**We would very much like to thank Bas de Boer for reviewing our study and for his constructive comments. Please find below the referee's comments in black font and the author's responses in blue font.**

**Responses to Bas de Boer (Referee #1)**

The paper by Plach et al. describes a simulation of the Greenland ice sheet (GrIS) with a higher-order model version of the ISSM ice-sheet model. The paper generally addresses the question to what extend surface mass balance models influence the simulated volume of the GrIS during the last interglacial, which is within the scope of TC. To my understanding this is at least one of the first papers that uses a higher-order model to run ice-sheet models simulations of the last interglacial, in that sense it presents novel concepts. However, I believe the conclusions reached do rely a lot on the experimental design and caveats of using a higher-order model (relative to the more common, but less advanced shallow ice/shelf models). I will discuss this below in more detail.

The methods used are well explained, but needs a bit more detail on some parts, see my main remark #3. Results are well presented in nice figures, and support the interpretation and conclusions, referencing is generally well done. The title is clear and concise and grasps the general conclusions of the paper. I think a clear goal (my main comment #1) is not well explained, which should be added at the end of the introduction. The overall presentation and structure, language and figures looks good. References are appropriate.

In general your results are presented well in the figures and especially Table 3, Figure 6 and 10. I do think that one can think of different experiments, specifically in the case of basal sliding or ice flow (e.g. ice-flow parameters) that can have a larger impact on your results as those summarised in figure 6. So the question is, is the suite of experiments you use here enough to draw the conclusion that SMB has the largest influence on the simulated GrIS for the Eemian? Or does it rely (too much) on the experimental design. As already was shown in previous papers (e.g. Van de Berg et al., 2011; Robinson and Goelzer, 2014), Insolation is a dominant forcing that controls the SMB and thus the retreat of the GrIS (since CO2 variations are small..), so in that sense external forcing already controls the retreat in a way. This should be discussed at the end and in the conclusions.

In summary, I would say my revisions are minor in the text, but I would like to see some additional experiments as mentioned in my comments.

**ref:**

Robinson, A. and Goelzer, H., 2014. The importance of insolation changes for paleo ice sheet modelling, The Cryosphere, 8, 1419–1428.
Van de Berg, W. J., van den Broeke, M., Ettema, J., van Meijgaard, E., and Kaspar, F., 2011. Significant contribution of insolation to Eemian melting of the Greenland ice sheet, Nat. Geosci., 4, 679–683.

We thank you for these constructive and positive comments and we addressed your comments below and in the revised manuscript.

## Main remarks:

**1) Clear goal of the paper**

Page 2, Line 29: Clear goal of the paper is lacking in the introduction. A (firm) sentence should be added at the end here.

We added a clear statement of the aim of the study as a last paragraph in the introduction section.

**2) Description of SMB methods**
In Section 2.1, I would definitely like a bit more explanation on the two SMB methods in this section, since it also largely determines your results. I do prefer to not fully read previous articles (Plach, 2018 or Helsen, 2013). Also add an explanation what the differences are between the 4 time slices you use (CO2, orbits?), and the differences between the two SMB methods. What is ice-sheet topography that is used in the NorESM simulations, etc.?

Yes, we acknowledge that additional details on the two SMB methods is useful and we added a more detailed description in Sec. 2.1.. The four time slices only differ in terms of GHG concentrations and orbital insolation. All climate simulations, both NorESM and MAR, use the present-day ice sheet geometry. We added more information on this and the climate model simulations in the Section 2.1 and 2.3.

**3) Experimental design**
I have a number of remarks on the experimental design, outlined on page 4 and 5. Although you do use a sophisticated model, which might be expensive to run, you also use a (faster) SSA-type setting of ISSM to test basal friction. The initial conditions of your simulation are not tested, but have been shown (e.g. Helsen et al., 2013) that it can influence your results. Although you mentioned in the discussion that it is hard to include a full glacial spin-up for your simulations, I do think it would be good to include an experiment (perhaps using the SSA-type model) to determine the influence of the initial conditions (or pre glacial changes) on your Eemian simulations.

We agree that it would be desirable to perform sensitivity experiments of the initial conditions. We present a very simple test of the influence of the initial state with our *relaxed* experiment, where we use an ice sheet which is spun-up for 10 kyr with a pre-industrial SMB, i.e., climate and ice sheet are in equilibrium. However, more comprehensive initial sensitivity tests would introduce many additional simulation choices (i.e., more unknowns) and a spin-up with our ice sheet model would be very costly. Furthermore, we lack a climate forcing older than 130 ka. Our climate and SMB simulations (taken from Plach et al. 2018) only cover the period 130 to 115 ka. Greenland ice cores also do not provide any information about the climate for the penultimate climate period. Our experiments are designed to show the influence of two SMB models on the ice sheet evolution during a warm climate period which is characterized by melting. We do not aim to provide an accurate estimate of the Eemian ice sheet minimum, but we rather want to illustrate the influence of the choice of SMB model. For a more comprehensive picture, of both the Eemian and the penultimate glacial period it is necessary to use more than one climate (model) forcing. All climate and SMB simulations in this study and the preceding Plach et al. 2018, only use one climate model. However, as previous Eemian climate model intercomparison papers have shown (Bakker et al., 2013 and Lunt et al., 2013) the simulated Eemian climate is quite different between climate models.

We clarified the aim of our study in the introduction section. Furthermore, we added additional discussion on the impact of the initial conditions (e.g., ice sheet size and thermal state) and how they would influence our results in Sec. 4.

Bakker, P., Stone, E. J., Charbit, S., Gröger, M., Krebs-Kanzow, U., Ritz, S. P., Varma, V., Khon, V., Lunt, D. J., Mikolajewicz, U., Prange, M., Renssen, H., Schneider, B., and Schulz, M.: Last interglacial temperature evolution – a model inter-comparison, Clim. Past, 9, 605–619, https://doi.org/10.5194/cp-9-605-2013, 2013.

Lunt, D. J., Abe-Ouchi, A., Bakker, P., Berger, A., Braconnot, P., Charbit, S., Fischer, N., Herold, N., Jungclaus, J. H., Khon, V. C., Krebs-Kanzow, U., Langebroek, P. M., Lohmann, G., Nisancioglu, K. H., Otto-Bliesner, B. L., Park, W., Pfeiffer, M., Phipps, S. J., Prange, M., Rachmayani, R., Renssen, H., Rosenbloom, N., Schneider, B., Stone, E. J., Takahashi, K., Wei, W., Yin, Q., and Zhang, Z. S.: A multi-model assessment of last interglacial temperatures, Clim. Past, 9, 699–717, https://doi.org/10.5194/cp-9-699-2013, 2013.

Plach, A., Nisancioglu, K. H., Le clec'h, S., Born, A., Langebroek, P. M., Guo, C., Imhof, M., and Stocker, T. F.: Eemian Greenland Surface Mass Balance strongly sensitive to SMB model choice, Clim. Past Discussions, pp. 1–37, https://doi.org/10.5194/cp-2018-81, 2018.

Secondly, in general this section could use a bit more explanation. About the SMB methods, but also about what you do with basal friction. Does it stay constant throughout an experiment, is it spatially varying in both the HO and SSA experiments? See also comment on page 4, lines 9-12.

The basal friction coefficient is spatially varying but constant over time in all experiments (in both the HO and SSA experiments). The following sentence in the manuscript (p. 4, l. 11-12) is a bit misleading and was revised: "...i.e., we exclude basal friction coefficients which lead to unrealistic elevation changes at the deep ice core locations." We performed all HO experiments with SSA first. In addition, we performed additional SSA experiments with more extreme basal friction coefficients. The most extreme basal friction coefficient values were excluded for the HO experiments as they lead to unrealistic elevation changes (in the SSA experiments). We clarified this in the revised text in Sec. 2.3.

Thirdly, why you would keep the temperature prescribed at the surface constant (bottom page 4)? Is this for reasons of numerical stability? Please explain. Otherwise you should include these in a simulation on these time scales.

We agree that the surface temperature is important for spin-ups and similarly long simulations. The evolving surface temperature has two impacts: 1) Influencing the SMB if a temperature dependent SMB scheme like PDD is used. Which is not the case in our setup; we use a SMB which is evolving over time (plus the SMB gradient method is applied). 2) The surface temperature affects the thermal structure of the ice sheet. However, our simulations run for 12,000 years (which takes around 3-4 weeks), and ice that is newly formed during this period will not reach deeper than a few hundred meters, i.e., this newly formed ice will not reach regions near the base where the largest deformation happens. We therefore think it is unlikely that the newly formed ice will have a large influence on the ice dynamical response. We added this reasoning in Sec. 2.3.

Finally, the same holds for bedrock adjustment. I think that it is necessary to include in paleoclimate simulations. At least use an ELRA model to include this please, I think it is vital that this is included when changes are relatively large (MAR-BESSI experiments in Fig. 1.2).

We agree that it would be good to include bedrock adjustment. However, ISSM does not include a GIA model (in its transient simulation mode) at the moment, because not many people have used ISSM for paleoclimate simulations until now. We made a simplified estimate of how the missing GIA is affecting our SMB based on the SMB-altitude gradients which are used in our simulations. In the NE where the MAR-BESSI simulations show the strongest retreat, the calculated SMB-altitude gradients are around minus 0.5m w.e./yr for a lowering of 1km. In the MAR-BESSI simulations the ice surface drops by around 2km, the total rebound will be approximately 1/3 of this, for simplicity lets say 700m. However, only a part of this (namely the elastic rebound) might uplift fast another to show significant effects on the SMB (within the time that our SMB is strongly negative). If we use 500m uplift, which is probably an overestimation, this would result in a SMB which is 0.25m w.e./yr less negative than it is without the GIA. Since the SMB in the NE is very negative it is unlikely that including GIA would change the results dramatically because the two SMBs are so different. Due to the simplified nature of these calculations, we chose not to include them in the revised manuscript. However, we discuss the principle problems of neglecting GIA in Sec. 4.

**4) Experiments**

Looking at Table 2 and reading the text on page 5,6 it is unclear to me how many experiments you performed and with what model. From the final note on page 6 (line 10.11), I think you did a lot of experiments also with the SSA version of ISSM, but from Table 1, it looks like you only did one. Perhaps number all experiments you did, individually, in Table 1, or make a clearer list, mentioned how many experiments you use in the analysis for this paper exactly. Make clear for which experiments you used the SSA version of ISSM. The 'relaxed' experiments is (sort of) an experiment testing the initial conditions I would say. But considering my previous comments it might be worthwhile to also include additional experiments that include a (glacial) spin-up (using the SSA version) of the GrIS. See also my specific comments in the attached pdf.

We performed all HO experiments beforehand with SSA. We also performed additional simulations with SSA to find the appropriate parameter values for our HO sensitivity experiments. However, we chose not to discuss the SSA experiments in detail to keep the manuscript concise. The idea behind using ISSM was to test the more advanced higher-order setup for paleo applications in a simplified setup.
We clarify in the revised text that we are using a simplified setup (missing GIA, no ocean forcing, ice sheet domain,…) at several points in the revised text and we clarify which experiments we performed in Sec. 2.3..

**5) Discussion of results**

I think it is essential, concerning your main results, that you explain what causes the differences between the SEB and BESSI models. An additional paragraph that would concisely explain the differences would be good. Shortly reading through your 2018 paper, the differences do not seem to be that large in terms of SMB, however in terms of final ice volume changes are rather significant. Also discuss which do you consider to be the most realistic, and what factors/processes could play a role in determining the SMB.

We added additional information about the two SMB models in Sec. 2.1.. However, it is challenging to provide a "most realistic" model. Although we chose SEB as a reference in Plach et al. (2018), because it uses the most comprehensive physics and has been validated extensively over Greenland. In a paleo application with large uncertainties of the climate forcing, it is challenging to clearly pick one model over the other.

Plach, A., Nisancioglu, K. H., Le clec'h, S., Born, A., Langebroek, P. M., Guo, C., Imhof, M., and Stocker, T. F.: Eemian Greenland Surface Mass Balance strongly sensitive to SMB model choice, Clim. Past Discussions, pp. 1–37, https://doi.org/10.5194/cp-2018-81, 2018.

Your discussion (starting on page 16, line 28) is in a way good to show what the HO version of ISSM can (and cannot) be used for. Considering you are not using bedrock adjustment, ocean forcing, and keep the boundary of the ice sheet fixed, it makes me wonder if ISSM is a suitable model to be used for forthcoming paleoclimate (glacial-interglacial) simulations. There are so many other options available nowadays. Nonetheless, I do feel it is a suitable tool to investigate warmer than present climates, but initial conditions and pre-glacial impact on the interglacial (e.g. GIA, ice rheology, relative sea level) are vital to assess the exact changes of the GrIS during the last interglacial.

We clarify in the revised text that we see our manuscript more as a sensitivity study rather than one aiming to provide an accurate estimate of the Eemian GrIS. The study focuses on impacts of SMB vs. higher-order/basal stress which clarify in several places in the text.

**Comments on the figures (also in the pdf).**
Add panel numbers to figures 3,4,5,7, 8 and 9. Use panel numbers when referring to the specific panels (have commented this at some locations, but not all).

Figure 1
add legend inside the figure (e.g. bottom right). I would suggest to put ice volume on the left axis and add sea-level contribution (relative to the modern ice sheet) on the right.

Figure 2
Definitely need a legend in, or next to, this figure. You might want to use a bit darker shade of yellow. Perhaps make all lines a bit thicker too. Same as fig. 1, switch the y-axis and use sea level contribution relative to PD on the right.

Figure 3
Why is SMB still positive in the southwest area in the BESSI experiment for 125 ka? Please discuss this in the text. It looks like it already stems from the beginning of the run (also slightly visible in the 127 ka picture).

Figure 5
I suggest to put the y-axis in meters. The grey lines are not so well visible, would use a colour (blue?).

We revised the figures.

## General comments

General remarks are provided in the attached pdf. Please also note the supplement to this comment:
https://www.the-cryosphere-discuss.net/tc-2018-225/tc-2018-225-RC1-supplement.pdf

**We thank Bas de Boer again for the overall positive evaluation of our manuscript and his thorough comments which will improve our manuscript significantly! The comments directly in the pdf are very useful, and will be implemented into the revised manuscript.**

**We would very much like to thank the anonymous referee #2 for their constructive comments. Please find below the referee's comments in black font and the author's responses in blue font.**

## Responses to Anonymous Referee #2

**— Overview —**

In this paper, the authors present a series of transient model simulations of the Eemian Greenland ice sheet (from 127 to 115 ka) where they compare the impact of a) discrepancies between external surface mass balance (SMB) forcings, b) perturbations to the assumed basal friction conditions, and c) two different ice flow model approximations. Most of these simulations are performed using both a recent version of a higher-order ice flow model and a simpler version of it that employs a faster shallow shelf approximation (SSA). The setup uses basal friction conditions obtained by an inversion from observed (modern) surface velocities, and leaves out some processes such as, e.g., glacial isostatic adjustment, ice-ocean interactions, and thermal spin-ups due to the computational expenses of the higher-order model. Based upon the results, the authors draw the conclusion that —for simulations of the Greenland ice sheet during warm periods— the representation of surface mass balance is more important than the representation of ice flow and that efforts should focus on improving the former rather than the latter.

Thus, the title of the paper is, in my opinion, well suited and highlights the interesting use of a higher-order ice sheet model on paleo-climatic setups, which so far have been dominated by models with simpler ice flow approximations. Therefore I think that this study is well within the scope of TC. The abstract is adequate. The presentation of the paper (structure, language, etc.) is very good, the text is easy to follow, experimental steps are for the most part clear (see my comments below), references are in general good, and the existing figures complement the text well (although I have some requests). I support this manuscript, providing that the authors address the minor issues described in the general and specific comments below.

We thank you for your overall positive evaluation of our study and we address your comments below and in the revised manuscript.

**— General Comments —**

Although I think that the conclusions do indeed follow the results, my main concern is that those conclusions could be limited by the methodology used to arrive at those results (although not necessarily incorrect). In other words, I am left with the impression that the ice flow representation (including basal friction) could have a stronger impact if the above-mentioned compromises due to computational expenses were not present. As an example, the lack of a spin-up implies that the initial conditions do not include thermal or isostatic rebound signals representing past ice sheet states. Related to this, those past ice sheets configurations can be dependent on the degree of complexity of the ice flow approximation used, particularly if the ice sheet's advances and retreats involve interaction with the ocean. At the end, the initial conditions could be very different depending on the ice flow representation used during a spin-up, and these impacts can be amplified by other model components such as glacial isostatic rebound. Connecting to this, I also wonder if the inclusion of rebound (and its interaction with the SMB altitude-feedback) would decrease the contribution to the ice thickness change from the differences in surface mass balance.

Furthermore, I think that the "parameter space" explored for the ice flow-related experiments is not enough to showcase the total range of impact, especially for the basal friction experiments. For example, the authors test a relative small change to these coefficients and an extreme change, and then discard the latter due to unreasonable (and preliminary, since these are not shown) results. However, there are no attempts at testing the impact of less extreme changes with the aim of finding a "maximum impact" that is still reasonable.

To sum up, from my experience I mostly agree that getting the surface mass balance right plays consistently a crucial role on the evolution of a modelled ice sheet (even outside of interglacials or land-based ice sheets), but from the paper it is not completely clear that the significantly smaller impact of ice flow-related processes is not (at least in part) a consequence of the limitations required in order to utilize the sophisticated higher-order ice flow model. If additional experiments using the higher-order model are not possible due to computational constraints, there is (almost) always the possibility to run those experiments in the simpler SSA model, especially since the authors do not find extreme differences between the models. This could be done at least as supplementary materials to shed some light on the mentioned issues. I will elaborate on these issues as they occur in the text below.

Thanks, we agree that the missing isostatic rebound will most likely lower the total ice loss, particularly in the MAR BESSI experiments. We added a discussion on the missing GIA in Sec. 4. Please also see the response to a similar question of reviewer #1. Furthermore, we emphasize that we use a simplified setup (missing GIA, no ocean forcing, ice sheet domain,…) in the revised text.

Concerning the “parameter space” issue you mention. We performed additional SSA experiments, but only discuss two of these SSA experiments to keep the manuscript concise. We clarify how many and which additional SSA experiments we performed in the revised text.

**— Specific Comments —**

Page (P) 2, Line (L) 20-23: These lines give the misleading impression that the SIA and SSA are used separately in hybrid models, with marked boundaries between the regions where each of them is applied. As far as I understand, there is a difference between using the SIA and SSA separately for, e.g., grounded and floating ice, respectively (i.e. with the grounding line as the "boundaries between these two approximations", as in the main experiments of Pollard and De Conto, 2009), and using what is currently known as "hybrid model". In fact, one of the main motivations stated in Bueler and Brown (2009) was to overcome the flux and velocity problems where SIA and SSA meet, when applied to model grounded ice streams, and to provide a scheme that generates well-behaved, "continuous" intermediate states. Modern hybrid models (mostly following Bueler and Brown, 2009) usually combine both approximations in various ways to obtain a smooth transition between SIA dominated and SSA dominated regions. Please reformulate.

Thank you, we added appropriate references.

P 3, L 9: In "best guess Eemian SMB simulations", "guess" sounds a bit out of place / redundant. Also, based on what are these simulations the best? A few words here giving the criteria used and the types of SMB models tested in Plach et al. (2018) would be appreciated.

We added more details on the differences between the two SMB models and why they are chosen in the method section. See also reply to reviewer #1. We rephrased to avoid the formulation “best guess”.

P 3, L 13: Since the SMB is computed using modern topography and the altitude-SMB feedback turns out to be quite important (as shown by your results), I wonder if the gap between the control and corresponding MAR-BESSI experiments would be smaller under a different topography. For example, (looking at both 125 ka panels of Figure 3) if you started the simulations from a lowered and/or retreated ice sheet in the north-east this could potentially trigger a positive feedback that turns the MAR-SEB SMB negative, causing a similar retreat to that in the MAR-BESSI experiment. You do mention something similar in page 11, line 10, but I would like to see an additional experiment testing this, or (if this is definitely not feasible) at least a discussion on this possibility in the manuscript, since I think it is within the scope of this study.

Thank you, we address this important issue in the discussion section of the revised version. However, we are afraid that additional MAR-SEB simulations with a lowered ice sheet are indeed unfeasible due to the high computational demands of the regional climate model MAR. Furthermore, a lowered ice sheet would be chosen rather arbitrarily, because Greenland ice cores do not constrain the GrIS geometry before 130 ka. As a result of the ill-constrained geometry, we would need to perform several sensitivity experiments with various geometries and we think this is beyond the scope of this paper. However, we discuss the differences in our *relaxed* experiment further (initiated with different ice sheet).

P 3, L 17: "... lower threshold of 100 points ..." points of what? Although I appreciate a summary of previously published methods, it seems to me that this description utilizes terms assuming that the reader is already familiar with those same methods. Please reformulate so the description can be read independently from the cited paper.

We reformulated the description of the SMB gradients method and extended its explanation in Sec. 2.1. The “100 points” is referring to 100 grid points. The methods looks at grid points in a radius of 150 km around each grid point for which the SMB gradient is calculated. For each grid point the method calculates an ablation and an accumulation gradient.

P 4, L 5: What is the (real) time required to run each of these 12 kyr simulations on your higher-order configuration? Since using a higher-order model is part of the novelty of this study, this could be an interesting detail to some readers.

One simulation takes about 3-4 weeks on a single node with 16 cores. We added this information in the revised text.

P 4, L 8: "with a modern GrIS" What is the internal thermal structure of the ice sheet at the beginning of the experiments? How is it computed? Please specify.

We prescribe pre-industrial temperatures at the surface (from the MAR climate simulations) and at the base we use the enthalpy formulation after Aschwanden et al., 2012 to determine the basal boundary conditions (cold or temperate ice) using a prescribed geothermal heat flux (from Shapiro and Ritzwoller, 2004). A thermal steady state calculation is performed, employing a heat transport equation to get the internal thermal structure. We updated the manuscript with additional details in Sec. 2.3.

Aschwanden, A., Bueler, E., Khroulev, C., and Blatter, H.: An enthalpy formulation for glaciers and ice sheets. J. Glaciol., 58(209):441--457, 2012.

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.

P 4, L 9-12: This is not clear to me. How are these limits for the friction coefficients computed? Do you simply prescribe different (homogeneous/spatially varying?) coefficients until the resulting elevations change "too much" compared to ice core data? Is this done before any inversion? If so, and considering that the inversion will produce spatially varying coefficients, why would these limits be valid for the entire domain? Please clarify.

We perform an initial inversion for the basal friction coefficient and then we multiply these inverted basal friction coefficients (which are spatially varying) by factors of 0.5, 0.9, 1.1, and 2.0 (for the >500m/a sections) and 0.9, and 1.1 (for the entire ice sheet). The limits are referring to these multiplication factors and the basal friction coefficient is always spatially varying. We revised the text and clarified the explanation in Sec. 2.3. Furthermore, we discuss examples of SSA experiments which do not fit proxy reconstructions of surface elevation change also in Sec. 2.3.

P 4, L 12-14: Do you run two independent inversions to derive the basal friction coefficients for the higher-order and SSA setups? Under what internal and boundary conditions is this inversion performed? Please clarify and elaborate a bit more on this procedure. Also, I would like to see a figure with the inverted distribution(s) of these coefficients, since the perturbation of these coefficients is an integral part of the study.

Yes, we perform independent inversions for the higher-order and SSA setup. The inversion chooses different basal friction coefficients because the stress balance is represented differently in the higher-order and the SSA setup. For the inversion to infer the basal friction coefficient, the ice viscosity is prescribed. After this thermal steady-state simulation the ice viscosity is updated according as a function of the newly calculated thermal profile (Cuffey and Paterson, 2010). The basal friction coefficients are then iterated to minimize three cost functions (Table 1 in the manuscript) --- absolute misfit between the modeled and observed velocity fields, logarithmic misfit between the modeled and observed velocity fields, and absolute gradient of the basal drag. We expanded the corresponding description in Sec. 2.3.

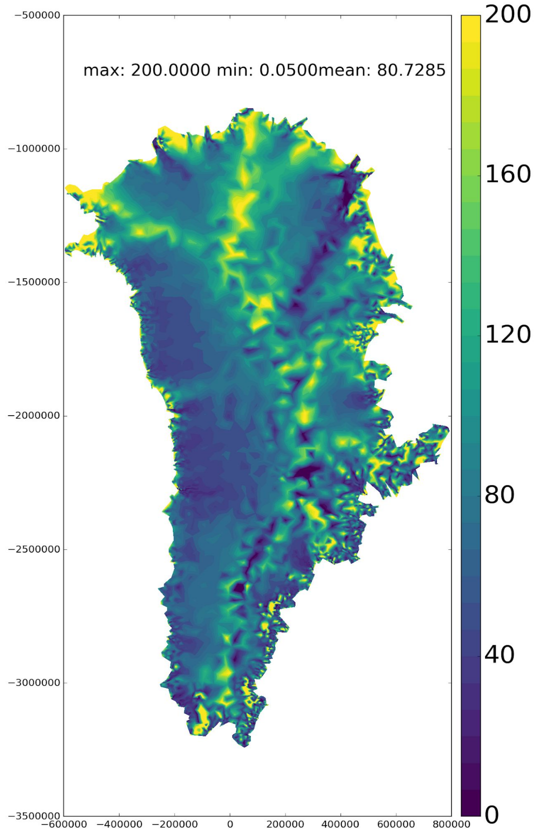


Figure 1: Distribution of basal friction coefficient for the 3D higher-order experiments after inversion from observed present-day surface velocities (no factors applied). The higher the value, the higher the friction.

Cuffey, K. M. and Paterson, W.: The Physics of Glaciers, Elsevier Science, Burlington, 4th edn., 2010.

P 4, L 25: "the ice sheet domain remains fixed throughout all simulations" This line is confusing at first, since it gives the impression that the ice sheet area is fixed (i.e. cannot retreat or advance). Then it is clarified that it cannot advance "beyond the (modern) ice domain", although it is not clear if it can retreat. Only in page 8, lines 12-14 it is clear that it can retreat and re-advance. Please reformulate so this is clear from the beginning.

Thank you, we rephrased the text.

P 4, L 27-29: Why is the surface temperature prescribed and kept fixed at pre-industrial values? Is this simplification necessary? I would like to see a confirmation that its influence on the thermal structure is negligible, particularly in the regions where the ice sheet elevation decreases significantly.

Although we agree that the surface temperature is very important for the thermal structure during a spin-up over a glacial cycle. We chose to do keep the surface temperature constant for simplicity as we think it has only minor impacts on our simulations. Our simulations run for 12,000 years (which takes around 3-4 weeks), and ice that is newly formed during this period will not reach deeper than a few hundred meters, i.e., this newly formed ice will not reach regions near the base where the largest deformation happens. Please also see a similar remark of reviewer #1 (remark 3, third point). We added a discussion in the revised manuscript.

P 5, L 16: Did you consider other velocity thresholds during initial testing? What is the reason for this particular value of 500 m/yr? Please elaborate.

The threshold of 500 m/yr was chosen to include all major outlet glaciers, large parts of ice streams or other fast flowing ice (See contours in Fig. 8c). We did not test other thresholds.

P 6, L 3-6: Did you test other values for the multiplying factors (i.e. between 0.5-0.9 and 1.1-2.0) over the entire ice sheet? While halving/doubling the value of the friction coefficients might indeed give unrealistic results, it would be interesting to see the rate of change of the ice volume curves (as in Fig. 1) for more modest increments (e.g. 0.7 and 1.5). Also, I think it might be useful to show anyway the curves for 0.5 and 2.0 (at least as a supplement), just to see how they relate to the rest of the results.

With the SSA setup we also tested factors of 0.8 and 1.2 for the outlet glaciers as well as for the entire ice sheet. We added more explanation in the revised manuscript in Sec. 2.3. Please, also note our respond to reviewer #1 (remark 4).

P 7, L 4-7: According to the text, the outlet glaciers are defined as the areas with ice (surface?) velocities > 500 m/yr. The resulting "outlet regions" are shown in Fig. 8 and 9. How much would the resulting outlet regions change if a lower threshold was used? Would the bigger area-of-effect impact the results/conclusions? Additional tests here are welcome. Also, it seems that these outlet regions are defined at the beginning and not updated over time as the ice sheet retreats and new areas reach the required threshold. Would a continuous identification of outlet regions change the results as well? I would like to see these points addressed in the discussion.

We address this in the discussion section of the revised manuscript.

P 9, L 4-5: How do these 600 m and 1500 m of elevation change compare to the changes due to halving/doubling the friction coefficients? Is the impact of the latter even stronger than, e.g., 1500 m? Connected to a previous specific comment (P6,L3-6), I think it would be useful to see the results of those particular discarded experiments.

At the EGRIP location more extreme changes of the basal friction coefficient do not show a stronger effect since the lowering at this location is already substantial and only a thin layer of ice remains. We added a discussion with examples of elevation change in the SSA experiments in Sec. 2.3.

P 11, L 11-16: There is a build-up of ice in the northeast margin (and most outlets) in the "basal*0.9" experiment, whereas there is a local thinning of the outlets in the outlets*0.5 experiment. Do you think that the latter would be able to compensate for the additional influx from the interior in a hypothetical experiment that uses *0.5 at the outlets and *0.9 elsewhere? This could cause a bigger impact than the cited experiments, while still keeping the assumptions in the manuscript. If possible, please test this. I would like to see this possibility addressed in the discussion.

P 12, L 2-3: "Note that the thinning affects ice thickness upstream from the outlet region". Yes, and this connects to my previous points regarding basal friction: I think it is very possible to maximize the impact of basal friction uncertainty if other choices are made, e.g., lower threshold for outlet identification (thus increasing the area-of-effect), lower multipliers for the coefficients, different multipliers for interior an outlets, etc. I think it would be useful to see the outcome of such choices at the "extremes" of reasonable assumptions in additional experiments.

Thank you, these are interesting ideas and we address them in the discussion section of the revised manuscript.

P 12, L 5-8: Fig. 9 (right) does not seem to clearly support the text, as the changes in the velocity field seem far from local, even reaching close the divides. In other basal friction configurations (see my previous point P12,L2-3), these changes could have significant effects. Please discuss.

This is a good point, there are also changes close to the ice divide. However, they are very small in magnitude (range of 1 m/yr). We rephrased the section to reflect your concerns.

P 13, L 3: While the sentence is technically correct, I would add "among our tests" (or similar) after "gives the biggest difference in the simulated Eemian ice sheet evolution", to acknowledge the possibility of different results under conditions or configurations not tested here.

The sentence was rephrased accordingly.

P 13, L 9-14: Following my previous points (e.g. P12,L2-3), I would like to see here a discussion on other basal friction configurations that could potentially have a larger impact on the Eemian ice sheet volume, addressing those points.

We address this issue in the revised discussion section.

P 14, L 6: "develop a new equilibrium ice sheet" The ice sheet configurations at the end of these transient experiments are not in equilibrium, at least not in the usual sense (e.g. steady-state simulations under non-varying climate conditions). Please replace using "a new ice sheet state" or similar.

Thank you for pointing this out. We rephrased accordingly.

P 14, L 11-12: Following my previous point (P3,L13), I would like to see here a discussion on the potential impacts of a smaller initial ice sheet and its interaction with the altitude-SMB feedback.

We address this in the revised discussion section.

P 16, L 4-5: This sentence highlights my main concern described above. On the one hand, the higher-order model is too expensive to perform additional experiments. On the other hand, the SSA model is described here as unable to run those simulations due to its limitations. Connecting to my previous comment (P2,L20-23), it seems that there are other options you could use to assess the impact of these important processes. Since one of your conclusions mentions a "limited influence of the ice flow approximation on the simulated minimum ice volume", would not a, e.g., hybrid model be a good candidate to (at least) clarify these issues?

We agree that a future study with more sensitivity experiments could indeed profit from a more cost-efficient hybrid model. However, here we wanted to focus on the impact of SMB vs. ice flow representationin the most realistic way feasible on millennial-scale simulations. Furthermore, we emphasize that we use a simplified setup and that our goal is not to provide the most accurate estimate of the Eemian GrIS in the revised manuscript.

P 16, L 10-12: These lines suggest that the inversion of friction coefficients is done separately for the higher-order and SSA models (see my previous point P4,L12-14). Please clarify this in Section 2.2.

Yes, this is correct. The inversion is performed separately for higher-order and SSA. We clarified in Section 2.2.

P 16, L 16-17: Would the impact of including basal hydrology on the computational expenses be large enough to make your experiments unfeasible? Has this been tested?

At the moment basal hydrology is not implemented in ISSM. However, the computational demands of colleagues in our institute working on the development of advanced basal hydrology schemes, are large, so that we concluded that an implementation within our experimental setup is unfeasible at the moment.

P 16, L 19-21: In connection with my previous point (P7,L4-7), if the goal is to compensate to some degree for the lack of basal hydrology, I think that a continuous identification of outlet regions would be a better choice; otherwise, you are accounting for it only where the initial conditions do not change. Please address the possibility of other basal friction / outlet regions configurations that could have a stronger impact on the results.

Yes, we agree that a continuous identification of the outlet regions would be a better choice. However, this would be technically very challenging with our current ISSM setup. The primary objective of our study was to provide a relative perspective on uncertainty in the SMB by showing it side by side with idealized variations in basal friction that cover a realistic range. It is not meant to be an exhaustive analysis of the latter. We emphasized this in the revised manuscript.

P 16, L 26-27: Similar to how the outlet experiments attempt to account for basal hydrology, additional experiments with a reduced initial ice sheet could attempt to account for the influence of pre-Eemian ocean forcing (see also my previous point P3,L13)

P 16, L 31-32: "Furthermore, a spin-up would require ..." It is still unclear to me what are the internal ice sheet temperatures at the beginning of the experiments, but what if the spin-up is performed with a fixed topography, i.e., letting ice velocities, temperatures, etc. evolve under a transient climate signal? Would not that be more realistic than a modern temperature profile or no profile at all? Please clarify.

For the initial thermal structure please note our response to P 4, L 8. Please also note our response to a similar issue of reviewer #1 (remark 3). A spin-up experiment would very much dependent on the used pre-130ka climate (SMB, temperature, ocean forcing,...) which is not well constrained (e.g. by Greenland ice cores). Furthermore, our climate simulations only cover the period 130 to 115 ka. We therefore conclude that initial sensitivity experiments would add many additional simulation choices (i.e., more unknowns) which would require many additional experiments which is unfeasible with our model setup. We added a discussion on this in the revised manuscript.

P 16, L 33-34: This is not clear to me. If the mesh cannot easily adapt to changes in topography, what happens with the mesh in, e.g., the MAR-BESSI experiment at 125 ka where the ice margins have retreated? Do you simply use the initial (low?) resolution mesh there? If so, does this low-res mesh affect the results (e.g. enhancing the retreat)? Please clarify this.

This is a challenging issue, which is also related to your comment on the identification of the outlet regions. We use the same mesh at all times and it would be desirable to adapt the mesh over time, and the outlet regions as well. However, this is not implemented in ISSM at the moment. We clarified in the revised text.

P 17, L 1-3: I am not 100% convinced that the uncertainties in the initial conditions are completely outside the scope of your study (see P3,L13; P14,L11-12; P16,L26-27). In any case, I would replace "will be attempted" with something like "will become feasible", so it sounds like a possibility rather than a promise.

We rephrased “will become feasible” and we think evaluating the uncertainties in the initial conditions would require many more experiments, which are unfeasible with our current setup. We rather focus on the difference impacts of SMB vs. higher-order ice flow.

P 17, L 5-6: I would like to read an interpretation after this observation. Although this result does not necessarily mean that MAR-BESSI is better than the control SMB, it could point to systematic biases in the modelling setup that cause the former (and the latter) to underestimate its contribution to sea level rise.

Thank you, this is an interesting point. We address this in the revised manuscript.

P 18, L 5-10: The conclusions do not mention the impact of basal friction conditions, which is a significant part of the study. Please summarize these results as well, keeping in mind the potentially stronger impact mentioned in many of my previous points.

We revised extended the conclusion and now also the basal friction conditions are included.

P 18, L 10-12: I think that the strength of this conclusion contrast (at least in magnitude) with the general conclusions the authors draw elsewhere (e.g. in lines 2 and 3 of this same page). Again, I agree that getting the SMB right is important, but do not think that reducing the focus on the representation of the ice flow (and here I include basal and internal processes too) is an appropriate call here. After all, a better (and more efficient) representation of ice flow could eventually allow the inclusion of the very same processes neglected in this study. Please reformulate.

Thank you, we rephrased this section and are now emphasizing we use a simplified setup.

**— Technical corrections —**

P 3, L 6: Here I am missing a core reference for MAR and the setup used.

P 3, L 25: Is there a reference that documents ISSM version 4.13? I suggest to merge this detail with the sentence in P 3, L 31: "... higher-order configuration of ISSM ver4.13 is used (Cuzzone et al, 2018)".

P 7, L 3: change -> changed

P 9, L 6: in simulated ice surface between -> in the simulated ice surface elevations between

P 10, L 2: within the reconstructed surface elevation change -> within the uncertainty of the surface elevation change reconstructed from total gas content

P 10, L 5: with ∼2.5 m difference -> with a difference in sea level rise of ∼2.5 m

P 12, L 7: 0.5 * -> outlets*0.5

P 16, L 30: is allows -> it allows

Thank you for these technical corrections. We revised the text accordingly.

**— Papers mentioned —**


Bueler and Brown: Shallow shelf approximation as a "sliding law" in a thermomechanically coupled ice sheet model, Journal of Geophysical Research: Earth Surface, 114, F03 008, https://doi.org/10.1029/2008JF001179, 2009.

Pollard and DeConto: Modelling West Antarctic ice sheet growth and collapse through the past five million years, Nature, 458, 329–332, https://doi.org/10.1038/nature07809, 2009.

Plach, Nisancioglu, Le clec'h, Born, Langebroek, Guo, Imhof, and Stocker: Eemian Greenland Surface Mass Balance strongly sensitive to SMB model choice, Clim. Past Discussions, pp. 1-37, https://doi.org/10.5194/cp-2018-81, 2018.

Cuzzone, Morlighem, Larour, Schlegel, and Seroussi: Implementation of higher-order vertical finite elements in ISSM v4.13 for improved ice sheet flow modeling over paleoclimate timescales, Geosci. Model Dev., 11, 1683-1694, https://doi.org/10.5194/gmd-11-1683-2018, 2018.


**We thank the Anonymous Referee #2 again for the overall positive evaluation of our manuscript. Her/his comments significantly helped to improve our manuscript.**

# Eemian Greenland ice sheet simulated with a higher-order model shows strong sensitivity to SMB forcing

Andreas Plach[1], Kerim H. Nisancioglu[1,2], Petra M. Langebroek[3], Andreas Born[1], and Sébastien Le clec'h[4,5]

[1]Department of Earth Science, University of Bergen and Bjerknes Centre for Climate Research, Bergen, Norway
[2]Centre for Earth Evolution and Dynamics, University of Oslo, Oslo, Norway
[3]NORCE Norwegian Research Centre, Bjerknes Centre for Climate Research, Bergen, Norway
[4]Laboratoire des Sciences du Climat et de l'Environnement, LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France
[5]Earth System Science and Department Geografie, Vrije Universiteit Brussel, Brussels, Belgium

*Correspondence to:* Andreas Plach (andreas.plach@uib.no)

**Abstract.** The Greenland ice sheet (GrIS) contributes increasingly to global sea level riseand its past history . Its history during past warm intervals is a valuable reference for future sea level projections. We present ice sheet simulations for the Eemian interglacial period (~125130,000 to 115,000 years ago), the period with the most recent a period with warmer-than-present summer climate over Greenland. The evolution of the Eemian GrIS Greenland ice sheet is simulated with a 3D higher-order ice sheet model, forced with surface mass balance (SMB) derived from regional climate simulations. Sensitivity experiments with different SMBvarious surface mass balances, basal friction, and ice flow approximations are discussed. We find that the SMB forcing is The surface mass balance forcing is identified as the controlling factor setting the Eemian minimum minimum in Eemian ice volume, emphasizing the importance of a reliable SMB model. Our surface mass balance model. Furthermore, the results suggest that when estimating the contribution from the GrIS to sea level rise during warm periods, such as the Eemian interglacial period, the SMB the surface mass balance forcing is more important than the representation of ice flow for simulating the large-scale ice sheet evolution. This implies that the future contribution of the Greenland ice sheet to sea level rise highly depends on an accurate surface mass balance.

## 1 Introduction

The simulation of the Greenland ice sheet (GrIS) under past warmer climates is a viable way to test methods used for sea level rise projections which remain uncertain for a future warmer climate (Church et al., 2013). This study investigates ice sheet simulations for the Eemian interglacial period. The Eemian period (~125130,000 to 115,000 years ago; thereafter 125hereafter 130 to 115 ka) is the most recent warmer-than-present period in Earth's history and thereby provides an analogue for future warm climates (e.g., Yin and Berger, 2015; Clark and Huybers, 2009)warmer climates (e.g., Clark and Huybers, 2009; Yin and Berger, 2015). The Eemian summer temperature is estimated to have been 4-5°C above present over most Arctic land areas (CAPE Last Interglacial Projec (e.g., Capron et al., 2017) and ice core records from NEEM (the North Greenland Eemian Ice Drilling project in northwest Greenland, NEEM community members, 2013) indicate a local warming of 8.5±2.5°C (Landais et al., 2016) compared to pre-industrial levels. In spite of this strong warming, total gas content measurements from the Greenland ice cores at GISP2, GRIP, NGRIP, and NEEM indicate an Eemian surface elevation no more than a few hundred meters lower than present (at these locations)~~, e. g.,~~ . NEEM data indicates that the ice thickness in northwest Greenland decreased by 400±250 m between 128 and 122 ka with a surface elevation of 130±300 m lower than the present at 122 ka, resulting in a modest sea level rise estimate of 2 m ~~(Raynaud et al., 1997; NEEM community members, 2013, c.f., Fig. 5)~~(NEEM community members, 2013, c.f., Fig. 5) . Nevertheless, coral reef derived global mean sea level estimates show values of at least 4 m above the present level (Overpeck et al., 2006; Kopp et al., 2013; Dutton et al., 2015). While this could suggest a reduced Antarctic ice sheet, the contribution from the GrIS to the Eemian sea level highstand remains unclear. Previous modeling studies (Letréguilly et al., 1991; Otto-Bliesner et al., 2006; Robinson et al., 2011; Born and Nisancioglu, 2012; Stone et al., 2013; Helsen et al., 2013) used very different setup and forcing, and show highly variable results.

~~However,~~ Ice sheets loose mass either due to a reduced surface mass balance (SMB) or accelerated ice dynamical processes. Therefore ice dynamical processes may ~~also~~ have contributed to the Eemian ~~mass~~ ice loss, e.g., through changes in basal conditions~~.~~ , similar to what is seen today and what is discussed for the future of the ice sheet: Zwally et al. (2002) associate surface melt with an acceleration of GrIS flow and argue that surface melt-induced enhanced basal sliding provides a mechanism for rapid, large-scale, dynamic responses of ice sheets to climate warming. Several other studies have attributed the recent and future projected sea level rise from Greenland partly to dynamical responses: Price et al. (2011) use a 3D higher-order model to simulate sea level rise caused by the dynamical response of the GrIS, and they find an upper bound of 45 mm by 2100 (without assuming any changes to basal sliding in the future). This dynamical contribution is of similar magnitude as previously published SMB-induced sea level rise by 2100 (40-50 mm; Fettweis et al., 2008). Pfeffer et al. (2008) provide a sea level rise estimate of 165 mm from the GrIS by 2100 based on a kinematic scenario with ~~doubled outlet glacier velocities, i.e.,~~ doubling ice transport through topography-constrained outlet glacier gates. Furthermore, Robel and Tziperman (2016) present synthetic ice sheet simulations and argue that the early part of the deglaciation of large ice sheets is strongly influenced by an acceleration of ice streams as a response to changes in climate forcing.

In this study, we apply a computationally efficient 3D higher-order ice flow setup (alias Blatter-Pattyn; BP; Blatter, 1995; Pattyn, 2003) implemented in the Ice Sheet System Model ~~(ISSM; Cuzzone et al., 2018)~~(ISSM; Larour et al., 2012; Cuzzone et al., 2018) . Including higher-order stress gradients provides a comprehensive ice flow representation ~~and enables us~~ to test the importance of the ice dynamics for modeling the Eemian GrIS. Furthermore, we avoid shortcomings in regions where simpler ice flow approximations, often used in paleo applications, are inappropriate, i.e., fast flowing ice in the case of the Shallow Ice Approximation (SIA; Hutter, 1983; Greve and Blatter, 2009) and regions dominated by ice creep in the case of the Shallow Shelf Approximation (SSA; MacAyeal, 1989; Greve and Blatter, 2009). The higher-order approximation is equally well suited to simulate slow as well as fast ice flow~~and applying it to the entire domain avoids any model-inherent discontinuities of "hybrid models" (i.e., combining SIA and SSA; Pollard and DeConto, 2009; Bueler and Brown, 2009; Pollard and DeConto, 2012; Aschwanden et al., 201 at the boundaries between these two approximations~~.

~~Plach et al. (2018a)~~ Plach et al. (2018b) show that the simulation of the Eemian SMB is strongly dependent on the ~~choice of SMB model~~ SMB model choice. Here, we test SMB forcing derived from dynamically downscaled Eemian climate simulations and two SMB models (a full surface energy balance model and an intermediate complexity SMB model) as described in Plach et al. (2018a)Plach et al. (2018b). Furthermore, we perform sensitivity experiments varying basal friction for the entire GrIS, as well as localized changes below the outlet glaciers. With these sensitivity experiments, in combination with the

The aim of this study is to compare the impact of SMB and basal sliding on the evolution of the Eemian GrIS. Furthermore, employing a 3D higher-order setup, we test the importance of the external SMB forcing and contrast this to the impact of internal ice dynamical processes for a period of climate warmingice flow setup, instead of simpler ice dynamical approximations often used in millennial-scale ice sheet simulations, is a novelty of this study. It allows us to evaluate the importance of the ice flow approximation used for Eemian studies.

## 2 Models and methodsexperimental setup

### 2.1 Model descriptionSMB methods

**SMB forcing**

The SMB forcing used in this study is based on Eemian time slice simulations with a fast version of the Norwegian Earth System Model (NorESM1-F; Guo et al., 2018) representing (NorESM1-F; Guo et al., 2019) representing the climate of 130, 125, 120, and 115 ka conditionsusing respective greenhouse gas concentrations and orbital parameters (details in Plach et al., 2018b). In the climate model simulations the present-day GrIS topography is used. These global simulations are dynamically downscaled over Greenland with the regional climate model Modèle Atmosphérique Régional (MAR). The (MAR; Gallée and Schayes, 1994; De Ridde . Subsequently, the SMB is calculated with (1) a full surface energy balance model as implemented within MAR (MAR-SEB) and (2) an intermediate complexity SMB model (MAR-BESSI; BEr*gen* Snow SImulator; BESSI; Born et al., in prep.) (MAR-BESSI; BEr*gen* Snow SImulator; BESSI; Born et al., 2018). Both models are physically based SMB models including a snowpack explicitly solving for the impact of solar shortwave radiation (this is essential for the Eemian period which has a significantly d . MAR-SEB is bidirectionally coupled to the atmosphere of MAR (i.e., evolving SEB impacts atmospheric processes, for example: albedo changes impact surface temperature, cloud cover, humidity, etc.), while MAR-BESSI is uncoupled. These two SMB estimates are the best guess Eemian SMB simulations models are selected as the most plausible Eemian SMBs from a wider range of simulations discussed in Plach et al. (2018a). Plach et al. (2018b); they show a negative total SMB during the Eemian peak warming. While MAR-SEB is used as a chosen as the control because it has been extensively validated against observations in previous studies (Fettweis, 2007; Fettweis et al., 2013, 2017)and , MAR-BESSI is used to test the sensitivity of our the ice sheet simulations to the SMB forcing (c.f., discussion in Sec. 4). MAR-SEB and MAR-BESSI employ a different temporal model time step, while MAR-SEB uses steps of 180 seconds, MAR-BESSI calculates in daily time steps. The longer time steps used by MAR-BESSI imply that extreme temperatures (e.g., lowest temperatures at night can lead to more refreezing) are damped and this is likely the cause for a lower amount of refreezing in MAR-BESSI compared to MAR-SEB. Furthermore, MAR-BESSI uses a simpler albedo representation than MAR-SEB: lower refreezing and simpler steps in albedo changing from fresh snow to glacier ice are identified as the main reasons for more negative SMB as calculated by MAR-BESSI. For a detailed discussion of the differences between the models the reader is referred to Plach et al. (2018b). The two different SMB models are employed to test the sensitivity of the ice sheet simulations to the prescribed SMB forcing.

All SMB time slice simulations are calculated offline using the modern ice surface elevation, given the lack of data constraining the configuration of the Eemian GrIS surface ~~. The change~~ elevation. The evolution of the SMB with the ~~evolving ice surface~~ changing ice surface elevation is simulated with local SMB-altitude gradients following Helsen et al. (2012, 2013). ~~For simplicity, the local gradients are calculated from the respective pre-industrial SMB simulations.~~ The SMB gradient method ~~uses a default search~~ is used to calculate SMB-altitude gradients at each grid point from the surrounding grid points within a default radius of 150 km ~~to derive a~~ (linear regression of SMB ~~versus altitude. If the lower threshold of 100 points is not reached, this search radius is extended~~vs. altitude). Since the SMB-altitude gradients ~~of~~ in the accumulation and the ablation zone are very different, they are calculated separately. ~~For further~~ If the algorithm is unable to find more than 100 grid points (of either accumulation or ablation) the radius is extended until a threshold of 100 data points for the regression is reached. For simplicity, the local gradients are calculated from the respective pre-industrial SMB simulations. Further details on the SMB gradient method ~~we refer to~~ are discussed in Helsen et al. (2012).

~~The transient SMB forcing from 130 to 115 ka is derived by linear interpolation of the SMBs at~~ Between the SMBs calculated for 130, 125, 120, and 115 ka ~~. The SMB during the simulation,i.e. , after applying the SMB gradient method, is~~ a linear interpolation is applied, giving a transient SMB forcing over 15,000 years. A more complicated interpolation approach is unnecessary given the smooth climate forcing and the uncertainties related to the Eemian climate and SMB simulations. Plach et al. (2018b) give a detailed discussion of the simulated climate evolution and show, for example, a Eemian peak warming of 4-5°C over Greenland, which is in agreement with proxy reconstructions (NEEM community members, 2013; Landais et al., 20
. The SMBs in the present study (after being corrected for topography) are shown and discussed in Sec. 3. ~~A full description of the Eemian climate and SMB simulations is provided in Plach et al. (2018a).~~

~~**Ice Sheet System Model (ISSM)**~~

## 2.2 The Ice Sheet System Model (ISSM)

The ISSM is a finite-element, thermo-mechanical ice flow model ~~which is based on~~ based on the conservation laws of momentum, mass, and energy (Larour et al., 2012) — ~~we use~~ here model version 4.13 is used (Cuzzone et al., 2018). ISSM employs an anisotropic mesh, which is typically refined by observed surface ice velocities, allowing fast flowing ice (i.e., outlet glaciers) to be modeled at higher resolution than slow flowing ice (i.e., interior of an ice sheet). Furthermore, ISSM offers inversion methods to ensure that an initialized model ice sheet matches the observed (modern) ice sheet configuration (i.e., observed ice surface velocities are inverted for basal friction or ice rheology; Morlighem et al., 2010; Larour et al., 2012). While ISSM offers a large range of ice flow representations~~— SIA, SSA, higher-order approximations, and the full Stokes equations. For the experiments~~, in this study ~~, a~~ the computationally efficient 3D higher-order configuration (Cuzzone et al., 2018) is used. This setup uses an interpolation based on higher-order polynomials between the vertical layers, instead of the default ~~method (a linear interpolation )~~ linear interpolation which requires a much higher number of vertical layers to capture the sharp temperature gradient at the base of an ice sheet. By using a quadratic interpolation, 5 vertical layers are sufficient to capture the thermal structure accurately, while a linear vertical interpolation requires 25 layers to achieve a similar result. This reduction in lower number of vertical layers reduces the computational demand for the thermal model , as well as for and the stress balance calculations, and makes it possible to run 3D higher-order simulations for thousands of years, e. g., here we perform . The simulations over 12,000 years in this study run between 3-4 weeks on a single node with 16 cores.

### 2.3 Experimental setup

All simulations (forced with MAR-SEB and MAR-BESSI) run from 127 to 115 ka . We follow following the Paleoclimate Modeling Intercomparison Project (PMIP4) (Otto-Bliesner et al., 2017) experimental design and initiate initiating the Eemian simulations at 127 ka with a modern GrIS. We apply the efficient 3D higher-order ice flow setup for our experiments. To save computational time, we also use the faster 2D SSA configuration of ISSM together with the same SMB forcing to efficiently identify a realistic range of the basal friction coefficients used for sensitivity experiments, i.e. , we exclude basal friction coefficients which lead to unrealistic elevation changes at the deep ice core locations. Our initial (spatially varying) The thermal structure is derived using a thermal steady-state simulation with prescribed pre-industrial temperature at the ice surface (from the regional climate simulations) and an enthalpy formulation (Aschwanden et al., 2012) at the base to determine the basal conditions (cold or temperature ice). At the base of the ice sheet a prescribed geothermal heat flux (Shapiro and Ritzwoller, 2004) as provided by the SeaRISE dataset (Bindschadler et al., 2013) is imposed. The basal friction coefficients are kept constant over time and are derived from an inversion of spatially varying, observed surface velocities, i.e., an inversion algorithm chooses the basal friction coefficients in a way that the modeled velocities match the observed velocities. In a first inversion, an initial ice viscosity is prescribed. After the thermal steady-state simulation, the ice viscosity is updated as a function of the new thermal profile (Cuffey and Paterson, 2010). In a second inversion, the basal friction coefficients are iterated to minimize three cost functions (Table 1). The inversion depends on the chosen ice flow approximation due to the different representation of the stress balance, i.e., simulations with the 2D SSA and the 3D higher-order approximations use different inversions.

We use the ISSM default friction law (Larour et al., 2012; Schlegel et al., 2013) based on the empirically derived friction law by Paterson (1994, p. 151):

$$\boldsymbol{\tau_b} = -\alpha^2 \, N_{\text{eff}} \, \boldsymbol{v_b} \tag{1}$$

where $\boldsymbol{\tau_b}$ is the basal shear stress (vector), $\alpha$ the basal friction coefficient (derived by inversion from surface velocities), $N_{eff}$ the effective pressure of the water at the glacier base (i.e., the difference between the overburden ice stress and the water pressure), and $\boldsymbol{v_b}$ the horizontal basal velocity (vector). The effective pressure is simulated with a first order approximation (Paterson, 1994):

$$N_{\text{eff}} = g \, \rho_{\text{ice}} \, H + \rho_{\text{water}} \, z_{\text{b}} \tag{2}$$

where $\rho_{\mathrm{ice}}$ and $\rho_{\mathrm{water}}$ are the densities of ice and water respectively, $H$ the ice thickness, and $z_{\mathrm{b}}$ the bedrock elevation~~, i.e. , $N_{\mathrm{eff}}$ evolves with $H$ over time~~ . From these equations it follows that the initial (modern) basal friction coefficients stay constant, while the basal sheer stress evolves over time with the ice thickness and the effective pressure.

~~Due to the still relatively high computational demand of the~~ Basal sensitivity experiments with changed basal friction are performed to investigate the importance of uncertainties related to basal friction. In order to minimize the number of 3D higher-order ~~setup, compromises are necessary. Therefore, no ice sheet spin-up is performed, and the ice sheet domain remains fixed throughout all simulations, i. e. , the~~ experiments, a number of test experiments are performed with the simpler 2D SSA configuration of ISSM to identify the range of basal friction coefficients which yield plausible results. For example, if the basal friction coefficients for the entire ice sheet are reduced by a factor of 0.8 and 0.5 (in the 2D SSA test experiments; not shown), the ice surface elevation at the NEEM location shows a late-Eemian lowering of 300 and 800 m, respectively. Proxy data indicates a surface lowering of no more than 300 m (NEEM community members, 2013) at time. Constrained by the proxy reconstructions the friction for the entire ice sheet is ~~unable to grow beyond the (modern) ice domain. The basal friction coefficients (spatially varying) are held constant at the initial (modern) values. However, the basal shear stress changes with ice thickness (Eq. 1 and 2). For simplicity, the temperature prescribed at the ice surface (influencing the rheology of newly formed ice) remains fixed at pre-industrial levels as we expect negligible influence on the thermal structure over our relatively short simulation time. The SMB forcing is adjusted over time using the SMB gradient method following Helsen et al. (2012) . At the moment~~ reduced by a factor of 0.9 in the 3D higher-order ice flow experiments. Two 2D SSA experiments (forced with MAR-SEB and MAR-BESSI, respectively) are discussed in detail here to illustrate the difference of the two ice flow approximations (Table 2).

Due to the high computational demand of the 3D higher-order setup, compromises are necessary. The simulations are initiated with the modern GrIS topography and the bedrock remains fixed at modern values (Glacial Isostatic Adjustment~~(GIA ) is not implemented in ISSM~~ ; GIA is not yet implemented for transient simulations ~~, i.e., the bed geometry remains fixed. Furthermore, the model setup used is incapable of modeling basal hydrology, and no ocean forcing is applied. We do not model calving, instead ice flowing out of the domain is removed.~~

with ISSM). The ice sheet is initialized with observed ice surface velocities from ~~Rignot and Mouginot (2012) — in the updated version v4Aug2014. These velocities are used to refine the~~ Rignot and Mouginot (v4Aug2014; 2012). The anisotropic ice sheet mesh is refined with these velocities with a minimum resolution of 40 km in the slow interior ~~to~~ and a maximum resolution of 0.5 km at the fast outlet glaciers. Since the mesh is based on observed velocities, the resolution of the mesh remains unchanged over time, and the ice sheet domain is fixed to the present-day ice sheet extent. The ice sheet can freely evolve within this domain, but is unable to grow outside the present-day limits.

Ice formed during the 12,000 simulation years will only reach several hundred meters deep (far away from the bottom layers which experience most deformation) and surface air temperature is not influencing the SMB (as it would in a degree day model; Reeh, 1989 because SMB is computed by either MAR-SEB or MAR-BESSI, models that account for temperature changes over the Eemian (as simulated by NorESM). Therefore the surface air temperature prescribed at the ice surface remains fixed at pre-industrial levels.

**Table 1.** ISSM model parameters

| ISSM model parameters | |
|---|---|
| minimum mesh resolution (adaptive) | 40 km |
| maximum mesh resolution (adaptive) | 0.5 km |
| number of horizontal mesh vertices | 7383 |
| number of vertical layers | 5 |
| ice flow approximation | 3D higher-order (Blatter, 1995; Pattyn, 2003) |
| degree of finite elements (stress balance) | P1 x P1 |
| degree of finite elements (thermal) | P1 x P2 |
| minimum time step (adaptive) | 0.05 years |
| maximum time step (adaptive) | 0.2 years |
| basal friction law | Paterson (1994, p. 151); Eq. 1 and 2 |
| basal friction coefficient inversion cost functions | 101, 103, 501 |
| ice rheology | Cuffey and Paterson (2010, p. 75) |

degree of finite elements: P1 - linear finite elements, P2 - quadratic finite elements, horizontal x vertical; inversion cost functions: 101 - absolute misfit of surface velocities, 103 - logarithmic misfit of surface velocities, 501 - absolute gradient of the basal drag coefficients

The simplified transient ISSM model setup does not explicitly resolve processes related to basal hydrology, ocean forcing, and calving. The ice rheology is calculated as a function of temperature following Cuffey and Paterson (2010, p. 75). Initial (modern) ice sheet surface, ice thickness, and bed topography are derived from BedMachine v3 ~~(Morlighem et al., 2017) — in the version v2017-09-20. At the ice-bedrock interface the geothermal heat flux from Shapiro and Ritzwoller (2004) as provided in the SeaRISE dataset (Bindschadler et al., 2013) is imposed~~(v2017-09-20; Morlighem et al., 2017). The most important parameters of the ice sheet model are summarized in ~~Tab.~~Table 1. Finally, the shortcomings of this simplified setup are discussed in Sec. 4.

~~**Control and sensitivity experiments**~~

~~The types of~~

## 2.4 Control and sensitivity experiments

The experiments performed are described below and summarized in ~~Tab.~~ Table 2. As discussed in Sec. 2.1-2.3, the experiments test the sensitivity to two different SMB models as well as different representations of the basal friction: The *control* experiment ~~uses MAR-SEB SMB~~ applies SMB from MAR-SEB and unchanged (modern) basal friction; the *SMB* ~~experiments testing~~ experiment tests the simplified, but efficient SMB model, MAR-BESSI; the *basal* experiments ~~testing~~ test spatially uniform changes to the basal friction for the entire ice sheet; the *outlets* experiments ~~testing~~ test the sensitivity to changes of basal friction locally at the outlet glaciers (slow down/speed up of outlet glaciers; high velocity regions ~~(~~with >500 m/yr)~~, i.e., the outlet glaciers~~. For the ~~whole ice sheet sensitivity tests~~ *basal* and *outlets* experiments the basal friction coefficient is multiplied by factors 0.9 and 1.1~~and for the friction at the outlet glaciers alone the same factors (0.9 or 1.1) are used, but also more extreme values~~ . Furthermore, the *outlets* experiments are repeated with more extreme factors of 0.5 and 2.0~~are applied~~.

In additional experiments, with the more efficient SSA version of the model~~we explore~~ , a larger range of basal friction for the entire ice sheet is explored (doubling/halving of basal friction similar to Helsen et al., 2013). However, ~~we found that~~ applying factors of 0.5 and 2.0 for the entire ice sheet ~~gives~~ results in unrealistic surface height changes at the deep ice core locations (not shown). Therefore, these extreme changes of basal friction are only applied to the outlet glaciers in our 3D higher-order experiments.

The *altitude* experiments test the sensitivity to the SMB-altitude feedback by neglecting this feedback; which means that the transient SMB forcing is prescribed without altitude changes affecting the SMB. Finally, we perform a *relaxed* ~~experiments~~ experiment testing the sensitivity to a larger, relaxed initial ice sheet (with the same SMB and ice dynamics as the ~~control experiment), i.e. , we start with a relaxed~~ *control* experiment). This *relaxed* experiment starts with a larger ice sheet which ~~was evolved~~ is spun-up for 10 ~~kyr~~ ,000 years under constant pre-industrial ~~MAR-SEB SMB . Since we performed most experiments first in a 2D SSA setup we compare the results of 2D SSA and 3D higher-order to show the sensitivity to~~ SMB from MAR-SEB. The difference arising from the different ice flow approximation are illustrated in the *ice flow* ~~approximation~~experiments.

## 3 Results

The importance of the SMB forcing is illustrated in Fig. 1 showing the evolution of the Greenland ice volume in the ~~control~~ *control* experiment (MAR-SEB; bold orange line) and the ~~SMB~~ *SMB* sensitivity experiment (MAR-BESSI; bold purple line). The corresponding sub-sets of experiments testing the basal friction (*basal*, *outlets*) are indicated in lighter colors. There is a distinct difference between the model experiments forced with the two SMBs: ~~Forcing~~ forcing the ice sheet with MAR-SEB SMB (bold orange line) gives a minimum ice volume of 2.73 x $10^{15}$ $m^3$ at 124.7 ka corresponding to a sea level rise of 0.5 m — the basal sensitivity experiments give a range of 0.3 to 0.7 m (thin orange lines). On the other hand, the experiments forced with MAR-BESSI (bold purple line) give a minimum of 1.77 x $10^{15}$ $m^3$ at 123.8 ka (2.9 m sea level rise) with a range from 2.7 to 3.1 m (thin purple lines). The minimum ice volume and the corresponding sea level rise from all experiments are summarized in ~~Tab.~~Table 3.

The ~~basal friction sensitivity experiments with change friction~~ *basal* experiments (thin solid lines; Fig. 1; friction *0.9/*1.1 for the entire ice sheet~~(factors 0.9 and 1.1~~) show the strongest influence on the ice volume compared to ~~other basal friction experiments(thin solid lines; Fig. 1). Changing~~ the *outlets* experiments: changing the basal friction locally at the outlet glaciers (*outlets*) by factors of 0.9 and 1.1 has very little effect on the integrated ice volume (not shown). However, a halving/doubling of the friction at the outlet glaciers also shows a notable effect on the ice volume (0.05 to 0.15 m at the ice minimum; thin dashed lines; Fig. 1).

**Table 2.** Overview of the performed experiments

| type of experiment | SMB forcingmethod | basal friction | ice flow approx. |
|---|---|---|---|
| *control* | MAR-SEB | modern | 3D higher-order |
| *SMB* | MAR-BESSI | modern | 3D higher-order |
| *basal* (reduced) | MAR-SEB / | 0.9 * modern (entire ice sheet) | 3D higher-order |
| *basal* (reduced) | MAR-BESSI | 0.9 * modern (entire ice sheet) | 3D higher-order |
| *basal* (enhanced) | MAR-SEB / | 1.1 * modern (entire ice sheet) | 3D higher-order |
| *basal* (enhanced) | MAR-BESSI | 1.1 * modern (entire ice sheet) | 3D higher-order |
| *outlets* (reduced) | MAR-SEB / | 0.5 * modern (outlet glaciers) | 3D higher-order |
| *outlets* (reduced) | MAR-BESSI | 0.5 * modern (outlet glaciers) | 3D higher-order |
| *outlets* (reduced) | MAR-SEB | 0.9 * modern (outlet glaciers) | 3D higher-order |
| *outlets* (reduced) | MAR-BESSI | 0.9 (0.5)* modern (regions >500 m/youtlet glaciers) | 3D higher-order |
| *outlets* (enhanced) | MAR-SEB / | 1.1 * modern (outlet glaciers) | 3D higher-order |
| *outlets* (enhanced) | MAR-BESSI | 1.1 (* modern (outlet glaciers) | 3D higher-order |
| *outlets* (enhanced) | MAR-SEB | 2.0 * modern (outlet glaciers) | 3D higher-order |
| *outlets* (enhanced) | MAR-BESSI | 2.0 )* modern (regions >500 m/youtlet glaciers) | 3D higher-order |
| *altitude* | MAR-SEB / | modern | 3D higher-order |
| *altitude* | MAR-BESSI | modern | 3D higher-order |
| *relaxed* | MAR-SEB | modern | 3D higher-order |
| *ice flow* | MAR-SEB / | modern | 2D SSA |
| *ice flow* | MAR-BESSI | modern | 2D SSA |

The importance of the SMB-altitude feedback is illustrated in Fig. 2 which shows the evolution of the ice volume with the two SMB forcings with (bold orange/purplelines(*control*, bold orange; *SMB*, bold purple) and without applying the SMB gradient method (*altitude*, thin orange/purplelines). Neglecting the evolution of the SMB with the changing ice sheetsurface elevation, i.e., using the offline calculated SMBs directly, results in significantly less melt. This is particularly pronounced in the MAR-BESSI experiments experiments forced with MAR-BESSI, because the ablation area in this SMB forcing is larger and therefore also larger regions are affected from by melt-induced surface lowering. The differences between 3D higher-order and 2D SSA are surprisingly small, particularly at the beginning of the simulations while the ice volume is decreasing (*ice flow*, black and graylines). The differences between the ice flow approximations become larger as the ice sheet approaches a new equilibrium statetowards enters into a colder state, at the end of the simulations. Finally, in the *relaxed* experiment (dark green) the evolution of the sensitivity experiment with a relaxed initial ice sheet (but same forcing and ice dynamics as control

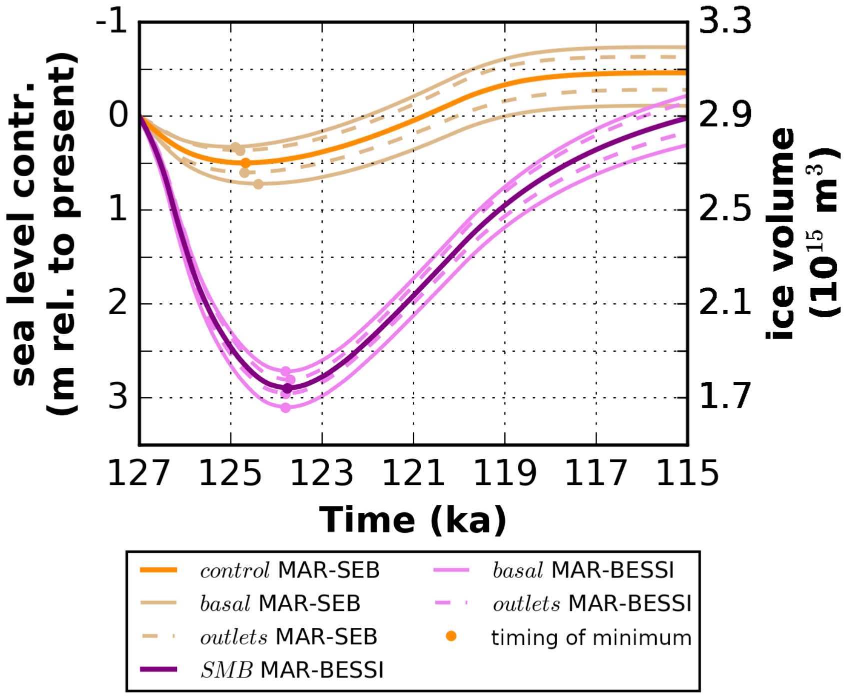


**Figure 1.** Evolution of the ice volume for the ~~control experiment and the sensitivity experiments testing for SMB and basal/outlets friction. The colors indicate different SMB forcings: orange colors -~~ *control* (MAR-SEB, ~~purple colors - MAR-BESSI. The bold~~ orange~~line is the control experiment. The~~ , bold~~purple is~~ ) and the ~~corresponding experiment with~~ *SMB* (MAR-BESSI~~forcing~~, purple, bold) experiments in comparison with the *basal/outlets* sensitivity experiments. The ~~thin solid lines show the ±10% basal~~ *basal* (friction ~~experiments~~ *0.9/*1.1 for the entire ice sheet) and *outlets* sensitivity experiments (friction *0.5/*2.0 at the outlet glaciers) are indicated with thin solid and thin dashed lines~~show the experiments with doubling/halving of~~ , respectively. Note that the ~~outlets friction —~~ lower friction experiments give lower volumes. The minimum of the respective experiments is indicated with circles. See ~~Tab.~~ Table 3 for the exact values.

~~experiment ) is shown (darkgreen line) . The~~ volume decrease is more pronounced because the relaxed ice sheet is larger and the SMB forcing is negative enough to melt the additional ice at the margins. However, at the end of the simulations the *control* and the *relaxed* experiments become indistinguishable.

~~Figure 3 shows~~ Comparing the SMB forcing for the ~~control~~ *control* experiment (MAR-SEB; ~~top row~~Fig. 3a-d) and the ~~corresponding sensitivity experiment with MAR-BESSI (bottom row) at the beginning of simulation (127 ka) , 125, 120, and 115~~*SMB* experiment (MAR-BESSI; Fig. ~~ka. This figure~~ 3e-h) emphasizes the importance of the SMB-altitude feedback~~, because~~ . While the offline calculated SMBs (i.e., modern and initial surface) are similar~~between 130 and 125 ka (not shown), but the lowering of the surface in the beginning of the simulations~~ , the surface lowering in combination with the SMB gradient method cause the resulting SMB to become very negative in the southwest (for both MAR-SEB and MAR-BESSI) and in the

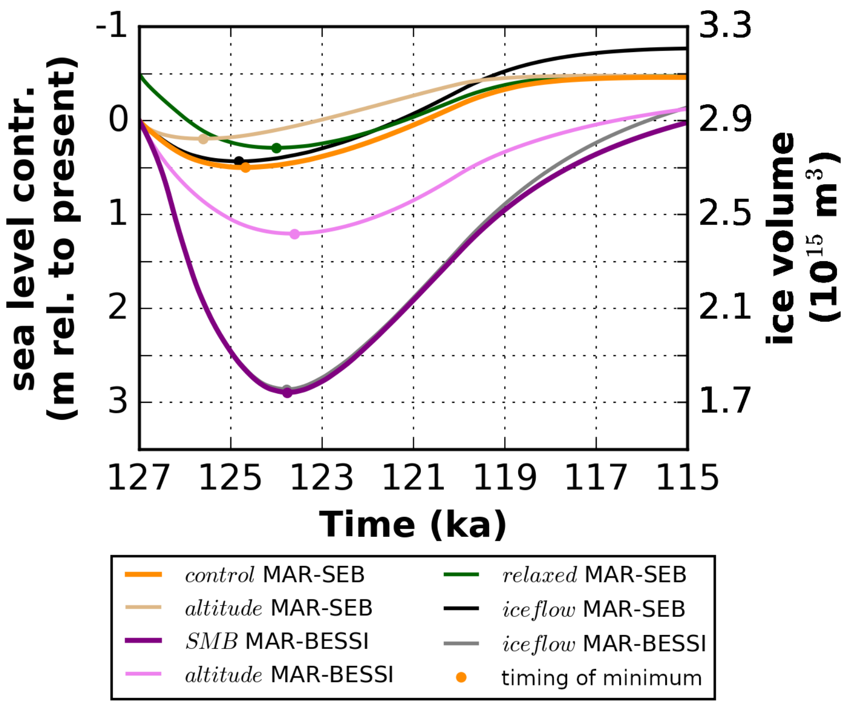


**Figure 2.** Evolution of the ice volume for the control experiment and the sensitivity experiments testing the influence of the SMB-altitude feedback*control* (MAR-SEB, the relaxed initial ice sheetorange, bold) and the ice flow approximation *SMB* experiments (3D higher-order vs. 2D SSA). The colors indicate different SMB forcings: orange colors - MAR-SEBMAR-BESSI, purplecolors - MAR-BESSI. The bold orange line is the control experiment. The , boldpurple is the corresponding experiment ) in comparison with MAR-BESSI forcingthe *altitude*, *relaxed*, and *iceflow* sensitivity experiments. The light colored lines are the corresponding experiments without the *altitude* (no SMB-altitude feedback. The dark green line is the relaxed initial ice sheet experiment with MAR-SEB forcing. ) and *iceflow* (2D SSA) sensitivity experiments corresponding to the bold lines are shown in bold black lighter colors and black/gray, respectively. The *relaxed* sensitivity experiment (relaxed larger initial ice sheet, but otherwise *control* forcing) is shown in dark green.

northeast (particularly for MAR-BESSI). Regions with extremely low SMB at 125 ka are ice-free at the time of the simulation (ice margins are indicated with a black solid line).

The simulated ice sheet thickness in the control *control* experiment (Fig. 4, top rowa-d; MAR-SEB) shows only moderate changes. However, there is significant melt in the southwest at 125 ka (actual minimum at 124.7 ka; see Fig. 7). Using the same setup, but with MAR-BESSI 4b). The *SMB* sensitivity experiment (Fig. 4, bottom row) e-h; MAR-BESSI) on the other hand gives a very different evolution of the ice thickness: The ice sheet retreat is significantly enhanced at At 125 ka (actual minimum at 123.8the *SMB* experiment (Fig. ka; not shown) , in particular for 4f) shows an enhanced retreat in the southwest, as well as but particularly strong in the northeast. The ice sheet also Furthermore, the ice sheet takes longer to recover in the

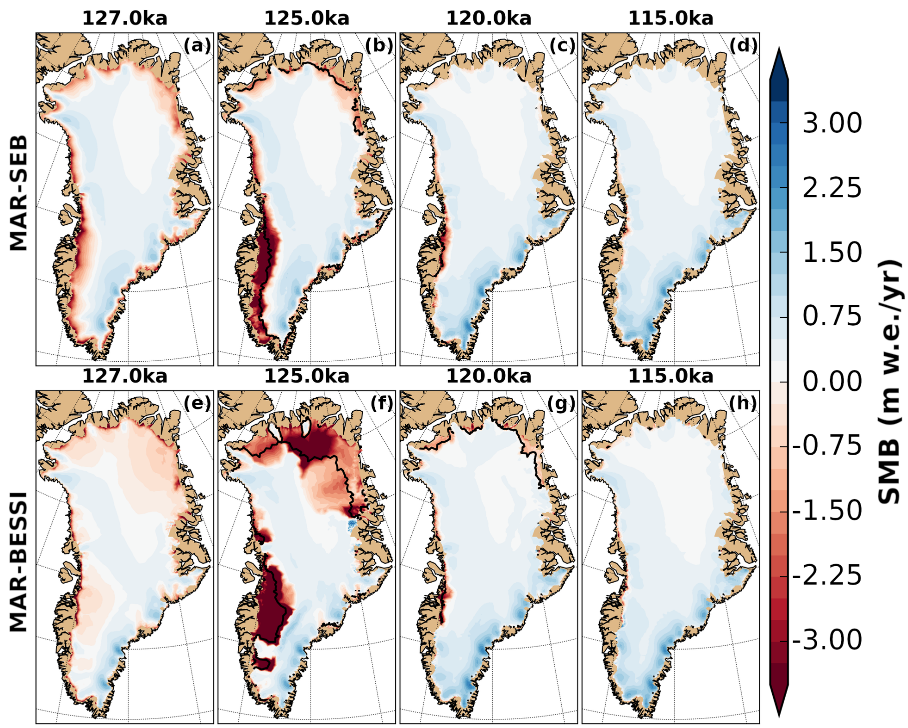


**Figure 3.** SMB forcing corrected for ~~altitude~~ surface elevation changes at 127, 125, 120, 115 ka for the *control* (a-d, MAR-SEB) and the *SMB* (e-h, MAR-BESSI) experiments. The ice margin is indicated with a solid black line (~~i.e.,~~ 10 m ice thickness remaining). ~~If the~~ A nonvisible ice margin is ~~not visible it is~~ identical with the domain margin. For a consistent comparison, the ice thickness is shown at 125 ka instead of the individual minimum (*control* at 124.7 ka ~~for MAR-SEB~~ and *SMB* at 123.8 ka~~for the MAR-BESSI~~).

*SMB* experiment, giving a ~~significantly~~ smaller ice sheet at 120 ka ~~, partly as a consequence of~~ (Fig. 4g), mainly due to the large ice loss in the northeast.

The ~~experiments with~~ MAR-SEB ~~forcing~~ forced experiments give only small changes (±200 m) in ice surface elevation at the deep ice core locations — Camp Century, NEEM, NGRIP, GRIP, Dye-3, EGRIP (Fig. 5). At most locations the surface elevation increases due to a positive SMB~~(~~, which is not in equilibrium with the initial ice sheet~~). Only~~ . The *relaxed* experiment (dark green), which is in equilibrium with the initial climate, shows damped elevation changes. Notably, Dye-3 ~~shows an initial lowering . Larger changes are seen in the MAR-BESSI experiments~~(Fig. 5c) shows the strongest initial lowering due to its southern location affected by the early Eemian warming. The MAR-BESSI-forced experiments show much larger changes in surface elevation, particularly at Dye-3 ~~and NGRIP~~ (Fig. 5c) and NGRIP (Fig. 5b) with a maximum lowering of around 600 m, and ~~EGRIP~~at EGRIP (Fig. 5f), where the the largest lowering is around 1500 m. In contrast to the ice volume evolution, where differences between the *control* and the *ice flow* experiment are small (Fig. 2), there is a larger difference in ~~simulated ice surface~~ ice surface elevation changes between the ice flow approximations. The 2D SSA experiments (Fig. 5, black and grey~~solid lines~~) show ice surface changes up to ~~several hundred meters~~ 200 m different from the 3D higher-order experiments ~~.~~

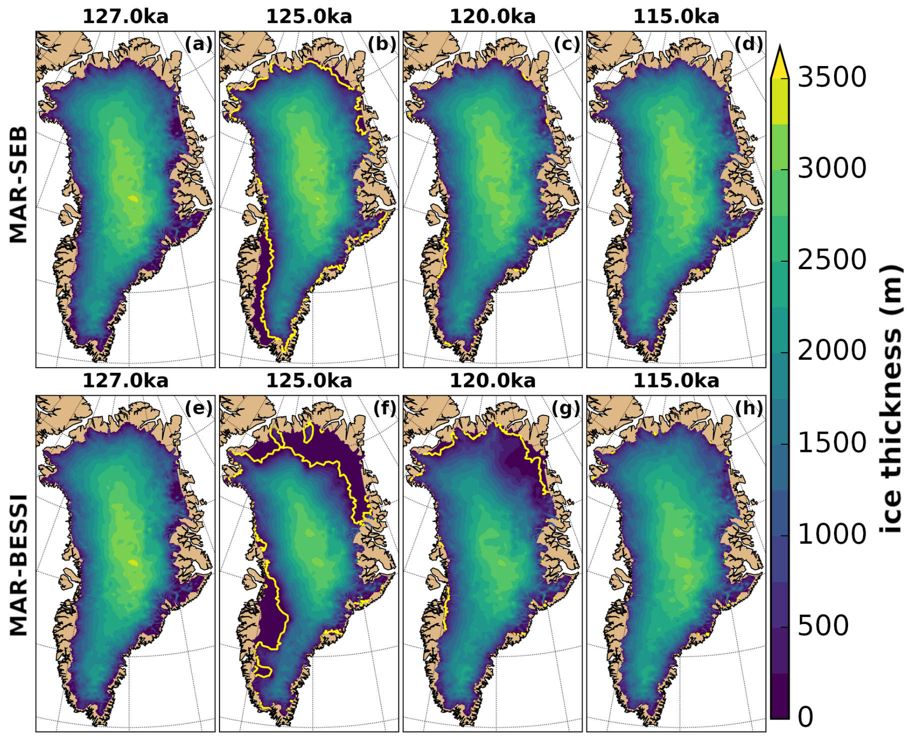


**Figure 4.** Ice thickness at 127, 125, 120, 115 ka for the *control* (a-d, MAR-SEB) and the *SMB* (e-h, MAR-BESSI) experiments. The ice margin is indicated with a solid yellow line (~~i.e.,~~ 10 m ice thickness remaining). ~~If the~~ A nonvisible ice margin is ~~not visible it is~~ identical with the domain margin. For a consistent comparison, the ice thickness is shown at 125 ka instead of the individual minimum (*control* at 124.7 ka ~~for MAR-SEB~~ and *SMB* at 123.8 ka~~for the MAR-BESSI~~).

~~At Dye-3 the differences are especially pronounced. Note that for NEEM, most of the simulations lie within the reconstructed surface elevation change (gray shading~~(Fig. 5, bold orange and purple).

The impact of ~~SMB forcing, basal friction, and ice flow approximation~~ all sensitivity experiments on the ice volume minimum is ~~shown~~ summarized in Fig. 6. The choice of SMB model (~~black bar~~*SMB*, black) shows the strongest influence with a difference in sea level rise of ~2.5 m ~~difference between the control~~ between the *control* experiment (with MAR-SEB) and the ~~corresponding MAR-BESSI experiment . The~~ *SMB* experiment (with MAR-BESSI). Furthermore, the SMB-altitude feedback is particularly important for the MAR-BESSI forced *altitude* experiment, due to the large regions affected by melt-induced surface lowering. The ~~sensitivity experiments with changed basal friction~~ *basal* and *outlets* sensitivity experiments show a limited effect on the simulated ~~minimum ice volume (both ice sheet as a whole and only outlets). Furthermore~~ice volume minimum. Finally, using a ~~relaxed ice sheet in the control experiments~~ larger, relaxed initial ice sheet (*relaxed*) results in a ~0.3 m larger sea level rise. A ~~comprehensive~~ complete summary of the ~~simulated~~ respective ice volume minima is given in ~~Tab.~~Table 3.

There are surprisingly small differences between the simulated ice thickness minimum of the ~~control experiment (with 3D higher-order;~~ *control* experiment (Fig. 7~~; left~~a; MAR-SEB and 3D higher-order) and the corresponding ~~experiment using~~

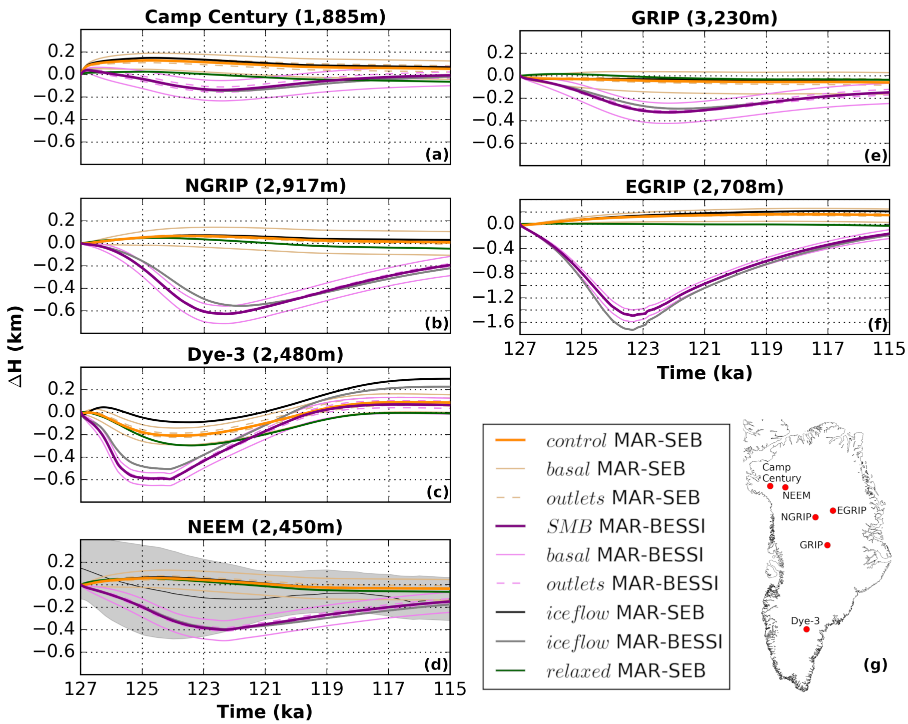


**Figure 5.** Ice surface evolution at Greenland ice core locations for the *control*, *SMB*, *basal*, *outlets*, *ice flow*, and *relaxed* experiments — Camp Century, NEEM, NGRIP, GRIP, and Dye-3 are shown on the same scale; EGRIP is shown on a different scale. Same color-coding as in Fig. 1~~, additionally including 2D SSA experiments with unchanged, modern friction in bold black~~ and~~gray~~ 2. ~~Reconstruction~~ Surface elevation reconstructions from total gas content at NEEM are indicated with gray shading. Note that the 2D experiments are plotted in the background and therefore hardly visible in some cases, particularly at NEEM.

~~2D SSA~~ *ice flow* experiment (Fig. 7~~; right~~b; MAR-SEB and 2D SSA). Only minor differences ~~can be found~~ are visible on the east coast, where the 2D SSA experiment shows a stronger thickening than ~~in~~ the 3D higher-order ~~control~~ experiment. The complex topography in this region might explain the problem in the 2D experiment. These small differences between the ice flow approximations emphasize the controlling role of the SMB forcing and the SMB-altitude feedback. However, ice flow induced thinning (e.g., due to increased basal sliding) could initiate or enhance the SMB-altitude feedback.

~~The impact of lower friction on the minimum ice thickness is illustrated in Fig. 8 for a selection of MAR-SEB lower friction experiments. The minimum ice thickness for the control experiment is shown on the left. Lowering~~ Reducing the friction at the base of the entire ice sheet by a factor of 0.9 (*basal**0.9, Fig. 8~~; middle~~b) results in a thinning on the order of 100 m in large parts of the ice sheet ~~. Interestingly, in the northeast this effect is inverted, i.e., a Greenland-wide lowering of friction leads to a thickening in the northeast margin.This is because a large amount of ice drains towards this region: afaster inflow~~ relative to the ice sheet minimum in the *control* experiment (Fig. 8a). The faster flowing ice sheet leads to a build up of ice at the ~~outlet. A closer look at the margins reveals that this observed build up of ice is visible at most outlets, including Jakobshavn Isbræ in the~~

**Table 3.** Summary of the simulated ice sheet minima for all experiments

| **experimental setup** | SLR [m] rel. to initial | ΔSLR [m] at resp. minima minimum | Minimum GrIS volume ($10^{15}m^3$) |
|---|---|---|---|
| ***control* MAR-SEB** | **0.51** | **0.00** | **2.73** |
| *basal**0.9 MAR-SEB | 0.73 | +0.22 | 2.64 |
| *basal**1.1 MAR-SEB | 0.33 | -0.17 | 2.80 |
| *outlets**0.9 (*0.5 ) MAR-SEB | 0.53 (0.61 ) | +0.02 (+0.10) | 2.72 (2.69 ) |
| *outlets**0.9 MAR-SEB | 0.53 | +0.02 | 2.72 |
| *outlets**1.1 (MAR-SEB | 0.48 | -0.02 | 2.74 |
| *outlets**2.0 ) MAR-SEB | 0.48 (0.36 ) | -0.02 (-0.15) | 2.74 (2.79 ) |
| *altitude* MAR-SEB | 0.18 | -0.32 | 2.86 |
| *relaxed* MAR-SEB | 0.79 | +0.28 | 2.82 |
| *ice flow* (2D) MAR-SEB | 0.43 | -0.07 | 2.76 |
| *SMB* MAR-BESSI | 2.90 | 0.00 | 1.77 |
| *basal**0.9 MAR-BESSI | 3.10 | +0.20 | 1.69 |
| *basal**1.1 MAR-BESSI | 2.72 | -0.18 | 1.84 |
| *outlets**0.9 (*0.5 ) MAR-BESSI | 2.90 (2.95 ) | +0.00 (+0.05) | 1.77 (1.75 ) |
| *outlets**0.9 MAR-BESSI | 2.90 | +0.00 | 1.77 |
| *outlets**1.1 (MAR-BESSI | 2.87 | -0.03 | 1.78 |
| *outlets**2.0 ) MAR-BESSI | 2.87 (2.80 ) | -0.03 (-0.10) | 1.78 (1.81 ) |
| *altitude* MAR-BESSI | 1.20 | -1.70 | 2.45 |
| *ice flow* (2D) MAR-BESSI | 2.85 | -0.05 | 1.79 |

For the *outlets* sensitivity experiments, the basal friction in regions with > 500 m/yr is changed. Sea level rise (SLR) values are relative to the initial ice sheet at 127 ka, i.e., the modern ice sheet for all experiments except the relaxed initial ice sheet experiment. The lost ice volume is equally spread over the modern ocean area. ΔSLR refers to anomalies relative to the respective SMB forcing experiments with unchanged friction.

southwest, but less pronounced. Lowering margins and the topographically constrained outlet glaciers, particularly visible in the northeast. Furthermore, reducing the basal friction only at the outlet glaciers by a factor of 0.5 (*outlets**0.5 Fig. 8; right)c), leads to a local thinning around the outlet glaciers of several hundred meters. Note that the thinning also affects ice thickness upstream from the outlet region.

The ice velocities in the basal sensitivity *basal**0.9 experiments indicate that a Greenland-wide reduction of basal friction by a factor of 0.9 leads to a speed up of the outlet glaciers by up to several 100 m/year (Fig. 9; middle) . Reducing b) relative to the *control* experiment. Furthermore, reducing the friction at the outlet glaciers by a factor of 0.5 has a large, but local effect

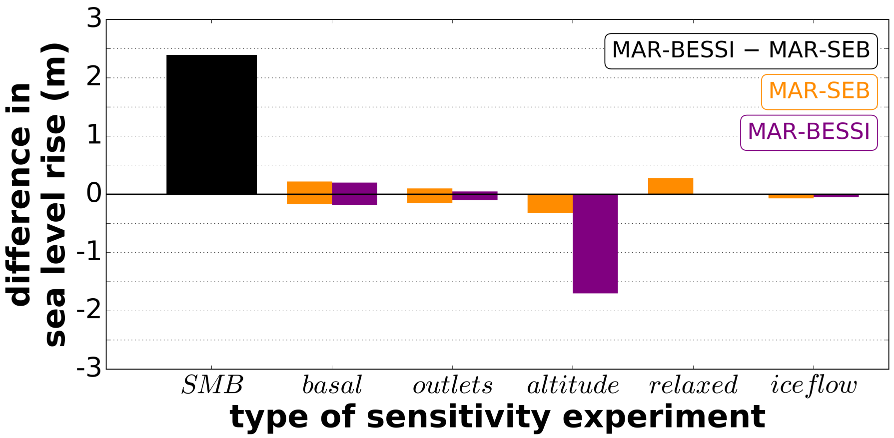


**Figure 6.** Differences in sea level estimates given between the minimum Eemian ice sheet simulated by the respective sensitivity experiments. : *SMB* (black)refers to the : difference between the two SMB forcings (incl. *control* and the SMB-altitude feedback*SMB* experiment (MAR-SEB and MAR-BESSI, respectively). *basal/outlets* refers to sensitivity *basal*: experiments with changes changed friction for the entire ice sheet/outlets. *altitude* shows *outlets*: experiments with changed friction at the outlet glaciers. *altitude*: experiments without the SMB-altitude feedback. *relaxed*uses : experiment with a relaxedlarger, relaxed initial ice sheet, and . *ice flow*shows : experiments with 2D SSA instead of the difference between default 3D higher-order and 2D SSA ice flow approximation. The results of the sensitivity experiments are different SMB forcing is shown in orange (MAR-SEB) and purple (MAR-BESSI). *basal/outlets* experiments show positive and negative values because they are performed with enhanced and reduced friction. The exact values are given in Tab.Table 3.

on the ice velocity (*outlets**0.5) results in a local speed-up of several 100 m/yr (Fig. 9; right). Both, this local c). Although the *outlets**0.5 experiment also shows a speed-up as well as the local thinning in the 0.5 * lower outlet friction experiment further upstream (in the order of several m/yr), in combination with the local ice thinning (Fig. 8; right)show that the outlet friction have a limited effect on regions further upstreamc), the effects of halving the friction at the outlet glaciers shows a minimal effect on the total ice volume (see also in Fig. 1).

## 4 Discussion

Changing the SMB forcing — between a full surface energy balance model (MAR-SEB) and an intermediate complexity SMB model (MAR-BESSI) — gives the biggest difference in the simulated largest difference in our simplified simulations of the Eemian ice sheet evolution (Fig. 6). Compromises such as the lack of ocean forcing and GIA, and limited changes of basal friction are necessary to keep 3D higher-order simulations feasible on a millennial-scale and are discussed in this section.

MAR-SEB and MAR-BESSI are two Eemian SMBs from a wide estimates of Eemian SMBs selected from a wider range of simulations analyzed in Plach et al. (2018a). Note that the same global climate model (NorESM) is used as a boundary condition for the SMB models. All available NorESM Plach et al. (2018b). The same Eemian global climate simulations

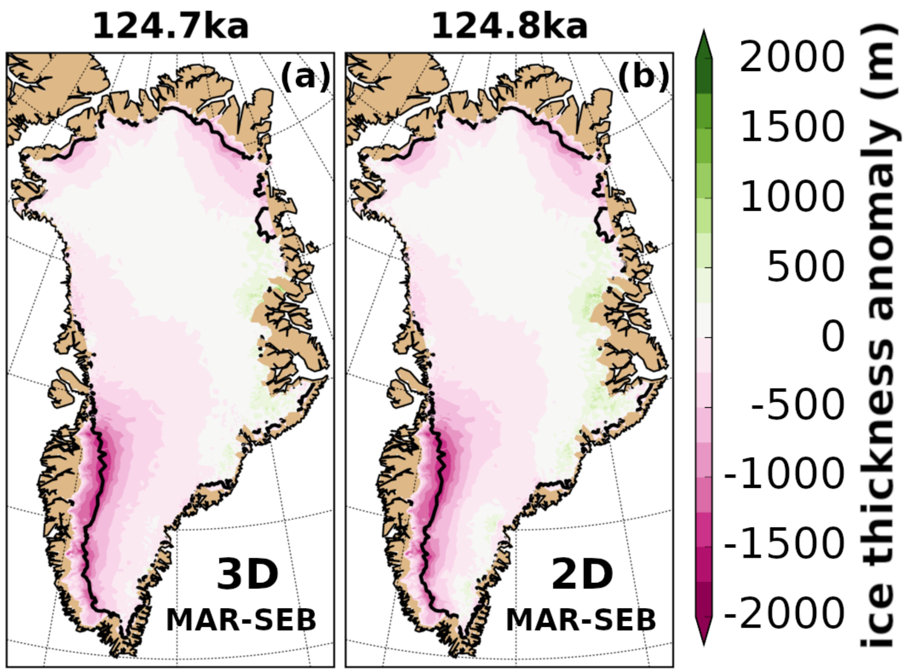


**Figure 7.** Ice thickness anomalies simulated with the ~~control~~ *control* (a; 3D higher-order~~(left~~) and ~~ice flow~~ the *ice flow* (b; 2D SSA~~(right~~) experiments at the respective ~~Eemian~~ ice minimum. ~~Relative~~ Anomalies are relative to the initial~~127 ka ice sheet (i.e.~~, modern ice sheet~~)~~. The respective minimum time ~~of the individual experiments~~ is indicated on the top of each panel. The ice margin is indicated with a solid black ~~bold~~ line (~~i.e.,~~ 10 m ice thickness remaining). If the ice margin is not visible it is identical with the domain margin.

~~covering the Eemian period are~~ from the NorESM, downscaled over Greenland ~~using~~ with the regional climate model MAR~~.~~ ~~Here we neglect the~~ , are used as forcing for the SMB models. Since only one global climate model is used in this study, uncertainties relating to the ~~global climate forcing. Including such uncertainties~~ Eemian climate cannot be evaluated here. Testing the impact of different global climate simulations is beyond the scope of this study. Instead the reader is referred to the discussion in ~~Plach et al. (2018a)~~Plach et al. (2018b).

Our ~~control~~ *control* experiment with the 3D higher-order ice flow ~~,~~ model with modern, unchanged basal friction coefficients, and forced with MAR-SEB ~~shows little melting (~~SMB shows minor melting (equivalent to 0.5 m sea level rise), while the *SMB* sensitivity experiment with MAR-BESSI ~~causes a large ice sheet reduction~~ SMB causes a much larger ice sheet retreat (2.9 m sea level rise). The basal sensitivity experiments *(basal/outlets)* give a range of approx. equivalent ±0.2 m sea level rise for both SMB models~~, where~~ ; with the Greenland-wide friction change ~~shows~~ *(basal)* showing the largest influence on the minimum ice volume. ~~Decreasing~~Reducing/~~increasing~~ enhancing the friction at the outlet glaciers *(outlets)* by a factor of 0.9/1.1 shows mainly local thinning/thickening at the outlets (Fig. 8c) with limited ~~effects~~ effect on the total ice volume (Fig. 1, Table 3). However, doubling ~~/halving~~ the friction at the outlet glaciers ~~leads to an ice volume change equivalent to 0.05-0.15~~reduces the

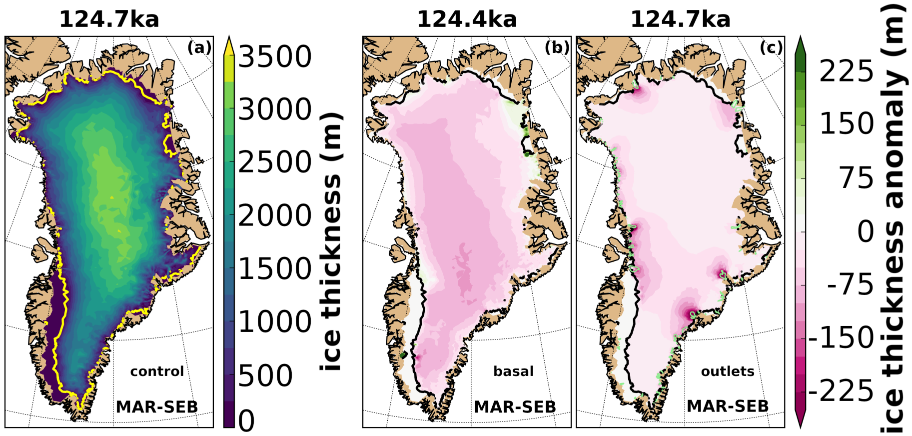


**Figure 8.** Minimum ice thickness of the ~~control~~ *control* experiment (~~left~~a)~~and~~ , the ~~basal*0~~basal*0.9 ~~/outlets*0.5~~ (b; reduced friction ~~experiments~~ of the entire ice sheet), and the outlets*0.5 (~~middle/right~~c; reduced friction at outlet glaciers) experiments at ~~the time of the~~ their respective ice sheet minimum (time indicated on top of panels). ~~basal*0.9 and outlets*0.5~~ Anomalies are ~~shown as anomaly~~ relative to the ~~control~~ *control* experiment. The ice margin is indicated with a solid yellow/black ~~bold~~ line (10 m ice thickness remaining). If the ice margin is not visible it is identical with the domain margin. The outlet regions are indicated with bright green contours (c).

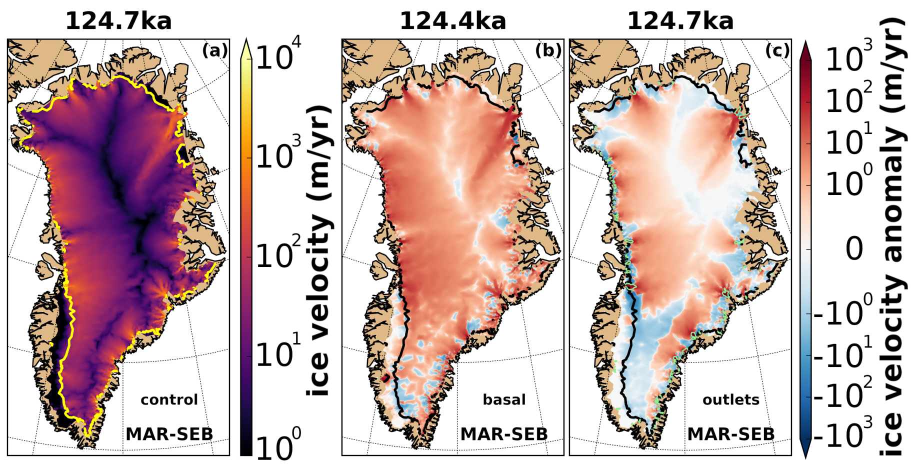


**Figure 9.** Ice velocity of the minimum ice sheet in the ~~control~~ *control* experiment (~~left~~a) and the ~~basal*0~~basal*0.9 ~~/outlets*0.5~~ (b; reduced friction ~~experiments~~ of the entire ice sheet), and the outlets*0.5 (~~middle/right~~c; reduced friction at outlet glaciers) experiments at ~~the time of the~~ their respective ice sheet minimum (time indicated on top of panels). ~~basal*0.9 and outlets*0.5~~ Anomalies are ~~shown as anomaly~~ relative to the ~~control~~ *control* experiment. The ice margin is indicated with a solid yellow/black ~~bold~~ line (~~i.e.,~~ 10 m ice thickness remaining). If the ice margin is not visible it is identical with the domain margin. The outlet regions are indicated with bright green contours (c).

sea level rise contribution by 0.15 and 0.10 ~~m sea level.~~ m for MAR-SEB and MAR-BESSI SMB forcing respectively (relative to the *control* experiment; Table 3).

The basal friction sensitivity experiments (*basal/outlets*) are non-exhaustive and further experiments could be envisioned: including a lower velocity threshold to define the outlet glaciers, continuous identification of outlet regions, combining *basal**0.9 and *outlets**0.5 experiments, to name a few. In such experiments the impact on the ice sheet evolution might be larger than in the experiments discussed. Regardless of the specific formulation of the anomalous basal friction, the sensitivity experiments shown here represent a substantial change in basal properties and there illustrate the magnitude of the uncertainties related to the basal conditions implying that caution is required when deriving the basal friction. Finding appropriate basal conditions of past ice sheets in challenging. We show that after applying a large range of friction it is unlikely that friction at the base has a stronger influence than changing the SMB forcing unless explicit dynamic sub-glacial hydrology linked to SMB is included.

The importance of coupling the climate (SMB) and the ice sheet has been demonstrated in previous studies, e.g., recently for regional climate models in a projected future climate assessment by Le clec'h et al. (2017)Le clec'h et al. (2019). However, running a high resolution regional climate model over several thousand years is not possible at present presently unfeasible due to the exceedingly high computational cost. This is even more true when the goal is to run an ensemble of long sensitivity simulations as presented here. Although a coupling between the ice sheet and climate model is absent in our simulations , we do account for the presented simulations are lacking the ice-climate coupling, the SMB-altitude feedback is accounted for by applying the SMB gradient method. The SMB becomes significantly lower is significantly lowered as the ice surface is lowered: neglecting the SMB-altitude feedback gives less than half the volume reduction (MAR-SEB: 0.2 vs. 0.5 m; MAR-BESSI: 1.2 vs. 2.9 m; Fig. 2 and 6).

Towards the end of the simulations, all model experiments develop a new equilibrium ice sheet ice sheet state which is larger than the initial state (Fig. 1 and 2). This relaxation development towards a larger ice sheet is likely due to related to a relaxation of the initial pre-industrial ice sheet configuration not being in equilibrium with the initial SMB forcing. A simulation over 10 kyr simulation ,000 years with constant pre-industrial SMB gives an ~10 % larger "relaxed " relaxed modern ice sheetwhich is in equilibrium with the forcing. Sensitivity . The *relaxed* sensitivity experiments with this "relaxed " relaxed initial ice sheet (~0.5 m larger initial state) result in a ~0.3 m larger sea level rise (at the minimum) compared to the control experiment. We don't expect *control* experiment. Although the 127 ka GrIS is not expected to be in equilibrium with pre-industrial forcing. However, the "relaxed" , the *relaxed* experiment demonstrates the impact of a larger initial ice sheet on our estimates of the contribution of Greenland to the Eemian sea level high-stand. Furthermore, the *relaxed* experiment illustrates the strong, but slow impact of the SMB forcing, even when starting with a different initial ice sheet, the final size is similar to the *control* experiment, because late-Eemian SMB results in a strong steady-state of the ice sheet.

Furthermore, the simplified initialization implies that the thermal structure of the simulated ice sheet is lacking the history of a full glacial-interglacial cycle, i.e., the ice rheology of our ice sheet is different to an ice sheet which is spun-up through a glacial cycle. Helsen et al. (2013) demonstrate the importance of the ice rheology for the pre-Eemian ice sheet size. They find differences of up to 20% in initial ice volume after a spin-up forced with different glacial temperatures (in simulations with basal conditions not based on assimilation of surface velocities as it is the case here). In our approach a biased thermal structure is partly compensated by basal friction optimized so that the simulated surface velocities represent the observed, modern velocities. A viable way to test the influence of the thermal structure on the ice rheology would be to perform additional sensitivity experiments. However, such rheology experiments can only be performed in the 3D higher-order setup (the 2D SSA setup neglects vertical shear) and the computational resources to run additional 3D experiments are limited.

~~The results of the~~ Starting the simulations with a smaller ice sheet would influence the simulated maximum sea level contribution. A smaller ice sheet, in combination with the SMB-altitude feedback, would result in a more negative SMB at the lower surface regions. This could potentially lead to smaller differences between the MAR-SEB and MAR-BESSI results because large regions in the MAR-BESSI forced simulations melt away completely, and a more negative SMB would show limited effect in such regions. However, the MAR-SEB forced simulations are more likely to be affected by the lower initial ice elevation. Note that, neglecting GIA could counteract the effect of a lower initial ice sheet as well as a negative SMB, as the isostatic rebound of the regions effected by melt would partly compensate for the height loss.

The *ice flow* experiments (2D SSA) show very similar results to the corresponding experiments with 3D higher-order ~~and 2D SSA experimentsare similar~~(*control* and *SMB* experiments), in particular for the simulated minimum ice volume. However, the ~~difference~~ differences in ice volume ~~becomes~~ become larger towards the end of the simulations under colder climate conditions (less negative SMB~~forcing~~). Furthermore, the ice surface evolution at the deep ice core locations ~~differs substantially for the two~~ show a similar behavior with both ice flow approximations~~.~~

: differences are less than ~150 m (at most locations). The strong similarities between 3D higher-order and 2D SSA — also noted by Larour et al. (2012) using ISSM for centennial simulations — are likely related to the inversion of the friction coefficients from observed velocities. The dynamical deficiencies of the 2D SSA ice flow are partly compensated by the inversion algorithm: this algorithm chooses basal conditions such that the model simulates surface velocities as close to the observations as possible. The relatively small difference between the 3D higher-order and 2D SSA experiments indicates that the SMB forcing is more important in our simulations than the ice dynamics.

Basal hydrology is neglected in ~~our~~ the simulations because it is not well understood and therefore difficult to implement in a robust way. Furthermore, an implementation of ~~basal hydrology~~ a basal hydrology model would increase the computational demand of ~~our~~ the simulations and make them unfeasible on the millennial time scales we are investigating. ~~We recognize~~ However, it is recognized that basal hydrology might have been important for the recent observed acceleration of Greenland outlet glaciers (e.g., Aschwanden et al., 2016). Therefore, the impact of changing basal ~~hydrology at the outlet glaciers~~ conditions is tested by varying the friction at the bed of the outlet glaciers. Although ~~we are not simulating basal hydrology explicitly, we can assess~~ basal hydrology is not explicitly simulated, its possible consequences ~~—~~ in form of a slow down, or speed up of the outlet glaciers can be assessed (see Sec. 3).

Furthermore, ~~we~~ the simplified setup chosen to neglect ocean forcing and processes ~~including~~ such as grounding line migration due to their complexity~~and because~~. The focus of this study is on the minimum Eemian ice sheet ~~is likely to have~~ which has likely been land based. ~~Note, however, that~~ However, these processes are thought to be important for the recent observed changes at Greenland's outlet glaciers (Straneo and Heimbach, 2013). In a recent study, Tabone et al. (2018) investigate the influence of ocean forcing on the Eemian GrIS. Their sensitivity experiments indicate that the Eemian minimum is governed by the atmospheric forcing, due to ~~the lack of contact between the ice margin and the ocean~~a lack of ice-ocean contact. However,

~~their estimated relative Eemian sea level rise~~ the resulting estimate of the Eemian GrIS sea-level contribution is dependent on the ocean forcing, as it influences ~~their~~ the pre-Eemian ice sheet size.

~~Our simulations , starting with the orbital configuration and greenhouse gas levels~~ The simulations are initiated at 127 ka ~~, are initiated~~ with the observed modern geometry of the Greenland ice sheet (following the PMIP4 protocol; Otto-Bliesner et al., 2017). This choice is based on the fact that the present-day ice sheet is relatively well known whereas the pre-Eemian ice sheet size is highly uncertain. Since the global sea level went from a glacial low stand to an interglacial high stand, during the course of the Eemian interglacial period, it is a fair assumption that the Eemian GrIS, at some point during this period, resembled the present-day ice sheet. In this study, this point is chosen to be at 127 ka. One advantage of this procedure, is that ~~is~~ it allows for a basal friction configuration based on inverted observed modern surface velocities. A spin-up over a glacial cycle ~~,~~ without adapting basal friction ~~,~~ would be unrealistic. Furthermore, a spin-up would require ice sheet boundary migration, i.e., implementation of calving, grounding line migration, and a larger ice domain. This would be challenging as the ~~resolution of the ISSM mesh~~ mesh resolution is based on observed surface velocities ~~. Furthermore, a time adaptive~~ and the domain therefore limited to the present-day ice extent. Additionally, a time-adaptive mesh, to allow for the migration of the high resolution mesh with the evolving ice streams, would be ~~adventurous but challenging to implement. Furthermore~~necessary. Unfortunately, a realistic spin-up with all these additions is presently unfeasible due to the high computational cost of the model. Moreover, the lack of a robust estimate of the pre-Eemian GrIS size and the ~~uncertainties in climate~~ climate uncertainties over the last glacial cycle would introduce ~~even~~ many more uncertainties to the initial ice sheet~~, which is outside the scope of this study. However, in the future, once these hurdles have been overcome, a 3D higher-order spin-up covering the last glacial cycle will be attempted~~.

~~Our simulated impact of the GrIS on the Eemian global mean sea level high-stand in our control experiment (~~The Eemian GrIS sea level contribution of ~0.5 m ~~)~~ in the *control* experiment is low compared to previous Eemian model studies (Fig. 10). ~~While, the sensitivity experiments with the second, less advanced, SMB model (~~Proxy studies based on marine sediment cores (Colville et al., 2011) and ice cores (NEEM community members, 2013), respectively, provide an sea level rise estimate of 2 m from the Eemian Greenland ice sheet, while assuming no contribution from the Northern part of the ice sheet, where no proxy constraints are available. However, scenarios with larger contributions from the North could be possible as in the MAR-BESSI ~~) show a significantly larger contribution to sea level (~~forced experiments. Although the *SMB* sensitivity experiment forced with SMB from MAR-BESSI shows a larger contribution of ~3.0 m ~~),~~ which is closer to previous ~~estimates.~~ model estimates, this does not necessarily mean that the MAR-BESSI SMB is more realistic. These results could indicate systematic biases in the experimental setup, causing a general underestimation of the Eemian sea level contribution.

Both SMB models are forced with a regionally downscaled climate based on ~~experiments~~ simulations with the global climate model NorESM. ~~This emphasises~~ NorESM, as other climate models, has biases, which end up in the MAR-derived SMBs. This present study can be seen as a sensitivity study to SMB forcing for millennial-scale ice sheet simulations. While the simplified setup has its limits, the study emphasizes the importance of ~~both an accurate global climate simulation and a realistic SMB model in estimating the GrIS minimum in a warm climate such as the Eemian interglacial period~~the accurate SMB forcing in

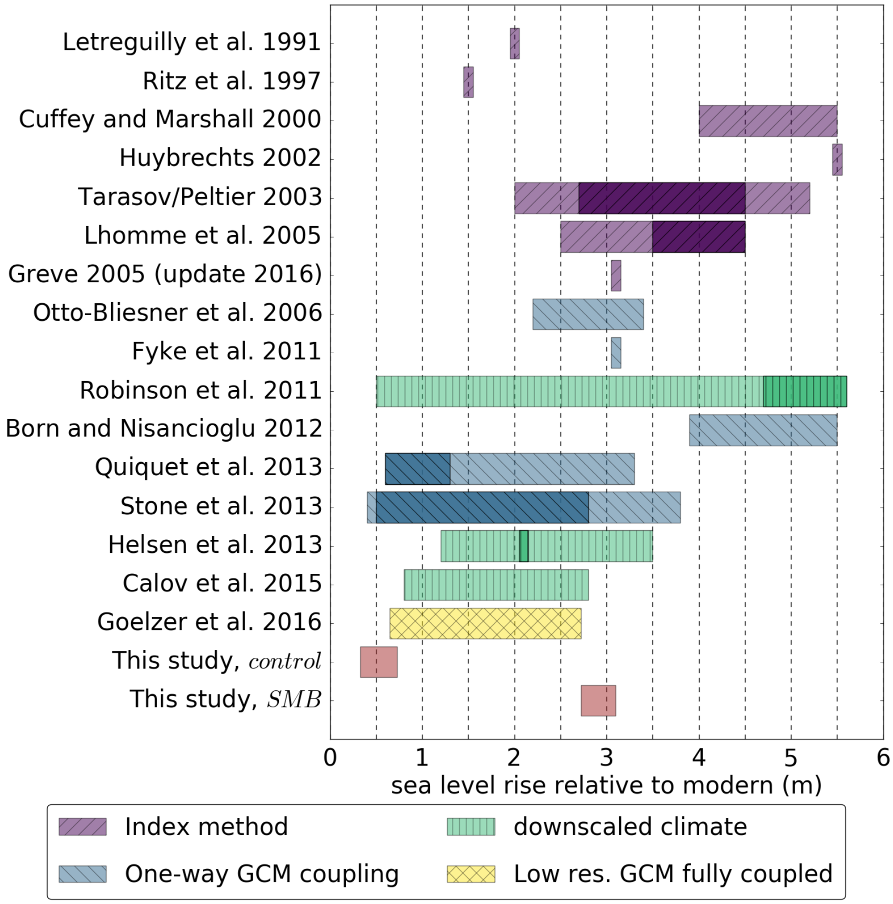


**Figure 10.** Simulated sea level rise contributions from this study and previous Eemian studies. For this study the results of the *control* (MAR-SEB; lower bound) and the *SMB* experiments (MAR-BESSI; upper bound) are shown (the ranges show the results of the respective basal/outlets fraction sensitivity experiments). Previous studies are color-coded according to the type of climate forcing used. More likely estimates are indicated with darker colors if provided in the respective studies. A common sea level rise conversion (distributing the meltwater volume equally on Earth's ocean area) is applied to Greve (2005), Robinson et al. (2011), Born and Nisancioglu (2012), Quiquet et al. (2013), Helsen et al. (2013), and Calov et al. (2015).

general, independent on how well the presented SMBs describe the Eemian SMB. Furthermore, it is important to keep in mind that an accurate SMB forcing not only depends on the choice of SMB model, but also the climate simulations used as input.

## 5 Conclusions

This study emphasizes the ~~importance of~~ higher importance of an accurate surface mass balance (SMB) forcing over ~~detailed ice sheet physics when simulating the past evolution~~ a more complex ice flow approximation for the simulation of the Eemian

Greenland ice sheet. ~~Our experiments~~ Experiments with two SMBs — a full surface energy balance model and an intermediate complexity SMB model — result in different Eemian sea level contributions (~0.5 to 3.0 m) when forced with the same detailed regional climate over Greenland. ~~Furthermore, we show~~ However, the comparison of experiments with 3D higher-order and 2D SSA ice flow, give only small changes in ice volume (<0.2 m). Furthermore, the importance of the SMB-altitude feedback is shown; neglecting this feedback reduces the simulated sea level contribution by more than 50%. ~~Moreover, our simulations~~ A non-exhaustive set of basal friction sensitivity experiments, affecting the entire ice sheet and outlet glacier regions respectively, indicate a limited influence ~~of the~~ on the total ice volume (maximum difference of ~0.2 m compared to experiments without changes to friction). While basal sensitivity experiments with larger impacts could be envisioned, it is unlikely that such experiments would exceed the magnitude of uncertainty related to SMB (at least not in this simplified setup). While it is challenging and arguably unfeasible at present to perform an exhaustive set of sensitivity experiments with 3D higher-order ice flow models, cost-efficient hybrid models (SIA + SSA) could be an option to further investigate the ice ~~flow approximation on the simulated minimum ice volume. For~~ dynamical processes (such as ocean forcing or basal hydrology) neglected here.

In conclusion, simulations of the long-term response of the Greenland ice sheet to warmer climates, such as the Eemian interglacial period, ~~efforts~~ should focus on ~~improving the representation of the SMB rather than the ice flow~~an accurate SMB estimate. Moreover, it is important to note that uncertainties in SMB are not only a result of the choice of SMB model, but also the climate simulations used as input. The climate simulation uncertainties are neglected in this study. However, they should be included in future Eemian ice sheet model studies in an effort to provide reliable estimates of the Eemian sea level contribution from the Greenland ice sheet.

## 6 Code availability

The ISSM code can be freely downloaded from http://issm.jpl.nasa.gov (last accessed: 18.10.2018). Model scripts and other datasets can be obtained upon request from the corresponding author. The NorESM model code can be obtained upon request. Instructions on how to obtain a copy are given at: https://wiki.met.no/noresm/gitbestpractice (last accessed: 18.10.2018). BESSI is under active development. For more information contact Andreas Born (andreas.born@uib.no). The MAR code is available at: http://mar.cnrs.fr (last accessed: 18.10.2018).

## 7 Data availability

The ISSM simulations and the MAR-SEB and MAR-BESSI SMBs are available upon request from the corresponding author. The SeaRISE dataset used is freely available at: http://websrv.cs.umt.edu/isis/images/e/e9/Greenland_5km_dev1.2.nc. (last accessed: 18.10.2018)

*Author contributions.* AP and KHN designed the study with contributions from PML and AB. SLC performed the MAR simulations. AP performed the ISSM simulations, made the figures and wrote the text with input from KHN, PML, AB, SLC.

*Competing interests.* The authors declare that they have no conflict of interest.

*Acknowledgements.* The research leading to these results has received funding from the European Research Council under the European Community's Seventh Framework Programme (FP7/2007-2013) / ERC grant agreement 610055 as part of the ice2ice project. The simulations were performed on resources provided by UNINETT Sigma2; the National Infrastructure for High Performance Computing and Data Storage in Norway (NN4659k; NS4659k). The publication of this manuscript was supported by the open access funding of the University of Bergen. PML was supported by the RISES project of the Centre for Climate Dynamics at the Bjerknes Centre for Climate Research. SLC acknowledges the financial support from the French–Swedish GIWA project, the ANR AC-AHC2, as well as the iceMOD project funded by the Research Foundation – Flanders (FWO-Vlaanderen). We thank J. K. Cuzzone for assisting in setting up the higher-order ISSM runs and M. M. Helsen for helping with the SMB gradient method. Furthermore, we thank B. de Fleurian for helping to resolve technical issues with ISSM.

## 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.

Aschwanden, A., Fahnestock, M. A., and Truffer, M.: Complex Greenland outlet glacier flow captured, Nature Communications, 7, 10 524, https://doi.org/10.1038/ncomms10524, 2016.

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, 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/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, https://doi.org/10.3189/S002214300001621X, 1995.

Born, A. and Nisancioglu, K. H.: Melting of Northern Greenland during the last interglaciation, The Cryosphere, 6, 1239–1250, https://doi.org/10.5194/tc-6-1239-2012, 2012.

Born, A., Imhof, M. A., and Stocker, T. F.: A surface energy and mass balance model for simulations over multiple glacial cycles, The Cryosphere Discuss., pp. 1–29, https://doi.org/10.5194/tc-2018-218, 2018.

Born, A., Imhof, M., and Stocker, T. F.: A surface energy and mass balance model for simulations over multiple glacial cycles, in prep.

Bueler, E. and Brown, J.: Shallow shelf approximation as a “sliding law” in a thermomechanically coupled ice sheet model, Journal of Geophysical Research: Earth Surface, 114, F03 008, https://doi.org/10.1029/2008JF001179, 2009.

Calov, R., Robinson, A., Perrette, M., and Ganopolski, A.: Simulating the Greenland ice sheet under present-day and palaeo constraints including a new discharge parameterization, The Cryosphere, 9, 179–196, https://doi.org/10.5194/tc-9-179-2015, 2015.

CAPE Last Interglacial Project Members: Last Interglacial Arctic warmth confirms polar amplification of climate change, Quaternary Science Reviews, 25, 1383–1400, https://doi.org/10.1016/j.quascirev.2006.01.033, 2006.

Capron, E., Govin, A., Feng, R., Otto-Bliesner, B. L., and Wolff, E. W.: Critical evaluation of climate syntheses to benchmark CMIP6/PMIP4 127 ka Last Interglacial simulations in the high-latitude regions, Quaternary Science Reviews, 168, 137–150, https://doi.org/10.1016/j.quascirev.2017.04.019, 2017.

Church, J., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M., Milne, G., Nerem, R., Nunn, P., Payne, A. J., Pfeffer, W., Stammer, D., and Unnikrishnan, A.: Sea Level Change, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)], pp. 1137–1216, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Clark, P. U. and Huybers, P.: Interglacial and future sea level: Global change, Nature, 462, 856–857, http://doi.org/10.1038/462856a, 2009.

Colville, E. J., Carlson, A. E., Beard, B. L., Hatfield, R. G., Stoner, J. S., Reyes, A. V., and Ullman, D. J.: Sr-Nd-Pb Isotope Evidence for Ice-Sheet Presence on Southern Greenland During the Last Interglacial, Science, 333, 620–623, http://doi.org/10.1126/science.1204673, 2011.

Cuffey, K. M. and Paterson, W.: The Physics of Glaciers, Elsevier Science, Burlington, 4th edn., 2010.

Cuzzone, J. K., Morlighem, M., Larour, E., Schlegel, N., and Seroussi, H.: Implementation of higher-order vertical finite elements in ISSM v4.13 for improved ice sheet flow modeling over paleoclimate timescales, Geosci. Model Dev., 11, 1683–1694, https://doi.org/10.5194/gmd-11-1683-2018, 2018.

De Ridder, K. and Gallée, H.: Land Surface–Induced Regional Climate Change in Southern Israel, Journal of Applied Meteorology, 37, 1470–1485, https://doi.org/10.1175/1520-0450(1998)037<1470:LSIRCC>2.0.CO;2, 1998.

Dutton, A., Carlson, A. E., Long, A. J., Milne, G. A., Clark, P. U., DeConto, R., Horton, B. P., Rahmstorf, S., and Raymo, M. E.: Sea-level rise due to polar ice-sheet mass loss during past warm periods, Science, 349, aaa4019, https://doi.org/10.1126/science.aaa4019, 2015.

Fettweis, X.: Reconstruction of the 1979–2006 Greenland ice sheet surface mass balance using the regional climate model MAR, The Cryosphere, 1, 21–40, https://doi.org/10.5194/tc-1-21-2007, 2007.

Fettweis, X., Gallée, H., Lefebre, F., and van Ypersele, J.-P.: The 1988–2003 Greenland ice sheet melt extent using passive microwave satellite data and a regional climate model, Climate Dynamics, 27, 531–541, https://doi.org/10.1007/s00382-006-0150-8, 2006.

Fettweis, X., Hanna, E., Gallée, H., Huybrechts, P., and Erpicum, M.: Estimation of the Greenland ice sheet surface mass balance for the 20th and 21st centuries, The Cryosphere, 2, 117–129, https://doi.org/10.5194/tc-2-117-2008, 2008.

Fettweis, X., Franco, B., Tedesco, M., Angelen, J. H. v., Lenaerts, J. T. M., Broeke, M. R. v. d., 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.

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, 2017.

Gallée, H. and Schayes, G.: Development of a Three-Dimensional Meso-gamma Primitive Equation Model: Katabatic Winds Simulation in the Area of Terra Nova Bay, Antarctica, Monthly Weather Review, 122, 671–685, https://doi.org10.1175/1520-0493(1994)122<0671:DOATDM>2.0.CO;2, 1994.

Gallée, H., Guyomarc'h, G., and Brun, E.: Impact Of Snow Drift On The Antarctic Ice Sheet Surface Mass Balance: Possible Sensitivity To Snow-Surface Properties, Boundary-Layer Meteorology, 99, 1–19, https://doi.org/10.1023/A:1018776422809, 2001.

Greve, R.: Relation of measured basal temperatures and the spatial distribution of the geothermal heat flux for the Greenland ice sheet, Annals of Glaciology, 42, 424–432, https://doi.org/10.3189/172756405781812510, 2005.

Greve, R. and Blatter, H.: Dynamics of ice sheets and glaciers, Springer, Berlin Heidelberg, https://doi.org/10.1007/978-3-642-03415-2, 2009.

Guo, C., Bentsen, M., Bethke, I., Ilicak, M., Tjiputra, J., Toniazzo, T., Schwinger, J., and Otterå, O. H.: Description and evaluation of NorESM1-F: A fast version of the Norwegian Earth System Model (NorESM), Geoscientific Model Development Discussions, pp. 1–37, https://doi.org/10.5194/gmd-2018-217, 2018.

Guo, C., Bentsen, M., Bethke, I., Ilicak, M., Tjiputra, J., Toniazzo, T., Schwinger, J., and Otterå, O. H.: Description and evaluation of NorESM1-F: a fast version of the Norwegian Earth System Model (NorESM), Geoscientific Model Development, 12, 343–362, https://doi.org/10.5194/gmd-12-343-2019, 2019.

Helsen, M. M., Wal, R. S. W. v. d., Broeke, M. R. v. d., Berg, W. J. v. d., and Oerlemans, J.: Coupling of climate models and ice sheet models by surface mass balance gradients: application to the Greenland Ice Sheet, The Cryosphere, 6, 255–272, https://doi.org/10.5194/tc-6-255-2012, 2012.

Helsen, M. M., Berg, W. J. v. d., Wal, R. S. W. v. d., Broeke, M. R. v. d., and Oerlemans, J.: Coupled regional climate–ice-sheet simulation shows limited Greenland ice loss during the Eemian, Clim. Past, 9, 1773–1788, https://doi.org/10.5194/cp-9-1773-2013, 2013.

Hutter, K.: Theoretical Glaciology: Material Science of Ice and the Mechanics of Glaciers and Ice Sheets, D. Reidel Publishing Company, Dordrecht, The Netherlands, 1983.

Kopp, R. E., Simons, F. J., Mitrovica, J. X., Maloof, A. C., and Oppenheimer, M.: A probabilistic assessment of sea level variations within the last interglacial stage, Geophysical Journal International, p. ggt029, https://doi.org/10.1093/gji/ggt029, 2013.

Landais, A., Masson-Delmotte, V., Capron, E., Langebroek, P. M., Bakker, P., Stone, E. J., Merz, N., Raible, C. C., Fischer, H., Orsi, A., Prié, F., Vinther, B., and Dahl-Jensen, D.: How warm was Greenland during the last interglacial period?, Clim. Past, 12, 1933–1948, https://doi.org/10.5194/cp-12-1933-2016, 2016.

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, F01 022, https://doi.org/10.1029/2011JF002140, 2012.

Le clec'h, S., Fettweis, X., Quiquet, A., Dumas, C., Kageyama, M., Charbit, S., Wyard, C., and Ritz, C.: Assessment of the Greenland ice sheet – atmosphere feedbacks for the next century with a regional atmospheric model fully coupled to an ice sheet model, The Cryosphere Discuss., 2017, 1–31, doi:10.5194/tc-2017-230, https://www.the-cryosphere-discuss.net/tc-2017-230/, 2017.

Le clec'h, S., Charbit, S., Quiquet, A., Fettweis, X., Dumas, C., Kageyama, M., Wyard, C., and Ritz, C.: Assessment of the Greenland ice sheet–atmosphere feedbacks for the next century with a regional atmospheric model coupled to an ice sheet model, The Cryosphere, 13, 373–395, https://doi.org/10.5194/tc-13-373-2019, 2019.

Letréguilly, A., Reeh, N., and Huybrechts, P.: The Greenland ice sheet through the last glacial-interglacial cycle, Palaeogeogr., Palaeoclimatol., Palaeoecol. (Global Planet. Change Sect.), 90, 385–394, https://doi.org/10.1016/S0031-0182(12)80037-X, 1991.

MacAyeal, D. R.: Large-scale ice flow over a viscous basal sediment: Theory and application to ice stream B, Antarctica, Journal of Geophysical Research: Solid Earth, 94, 4071–4087, https://doi.org/10.1029/JB094iB04p04071, 1989.

Morlighem, M., Rignot, E., Seroussi, H., Larour, E., Ben Dhia, H., 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, L14 502, https://doi.org/10.1029/2010GL043853, 2010.

Morlighem, M., Williams, C. N., Rignot, E., An, L., Arndt, J. E., Bamber, J. L., Catania, G., Chauché, N., Dowdeswell, J. A., Dorschel, B., Fenty, I., Hogan, K., Howat, I., Hubbard, A., Jakobsson, M., Jordan, T. M., Kjeldsen, K. K., Millan, R., Mayer, L., Mouginot, J., Noël, B. P. Y., O'Cofaigh, C., Palmer, S., Rysgaard, S., Seroussi, H., Siegert, M. J., Slabon, P., Straneo, F., van den Broeke, M. R., Weinrebe, W., Wood, M., and Zinglersen, K. B.: BedMachine v3: Complete Bed Topography and Ocean Bathymetry Mapping of Greenland From Multibeam Echo Sounding Combined With Mass Conservation: BEDMACHINE GREENLAND V3, Geophysical Research Letters, 44, 11,051–11,061, https://doi.org/10.1002/2017GL074954, 2017.

NEEM community members: Eemian interglacial reconstructed from a Greenland folded ice core, Nature, 493, 489–494, https://doi.org/10.1038/nature11789, 2013.

Otto-Bliesner, B. L., Marshall, S. J., Overpeck, J. T., Miller, G. H., and Hu, A.: Simulating Arctic climate warmth and icefield retreat in the last interglaciation, science, 311, 1751–1753, https://doi.org/10.1126/science.1120808, 2006.

Otto-Bliesner, B. L., Braconnot, P., Harrison, S. P., Lunt, D. J., Abe-Ouchi, A., Albani, S., Bartlein, P. J., Capron, E., Carlson, A. E., Dutton, A., Fischer, H., Goelzer, H., Govin, A., Haywood, A., Joos, F., LeGrande, A. N., Lipscomb, W. H., Lohmann, G., Mahowald, N., Nehrbass-Ahles, C., Pausata, F. S. R., Peterschmitt, J.-Y., Phipps, S. J., Renssen, H., and Zhang, Q.: The PMIP4 contribution to CMIP6 – Part 2:

Two interglacials, scientific objective and experimental design for Holocene and Last Interglacial simulations, Geosci. Model Dev., 10, 3979–4003, https://doi.org/10.5194/gmd-10-3979-2017, 2017.

Overpeck, J., Otto-Bliesner, B. L., Miller, G., Muhs, D., Alley, R., and Kiehl, J.: Paleoclimatic Evidence for Future Ice-Sheet Instability and Rapid Sea-Level Rise, Science, 311, 1747–1750, https://doi.org/10.1126/science.1115159, 2006.

Paterson, W.: The Physics of Glaciers (3rd edn), Pergamon Press, Oxford, 1994.

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, 2003.

Pfeffer, W. T., Harper, J. T., and O'Neel, S.: Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise, Science, 321, 1340–1343, https://doi.org/10.1126/science.1159099, 2008.

Plach, A., Nisancioglu, K. H., Le clec'h, S., Born, A., Langebroek, P. M., Guo, C., Imhof, M., and Stocker, T. F.: Eemian Greenland Surface Mass Balance strongly sensitive to SMB model choice, Clim. Past Discussions, pp. 1–37, https://doi.org/10.5194/cp-2018-81, 2018a.

Plach, A., Nisancioglu, K. H., Le clec'h, S., Born, A., Langebroek, P. M., Guo, C., Imhof, M., and Stocker, T. F.: Eemian Greenland SMB strongly sensitive to model choice, Climate of the Past, 14, 1463–1485, https://doi.org/10.5194/cp-14-1463-2018, 2018b.

Pollard, D. and DeConto, R. M.: Modelling West Antarctic ice sheet growth and collapse through the past five million years, Nature, 458, 329–332, https://doi.org/10.1038/nature07809, 2009.

Pollard, D. and DeConto, R. M.: Description of a hybrid ice sheet-shelf model, and application to Antarctica, Geosci. Model Dev., 5, 1273–1295, https://doi.org/10.5194/gmd-5-1273-2012, 2012.

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.

Quiquet, A., Ritz, C., Punge, H. J., and Salas y Mélia, D.: Greenland ice sheet contribution to sea level rise during the last interglacial period: a modelling study driven and constrained by ice core data, Clim. Past, 9, 353–366, https://doi.org/10.5194/cp-9-353-2013, 2013.

Raynaud, D., Chappellaz, J., Ritz, C., and Martinerie, P.: Air content along the Greenland Ice Core Project core: A record of surface climatic parameters and elevation in central Greenland, Journal of Geophysical Research: Oceans, 102, 26 607–26 613, https://doi.org/10.1029/97JC01908, 1997.

Reeh, N.: Parameterization of melt rate and surface temperature on the Greenland ice sheet, Polarforschung, 59, 113–128, http://hdl.handle.net/10013/epic.13107, 1989.

Rignot, E. and Mouginot, J.: Ice flow in Greenland for the International Polar Year 2008–2009, Geophysical Research Letters, 39, L11 501, https://doi.org/10.1029/2012GL051634, 2012.

Robel, A. A. and Tziperman, E.: The role of ice stream dynamics in deglaciation, Journal of Geophysical Research: Earth Surface, 121, 2016JF003 937, https://doi.org/10.1002/2016JF003937, 2016.

Robinson, A. and Goelzer, H.: The importance of insolation changes for paleo ice sheet modeling, The Cryosphere, 8, 1419–1428, https://doi.org/10.5194/tc-8-1419-2014, 2014.

Robinson, A., Calov, R., and Ganopolski, A.: Greenland ice sheet model parameters constrained using simulations of the Eemian Interglacial, Clim. Past, 7, 381–396, https://doi.org/10.5194/cp-7-381-2011, 2011.

Schlegel, N.-J., Larour, E., Seroussi, H., Morlighem, M., and Box, J. E.: Decadal-scale sensitivity of Northeast Greenland ice flow to errors in surface mass balance using ISSM, Journal of Geophysical Research: Earth Surface, 118, 667–680, https://doi.org/10.1002/jgrf.20062, 2013.

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.

Stone, E. J., Lunt, D. J., Annan, J. D., and Hargreaves, J. C.: Quantification of the Greenland ice sheet contribution to Last Interglacial sea level rise, Clim. Past, 9, 621–639, https://doi.org/10.5194/cp-9-621-2013, 2013.

Straneo, F. and Heimbach, P.: North Atlantic warming and the retreat of Greenland's outlet glaciers, Nature, 504, 36–43, doi:10.1038/nature12854, http://www.nature.com/nature/journal/v504/n7478/abs/nature12854.html, 2013.

Tabone, I., Blasco, J., Robinson, A., Alvarez-Solas, J., and Montoya, M.: The sensitivity of the Greenland Ice Sheet to glacial–interglacial oceanic forcing, Clim. Past, 14, 455–472, https://doi.org/10.5194/cp-14-455-2018, 2018.

Van de Berg, W. J., van den Broeke, M., Ettema, J., van Meijgaard, E., and Kaspar, F.: Significant contribution of insolation to Eemian melting of the Greenland ice sheet, Nature Geoscience, 4, 679–683, https://doi.org/10.1038/ngeo1245, 2011.

Yin, Q. and Berger, A.: Interglacial analogues of the Holocene and its natural near future, Quaternary Science Reviews, 120, 28–46, https://doi.org/10.1016/j.quascirev.2015.04.008, 2015.

Zwally, H. J., Abdalati, W., Herring, T., Larson, K., Saba, J., and Steffen, K.: Surface Melt-Induced Acceleration of Greenland Ice-Sheet Flow, Science, 297, 218–222, https://doi.org/10.1126/science.1072708, 2002.