We would very much like to thank Arjen Stroeven for editing our study and for his constructive comments. Please find below the editor's comments in black font, the referred referee comments in orange font and the author's responses in blue font.

Dear Dr. Plach,

I have read your revised manuscript and, aside from some technical corrections that I enclose, I also offer the following reflections to your response that I would like to have your final response to:

1. You state in your response that "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." I believe the suggestion by the reviewer needs to be included, or argued against more substantially. A description, and perhaps a Table as suggested, can be lodged as a supplementary file to avoid clogging the main manuscript.

Comment of Referee #1 the editor is referring to:
"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."

2. You wrote "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. Again, although brevity is good, this does not suffice as a response. Hence, act, or argue against more substantially.

Comment of Referee #2 the editor is referring to:
"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."

We added a table of all 2D SSA experiments and two figures illustrating the evolution of the ice surface (at the ice core locations) and the ice volume in the 2D SSA experiments with a description as a supplement to the manuscript.

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3. When the reviewer has an argumentation that end in "Please reformulate", then your response of "we added appropriate references" is non-informative and likely insufficient. Please, reformulate, or argue against more substantially.

Comment of Referee #2 the editor is referring to:
“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.”

We apologize, this is indeed an insufficient response to the reviewer's comment. We did some modifications concerning the references in the paragraph in questions, but this is not the main change we did. We adapted the paragraph by removing the misleading sentence about the hybrid models, and although we also included the more important second change in the initial revised mark-up file, we failed to communicate this in the author's response. The paragraph (page 2, line 20-27) in the revised manuscript now reads:

"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; Larour et al., 2012; Cuzzone et al., 2018). Including higher-order stress gradients provides a comprehensive ice flow representation 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."

We hope that we address the reviewer's concerns with this modification of the paragraph.

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4. In response to the reviewers request that "...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." you presented such a figure. Have you considered including it in the manuscript?

Comment of Referee #2 the editor is referring to:
“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.”

In addition to the clarification that we indeed perform independent inversion for higher-order and SSA in the manuscript, we now added a figure of the distribution of the basal friction coefficients for the *control* experiment as a supplement to avoid clogging the main manuscript.

I look forward to a final updated manuscript that considers the technical corrections and the four reflections that I have offered.

Attached to this response you will find the new supplement to the manuscript and a mark-up manuscript version showing all changes since the initial submission of the manuscript. Two references to the supplement where added to the manuscript in Section 2.3.

1 Additional simulations using the shallow shelf approximation (SSA)

In addition to the computationally costly 3D higher-order simulations, we carried out a series of simulations with a computationally efficient 2D SSA model for a more comprehensive study of the parameter space. The range of 2D SSA experiments was used to select the parameters for the 3D higher-order simulations discussed in the manuscript. A list of the 2D SSA experiments is shown in Table S1 where experiments with different basal friction as in the manuscript are highlighted with gray shading. The 2D *control* and 2D *SMB* experiments in Table S1 are discussed as the *ice flow* experiments in the manuscript to illustrate the differences resulting from using the 3D higher-order compared to the 2D SSA ice flow approximation.

The additional, more extreme experiments ($\geq$ 20% change of basal friction) show unrealistically large changes in ice surface elevation at most ice core locations (red (MAR-SEB) and blue (MAR-BESSI) lines in Fig. S1). While changes of 10% of the basal friction in the *basal* experiments (as discussed in the manuscript; solid light orange lines in Fig. S1d)) result in changes of ice surface elevation which are still within the NEEM surface change reconstructions (gray shading in Fig. S1d), the $\geq$ 20% change experiments (red lines in Fig. S1d) lead to changes outside of these NEEM reconstructions.

Additionally, we illustrate the evolution of the ice volume in the 2D SSA experiments (Fig. S2) and the consequences of $\geq$ 20% change to the basal friction on the evolution of the ice volume (red (MAR-SEB) and blue (MAR-BESSI) lines in Fig. S2).

Table S1: Overview of SSA experiments

type of experiment	**SMB method**	**basal friction**	**ice flow approx.**
2D *control*	MAR-SEB	modern	2D SSA
2D *SMB*	MAR-BESSI	modern	2D SSA
2D *basal* (reduced)	MAR-SEB	0.5 * modern (entire ice sheet)	2D SSA
2D *basal* (reduced)	MAR-BESSI	0.5 * modern (entire ice sheet)	2D SSA
2D *basal* (reduced)	MAR-SEB	0.8 * modern (entire ice sheet)	2D SSA
2D *basal* (reduced)	MAR-BESSI	0.8 * modern (entire ice sheet)	2D SSA
2D *basal* (reduced)	MAR-SEB	0.9 * modern (entire ice sheet)	2D SSA
2D *basal* (reduced)	MAR-BESSI	0.9 * modern (entire ice sheet)	2D SSA
2D *basal* (enhanced)	MAR-SEB	1.1 * modern (entire ice sheet)	2D SSA
2D *basal* (enhanced)	MAR-BESSI	1.1 * modern (entire ice sheet)	2D SSA
2D *basal* (enhanced)	MAR-SEB	1.2 * modern (entire ice sheet)	2D SSA
2D *basal* (enhanced)	MAR-BESSI	1.2 * modern (entire ice sheet)	2D SSA
2D *basal* (enhanced)	MAR-SEB	2.0 * modern (entire ice sheet)	2D SSA
2D *basal* (enhanced)	MAR-BESSI	2.0 * modern (entire ice sheet)	2D SSA
2D *outlets* (reduced)	MAR-SEB	0.5 * modern (outlet glaciers)	2D SSA
2D *outlets* (reduced)	MAR-BESSI	0.5 * modern (outlet glaciers)	2D SSA
2D *outlets* (reduced)	MAR-SEB	0.8 * modern (outlet glaciers)	2D SSA
2D *outlets* (reduced)	MAR-BESSI	0.8 * modern (outlet glaciers)	2D SSA
2D *outlets* (reduced)	MAR-SEB	0.9 * modern (outlet glaciers)	2D SSA
2D *outlets* (reduced)	MAR-BESSI	0.9 * modern (outlet glaciers)	2D SSA
2D *outlets* (enhanced)	MAR-SEB	1.1 * modern (outlet glaciers)	2D SSA
2D *outlets* (enhanced)	MAR-BESSI	1.1 * modern (outlet glaciers)	2D SSA
2D *outlets* (enhanced)	MAR-SEB	1.2 * modern (outlet glaciers)	2D SSA
2D *outlets* (enhanced)	MAR-BESSI	1.2 * modern (outlet glaciers)	2D SSA
2D *outlets* (enhanced)	MAR-SEB	2.0 * modern (outlet glaciers)	2D SSA
2D *outlets* (enhanced)	MAR-BESSI	2.0 * modern (outlet glaciers)	2D SSA
2D *altitude*	MAR-SEB	modern	2D SSA
2D *altitude*	MAR-BESSI	modern	2D SSA
2D *relaxed*	MAR-SEB	modern	2D SSA

Additional 2D SSA experiments with different parameters as in the manuscript are indicated by gray shading.

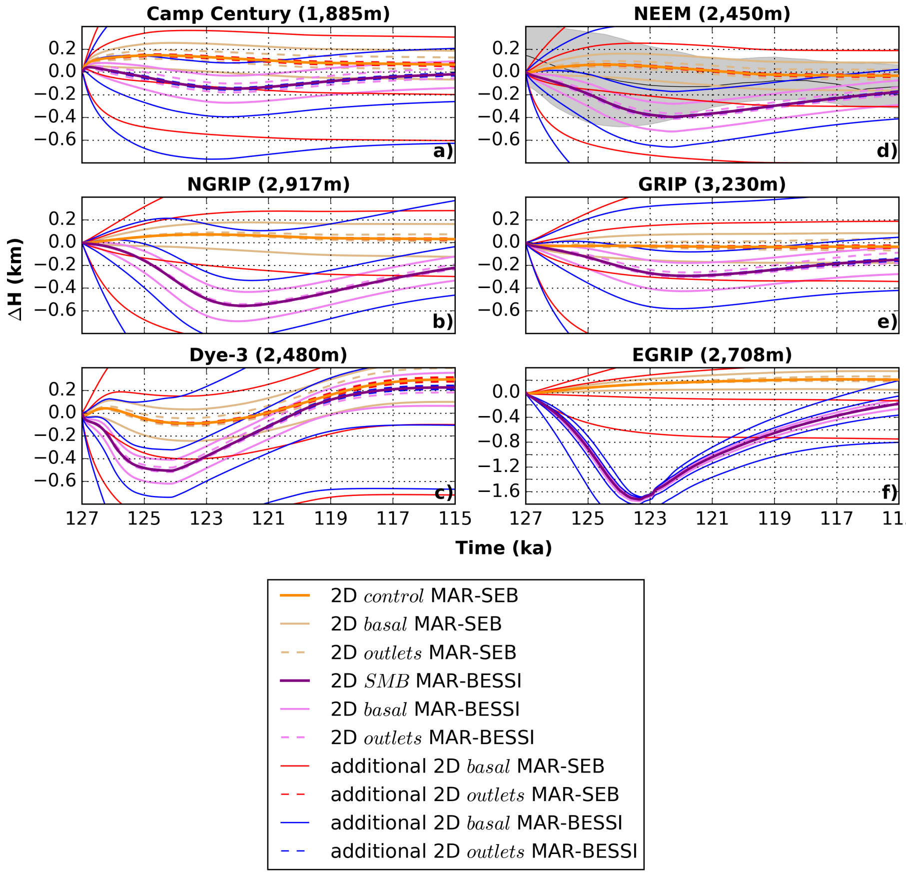

Figure S1: Ice surface evolution at Greenland ice core locations for the 2D *control* (MAR-SEB, orange, bold) and the 2D *SMB* (MAR-BESSI, purple, bold) experiments in comparison with the 2D *basal/outlets* sensitivity experiments. The 2D *basal* (friction *0.9/*1.1 for the entire ice sheet) and 2D *outlets* sensitivity experiments (friction *0.5/*2.0 at the outlet glaciers) are indicated with thin solid and thin dashed lines, respectively. Additional 2D *basal/outlets* sensitivity experiments (see Tab. S1) are shown with red (MAR-SEB) and blue (MAR-BESSI) solid/dashed lines. Camp Century, NEEM, NGRIP, GRIP, and Dye-3 are shown on the same scale; EGRIP is shown on a different scale. Surface elevation reconstructions from total gas content at NEEM are indicated with gray shading.

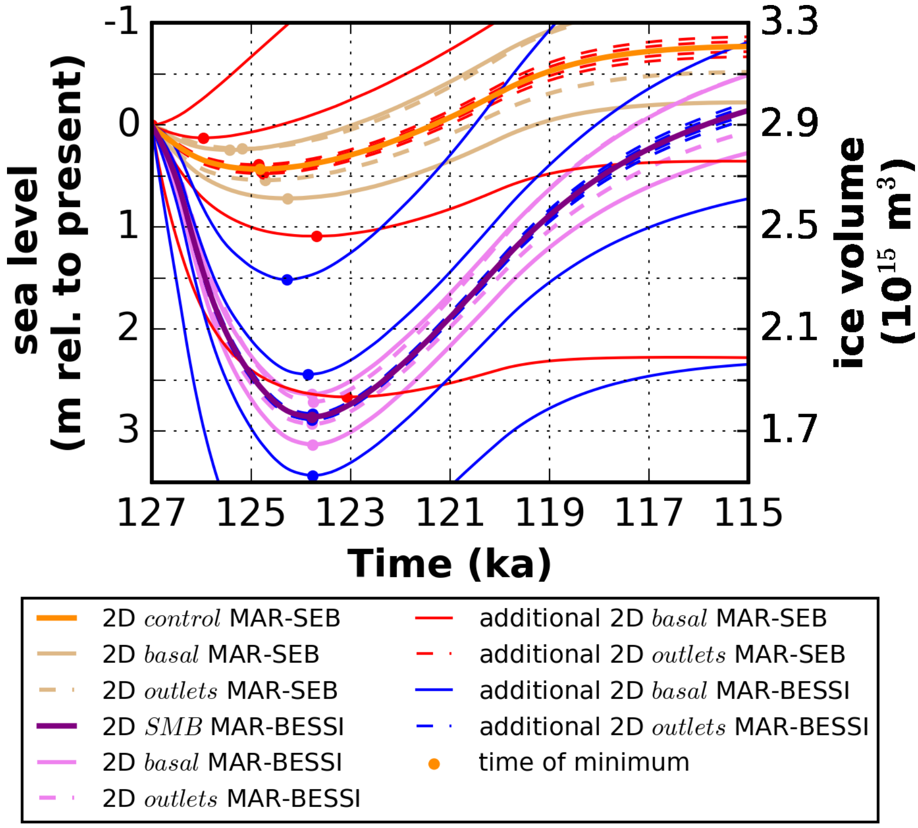

Figure S2: Evolution of the ice volume for the 2D *control* (MAR-SEB, orange, bold) and the 2D *SMB* (MAR-BESSI, purple, bold) experiments in comparison with the 2D *basal/outlets* sensitivity experiments. The 2D *basal* (friction *0.9/*1.1 for the entire ice sheet) and 2D *outlets* sensitivity experiments (friction *0.5/*2.0 at the outlet glaciers) are indicated with thin solid and thin dashed lines, respectively. Additional 2D *basal/outlets* sensitivity experiments (see Tab. S1) are shown with red (MAR-SEB) and blue (MAR-BESSI) solid/dashed lines. Note that the lower friction experiments give lower volumes. The minimum of the respective experiments is indicated with circles.

2 Map of basal friction coefficients

Figure S3 shows the spatial distribution of the basal friction coefficients in the *control* experiment discussed in the manuscript. The basal friction coefficients are derived from inversion employing modern surface velocities (see Sec. 2.2 in the manuscript). This map of basal frictions coefficients is modified in the *basal* and *outlets* experiments.

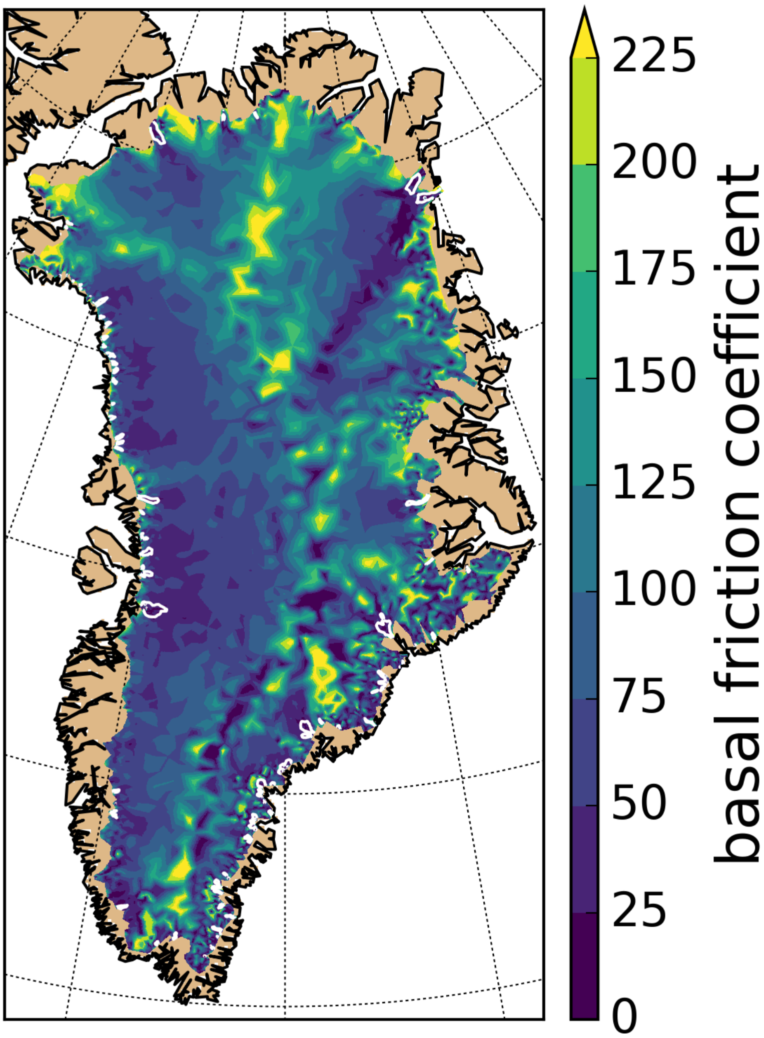

Figure S3: Basal friction coefficients for the *control* experiment in the manuscript. Regions affected in the *outlets* experiments are indicated with white contours.

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

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Abstract. The Greenland ice sheet ~~(GrIS)~~ contributes increasingly to global sea level rise~~and 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 (~~~125~~130,000 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~~, forced with a surface mass balance ~~(SMB)~~ derived from regional climate simulations. Sensitivity experiments with ~~different SMB~~various 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 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~~ surface mass balance model. Furthermore, the results indicate that 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 modeling of 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~~ valuable 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 (~125~~(~130,000 to 115,000 years ago; ~~thereafter 125~~hereafter 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 B
. The Eemian summer temperature is estimated to have been 4-5 °C above present over most Arctic land areas ~~(CAPE Last Interglacial Proje~~ ~~and ice core records~~ (e.g., Capron et al., 2017) and an ice core record from NEEM (the North Greenland Eemian Ice Drilling project in northwest Greenland, NEEM community members, 2013) ~~indicate~~ indicates 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). Nevertheless, coral ~~reef derived~~ 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~~ indicate 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.,~~ focusing on Greenland (e.g., Letréguilly et al., 1991; Otto-Bliesner et al., 2006; Robinson et al., 2011; Born and Nisancioglu, 2012; Stone used very different setup and forcing, and show highly variable results.

~~However,~~ Ice sheets lose mass either due to a reduced surface mass balance (SMB) or accelerated ice dynamical processes~~may also~~. Ice dynamical processes may have contributed to the Eemian ~~mass loss, e.g.,~~ ice loss, for example 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)~~. Price et al. (2011), for example, 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 estimates 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~~topographically-constrained outlet glaciers. 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~~ approximation (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 . 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.,~~ especially 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; Aschw at the boundaries between these two approximations~~flowing ice.

~~Plach et al. (2018a)~~ Plach et al. (2018b) show that the ~~simulation~~ derivation of the Eemian SMB ~~is strongly dependent on the choice of SMB model~~ strongly depends on the 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~~ and 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 warming~~ice flow model, 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 ~~methods~~experimental setup

2.1 ~~Model description~~SMB 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 ~~conditions~~using 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~~ (SEB) model as implemented within MAR (MAR-SEB) and (2) an intermediate complexity SMB model ~~(MAR-BESSI; BErgen Snow SImulator; BESSI; Born et al., in prep.)~~ (MAR-BESSI; BErgen Snow SImulator; BESSI; Born et al., 2019). 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, and humidity), 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.~~ . MAR-SEB and MAR-BESSI employ a different temporal model time step, while MAR-SEB uses steps of 180 ~~4)~~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~~ zones 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, an 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 using 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~~ configuration 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 take 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)~~ (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 model simulations) and an enthalpy formulation (Aschwanden et al., 2012) at the base to determine the basal conditions (cold or temperate 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~~. In this case, an 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). A map of the basal friction coefficients is provided as a supplement to this manuscript. The inversion depends on the chosen ice flow approximation due to the different representations of the stress balance. Hence, 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 ~~τ_b~~ $\boldsymbol{\tau_b}$ is the basal shear stress (vector), α the basal friction coefficient (derived by inversion from surface velocities), ~~N_{eff}~~ 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 ~~v_b~~ $\mathbf{v_b}$ the horizontal basal velocity (vector). The effective pressure is simulated with a first order approximation (Paterson, 1994):

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

where ρ_{ice} and ρ_{water} are the densities of ice and water, respectively, H is the ice thickness, and z_{b} is the bedrock elevation~~, i.e. , N_{eff} evolves with H over time~~. From these equations it follows that the initial (modern) basal friction coefficients stay constant, while the basal shear 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 m and 800 m, respectively. Proxy data indicates a surface lowering of no more than 300 m (NEEM community members, 2013) at this point in time. In order to stay clearly within 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) are discussed in detail here to illustrate the difference of the two ice flow approximations (Table 2). A full list of 2D SSA experiments is given as a supplement to this manuscript.

Due to the high computational demand of the 3D higher-order model, 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.

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 air temperature prescribed at the ice surface remains fixed at pre-industrial levels. Ice formed during the 12,000 year simulations will only reach several hundred meters deep (not reaching 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).

The simplified transient ISSM model configuration 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 configuration 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, defined as 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~~ central Greenland 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~~ impact of the SMB-altitude feedback by ~~neglecting this feedback~~ignoring this feedback; which means that the transient SMB forcing is prescribed without correcting for altitude changes. 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.

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

type of experiment	SMB ~~forcing~~method	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/yr~~outlet 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/yr~~outlet 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 ~~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~~) show a stronger influence on the ice volume ~~compared to other basal friction experiments(thin solid lines; Fig. 1). Changing~~ than 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~~ does show a notable effect on the ice volume (0.05 to 0.15 m at the ice minimum; thin dashed lines; Fig. 1).

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/purple~~lines~~). Neglecting the ~~evolution~~ correction of the SMB ~~with the changing ice sheet, i.e.,~~ for a changing ice surface elevation, that is using the offline calculated SMBs directly, results in significantly

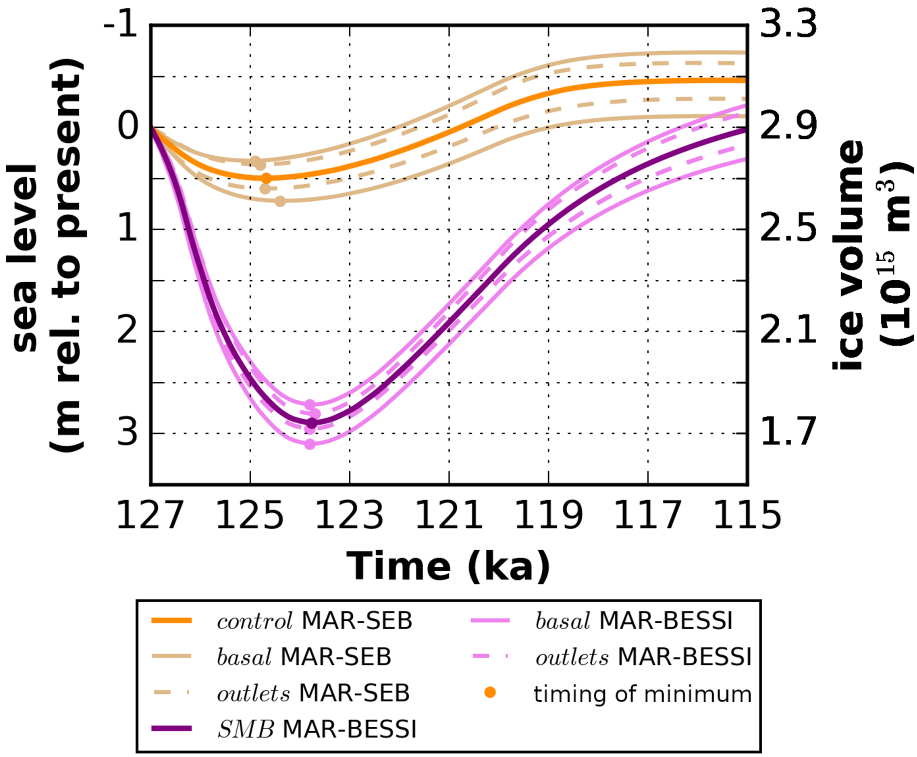

Figure 1. Evolution of the ice volume for the ~~control experiment and the sensitivity experiments testing for SMB and basal/outlets friction. The colors indicate different SMB forcings: orange colors -~~ *control* (MAR-SEB, ~~purple colors - MAR-BESSI. The bold~~ orange~~line is the control experiment. 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.

less melt. This is particularly pronounced in ~~the MAR-BESSI experiments~~ experiments forced with MAR-BESSI, because the ablation area in ~~this SMB forcing~~ these simulations 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 gray~~lines~~). The differences between the ice flow approximations become larger as the ice sheet ~~approaches a new equilibrium statetowards~~ enters 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 experiment) is shown (darkgreen line) . The~~ volume decrease is more pronounced because the relaxed initial 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.

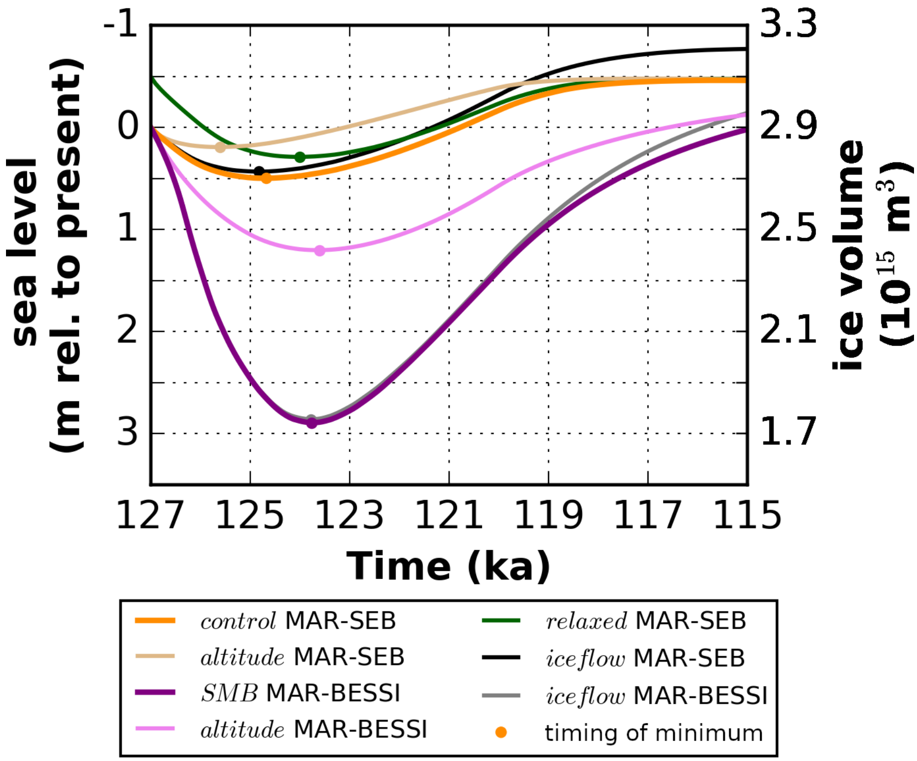

Figure 2. Evolution of the ice volume for the ~~control experiment and the sensitivity experiments testing the influence of the SMB-altitude feedback~~*control* (MAR-SEB, ~~the relaxed initial ice sheet~~orange, bold) and the ~~ice flow approximation~~ *SMB* experiments (~~3D higher-order vs. 2D SSA). The colors indicate different SMB forcings: orange colors - MAR-SEB~~MAR-BESSI, purple~~colors - MAR-BESSI. The bold orange line is the control experiment. The~~, bold~~purple is the corresponding experiment~~) in comparison with ~~MAR-BESSI forcing~~the *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.

~~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~~ *SMB* experiment (MAR-BESSI~~(bottom row) at the beginning of simulation (127 ka), 125, 120, and 115~~; 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~~ using a modern ice 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 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).

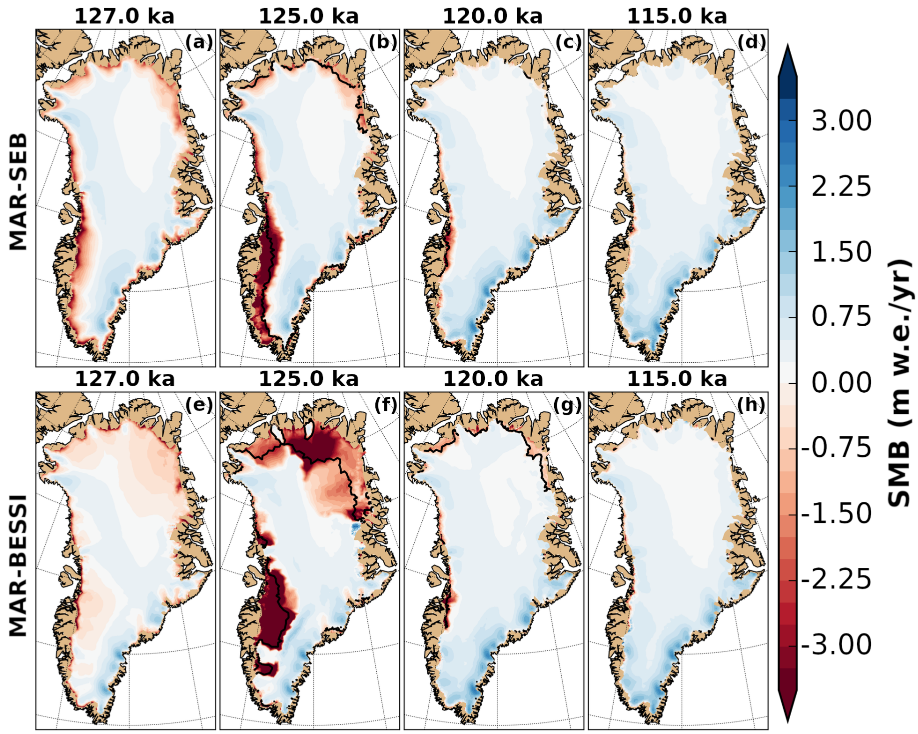

Figure 3. SMB forcing corrected for ~~altitude~~ surface elevation changes at 127, 125, 120, 115 ka for the *control* (a-d, MAR-SEB) and the *SMB* (e-h, MAR-BESSI) experiments. The ice margin is indicated with a solid black line (~~i.e.,~~ 10 m ice thickness remaining). ~~If the~~ A nonvisible ice margin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

The simulated ice sheet thickness in the ~~control~~ *control* experiment (Fig. 4~~, top row~~a-d; MAR-SEB) shows only moderate changes. However, there is ~~significant melt~~ a significant retreat of the ice margin 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 123.8~~the *SMB* experiment (Fig. ~~ka; not shown) , in particular for~~ 4f) shows an enhanced retreat in the southwest, ~~as well as~~ and additionally a particularly strong retreat in the northeast. ~~The ice sheet also~~ Furthermore, the ice sheet takes longer to recover in the *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 ~~—~~ of Camp Century, NEEM, NGRIP, GRIP, Dye-3, and 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

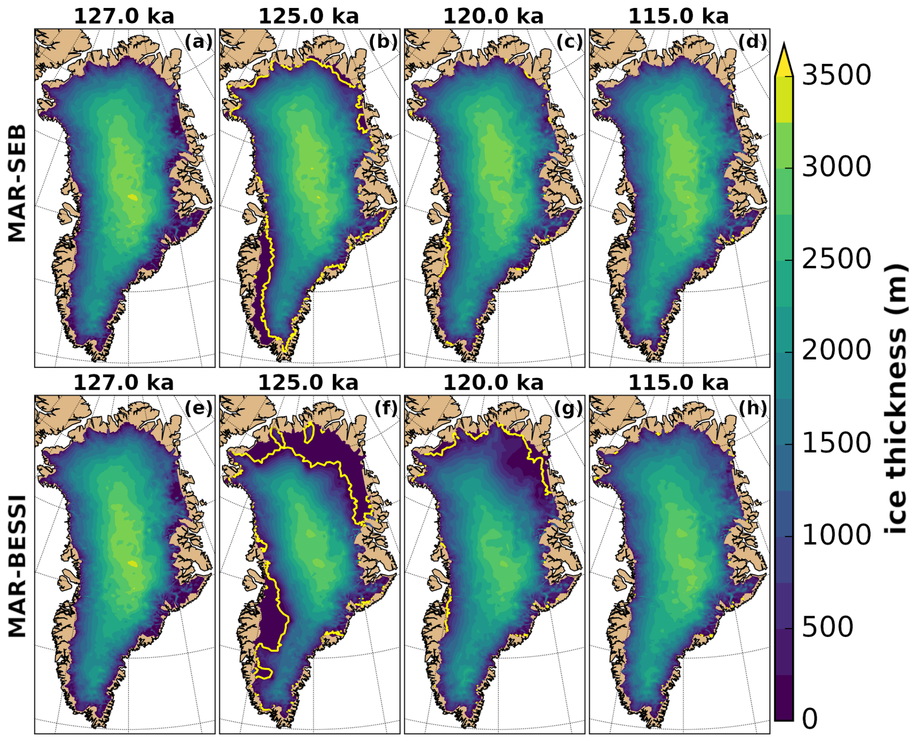

Figure 4. Ice thickness at 127, 125, 120, 115 ka for the *control* (a-d, MAR-SEB) and the *SMB* (e-h, MAR-BESSI) experiments. The ice margin is indicated with a solid yellow line (~~i.e.,~~ 10 m ice thickness remaining). ~~If the~~ A nonvisible ice margin is ~~not visible it is~~ identical with the domain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

lowering due to its southern location affected by the early Eemian warming. The MAR-BESSI-forced experiments show the largest 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 ~~. 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 sur-

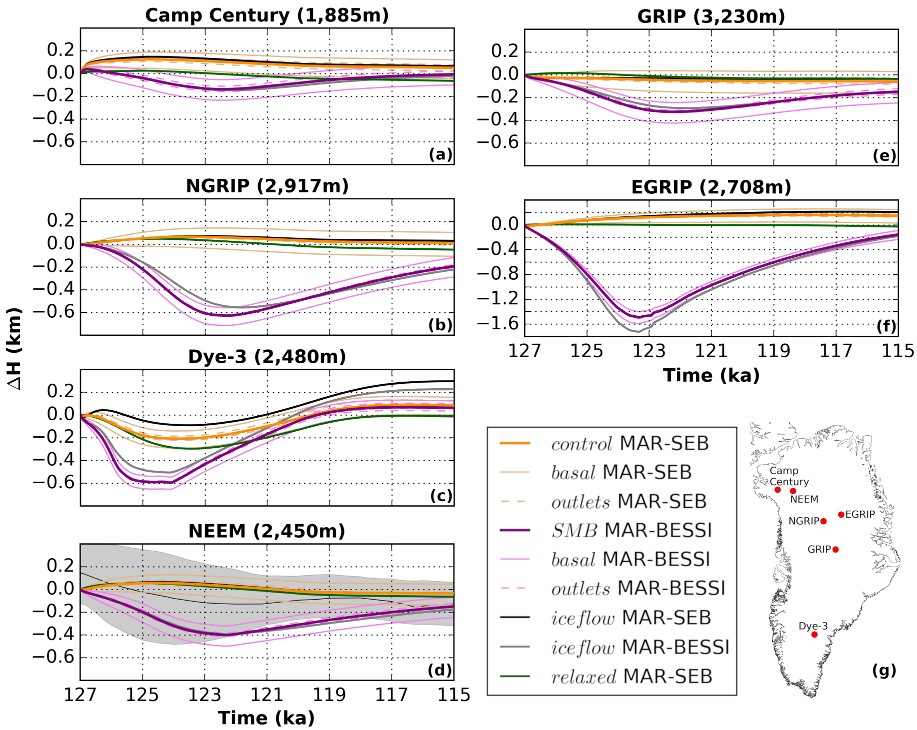

Figure 5. Ice surface evolution at Greenland ice core locations for the *control*, *SMB*, *basal*, *outlets*, *ice flow*, and *relaxed* experiments — Camp Century, NEEM, NGRIP, GRIP, and Dye-3 are shown on the same scale; EGRIP is shown on a different scale. Same color-coding as in ~~Fig~~Figs. 1~~, 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.

face 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 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.~~ experiment.

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.

~~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~~

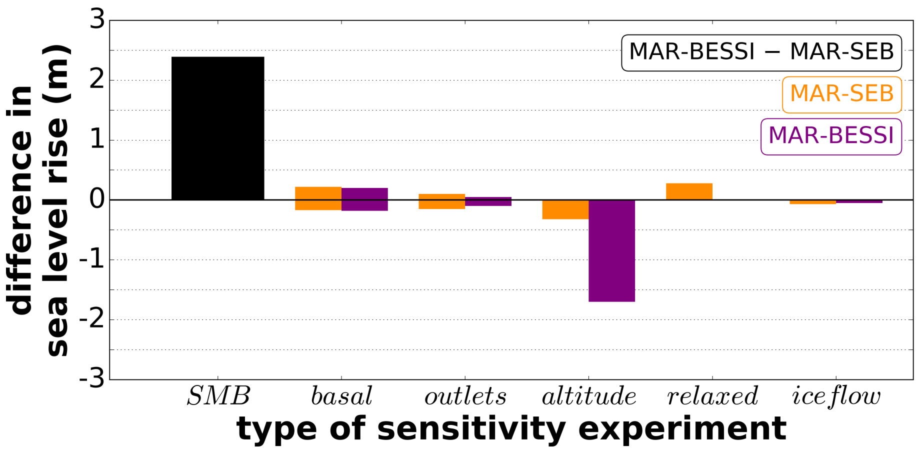

Figure 6. Differences ~~in sea level estimates given~~ between the minimum Eemian ice sheet simulated by the respective sensitivity experiments~~.~~ : *SMB* (black)~~refers to the~~ : difference between the ~~two SMB forcings (incl.~~ *control* and the ~~SMB-altitude feedback~~*SMB* experiment (MAR-SEB 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 ~~relaxed~~larger, 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.

~~Isbræ in the southwest, but less pronounced. Lowering~~ margins and the topographically constrained outlet glaciers, particularly visible in the northeast. In contrast, 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~~ regional thinning of several hundred meters focused around the outlet glaciers. 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 on the ice velocity~~ (*outlets**0.5) results in a regional 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 upstream~~c), the effects of halving the friction at the outlet glaciers shows a minimal effect on the total ice volume (see also in Fig. 1).

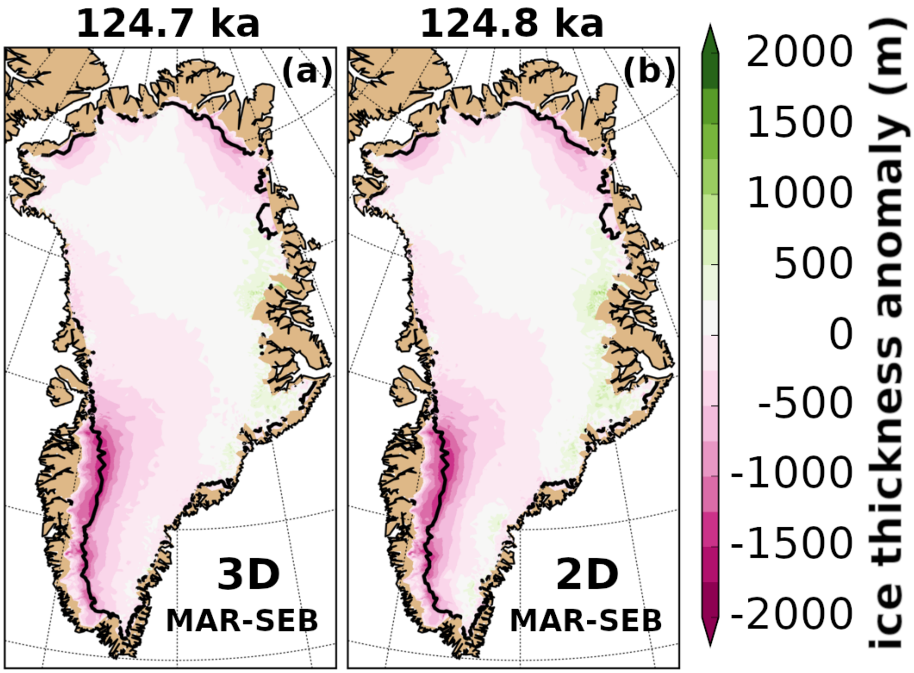

Figure 7. Ice thickness anomalies simulated with the ~~control~~ *control* (a; 3D higher-order~~(left~~) and ~~ice flow~~ the *ice flow* (b; 2D SSA~~(right~~) experiments at the respective ~~Eemian~~ ice minimum. ~~Relative~~ Anomalies are relative to the initial~~127 ka ice sheet (i.e.~~, modern ice 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.

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

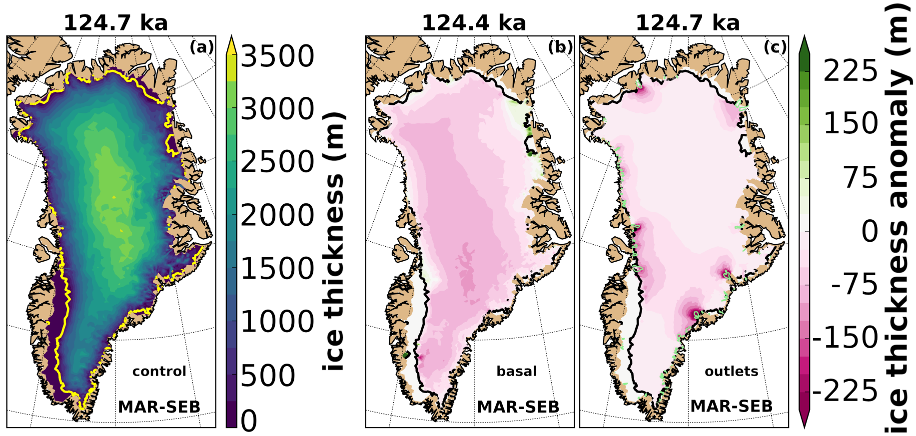

Figure 8. ~~Minimum ice~~ Ice thickness of the ~~control~~ *control* experiment (~~left~~a)~~and~~ , the ~~basal*0~~ basal*0.9 ~~/outlets*0.5~~ (b; reduced friction ~~experiments~~ of the entire ice sheet), and the outlets*0.5 (~~middle/right~~c; reduced friction at outlet glaciers) experiments at ~~the 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).

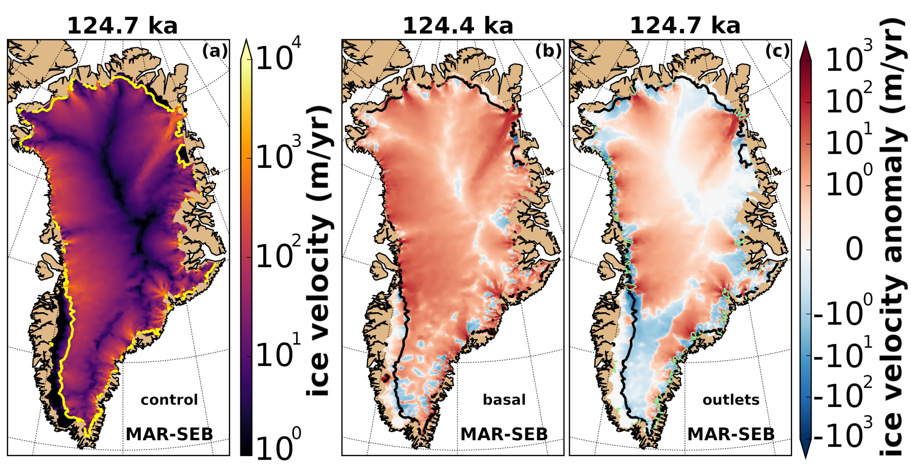

Figure 9. Ice velocity of the ~~minimum~~ ice sheet in the ~~control~~ *control* experiment (~~left~~a) and the ~~basal*0~~ basal*0.9 ~~/outlets*0.5~~ (b; reduced friction ~~experiments~~ of the entire ice sheet), and the outlets*0.5 (~~middle/right~~c; reduced friction at outlet glaciers) experiments 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).

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; Fig. 1). The basal sensitivity experiments ~~give a range of approx.~~ (*basal/outlets*) give an uncertainty of ±0.2 m ~~for both SMB models, where~~ sea level rise on top of the SMB simulations (Fig. 1); with the Greenland-wide ~~friction change shows~~ basal friction change (*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 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, and combining *basal**0.9 and *outlets**0.5 experiments. 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 they 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 is challenging. We show that after applying a large range of frictions it is unlikely that friction at the base has a stronger influence than changing the SMB forcing. This might be different if sub-glacial hydrology fed by SMB is dynamically 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~~Figs. 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~~Figs. 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~~ (initial ice sheet is not in equilibrium with the initial SMB forcing~~. A 10~~) and the colder-than-present 115 ~~kyr simulation~~ ka climate. A simulation over 10,000 years with constant pre-industrial SMB gives ~~an~~ a ~10~~-~~% larger ~~"relaxed "~~ relaxed modern ice sheet~~which is in equilibrium with the forcing. Sensitivity~~ . The *relaxed* sensitivity experiments with this ~~"relaxed "~~ relaxed initial ice sheet (~0.5 m global sea level equivalent 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 configuration, the final size is similar to the *control* experiment, because late-Eemian SMB results in a 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~~ using a 3D higher-order ~~setup~~ model (the 2D SSA setup neglects vertical shear)~~and the computational resources to run additional 3D experiments are limited~~ .

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 simulations melted away completely, and a more negative SMB would show limited effect in such regions. However, the MAR-SEB 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 affected by melt would partly compensate for the height loss.

The ~~results of the~~ *ice flow* experiments (2D SSA) show very similar results to the corresponding experiments with 3D higher-order ~~and~~ (*control* and *SMB* experiments; Fig. 7). The minor differences in the east, a stronger thickening in the 2D SSA experiments~~are similar, in particular for the simulated minimum ice volume. However, the difference~~ , might be explained by the complex topography in this region. The differences in ice volume ~~becomes~~ between 3D higher-order and 2D SSA experiments (Fig. 2) 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~~ . 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~~ emphasize the controlling role of the SMB forcing ~~is more important~~ and the SMB-altitude feedback in our simulations~~than the ice dynamics.~~ . However, ice flow induced thinning (for example due to increased basal sliding) could initiate or enhance the SMB-altitude feedback.

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 would increase the computational demand of our 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~~ , or speed-up of the outlet glaciers ~~.~~ is assessed (Figs. 8 and 9).

~~Furthermore, we neglect ocean forcing and processes including grounding line migration due to their complexity andbecause~~ The focus of this study is on the minimum Eemian ice sheet ~~is likely to have been land based. Note, however, that these processes are thought to be important for the recent observed changes at Greenland's outlet glaciers (Straneo and Heimbach, 2013). Tabone et al. (2018) investigate the influence of ocean forcing on~~ which has likely been land-based. Our Greenland-wide simulations neglect ocean forcing and processes such as grounding line migration. Although ocean interaction is deemed an important process for marine-termination glaciers in observations (Straneo and Heimbach, 2013), a recent study presenting ocean forcing sensitivity experiments for the Eemian GrIS ~~. Their sensitivity experiments indicate~~ indicates that the Eemian minimum is governed by the atmospheric forcing, due to ~~the lack of contact between the ice margin and the ocean. However, their estimated relative Eemian sea level rise is dependent on the ocean forcing, as it influences their pre-Eemian ice sheet size.~~

a lack of ice-ocean contact (Tabone et al., 2018). In contrast, the size of the glacial pre-Eemian ice sheet in their simulations is strongly influenced by the ocean heat flux and submarine melting parameter choice, implying a large impact of ocean forcing on the magnitude of ice loss over the transition into the Eemian. Our simulations, ~~starting with the orbital configuration and greenhouse gas levels~~ however, are initiated at 127 ka ~~, are initiated~~ with the observed modern GrIS geometry, not with a large glacial ice sheet (following the PMIP4 protocol; Otto-Bliesner et al., 2017). Similar to Tabone et al. (2018) we therefore do not expect our smaller-than-present Eemian minimum ice sheet to be strongly sensitive to ocean forcing and conclude that the disregard of ocean forcing and processes such as grounding line migration only represents a negligible error in the magnitude of ice loss and our sea level rise estimates.

The choice of starting the simulations with the observed modern ~~geometry of the Greenland ice sheet (following the PMIP4 protocol; Otto~~ GrIS geometry is based on the fact that the present-day ice sheet is relatively well known whereas the configuration of the pre-Eemian ice sheet is highly uncertain. Since 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 transition, resembled the present-day ice sheet. In this study, this point is chosen to be at 127 ka. One advantage of this initialization 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~~configuration.

~~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) provide a sea level rise estimate of 2 m from the Greenland ice sheet during the Eemian, 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 global sea level 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. The low sea level contribution of the *control* experiment could indicate systematic biases in the experimental setup, causing a general underestimation of the Eemian sea level contribution in all simulations.

No GIA processes are currently included in the transient mode of ISSM. However, including rebound of the solid Earth would have the tendency to counteract the surface melting. Especially, the MAR-BESSI experiments are affected by considerable melt-induced surface lowering. The solid Earth responds in time-scales of several thousand years, and therefore can oppose part of the extreme surface lowering during the warmest part of the Eemian, resulting in a reduced GrIS contribution to global sea level rise. The MAR-SEB experiments show less extensive melting and less surface lowering and as a result the potential for GIA to influence the MAR-SEB SMBs is smaller. The tendencies of how the sea level rise estimates could be influenced by an inclusion of GIA are indicated by blue arrows in Fig. 10.

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 SMBs through downscaling procedures. 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 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.

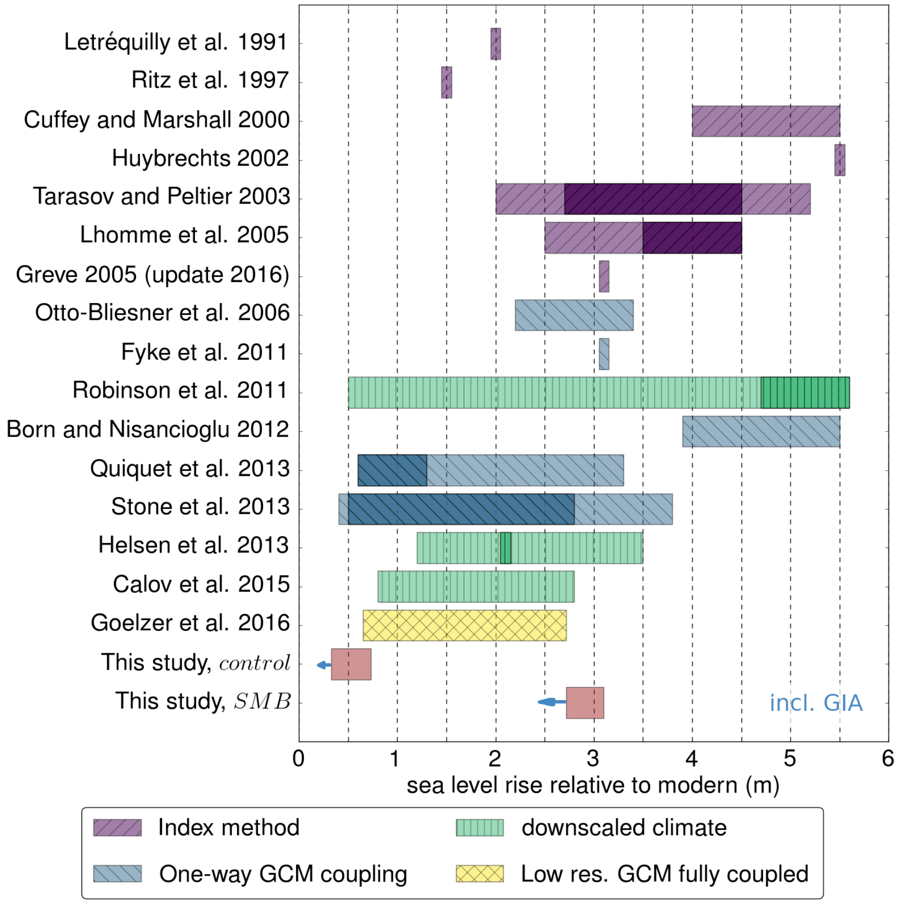

Figure 10. Simulated sea level rise contributions from this study and previous Eemian studies. For this study the results of the *control* (MAR-SEB; lower bound) and the *SMB* experiments (MAR-BESSI; upper bound) are shown (the ranges show the results of the respective basal/outlets fraction sensitivity 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). Tendencies of a GIA inclusion are indicated by blue arrows. The simulations of Greve (2005) were repeated with an updated ice sheet model version in 2016 (personal communication).

5 Conclusions

This study emphasizes the importance of an accurate surface mass balance (SMB) forcing over ~~detailed ice sheet physics when simulating the past evolution of the Eemian~~ a more complex ice flow approximation for the simulation of the Greenland ice sheet ~~. Our experiments~~ during the Eemian. 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~~ In contrast, the comparison of experiments with 3D higher-order and 2D SSA ice flow, give only small differences 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 indicate a limited influence of the~~ A non-exhaustive set of basal friction sensitivity experiments, affecting the entire ice sheet and only the outlet glacier regions, indicate their limited influence on the total ice volume (maximum difference of ~0.2 m compared to experiments with default friction). While basal friction sensitivity experiments with larger impacts on the ice configuration could be envisioned, it is unlikely that such experiments would exceed the magnitude of uncertainty related to SMB. 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. Climate model uncertainties and biases 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 source code for BESSI is available as a supplement to Born et al. (2019). 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.

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