in terms of sea level equivalent (SLE, black dashed line in Fig. 9 and section 3.2).

The final surface mass balance that the numerical ice flow model sees is composed of several components

$$\mathrm{SMB} = \underline{\mathrm{SMB}}_{\mathrm{clim}}(x, y, t) = \underline{\mathrm{RACMO}}^{(1960-1990)}(x, y) + \Delta_{\sim} \mathrm{SMB}_{\mathrm{corr}}(x, y, \underline{t}) + \mathrm{SMB}_{\underline{\mathrm{corr}}\,\mathrm{dyn}}(x, y, t),$$
(8)

with the anomaly defined as-

30
$$\Delta \text{SMB}(x, y, t) = \text{SMB}_{\text{SEMIC}}(x, y, t) - \overline{\text{SMB}}_{\text{SEMIC}}^{(1960-1990)}(x, y),$$

where t={

3 Results

3.1 Present day elevation and velocities

Figure 7 displays exemplary the observed and simulated velocities for the year 2000 (defined here as present day) after a period of forcing with HadGEM2-ES from 1960 , 1961, ..., 2299} and GCM={HadGEM2-ES, IPSL-CM5A-LR, MIROC5}.

- 5 Note that the historical scenario is run from 1960–2005 and the RCP2.6 scenario from 2006–2299 (?). The same equations hold for the ice temperature imposed on the ice-surface without acorrection term. By doing so, onwards. The resulting horizontal velocity field captures all major features well, including the North East Greenland Ice Stream (NEGIS). Outlet glaciers terminating in narrow fjords in the southeastern region are resolved, however, slow moving areas tend to retreat below minimum ice thickness and with that the ice extent in this area is underestimated. However, ice surface elevations agree fairly
- 10 well (Fig. 8a). In general large outlet glaciers like Kangerdlusuaq, Helheim and Jakobshavn Isbræ reveal lower velocities in their fast termini that reflects the high RMS of about 390 m a^{-1} (Fig. 8b). Compared to the low RMS values of $<20 \text{ m a}^{-1}$ for the unforced control experiment produces identical behaviour for each GCM.Results for future projection depend only on the atmospheric GCM input, or similarly SEMIC output, and therefore the results can be compared quantitatively AWI-ISSM results on the regular 5 km grid given in Goelzer et al. (2018), the analysis here was done on the original native grid with the
- 15 high resolution in fast flow regions and on other hand the model was already run forward in time.

3.1.1 Dynamic surface mass balance parameterization

The GCM data from the ISIMIP2b simulation protocol were bias corrected onto the regular 0.5° EWEMBI grid (?), where the surface elevation of the ice sheet is fixed in time. In order to account for ongoing height changes between the ISSM surface and

20 3.2 Projections of mass change

After passing the assumed critical time of decreasing SMB of GrIS and the present day state, the GCM surface we rely on the dynamic SMB parameterization by Edwards et al. (2014a, b) and previously applied by Goelzer et al. (2013). This parameterization assumes that the effect of SMB trends follow a linear relationship

$\mathrm{SMB}_{\mathrm{dyn}}(x,y,t) = \mathrm{SMB}_{\mathrm{fix}}(x,y,t) + b_i(h(x,y,t) - h_{\mathrm{fix}}(x,y)),$

- 25 where $SMB_{dyn}(x,y,t)$ and $SMB_{fix}(x,y,t)$ are the SMB values with ice sheet experienced a warming and associated mass loss from surface mass balance. Projections of the evolution of SLE of the ice sheet under RCP2.6 scenario with overshoot until 2100 and without taking height changes into account, espectively ($SMB_{fix}(x,y,t)$ is equal to SMB(x,y,t) in Eq. 4). The surface elevation changes are taken from the ISSM elevation, h(x,y,t) while running the simulation and a reference elevation $h_{fix}(x,y)$ 2300 are shown in Fig. 9 for each GCM (straight lines) and Table 4. The simulated volume above floatation
- 30 is converted into the total amount of global sea level equivalent (SLE) by assuming an ocean area of about 3.618×10^8 km².

Although the control run shows a negligible model drift in terms of SLE, the RCP2.6 projected SLE is corrected by the control

run. By 2100, the present-day surface provided by the BedMachine Greenland dataset (Morlighem et al., 2014)).

In this parameterization the SMB gradient b_i , is dependent of both location and sign. It can take four values and a separation is made on the location relative to 77°N and on the sign of the SMB. This separates regions of largely different sensitivity, namely

5 the ablation zone with a larger gradient model range of Greenland sea-level contributions is between 21.3 and 38.1 mm with an average of 27.9 mm and by 2300 between 36.2 and 85.1 mm with and average of 53.7 mm. Compared to Fürst et al. (2015) our mean values are lower but still in their model variability.

The evolution of the mass change is showing distinct behaviours: between 1960–2000 almost no change for HadGEM2-ES and IPSL-CM5A-LR while MIROC5 is gaining mass; a change in trend with a minor increase between 2000–2015 and a steep

- 10 increase from then on for HadGEM2-ES and IPSL-CM5A-LR; SLE increase for MIROC5 is more gently. The steep rise in SLE for HadGEM2-ES and IPSL-CM5A-LR is linked to the steep reduction in SMB for both models at the same time. The kink of SLE in HadGEM2-ES and IPSL-CM5A-LR around 2050 is caused by a positive SMB anomaly (compare Fig. 3). Also MIROC5 represents this peak in SMB, however slightly later, around 2060. These short-term drops in SLE are linked to positive anomalies in SMB. For HadGEM2-ES the ice sheet contribution until 2300 generally increases continuously while for
- 15 IPSL-CM5A-LR and MIROC5 the increase levels off. This is an intriguing effect as HadGEM2-ES and IPSL-CM5A-LR are showing in terms of warming over GrIS a similar behaviour (Fig. 1). In fact, the SMB of IPSL-CM5A-LR recovers from 2050 onwards (Fig. 3), while the SMB of HadGEM2-ES remains on a low level

For the RCP2.6 scenario without overshoot the behaviour of SLE for HadGME2-ES is similar but with lower values. The SLE for MIROC5 is by 2100 approx. 5 mm lower but approaches the same value at 2300 without attaining a pronounced

20 plateau. A striking feature is the much lower SLE estimated from IPSL-CM5A-LR which never exceeds a value of 10 mm and gains mass about 2225 onwards. The average SLE from all three GCMs is 17.4 mm by 2100 and 37.1 mm by 2300, that is approximately one third less compared to the accumulation zone, and RCP2.6 scenario with overshoot.

The observed sea level contribution between 2002 and 2014 is 0.73 mm a^{-1} (Rietbroek et al., 2016). In the same period the simulated contribution is only 0.16 mm amore sensitive ablation zone in the South compared to the North. While a complete uncertainty analysis is given by Edwards et al. (2014a), only the maximum likelihood gradient set, $\boldsymbol{b} = (b_p^N, b_n^N, b_p^S, b_n^S)$, is used

here:-

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- $b_p^N = 0.085 \,\mathrm{kg}\,\mathrm{m}^{-3}\,\mathrm{a}^{-1},$
- $\underline{b_n^N} = 0.543 \,\mathrm{kg}\,\mathrm{m}^{-3}\,\mathrm{a}^{-1},$
- $b_p^S = 0.063 \,\mathrm{kg}\,\mathrm{m}^{-3}\,\mathrm{a}^{-1},$
- **30** $\underline{b_n^S} = 1.890 \,\mathrm{kg \, m^{-3} \, a^{-1}},$

where the subscripts (p,n) and the superscripts (N,S) indicate the evaluation of the SMB sign and the region separation, respectively⁻¹ for HadGEM2-ES, 0.17 mm a⁻¹ for IPSL-CM5A-LR and lowest for MIROC5 with 0.13 mm a⁻¹. In order to assess a potential temporal lag between simulated and observed value, mean values of similar periods are calculated (Fig. 10).

 Table 4. Contribution of the Greenland ice sheet to global sea-level change by 2100 and 2300 in mm SLE under RCP2.6 scenario with and without overshoot.

Model / Study	2100 with overshoot	without overshoot	2300 with overshoot	without overshoot
HadGEM2-ES	38.1	29.6	<u>85.1</u>	<u>.66.9</u>
IPSL-CM5A-LR	24.4	<u>7.5</u>	36.2	3.4
MIROC5	21.3	15.0	<u>39.9</u>	40.9
Average	27.9	17.4	53.7	37.1
Fürst et al. (2015)	42.3±18.0	~	<u>88.2±44.8</u>	~

None of the models reach the observed value; HadGEM2-ES reaches a maximum value of 0.59 mm a^{-1} 13 years later; IPSL-CM5A-LR a value of 0.48 mm a⁻¹ 12 years later and MIROC5 a value of 0.36 mm a⁻¹ 40 years later. For the RCP2.6 scenario without overshoot, the values are smaller.

3.3 Forcing Future climatic forcing fields

- 5 For the different GCMs used we compute ice-surface temperature ice surface temperature *T_s* differences between 2100/2300 and 2000 as a multi-year mean over five years do reduce the high-inter-annual variability . Figure 11displays the resulting fields for areas that remain ice covered by the year 2100. (Fig. 11). HadGEM2-ES leads to increase an increase in temperatures along the northern margins by up to 4°C. By 2100 the Western areas and vast majority of the ice sheet exceed 2°C of warming. The only pronounced warming by 2300 is in the Northwestern regions, while the ice sheet surface temperatures decreases
- 10 significantly decrease from 2100. IPSL-CM5A-LR reveals exhibits a significantly different pattern. This simulation produces pronounced warming in the center (up to 3° C) and in the Southeast (up to 4° C) of the ice sheet, while the Northern areas are only moderately warming around 1° C during the 20th. The pattern is similar in 2300, with a cooling in the West. The cooling after 2100 is by far less than in HadGEM2-ES. The least warming is found in MIROC5, which even exhibits cooling in the southern areas by about -1°C and +1°C is only reached in 2100 in the North. By 2300 the entire ice sheet experiences warming;
- 15 however this warming is quite moderate compared to the other two GCMs. The low magnitude of warming compared to global warming let us infer that the mechanisms of polar arctic amplification is not well represented in MIROC5. Concluding, we find the-

Although we do not have a measure to judge future climate warming trends, but with respect to the Arctic amplification phenomena the most plausible distribution of surface warming to be those is produced by HadGEM2-ES and MIROC5, while

20 only HadGEM2-ES also reaching a plausible magnitude of warming with overshooting the global mean values. IPSL-CM5A-LR is spatially and temporally experiencing the greatest-largest warming; however, the distribution does not appear particularly plausible. is not in agreement with the Arctic amplification. However, the assessment of the GCMs is in line with skill tests performed by Watterson et al. (2014). They assigned skill cores by comparing individual GCM output data against re-analysis data. The analysis indicates that all 25 models have a substantial degree of skill, however, HadGEM2-ES is ranked in the top, MIROC5 in the middle, and IPSL-CM5A-LR in lower part.

Figure 12 presents in a similar fashion as Fig. 11 the differences in SMB between 2100/2300 and 2000 as as-multi-year mean over five years each. The difference in SMB 2100-2000-2100-2000 of HadGEM2-ES indicates a similar pattern to that

- 5 presented by Krapp et al. (2017) using MAR (Fettweis et al., 2013). Increasing SMB in the Eastern eastern part of the ice sheet with a maximum in the Southern southern half of the ice sheetis-; at the ice sheet margins ablation is increased. The same pattern is characteristic for 2300-2000as well as 2100-2000. Both time periods indicate small glacier vallies in the Southeast and Northwest are exhibiting a strong increase in SMB. This effect arises from the time dependent SMB _{corr} which is in, but with a further increase of melting and decrease of accumulation in the years 2100 or 2300 much smaller than in the year 2000.
- 10 After 2100, the SMB is reduced, center of the ice sheet. The SMB is reduced in the center, leaving a wide area with differences in SMB of 0.5 m a^{-1} and more, except for the ablation at the ice sheet margin. Moreover, most evident is a decreasing SMB in the Northeast. The SMB difference of IPSL-CM5A-LR is showing an extreme pattern, with SMB reduction as well as increase exceeding \pm a similar pattern with enhanced amplitudes compared to HadGEM2-ES, in particular, an the southwestern margin; melting in the Southwest is increased up to 1 m a⁻¹. The In contrast a SMB gain is concentrated in the center-East and similar
- 15 for HadGEM2-ES within the glacier vallies in Southeast and Northwest. The trend in Δ SMB is continuing after 2100, with an even wider area experiencing Northwest by 2300; the margin in the northwest is experiencing a SMB increase of +1 m a⁻¹ in the high accumulation are in the east, while the North is experiencing less accumulation than in the 21st century. The most astonishing result is the Δ SMB pattern in MIROC5. Increasing SMB along the western southwestern and southern margins in contrast to gently decreasing SMB in the southwest, center of the ice sheet. By 2300 Δ SMB is be far less in the period
- 20 2300–2100, however, the pattern remains. Similar to changes in temperature, we find HadGEM2-ES to be a GCM with most plausible patterns in the pattern changes and SMB is generally increasing in the East and decreasing at the western margins; the magnitude of Δ SMB - A distinct pattern for all GCMs is a pronounced reduction in SMB at the grounding zone of 79°N Glacier and increasing SMB over many glacier valleys in the Southwest and Northeast.
- Beside the pattern of the surface mass balance, the magnitude of the mean SMB over Greenland is a quantity of interest.
 25 Therefore, we present a time series of SMB as a five year running mean which is computed as mean over the present day ice covered area (Fig. 3). The grey shaded box and black line depicts the range and the mean SMB between 1981–2000 from Polarportal (polarportal.dk) derived from a combination of observations and a weather model for Greenland (Hirlam-Newsnow). Although our simulated order of magnitude of SMB is broadly consistent with their range, differences more than hundred Gt a⁻¹ occur, which is quite large. There appears to be no covariance of SMB over time between the GCMs. Periods of
- 30 positive accumulation anomalies are not coincident for the three GCMs. However, the drop in SMB after 2000 is present in all three GCMs. Each GCMs indicates decades of strong accumulation anomalies which are compared with mass loss below. IPSL-CM5A-LR is projecting negative SMB for a large number of years; however even MIROC5 is obtaining negative SMB for numerous years and only is less compared to HadGEM2-ES is exhibiting few years of negative SMB. Despite the strong variability over time, the underlying pattern is a recovery of the SMB to values of about 250 Gt a⁻¹ by 2300.

4 Projections

3.1 Present day elevation and velocities

Figure ?? displays exemplary the observed and simulated velocities for the year 2000 after a period of forcing with IPSL-CM5A-LR from 1960 onwards. The resulting horizontal velocity field captures all major features well, including the North East Greenland

- 5 Ice Stream (NEGIS). Outlet glaciers terminating in narrow fjords in the southeastern region are resolved, however, slow moving areas tend to retreat below minimum ice thickness and with that the ice extent in this area is underestimated. This is also true for slow moving regions in the eastern to northeastern areas. In general large outlet glaciers like Kangerdlusuaq, Helheim and Jakobshavn Isbræreveal lower velocities in their fast termini. In general the glaciers tend to have a wider area of medium velocities further upstream in the catchment. The numerous glaciers in the western region are all well resolved, with the overall 10 trend of underestimating velocities at the termini.
 - 3.1 Mass loss

To convert the simulated volume above floatation into the total amount of global sea level equivalent (SLE) we assume an ocean area of about 3.618×10^8 km². Projections of the evolution of SLE of the ice sheet until 2100 and 2300 are shown in IPSL-CM5A-LR.

15 3.1 Ice thickness change and dynamic response

Extensive marginal thinning is experienced by forcing the ice sheet with HadGEM2-ES and IPSL-CM5A-LR (Fig. 9. In addition to the projections for different GCMs we present our control run (grey colour). The model drift is leading to a negative contribution to sea level, resulting in rather conservative mass loss estimates, as the drift accounts for -16.2 mm by 2100. All values for sea level contribution are not corrected with the model drift. Figure 9 includes vertical lines which represent

- 20 the onset of overshooting of 1.5°C (dotted-dashed lines) in the global annual mean near-surface air temperature, as well as crossing of 1.5°C (dashed lines) over GrIS. The evolution of the mass loss is showing distinct behaviours: between 1960–2000 a reduction, a change in trend with a minor increase between 2000–2015 and a steep increase from then on for HadGEM2-ES and IPSL-CM5a-LR; SLE increases for MIROC5 is more gently. The steep rise in SLE for HadGEM2-ES and IPSL-CM5a-LR is linked to the steep reduction in SMB for both models at the same time. The kink of SLE in HadGEM2-ES and 13). In
- 25 contrast to the mass loss near the margin the interior shows increased thickening; IPSL-CM5A-LR around 2050 is caused by a positive SMB anomaly (compare Fig. 3). Also MIROC5 represents this peak in SMB, however slightly later, around 2060. These reductions in SLE are not linked to the end of an overshooting of the global temperature. Similar to this, all short-term drops in the SLE are linked to positive anomalies in SMB. By ~2230 the differences in SMB between the three GCMs is considerably reduced and also the inter-annual variability has decreased. This is linked to the end of overshooting in
- 30 global temperatures in HadGEM2-ES and IPSL-CM5A-LR. The cumulative SLE does in that time period approach a plateau for MIROC5 and IPSL-CM5A-LR, while for HadGEM2-ES the ice sheet contribution is still increasing. This is potentially

an effect of ice dynamics that may be underrepresented with the forcings from MIROC5 and IPSL-CM5A-LR reveals more thickening in the interior. Generally the pattern correlates with observations (Helm et al., 2014) except that Petermann and Kangerdlusuaq glaciers shows an opposite trend.

Forcing the ice sheet with HadGEM2-ES leads to a mass loss that is concentrated in the Western and Southwestern regions of

- 5 the ice sheet with moderate elevation reduction in the Eastern region and an increase in elevation in the center-North (Fig. 13). IPSL-CM5A-LR forcing is to a gradient pattern with high elevation reduction in the West and increase in ice sheet height in the East. In particular the catchments of Helheim and Kangerdlusuaq glaciers are showing a false trendcompared to observations. With a forcing of MIROC5 the pattern of the elevation change is more similar to HadGEM2-ES result with a slight shift of the maximum elevation and a general lower magnitude of elevation change. Compared to HadGEM2-ES the south experience
- 10 more elevation reduction in the higher elevated parts, whereas HadGEM2-ES is showing a pronounced surface lowering at the coastal margins. In conclusion, the elevation change resulting from HadGEM2-ES appears most plausible in pattern and magnitude different with thinning in the southern center of the ice sheet; the northern center experienced thickening. Although thinning occurs at the margin it is less extensive compared to the other GCMs. The ice tongues of Petermann, Ryder and tongue 79°N glaciers are Glacier is in all forcings threatened in their existence, even with the moderate forcing of MIROC5.
- 15 Kong Christian IX Land vanish nearly entirely in the simulations forced with HadGEM2-ES and also the area in vicinity of the Renland ice cap would become ice free in this projection by 2100. All three GCM forcings lead to a spot of elevation drop in the north around CH Ostenfeld Glacier which is suspicious, as there is no link to any SMB forcing present in this area in all three GCMs. We expect this to be an effect of errors in vertical ice velocities in this area.
- The observed sea level contribution between 2002 and 2014 is 0.73 mm a⁻¹ (Rietbroek et al., 2016), while we find in the same period only 0.21 mm a⁻¹ for HadGEM2-ES, as low as 0.13mm a⁻¹ for IPSL-CM5A-LR and largest for MIROC5 with 0.26 mm a⁻¹. In order to assess with which temporal lag our simulations are reaching the observed value, we present in Fig. 10 mean values of a similar period of time. HadGEM2-ES reaches the observed values 5-6 years later, IPSL-CM5A-LR about 9 years and MIROC5 about 33-35 years. In general the comparison with observations obey the drawback that the emission scenarios are based on emissions cuts that have not yet been fully set into practise. Thus the observations show a response of
- 25 the ice sheet to an emission scenario that is different to our forcing and this not only due to elimate models capabilities, but due to differences in prescribed RCP and real RCP. This would result at least in a temporal lag.

3.2 Acceleration

The response of ice velocities to atmospheric response of ice velocities to RCP2.6 forcing is presented in Fig. 14, where the change in horizontal surface velocities is shown for all scenarios as a difference between 2100–2000 and 2300–2000 (each as

30 five year mean). All GCM forcings lead to deceleration of the glaciers in the west and southeast, while glaciers in the north and northeast accelerate. By 2300 HadGEM2-ES For all GCM forcings the ice response shows relatively the same behaviour. The NEGIS, Jakobshavn Isbræ, Helheim, Ryder glaciers and IPSL-CM5A-LR project a slight increase in flow speeds in the higher elevated areas indicating a shift in future ice divide positions. A common pattern among all GCM forcings is an acceleration of NEGISand in particular 79°N, ranging into both branches of this glacier by 2300. Also Ryder glacier and Hagen Bræ experience among all simulations an acceleration.

Acceleration acceleration; deceleration is present at Petermann and Kangerdlusuaq glaciers. However, the magnitude of response is among all models different. Most prominent at the western margin where HadGEM2-ES lead the strongest acceleration

5 while MIROC5 to the lowest. Though, the acceleration of Jakobshavn Isbræ is present in our simulations, however, not to the extent of the observations (Joughin et al., 2014). This is due to the lack of forcing with calving rates in our simulations, which has been key for reproducing the observed acceleration and retreat in Bondzio et al. (2017).

Helheim Glacier experience in nearly all simulations an acceleration in its main trunk, while its upstream catchment is decelerating. The glaciers in the southwest and Kangerdlussaq Glacier are decelerating in our projections. This is corresponding

- 10 to elevation increase in the south-east. We suggest this to be an effect of the SMB in this area, which appears to be too large. Also the synthetic SMB is quite high in this area undermining this to be an effect of overestimated SMB. Helheim Glacier acceleration is thus likely a dynamic response by its special bed topography which is not levelled out by artificially high SMB. Also in the western areas, we find nearby glaciers altering between acceleration and deceleration that indicates their response to geometric settings at their base. This is also exemplifying that our model is able to resolve the glacier valleys well.
- 15 Our estimated results of a sea level contribution are substantially higher than results by Fürst et al. (2015). They-

4 Discussion

Fürst et al. (2015) performed a comprehensive ensemble study for a suite of 10 atmosphere and ocean general circulation models <u>GCMs</u> (HadGEM2-ES, IPSL-CM5A-LR and MIROC5 included) and four representative concentration pathway different <u>RCP</u> scenarios. For the RCP2.6 scenario they estimate <u>a an abated</u> sea level contribution of $42.3\pm18.0 \text{ mm} \cdot a^{-1}$ by 2100 and

- 88.2±44.8 mm a⁻¹ by 2300. At least for Our averaged result of a sea level contribution under RCP2.6 forcing is slightly lower but still in their ensemble variability. The resultant projection by Fürst et al. (2015) included contributions from lubrication, marine melt and SMB-coupling while ours account for SMB forcing only. The lubrication effect was diagnosed to have a negligible effect on the overall mass budget, but the oceanic influence on the total ice loss explains about half of the mass loss for RCP2.6. Since a future ocean forcing and calving front retreat is not considered here, the response of the ice sheet is likely
- 25 underestimated here. By 2010 the cumulative ice discharge for HadGEM2-ES contributes with about 15% to the ice loss. By 2100 and 2300 the contribution is below 3 and 7%, respectively and becomes negligible. For IPSL-CM5A-LR and MIRCO5 the abated contribution with the warming peak in this century is consistent. Although, they have an future ocean forcing included they estimate a lower contribution. In fact, MIROC5 the cumulative effect of ice discharge shares less than 10% of the total mass budget by 2010 and 2100 but increases towards 17% by 2300. The different behaviour can be explained by the interaction
- 30 with the SMB and ice dynamics as the effect of the ocean forcing is not dominant and tend to decrease with a shrinking ice sheet that loose the contact to the ocean. A major difference between our models is certainly the resolution, as our model does resolve the outlet glaciers reasonably well. However, this does so far not contribute too strongly, as our setup does not apply particular strong ocean forcings and lacks any additional lubrication effects relative importance of outlet glacier dynamics decreases

with increasing surface melt (Goelzer et al., 2013; Fürst et al., 2015). Increased ice discharge causes dynamic thinning further upstream, lowering of the ice surface and thereby intensifies surface melting due to the associated warming of the near surface. Surface melting in turn competes with the discharge increase by removing ice before it reaches the marine margin. The simulated increase of ice discharge for IPSL-CM5A-LR and MIROC5 is therefore linked to the recovery of SMB of the

5 course of the 22nd century. Still, the SMB remains the dominant factor for mass loss. The speed-up observed from all scenarios merely transport ice form the interior but is melted before it reaches the ice sheet margin. However, the values for sea level contribution of this study may serve as a lower bound, as processes proven to play a major role in GrIS mass loss are not yet represented by the model.

The question why our values are substantially higher needs to be assessed for two different aspects, one is the models

- 10 sensitivity, the other one is the difference in forcing. Compared Additionally, the calculation of the surface mass balance are based on different methods. Fürst et al. (2015) rely on the rather simple and empirical derived PDD scheme, while we use an more advanced energy-balance approach. So far the sensitivity of melting to warming of these class of models is not well understood. Comparisons of PDD models and energy-balance models suggested that the former are too sensitive to climate change and produce a larger runoff response (van de Wal, 1996; Bougamont et al., 2007; Graversen et al., 2011). On
- 15 the other hand Goelzer et al. (2013) attempted to make a robust comparison and find that a PDD model underestimates sea level rise by 14–31% compared to MAR. An Assessment of the SMB and its impact on sea level contribution calculated by the PDD scheme in Fürst et al. (2015) and the SEMIC model from this study cannot be drawn, because of the strong interaction between ice loss, ice dynamics and external forcings. As the cumulative discharge rates in the mass budget are higher compared to Fürst et al. (2015) may indicate a lower SMB forcing. However, compared to other models that participate in the initMIP
- 20 initMIP-GrIS exercise (Goelzer et al., 2018), our model is not in general setup is whether on the higher end of the nor of the lower spectrum of estimated mass loss. We Additionally, we have conducted SeaRISE experiments similar to Bindschadler et al. (2013)(not shown here), which showed us that we are within the spread among the modelswith higher sensitivity to climate forcing. Together with selecting, in particular, for the amplified climatic scenarios C1, C2, and C3 (not shown here).

The modified RCP2.6 scenarios with an pronounced overshooton purpose, this is very likely to lead to higher values for mass

- 25 loss scenario without overshoot projected a sea level contribution that is on average about 38% and 31% less by 2100 and by 2300, respectively. For HadGEM2-ES and MIROC5 the partition of the mass budget is relatively similar to the scenario with overshoot but with a slightly increased cumulative discharge. For IPSL-CM5A-LR the behaviour is more irregular. It gains mass during the last century, as a result from an increasing SMB which is partly compensated by enhanced ice discharge up to 40%. However, the spread of sea level contribution is much larger compared to the RCP2.6 scenario with overshoot. In particular,
- 30 in 2300 the range of sea level contribution is between 3.4–66.9 mm. The very low estimated contribution of 3.4 mm is a result from the IPSL-CM5A-LR forcing that predicts a relatively high SMB for the characteristic time of overshooting 1.5°C (Tab. 2). The SMB is close to present-day and therefore IPSL-CM5A-LR maintains a geometry close to present day. The prolongation of these scenarios were done by repeating the forcing from a time window that reveals a stabilized climate. Repeating the last 30-year forcing field window before the characteristic time is not reasonable, because the change in warming is strongest
- 35 during that period and a stabilized climate would not be reached. In fact, we would generate a non-mitigation pathway scenario

with constant warming rates that will have larger melt and therefore likely contributes more to sea level contribution (not shown here).

The generally abated sea level contribution confirms with the inferred threshold in global mean temperature before irreversible ice sheet topography changes occur. The simplified assumption behind these threshold is an integrated SMB over the whole

- 5 ice sheet that becomes negative (Gregory and Huybrechts, 2006). Fettweis et al. (2013) reported a threshold of 3.5° C relative to pre-industrial, which is never exceeded under the RCP2.6 scenario. Assuming a steady state ice-sheet SMB of 400 Gt yr⁻¹ the decline in SMB must be larger than -400 Gt yr⁻¹ to get a continuous retreating ice sheet margin. If the mean SMB of the GrIS remains positive a new steady state ice sheet geometry may be possible, but require a balancing with the ice outflow. At last we want to discuss if studying RCP2.6 allows to draw significant conclusions on the development of sea level rise
- 10 due to mass loss in Greenland. We found that only a fraction of the current observed mass loss in the first two decades is represented by the model in RCP2.6. This can be attributed to different factors: the current emissions are above the RCP2.6 limit and hence the natural system evolves on a different route than RCP2.6. Secondly, the three GCMs are quite different in response to the RCP2.6 forcing and last but not least, the model itself does not represent all mechanisms, in particular the lack of oceanic forcing is causing a reduced sea level rise. Hence, a new emission scenario, that represent the real RCP pathway in
- 15 the recent past, would be most useful for future studies like ours.

5 Conclusions

We have applied three different GCM-climate forcings based on the low-emission scenario CMIP5 RCP2.6 of three underlying GCMs (HadGEM2-ES, IPSL-CM5A-LR, MIROC5) foreings for RCP2.6 to estimate the response of GrIS to overshooting scenarios ISSM. Despite all three GCMs are based on RCP2.6, their variation temperature variation – globally and regionally

- 20 for GrIS is considerably large. Polar Arctic amplification causes a near-surface air temperature increase over Greenland by a factor of ≈ 2.4 and 2 in HadGEM2-ES and IPSL-CM5A-LR, respectively. MIROC5 reveals nearly no polar amplification. Sea level rise arctic amplification. In order to force the ice sheet model with a reliable SMB, a physically based surface energy balance model was applied. The estimated sea level contribution for the RCP2.6 peak and decline scenario is ranging in our simulations from 46 to 7121–38 mm by 2100 and 114 to 18936–85 mm by 2300. The most plausible forcing HadGEM2-ES
- 25 leads to 71 mm by 2100 and 189 mm by 2300. Surface elevation drops in the southwest by up to 100 m and leads also to considerable retreat along the eastern coast, with leaving Kong Christian IX Land nearly ice free by 2300. The ice tongues of 79°N glacier, Ryder and Petermann glacier are lost already by 2100. Acceleration 2300 and are up to 30–40% higher compared to a scenario without overshoot. Despite the reduced SMB is the warmer climate, a future steady-state ice sheet with lower surface and volume might be possible.
- 30 <u>Although the thickness change pattern agrees well with observations and acceleration of NEGIS</u>, Helheim Glacier and Jakobshavn Isbræ is represented in our model, but captured in our simulations, the estimated sea level contribution is potentially underestimated due to the following drawbacks of our study: (i) retreat of glaciers due to oceanic forcing (melt at vertical cliffs and/or calving rates) is not included so far, and (ii) model drift is still quite large, resulting from the switching between spin-up

to RCP foreings and (iii) seasonality due to lubrication arising from supra-glacial melt water is not included. This leads to the conclusion that the projections may serve as a lower bound of the contribution of Greenland to sea level rise under RCP2.6 climate scenario. This limits also the advantageous treatment of the physics in our model setup, meaning that all the benefits from a high-resolution higher order model are not yet contributing to the extent they potentially could. This leads to the

5 conclusion that the projections may serve as a lower bound of the contribution of Greenland to sea level rise under RCP2.6Our results further indicate, that uncertainties stem from the underlying climate model to calculate the surface mass balance.

Code availability. The ice sheet model ISSM is available at issm.jpl.nasa.gov and not distributed by the authors of this manuscript. SEMIC is available from https://gitlab.pik-potsdam.de/krapp/semic-project and not distributed by the authors of this manuscript.

Author contributions. M.R. conducted ISSM simulations, coupled SEMIC output to ISSM. M.R. and A.H. designed the study, analysed the
 results and wrote major parts of the manuscript. K.F. and S.L. selected, prepared and contributed GCM forcings. U.F. has contributed advice on the albedo scheme and checked the GCM input data.

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References

Aschwanden, A., Bueler, E., Khroulev, C., and Blatter, H.: An enthalpy formulation for glaciers and ice sheets, Journal of Glaciology, 58, 441–457, https://doi.org/10.3189/2012JoG11J088, 2012.

Bauer, E. and Ganopolski, A.: Comparison of surface mass balance of ice sheets simulated by positive-degree-day method and energy balance

- 5 approach, Climate of the Past, 13, 819, 2017.
- Beckmann, A. and Goosse, H.: A parameterization of ice shelf-ocean interaction for climate models, Ocean Modelling, 5, 157-170, https://doi.org/10.1016/S1463-5003(02)00019-7, 2003.
 - Bindschadler, R. A., Nowicki, S., Abe-Ouchi, A., Aschwanden, A., Choi, H., Fastook, J., Granzow, G., Greve, R., Gutowski, G., Herzfeld, U., Jackson, C., Johnson, J., Khroulev, C., Levermann, A., Lipscomb, W. H., Martin, M. A., Morlighem, M., Parizek, B. R., Pollard,
- 10 D., Price, S. F., Ren, D., Saito, F., Sato, T., Seddik, H., Seroussi, H., Takahashi, K., Walker, R., and Wang, W. L.: Ice-sheet model sensitivities to environmental forcing and their use in projecting future sea level (the SeaRISE project), Journal of Glaciology, 59, 195– 224, https://doi.org/doi:10.3189/2013JoG12J125, 2013.
 - Blatter, H.: Velocity and stress fields in grounded glaciers: a simple algorithm for including deviatoric stress gradients, Journal of Glaciology, 41, 333–344, 1995.
- 15 Bondzio, J. H., Seroussi, H., Morlighem, M., Kleiner, T., Rückamp, M., Humbert, A., and Larour, E. Y.: Modelling calving front dynamics using a level-set method: application to Jakobshavn Isbræ, West Greenland, The Cryosphere, 10, 497–510, https://doi.org/10.5194/tc-10-497-2016, 2016.
 - Bondzio, J. H., Morlighem, M., Seroussi, H., Kleiner, T., Rückamp, M., Mouginot, J., Moon, T., Larour, E. Y., and Humbert, A.: The mechanisms behind Jakobshavn Isbræ's acceleration and mass loss: A 3-D thermomechanical model study, Geophysical Research Letters,
- 20 44, 6252–6260, https://doi.org/10.1002/2017GL073309, 2017GL073309, 2017.
- Bougamont, M., Bamber, J. L., Ridley, J. K., Gladstone, R. M., Greuell, W., Hanna, E., Payne, A. J., and Rutt, I.: Impact of model physics on estimating the surface mass balance of the Greenland ice sheet, Geophysical Research Letters, 34, https://doi.org/10.1029/2007GL030700, 2007.
 - Choi, Y., Morlighem, M., Rignot, E., Mouginot, J., and Wood, M.: Modeling the Response of Nioghalvfjerdsfjorden and Zachariae
- 25 Isstrøm Glaciers, Greenland, to Ocean Forcing Over the Next Century, Geophysical Research Letters, 44, 11,071–11,079, https://doi.org/10.1002/2017GL075174.
 - Courant, R., Friedrichs, K., and Lewy, H.: Über die Partiellen Differenzengleichungen der Mathematischen Physik, Mathematische Annalen, 100, 32–74, 1928.
 - Dansgaard, W., Johnsen, S., Clausen, H., Dahl-Jensen, D., Gundestrup, N., Hammer, C., Hvidberg, C., Steffensen, J., Sveinbjörndottir,
- 30 A., Jouzel, J., and Bond, G.: Evidence for general instability of past climate from a 250-kyr ice-core record, Nature, 364, 218–220, https://doi.org/doi:10.1038/364218a0, 1993.
 - Denby, B. and Greuell, W.: The use of bulk and profile methods for determining surface heat fluxes in the presence of glacier winds, Journal of Glaciology, 46, 445–452, 2000.
 - Edwards, T. L., Fettweis, X., Gagliardini, O., Gillet-Chaulet, F., Goelzer, H., Gregory, J. M., Hoffman, M., Huybrechts, P., Payne, A. J.,
- 35 Perego, M., Price, S., Quiquet, A., and Ritz, C.: Probabilistic parameterisation of the surface mass balance elevation feedback in regional climate model simulations of the Greenland ice sheet, The Cryosphere, 8, 181–194, https://doi.org/10.5194/tc-8-181-2014, 2014a.

Edwards, T. L., Fettweis, X., Gagliardini, O., Gillet-Chaulet, F., Goelzer, H., Gregory, J. M., Hoffman, M., Huybrechts, P., Payne, A. J., Perego, M., Price, S., Quiquet, A., and Ritz, C.: Effect of uncertainty in surface mass balance elevation feedback on projections of the future sea level contribution of the Greenland ice sheet, The Cryosphere, 8, 195–208, https://doi.org/10.5194/tc-8-195-2014, 2014b.

Erokhina, O., Rogozhina, I., Prange, M., Bakker, P., Bernales, J., Paul, A., and Schulz, M.: Dependence of slope lapse rate over the Greenland ice sheet on background climate, Journal of Glaciology, 63, 568, https://doi.org/10.1017/jog.2017.10, 2017.

Ettema, J., van den Broeke, M. R., van Meijgaard, E., van de Berg, W. J., Bamber, J. L., Box, J. E., and Bales, R. C.: Higher surface mass balance of the Greenland ice sheet revealed by high-resolution climate modeling, Geophysical Research Letters, 36, n/a–n/a, https://doi.org/10.1029/2009GL038110, 112501, 2009.

Fettweis, X., Franco, B., Tedesco, M., van Angelen, J. H., Lenaerts, J. T. M., van den Broeke, M. R., and Gallée, H.: Estimating the Greenland ice sheet surface mass balance contribution to future sea level rise using the regional atmospheric climate model MAR, The Cryosphere,

7, 469–489, https://doi.org/10.5194/tc-7-469-2013, 2013.

5

10

- Fettweis, X., Box, J. E., Agosta, C., Amory, C., Kittel, C., Lang, C., van As, D., Machguth, H., and Gallée, H.: Reconstructions of the 1900–2015 Greenland ice sheet surface mass balance using the regional climate MAR model, The Cryosphere, 11, 1015–1033, https://doi.org/10.5194/tc-11-1015-2017, https://www.the-cryosphere.net/11/1015/2017/, 2017.
- 15 Frieler, K., Lange, S., Piontek, F., Reyer, C. P. O., Schewe, J., Warszawski, L., Zhao, F., Chini, L., Denvil, S., Emanuel, K., Geiger, T., Halladay, K., Hurtt, G., Mengel, M., Murakami, D., Ostberg, S., Popp, A., Riva, R., Stevanovic, M., Suzuki, T., Volkholz, J., Burke, E., Ciais, P., Ebi, K., Eddy, T. D., Elliott, J., Galbraith, E., Gosling, S. N., Hattermann, F., Hickler, T., Hinkel, J., Hof, C., Huber, V., Jägermeyr, J., Krysanova, V., Marcé, R., Müller Schmied, H., Mouratiadou, I., Pierson, D., Tittensor, D. P., Vautard, R., van Vliet, M., Biber, M. F., Betts, R. A., Bodirsky, B. L., Deryng, D., Frolking, S., Jones, C. D., Lotze, H. K., Lotze-Campen, H., Sahajpal, R., Thonicke,
- K., Tian, H., and Yamagata, Y.: Assessing the impacts of 1.5 °C global warming simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b), Geoscientific Model Development, 10, 4321–4345, https://doi.org/10.5194/gmd-10-4321-2017, https://www.geosci-model-dev.net/10/4321/2017/, 2017.
 - Fürst, J. J., Goelzer, H., and Huybrechts, P.: Ice-dynamic projections of the Greenland ice sheet in response to atmospheric and oceanic warming, The Cryosphere, 9, 1039–1062, https://doi.org/10.5194/tc-9-1039-2015, https://www.the-cryosphere.net/9/1039/2015/, 2015.
- Gill, A. E.: Atmosphere-Ocean dynamics (International Geophysics Series), academic press, 1982.
 GISTEMP Team: GISS Surface Temperature Analysis (GISTEMP), NASA Goddard Institute for Space Studies. Dataset accessed 2018-04-25 at https://data.giss.nasa.gov/gistemp/, 2018.
 - Goelzer, H., Huybrechts, P., Fürst, J., Nick, F., Andersen, M., Edwards, T., Fettweis, X., Payne, A., and Shannon, S.: Sensitivity of Greenland Ice Sheet Projections to Model Formulations, Journal of Glaciology, 59, 733–749, https://doi.org/10.3189/2013JoG12J182, 2013.
- 30 Goelzer, H., Nowicki, S., Edwards, T., Beckley, M., Abe-Ouchi, A., Aschwanden, A., Calov, R., Gagliardini, O., Gillet-Chaulet, F., Golledge, N. R., Gregory, J., Greve, R., Humbert, A., Huybrechts, P., Kennedy, J. H., Larour, E., Lipscomb, W. H., Le clec'h, S., Lee, V., Morlighem, M., Pattyn, F., Payne, A. J., Rodehacke, C., Rückamp, M., Saito, F., Schlegel, N., Seroussi, H., Shepherd, A., Sun, S., van de Wal, R., and Ziemen, F. A.: Design and results of the ice sheet model initialisation experiments initMIP-Greenland: an ISMIP6 intercomparison, The Cryosphere, 12, 1433–1460, https://doi.org/10.5194/tc-12-1433-2018, 2018.
- 35 Graversen, R. G., Drijfhout, S., Hazeleger, W., van de Wal, R., Bintanja, R., and Helsen, M.: Greenland's contribution to global sea-level rise by the end of the 21st century, Climate Dynamics, 37, 1427–1442, https://doi.org/10.1007/s00382-010-0918-8, 2011.

- Gregory, J. and Huybrechts, P.: Ice-sheet contributions to future sea-level change, Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 364, 1709-1732, https://doi.org/10.1098/rsta.2006.1796, http://rsta. royalsocietypublishing.org/content/364/1844/1709, 2006.
- Greve, R.: Relation of measured basal temperatures and the spatial distribution of the geothermal heat flux for the Greenland ice sheet,
- 5 Annals of Glaciology, 42, 424-432, 2005.
 - Helm, V., Humbert, A., and Miller, H.: Elevation and elevation change of Greenland and Antarctica derived from CryoSat-2, The Cryosphere, 8, 1539-1559, https://doi.org/10.5194/tc-8-1539-2014, 2014.
 - Huybrechts, P., Letreguilly, A., and Reeh, N.: The Greenland ice sheet and greenhouse warming, Palaeogeography, Palaeoclimatology, Palaeoecology, 89, 399-412, https://doi.org/https://doi.org/10.1016/0031-0182(91)90174-P, http://www.sciencedirect.com/science/ article/pii/003101829190174P, 1991.
- 10
 - IPCC: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://doi.org/10.1017/CBO9781107415324, www.climatechange2013.org, 2013.

Joughin, I., Smith, B. E., Shean, D. E., and Floricioiu, D.: Brief Communication: Further summer speedup of Jakobshavn Isbræ, The

- 15 Cryosphere, 8, 209–214, https://doi.org/10.5194/tc-8-209-2014, https://www.the-cryosphere.net/8/209/2014/, 2014.
 - Kleiner, T., Rückamp, M., Bondzio, J. H., and Humbert, A.: Enthalpy benchmark experiments for numerical ice sheet models, The Cryosphere, 9, 217–228, https://doi.org/10.5194/tc-9-217-2015, 2015.
 - Krapp, M., Robinson, A., and Ganopolski, A.: SEMIC: an efficient surface energy and mass balance model applied to the Greenland ice sheet, The Cryosphere, 11, 1519–1535, https://doi.org/10.5194/tc-11-1519-2017, 2017.
- Lange, S.: Bias correction of surface downwelling longwave and shortwave radiation for the EWEMBI dataset, Earth System Dynamics 20 Discussions, 2017, 1–30, https://doi.org/10.5194/esd-2017-81, https://www.earth-syst-dynam-discuss.net/esd-2017-81/, 2017.
 - Larour, E., Seroussi, H., Morlighem, M., and Rignot, E.: Continental scale, high order, high spatial resolution, ice sheet modeling using the Ice Sheet System Model (ISSM), Journal of Geophysical Research: Earth Surface, 117, https://doi.org/10.1029/2011JF002140, 2012.

Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L. T., Lamarque, J.-F., Matsumoto, K., Montzka, S. A., Raper, S. C. B.,

- 25 Riahi, K., Thomson, A., Velders, G. J. M., and van Vuuren, D. P.: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300, Climatic Change, 109, 213, https://doi.org/10.1007/s10584-011-0156-z, https://doi.org/10.1007/s10584-011-0156-z, 2011.
 - Morlighem, M., Rignot, E., Seroussi, H., Larour, E., Dhia, H. B., and Aubry, D.: Spatial patterns of basal drag inferred using control methods from a full-Stokes and simpler models for Pine Island Glacier, West Antarctica, Geophysical Research Letters, 37, https://doi.org/10.1029/2010GL043853, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2010GL043853, 2010.
- Morlighem, M., Rignot, E., Mouginot, J., Seroussi, H., and Larour, E.: Deeply incised submarine glacial valleys beneath the Greenland ice 30 sheet, Nature Geoscience, 7, 418-422, https://doi.org/10.1038/ngeo2167, 2014.
 - Morlighem, M., Bondzio, J., Seroussi, H., Rignot, E., Larour, E., Humbert, A., and Rebuffi, S.: Modeling of Store Gletscher's calving dynamics, West Greenland, in response to ocean thermal forcing, Geophysical Research Letters, 43, 2659-2666, https://doi.org/10.1002/2016GL067695, 2016GL067695, 2016.
- Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., 35 Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P., and Wilbanks, T. J.: The next generation of scenarios for climate change research and assessment, Nature, 463, 747–756, http://dx.doi.org/10. 1038/nature08823, 2010.

Nerem, R. S., Beckley, B. D., Fasullo, J. T., Hamlington, B. D., Masters, D., and Mitchum, G. T.: Climate-change–driven accelerated sea-level rise detected in the altimeter era, Proceedings of the National Academy of Sciences, https://doi.org/10.1073/pnas.1717312115, http://www.pnas.org/content/early/2018/02/06/1717312115, 2018.

Noël, B., van de Berg, W. J., Machguth, H., Lhermitte, S., Howat, I., Fettweis, X., and van den Broeke, M. R.: A daily, 1 km resolution data

- 5 set of downscaled Greenland ice sheet surface mass balance (1958–2015), The Cryosphere, 10, 2361–2377, https://doi.org/10.5194/tc-10-2361-2016, 2016.
 - Noël, B., van de Berg, W., Lhermitte, S., Wouters, B., Machguth, H., Howat, I., Citterio, M., Moholdt, G., Lenaerts, J., and van den Broeke, M. R.: A tipping point in refreezing accelerates mass loss of Greenland's glaciers and ice caps, Nature Communications, 8, 14730, 2017.
 Noël, B., van de Berg, W. J., van Wessem, J. M., van Meijgaard, E., van As, D., Lenaerts, J. T. M., Lhermitte, S., Kuipers Munneke, P.,
- Smeets, C. J. P. P., van Ulft, L. H., van de Wal, R. S. W., and van den Broeke, M. R.: Modelling the climate and surface mass balance of polar ice sheets using RACMO2 – Part 1: Greenland (1958–2016), The Cryosphere, 12, 811–831, https://doi.org/10.5194/tc-12-811-2018, https://www.the-cryosphere.net/12/811/2018/, 2018.
 - Nowicki, S., Bindschadler, R. A., Abe-Ouchi, A., Aschwanden, A., Bueler, E., Choi, H., Fastook, J., Granzow, G., Greve, R., Gutowski, G., Herzfeld, U., Jackson, C., Johnson, J., Khroulev, C., Larour, E., Levermann, A., Lipscomb, W. H., Martin, M. A., Morlighem, M., Parizek,
- B. R., Pollard, D., Price, S. F., Ren, D., Rignot, E., Saito, F., Sato, T., Seddik, H., Seroussi, H., Takahashi, K., Walker, R., and Wang, W. L.: Insights into spatial sensitivities of ice mass response to environmental change from the SeaRISE ice sheet modeling project II: Greenland, Journal of Geophysical Research: Earth Surface, 118, 1025–1044, https://doi.org/10.1002/jgrf.20076, 2013.
 - Nowicki, S. M. J., Payne, A., Larour, E., Seroussi, H., Goelzer, H., Lipscomb, W., Gregory, J., Abe-Ouchi, A., and Shepherd, A.: Ice Sheet Model Intercomparison Project (ISMIP6) contribution to CMIP6, Geoscientific Model Development, 9, 4521–4545,
- 20 https://doi.org/10.5194/gmd-9-4521-2016, 2016.
 - Oerlemans, J. and Knap, W. H.: A 1 year record of global radiation and albedo in the ablation zone of Morteratschgletscher, Switzerland, Journal of Glaciology, 44, 231–238, https://doi.org/10.3189/S0022143000002574, 1998.
 - Pattyn, F.: A new three-dimensional higher-order thermomechanical ice sheet model: Basic sensitivity, ice stream development, and ice flow across subglacial lakes, Journal of Geophysical Research: Solid Earth, 108, https://doi.org/10.1029/2002JB002329, https://agupubs.
- 25 onlinelibrary.wiley.com/doi/abs/10.1029/2002JB002329, 2003.
 - Pithan, F. and Mauritsen, T.: Arctic amplification dominated by temperature feedbacks in contemporary climate models, Nature Geoscience, 7, 181–184, https://doi.org/10.1038/ngeo2071, https://www.nature.com/articles/ngeo2071, 2014.
- Price, S. F., Payne, A. J., Howat, I. M., and Smith, B. E.: Committed sea-level rise for the next century from Greenland ice sheet dynamics during the past decade, Proceedings of the National Academy of Sciences, 108, 8978–8983, https://doi.org/10.1073/pnas.1017313108, 2011.
 - Rietbroek, R., Brunnabend, S.-E., Kusche, J., Schröter, J., and Dahle, C.: Revisiting the contemporary sea-level budget on global and regional scales, Proceedings of the National Academy of Sciences, 113, 1504–1509, https://doi.org/10.1073/pnas.1519132113, 2016.

Rignot, E. and Mouginot, J.: Ice flow in Greenland for the International Polar Year 2008–2009, Geophysical Research Letters, 39, n/a–n/a, https://doi.org/10.1029/2012GL051634, 2012.

35 Rogelj, J., Luderer, G., Pietzcker, R. C., Kriegler, E., Schaeffer, M., Krey, V., and Riahi, K.: Energy system transformations for limiting end-of-century warming to below 1.5°C., Nature Clim. Change, 5, 519–527, http://dx.doi.org/10.1038/nclimate2572, 2015. Schlegel, N. J., Larour, E., Seroussi, H., Morlighem, M., and Box, J. E.: Decadal-scale sensitivity of Northeast Greenland ice flow to error in a surface masss balance using ISSM, Journal of Geophysical Research: Earth Surface, 118, 667–680, https://doi.org/10.1002/jgrf.20062, 2013.

Seroussi, H., Morlighem, M., Rignot, E., Khazendar, A., Larour, E., and Mouginot, J.: Dependence of century-scale projections of the Greenland ice sheet on its thermal regime, Journal of Glaciology, 59, 1024–1034, https://doi.org/doi:10.3189/2013JoG13J054, 2013.

Seroussi, H., Morlighem, M., Larour, E., Rignot, E., and Khazendar, A.: Hydrostatic grounding line parameterization in ice sheet models, The Cryosphere, 8, 2075–2087, https://doi.org/10.5194/tc-8-2075-2014, 2014.

Shapiro, N. and Ritzwoller, M.: Inferring surface heat flux distributions guided by a global seismic model: Particular application to Antarctica, Earth and Planetary Science Letters, 223, 213–224, https://doi.org/10.1016/j.epsl.2004.04.011, 2004.

- 10 Tedesco, M., Mote, T., Fettweis, X., Hanna, E., Jeyaratnam, J., Booth, J. F., Datta, R., and Briggs, K.: Arctic cut-off high drives the poleward shift of a new Greenland melting record, Nature Communications, 7, 11723 EP –, http://dx.doi.org/10.1038/ncomms11723, 2016.
 - UNFCCC: Adoption of the Paris Agreement, Decision 1/CP.21 of FCCC/CP/2015/10/Add.1, available at: http://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf (last access: April 2018), 2015.

van de Wal, R. S. W.: Mass-balance modelling of the Greenland ice sheet: a comparison of an energy-balance and a degree-day model,

15 Annals of Glaciology, 23, 36–45, https://doi.org/10.3189/S0260305500013239, 1996.

5

- van den Broeke, M. R., Enderlin, E. M., Howat, I. M., Kuipers Munneke, P., Noël, B. P. Y., van de Berg, W. J., van Meijgaard, E., and Wouters, B.: On the recent contribution of the Greenland ice sheet to sea level change, The Cryosphere, 10, 1933–1946, https://doi.org/10.5194/tc-10-1933-2016, 2016.
- Vizcaíno, M., Mikolajewicz, U., Jungclaus, J., and Schurgers, G.: Climate modification by future ice sheet changes and consequences for ice
 sheet mass balance, Climate Dynamics, 34, 301–324, https://doi.org/10.1007/s00382-009-0591-y, 2010.
 - Watterson, I. G., Bathols, J., and Heady, C.: What Influences the Skill of Climate Models over the Continents?, Bulletin of the American Meteorological Society, 95, 689–700, https://doi.org/10.1175/BAMS-D-12-00136.1, 2014.
 - Wilson, N., Straneo, F., and Heimbach, P.: Submarine melt rates and mass balance for Greenland's remaining ice tongues, The Cryosphere Discussions, 2017, 1–17, https://doi.org/10.5194/tc-2017-99, 2017.



Figure 1. Time series of annual global mean near-surface temperature change (a) and over the GrIS (b) for all three GCMs relative to 1661–1880. The thick line is 30-year moving mean. The coloured dots represent the onset years of overshooting 1.5°C in the global mean near-surface air temperature in a 11-year moving window relative to pre-industrial levels. The light grey shaded area indicates the reused time period for the scenario without overshoot.



Figure 2. Scatter plot of annual mean near-surface air temperatures over GrIS versus annual global mean near-surface air temperatures for the years 1861–2299. The grey line depicts a linear course the identity.



Figure 3. Comparison Time series of multi-year the annual mean surface temperature integrated SMB_{clim} (T_sGtyr^{-1}) differences between 2100-2000 (top row) and 2300-2000 (bottom row) according to Eq. 3 for (all three GCMs under RCP2.6 forcing. The thick line is a , d) HadGEM2-ES, (b, c) IPSL-CM5A-LR-30-year moving mean. In grey colour and black line the range and mean of SMB between 1981–2010 from Polarportal is marked (e, fpolarportal.dk)MIROC5. The black contour dashed line depicts shows the present-day ice maskSMB time series of RACMO2.3 (Noël et al., 2018) from 1958-2016. The coloured dots represent the onset years of overshooting 1.5°C in the global mean near-surface air temperature in a 11 year moving window relative to pre-industrial levels. The light grey shaded area indicate the reused time period for the scenario without overshoot.



Figure 4. Comparison Coefficients of multi-year determination r^2 (straight lines and left y-axis) and mean singed difference MSD (dashed lines and right y-axis) between the GCM and RACMO2.3 SMB components. GCM colour code is the same as Fig. 3.



Figure 5. Comparison of the surface mass balance (SMB_{clim}) differences between 2100-2000 for the year 1990; (top rowa) and 2300-2000 surface mass balance of RACMO2.3 (Noël et al., 2018); (bottom rowb) surface mass balance for HadGEM2-ES according to Eq. 4; (a, dc) HadGEM2-ES, scatter plot of both fields. Positive values represent accumulation (b, ered dots) IPSL-CM5A-LR and ; negative melting (e, fblue dots) MIROC5 with respect to RACMO field. The black contour line depicts the present-day ice mask.



Figure 6. Time series of Synthetic surface mass balance SMB(five_corr_calculated from an one year running mean) according to Equnforced relaxation run. -4 for all three GCMs. In grey colour As the range and mean of SMBbetween 1981–2000 from Polarportal is marked (polarportal_corr_will be subtracted in Eq.dk) 8 positive values represent enforced thinning; negative values thickening.



Figure 7. Current state for Present day velocities (year 2000) using IPSL-CM5A-LRHadGEM2-ES: (a) simulated observed velocities, (b) observed velocities, (c) simulated surface elevation, (d) observed surface elevation velocities. Observed velocities: Rignot and Mouginot (2012); Observed surface elevation: Morlighem et al. (2014).



Figure 8. Comparison Scatter plots of multi-year mean surface elevation the present day state (h_s year 2000) differences between 2100-2000 using HadGEM2-ES: (top row) and 2300-2000 (bottom row) for (a, d) HadGEM2-ES velocities, (b, e) IPSL-CM5A-LR and (c, f) MIROC5. The black contour line depicts the present-day ice masksurface elevation. Observed velocities: Rignot and Mouginot (2012); Observed surface elevation: Morlighem et al. (2014).

Sea level equivalent until the year 2100 (left panel) and 2300 (right panel) for all GCMs. Additionally the relaxation and control run are shown. The dotted-dashed and dashed lines represent the onset of overshooting 1.5°C in the global mean near-surface air temperature and the corresponding overshoot over GrIS, respectively.



Figure 9. Sea level equivalent (SLE in mm) until the year 2100 (left panel) and 2300 (right panel) for all GCMs. Straight lines represent scenario with overshoot; dotted-dashed line without overshoot. Additionally the control run (black dashed line) and the model mean and rms deviation from Fürst et al. (2015, Table B1) are shown. The coloured dots represent the onset years of overshooting 1.5°C in the global mean near-surface air temperature in a 11-year moving window relative to pre-industrial levels.



Figure 10. Lag (j) of projected sea level rise per year for three GCMs as mean for a time period similar to the observational period (2002–14). The black line indicates the observed value of 0.73 mm a^{-1} by Rietbroek et al. (2016).



Figure 11. Comparison of multi-year mean surface <u>velocity-temperature</u> (ψT_s) differences between 2100-2000 (top row) and 2300-2000 (bottom row) for (a, d) HadGEM2-ES, (b, e) IPSL-CM5A-LR and (c, f) MIROC5. The black contour line depicts the present-day ice mask.



Figure 12. Comparison of multi-year mean surface mass balance (SMB) differences between 2100-2000 (top row) and 2300-2000 (bottom row) for (a, d) HadGEM2-ES, (b, e) IPSL-CM5A-LR and (c, f) MIROC5. The black contour line depicts the present-day ice mask.



Figure 13. Comparison of multi-year mean surface elevation (h_s) differences between 2100-2000 (top row) and 2300-2000 (bottom row) for (a, d) HadGEM2-ES, (b, e) IPSL-CM5A-LR and (c, f) MIROC5. The black contour line depicts the present-day ice mask. Positive values represent glacier thinning; negative values thickenning. The data are clipped at ice thickness of 10 m (grey shaded area).



Figure 14. Comparison of multi-year mean surface velocity (*v*) differences between 2100-2000 (top row) and 2300-2000 (bottom row) for (a, d) HadGEM2-ES, (b, e) IPSL-CM5A-LR and (c, f) MIROC5. The black contour line depicts the present-day ice mask. Positive values represent glacier acceleration; negative values deceleration. The data are clipped at ice thickness of 10 m (grey shaded area).