Response to Anonymous Referee ♯1

We thank Referee ♯1 for a number of detailed review that significantly helped us to improve the quality of our submission. Our full response is as follows.

(A001) ***In this paper, Saito et al. examine and revisit the SeaRISE experiments for the Greenland ice sheet to identify possible sources in the spread of results. While SeaRISE is a multimodel as well as multiparametric ensemble analysis, the authors try to limit the analysis to a multiparametric one, which enables the identify in a coherent way differences in the spread. The main parameters that are tested relate to different ways on how to parameterize basal sliding (sliding at sub-freezing temperatures), initialization of the ice sheet, mass balance parametrization, allowing advance of the ice sheet margin, ... The authors conclude that major uncertainties (causes of large spread) are due to the initialization method and mass balance parametrization, and to a lesser extent margin migration.***
These conclusions are in line with the findings of Nowicki et al; Bindschadler et al., but shed a new light on the influence of initialization (However, at the end of the manuscript this is stated otherwise). While the content of the paper is informative, there are major improvements that need to be made to make the paper more sound and readable.

Thanks a lot for positive evaluation. We took all the points you made seriously. Most of them are already included in the manuscript. Revision related to the additional experiment will be included in the submission.

(A002) ***First of all, the English needs to be improved. The manuscript should be carefully re-read by a native English speaker to remove small errors and to improve the flow.***

English will be checked before the submission of the revised manuscript.

(A003) ***Secondly, the authors miss a great opportunity to properly investigate the major source of spread, i.e., initialization. As a matter of fact, the authors describe that two methods are used for initialization of ice sheet models, i.e., a (1) paleo-climatic spinup and (2) inversion methods to initialize the basal conditions of the ice sheet. They add a (3) third method, based on a temperature spinup with keeping the surface elabation fixed (which in my opinion is not a widespread initialization method but merely a spinoff of the paleo-climatic spinup). However, in the analysis, only two of these methods are evaluated (1 and 3), and of these methods, method 3 is the one that raises major questions. Initialization by spinup of the temperature field is maybe a common method, but the relaxation of the ice thickness for a short period (or no relaxation at all) may lead to spurious behaviour. I therefore wonder why the authors did not use an inversion (control) method as spinup to investigate the parameter that according to their analysis is the most sensitive. Pollard and DeConto (2012) describe a very easy implementable method to optimize basal friction coefficients for any basal sliding law by an iterative method. Convergence is reached after 50 to 100,000 years and results in a steady state surface elevation and temperature field that fits the observed surface. This way the model drift is limited, which enables to correctly interpret the response of the ice sheet to any climate or other perturbation. Due to the ease by which the method can be applied to any ice sheet model, I urge the authors to implement this method to improve their analysis.***

Thanks a lot for your suggestion.

This comment may relate to a comment by the second referee, "The main problem with the presentation of the results is that they over-claim their ability to explain the reasons for the SeaRISE spread." In the present paper, actually we do not intent to identify a definite reason for the SeaRISE spreads (in introduction we state that 'This paper does not intend to cover the sensitivities of all of the aspects'). Due to the original title and/or some improper phrasing in the text, we may give to the readers/referees an impression that we solved the SeaRISE spreads by comprehensive sensitivity experiments, however, we agree, not true. This is one of the reason why we skip to include an inversion experiment.

There are already three models (ISSM, AIF, CISM) in the SeaRISE Greenland experiment that use inversion methods, which are all different: they are different in not only the inversion methods but also in many other aspects (such as basal sliding formulation, surface mass balance and so on), and their results has already a dispersion as shown in Bindschadler et al. (2013), Fig. 3. For the objective of this paper, one can perform an inversion experiment using the same method of the three models, but still it may have much degrees of freedom than the method we tried in the present paper (that is, fixed topography spin-up). Such inversion of, e.g., spatial distribution of the basal sliding coefficients, depends on the boundary condition and ice flow characteristics in individual models, but these are all different among the models. It is possible that IcIES does an inversion under the IcIES configuration, which may not be easy to isolate the impact of the inversion method only because the inversion already includes influences from the other differences. Even if we use the same method of three models for inversion, the result may not give a potential to explain the spread. Using another method (e.g. simple relaxation presented by Pollard and DeConto) may further expand the spread. This is another reason why we skip to include an inversion experiment.

Actually, we already performed several inversion experiments using the method of Pollard and DeConto before the submission of this manuscript. As far as we tried, the method never succeeds to have a reasonable basal sliding coefficients under *standard* IcIES configuration. Even when we allow zero (no sliding) as the lower limit of the coefficients, the interior part is still lower by more than 400m, and the simulated volumes are worse than the results by other spin-up. In order to have a reasonable field, we need modify something from the standard configuration, such as the surface mass balance or the ice enhancement factor (like Pollard and DeConto). It means that we need one or two more 'experiment axis' for this paper, which are quite demanding and really beyond the scope of the paper, because anyway all we want to show is a potential source of the spreads. This is one more reason why we skip to include an inversion experiment.

So, we modify the tones of these phrasing down to "potential" explanations in the revised manuscript to skip a comprehensive series of sensitivity experiments. But, at the same time, even in terms of 'potential' explanations, it is very good to show 'potential' explanations of the impact of an inversion spin-up, or more precisely, that of spatially distributed basal sliding coefficients, for example. During the open discussion, we performed one optimization experiment using Pollard and DeConto, with a different enhancement factor to have ice-sheet topography reasonably close to the observation. Additional sensitivity experiments relating to this variation are also performed just for analysis. The results will be included in the main text of the revised manuscript as well as supplementary, in order to demonstrate as a potential source for the SeaRISE spread. We hope you agree and give us another time to include this additional experiments.

(A004) Some discussion should be given on features that have not been tested explicitly, such as the sensitivity to spatial resolution and the importance of marine-ice sheet instability, as a marine boundary is present for major Greenland outlet glaciers and such instabilities have been identified in other numerical model studies (Nick et al., 2012) More detailes on the advance/retreat of the ice-sheet margin need to be given. Does this pertain to a marine boundary or not? What are the conditions for advance/retreat (numerically). Is the process occurring on sub-grid level or simply when $H < 0$, then $H = 0$? How is this generally implemented in the SeaRISE models and in the model presented in this paper?

As mentioned in detailed comments below, the effect of the resolution is already investigated by Greve and Herzfeld (2013). We cited the result in the revised manuscript.

About the advance/retreat. Numerical treatments in the other SeaRISE models are described in Nowicki et al. (2013). First of all, 'None of the models taking part in the Greenland suite of experiment include ice shelves as indicated in Table A1.' ([31] of Nowicki et al., 2013). It is not mentioned explicitly, but most SeaRISE models determine the grounding line by a floating criterion (set $H = 0$ when surface falls below flotation height) or fix the grounding line through the time. So, we really agree the importance of marine-ice sheet instability of Greenland ice-sheet, SeaRISE models do not have capability enough to discuss the marine-ice sheet processes.

There are already M1 M2 M3 experiment in SeaRISE, which are called ice-shelf melting experiment. Since the SeaRISE Greenland models do not have explicit ice-shelf processes, the implementation of the ‘ice-shelf melting’ varies much among the models, that is one of the reason why the spread of the results are very large (larger than C1 C2 C3 spreads presented in this paper). Nowicki et al. (2013) state that: ‘Thus, the current generation of Greenland whole ice sheet models is not yet able to simulate the potential response to a warming ocean, and caution is needed when interpreting the SeaRISE response to this scenario, as the ensemble mean response likely underestimates the true potential response.’ With the same reason, the present paper focuses on the climate warming scenarios only, which means that impact of the margin retreat purely by the surface mass balance is discussed.

When we really including marine-ice instability processes, the problem of margin advance/retreat will become more significant than the present paper. Thanks a lot for comment. Such discussion about marine-ice sheet instability is appended in the revised manuscript.

Detailed comments

(A005) Title: experiments instead of experiment

Corrected accordingly.

(A006) p1384 L8-9: diversion is probably not the best word here. It appears at many other places in the manuscript. Preference for 'dispersion' or 'disparity'

Yes, we do agree. Replaced with ‘Dispersion’.

(A007) p1386 L11: ranging from 8.5 to 142.6 cm.

Replaced accordingly.

(A008) p1387 L4-7: rephrase sentence

Rephrased as: ‘There are at least ten characteristics that differ among the ice-sheet models participating in SeaRISE (see Table 2 in Bindschadler et al., 2013), and most have two or more variations.’

(A009) p1388, section 2.1: You should also investigate the effect of spatial resolution next to the use of different data sets, otherwise this has makes not much sense (see general remarks).

Effect of the resolution is already investigated by Greve and Herzfeld (2013). The paper is already referred in the manuscript but not with above context. We cited the paper again in the introduction to present the previous discussion of the effect of spatial resolution, as: “The effects of some of the characteristics have already been argued in previous studies. Greve and Herzfeld (2013) compared 500-year future climate experiment with three different grid spacings, 20, 10 and 5 km and concluded that the sensitivities in the simulated ice sheet volume is insignificant.”

(A010) p1388 top: Possible sources of spread, instead of Candidates for sources of spread.

Replaced accordingly.

(A011) p1388 L8: Isbrae

Corrected accordingly.

(A012) p1388 L10: referred to

Corrected accordingly.

(A013) p1388 L11: localized

Corrected accordingly.

***(A014)* p1388 L12: present a significant difference in the present-day**

Corrected accordingly.

***(A015)* p1388 L19: have several degrees of freedom**

Revised accordingly.

***(A016)* p1389 L16: This method is called 'inversion or optimization' method. It is not an initialization by 'tuning'. Basal friction coefficients are obtained by an optimization method (such as control methods). However, more simple approaches exist (that can be called 'by tuning', but is not preferred), such as the method presented by Pollard and DeConto (2012).**

The terminology 'tuning' is just what Bindschadler et al (2013) used (see Sec. 2.2.2 in the paper). We modified the sentence to make it clearer, as 'One method is called initialization by "tuning" in Bindschadler et al. (2013), which may be better termed 'inversion' or 'optimization'. This method inverts given data fields, e.g. basal friction coefficients, to adjust present-day observation fields, e.g. surface velocity.'

***(A017)* p1390 L4: remove 'previous'**

Removed accordingly.

***(A018)* p1390: The method due to Pollard and DeConto (2012) should be discussed here. Although this method has not been applied to Greenland, but to Antarctica instead, it is a general method that can be applied to any ice sheet and an inversion method that is easy to derive compared to other control methods. Furthermore, mention should be made to Morlighem et al. (2011) in which bedrock uncertainties are also taken into account in the inversion method based on mass conservation and surface velocities.**

The two papers are cited here in the revision.

***(A019)* p1391: Treatment of advance of the ice sheet margin. Since this variable seems also to play a more or less important role in the sensitivity of the ice sheet, a more thorough description should be given on how this is implemented numerically and how models generally deal with this in the SeaRISE sample.**

We have no idea how other models actually implement these treatment. A text to explain this is added at this part as, "Although detailed numerical implementation are not shown in Bindschadler et al. (2013), some participants in SeaRISE describe their methods as either fixing the ice-sheet margin (calving front) or limiting its advance (i.e., only retreat is allowed)." In addition, detail numerical implementation of IcIES are inserted in section 4.4, as "The thickness can be non-zero over the entire model domain during one step in the numerical time integration, but those grids that match a floating condition are immediately cut off."

***(A020)* p1392 L3: Most participants adopt some form of the ...**

Revised accordingly.

***(A021)* p1392 L7: Previous studies present ...**

Revised accordingly.

(A022) p1396 L1: "Although it is important, such fine tuning is beyond the scope of the present paper." First of all, this is not fine tuning; Secondly, any form of inversion needs to be performed within the context of this paper, since the initialization phase is found to be the most sensitive parameter in the analysis. Furthermore, the types of initialization presented is probably the most biased in its nature. Therefore, at least an initialization procedure that represents as best the present-day observations of the ice sheet, should be favoured.

This text is deleted in the revision. About initialization, please see our main response above.

(A023) 1397 eq. 3: what are the units of TB ? Does γ have units?

Both units are degree C. Explanation of the Eq. 3 is revised.

(A024) p1397 bottom and 1398 top: How does this method behave as a function of sudden changes in dH/dt once the spinup is done? Are the changes sudden? Are they in line with present-day observations of imbalance of the Greenland ice sheet? The performance of the initialization method should be further discussed, especailly since it is the major sensitive parameter in the analysis.

They are sudden and not in line with the observations, as already described in Bindschadler et al. (2013) (Fig. 1 and p201 right columns). Performance of the initialization is described in the text (results section).

(A025) p1398 L21: Why is the advance of the margin not allowed in these runs? Glacier speedup may also result in advance before increased melting at lower elevations reduces the ice thickness. I don't understand why the aspect of 'not advancing ice sheet' can be used as a parameter in a sensitivity study.

Because some models in SeaRISE do not allow ice sheet advancing in the future climate runs, due to their each unspecified reason. We definitely agree with your comment and that is why the IcIES original submission freely allows the advance to include the effect you mention. We speculate the reasons are (1) the 'inversion' models have no constrain how to specify the basal sliding coefficient beyond the present-day ice margins (2) it is much easier to fix the computation domain than to allow domain regeneration for complex models such as finite element models. We inserted a text not in this part but in Sect.2.4.

(A026) p1399 L24: both having an identical initial topography.

Inserted accordingly.

(A027) p1400 top: if there is an overestimation, please explain where this overestimation of the volumes is essentially situated. Is this at the margin near the large outlet glaciers?

Figures to show the difference in topography are included in supplementary. Margin is overestimated overall the margin area except for the northwest and northeast region (as shown in Nowicki et al., 2013, Fig. 2c).

(A028) p1400 L19: shows the largest response. Moreover, I don't understand this sentence. Configuration 'O': is this the bottom curve (see my remarks on that figure)?

We are very sorry that this sentence is wrong. We correct this sentence, and revised the figure to move the O mark to the right.

(A029) p1402: Initialization method. Since the choice of method has the largest impact, some discussion is needed on the realism of the initialization methods used. See also general remark.

This part is already revised according to the comment above (p1397 bottom and 1398 top...).

(A030) p1402 L28: the the

Corrected.

(A031) p1403 L18: Ice-margin advance has a smaller impact. Is this because overall the margins are retreating and no advance is observed in the model for the future scenarios (should be advancing if basal sliding is cranked up under a relative mild climate scenario, such as C1)?

Thanks a lot. You are right. If climate scenario is strong as C2 or C3, then advance in the ice sheet margin is not significant even free-margin experiments. Discussion following your comment is inserted.

(A032) p1407 First paragraph. You should discuss why the sensitivity to initialization does not show up as primary source in the SeaRISE experiments, but does so in this paper.

The sentence in the manuscript is confusing. This part no more exists according to other modification.

(A033) p1408 L22: "Thus, a future-climate experiment initialized by fixed-topography spin-up can be considered a suitable approach for characteristic projections by an ice-sheet model." I don't agree with this statement. The analysis does not show it. The question is whether the spinup presented is adequate in the first place and explains the observations of the present-day ice sheet in terms of imbalance, velocity field and surface elevation (ice thickness).

The SeaRISE papers and the present paper all present the result by 'experiment minus control' methods (Bindschadler et al., 2013 p201). It means that, only **changes** from the present-day trend due to changes in forcings are mentioned and discussed, no matter how the present-day simulation is bad (or good). The next section which describes this point moved before this section, to be clearer.

(A034) p1410: Prospects: in view of the large sensitivity to spinup and the fact that the authors perform a very limited analysis in terms of spinup, this section needs to be re-analysed in a revised version.

Please see the main response above. We agree this paper is quite limited in terms of spin-up, but rather, that is why we propose a benchmark experiment. Since the resources are limited more or less, one model cannot cover all the variations of the models. Instead, if all the models perform a highly controlled experiment, it is easier to analyze the uncertainty due to model spin-up, within the variation of current ice-sheet model structures. This section is revised to add such discussion.

(A035) p1411 Appendix 1: Demonstration of the benchmark experiment

Inserted accordingly.

(A036) p1411 L19: SeaRISE has a similar configuration

Inserted.

(A037) p1420 Figure 1: What is the order of the curves here. I see 6 curves and 5 letters next to the figure. Is O the bottom curve? Not clear at all.

Sorry for confusing. The letter O is not along the right border but in the graph (around 250, -1.4). In the revised figures all the letters are along the border.

Response to Referee ♯2

We thank Tamsin Edwards, for a number of detailed review that significantly helped us to improve the quality of our submission. Our full response is as follows.

(B001) Congratulations to the authors on a thorough study of an important scientific question. It is a systematic study of a number of important ice sheet modelling uncertainties, mirroring as closely as possible many of the choices made by modellers in the SeaRISE multi-model ensemble (with additional combinations to deconvolve aspects of these). The aim is to quantify which are the most important uncertainties, and therefore to try and understand the source(s) of the large spread in that ensemble.
The ice sheet modelling community should be assessing the impacts of initialisation and parameterisation choices systematically, like this, as standard. It is good to apply this to the SeaRISE choices, but the study is also more widely applicable - for general considerations of how to do ice sheet modelling, but also for the current question of how to perform the experiments for the first CMIP endorsed ice sheet model intercomparison project, ISMIP6. I heartily agree with the authors statement that "It would be preferable that all participating models perform one common and highly controlled experiment which allows effective identification of the uncertainties due to specific variations in ice-sheet models."
I therefore think the results presented here are an important contribution to the growing literature on this challenging topic.

Thanks a lot for encouraging us. We took all the points you made seriously. Most of them are already included in the manuscript. Revision related to the additional experiment will be included (in the main text and/or supplementary) in the submission.

(B002) I am happy to see the authors test multiple combinations of changes, to check for interactions between the uncertainties. Not every combination is performed, but the simulations presented are substantial.

Actually to test multiple combinations of changes not shown in the present paper is much harder a task than that at a glance. We have performed many additional combinations during the open discussion, which will be inserted in the text, figures and/or supplementary.

(B003) The main problem with the presentation of the results is that they over-claim their ability to explain the reasons for the SeaRISE spread. The title should say "potential" sources for spread — and similarily throughout the paper. The study highlights which SeaRISE choices could explain the spread, but due to the limits of using one model and only exploring part of the matrix of choices, they cannnot definitively say if they have found the reasons.

In the present paper, actually we do not intent to identify a definite reason for the SeaRISE spread (in introduction we state that 'This paper does not intend to cover the sensitivities of all of the aspects'). Due to the original title and/or some improper phrasing in the text, we may give to the readers/referees an impression that we solved the SeaRISE spread by comprehensive sensitivity experiments, but, we agree, not true. So, we modify the tones of these phrasing down to "potential" explanations in the revised manuscript (titles and through the text). Thanks a lot for your comment.

(B004) The authors also go part of the way towards defining a useful "benchmark" experiment, but not quite far enough in either the definition or its justification. Is this purely for model intercomparison purposes, or for more realistic projections? If the latter, the authors should comment on the quality of spin-up (see comments: the sum of the squared residuals would be a better assessment of agreement with observed geometry). It would also require other discussion of the quality of the initial state — e.g. realistic velocities, size of drift? If the benchmark is only intended as an abstract test for model intercomparison, this should be made clearer.

No, the former, just for an abstract test as you pointed out. This section is revised to be clearer.

(B005) There should be a clear summary of the SeaRISE choices that have not been explored (whether the choices themselves, or particular combinations of them) — how much of the SeaRISE "matrix" have you covered? There should also be a list of the major other modelling choices not tested — i.e. not "SeaRISE" choices but the main things that vary across models such as enhancement factor, method of obtaining basal friction, flow approximation, resolution. These are mentioned briefly in the Conclusion but should also be in the methods and discussion.

Yes, we expand the SeaRISE description in the methods and discussion. Actually we cover only a portion of the SeaRISE matrix, partly because not all the aspects are explicitly documented enough to emulate by IcIES, and partly because it is too much.

(B006) Related to this, there is not enough comparison with the dependence of SeaRISE results on these choices. Do the models with free geometry tend to show larger changes than those without, as found in this study? Similarly, do the models that use the Tarasov melting parameterisation tend to show larger changes than those with the Huybrechts? If they do, it confirms the results of this study across multiple models. If not, it would show that (a) the effect of initialisation choices are highly model dependent or, more likely, (b) structural and parametric uncertainties are just as important as initialisation. It would not negate the importance of this study at all - but it would show the situation is worse than we thought! In other words, it would show that if all SeaRISE models repeated this study, the range could widen by a lot more. This would be further support for the authors statement that it is important to systematically control and study uncertainties with designed experiments.

Mostly no. Tarasov melting is only used by IcIES original submission. Huybrechts melting is used by some models, but we are afraid that there are not enough number of models to confirm the results. So we took your latter suggestions in the text, which further encourages our 'benchmark' experiment. Thanks a lot for the suggestion.

(B007) Without the above comparisons to SeaRISE, the authors should remove their claims of explaining the SeaRISE spread. Even with them, they should still tone these down to "potential" explanations.

Yes, we have changed the tone as explained already.

(B008) Some minor points occur throughout. In terms of clarity, the authors frequently use the broad phrase "initialization methods" when they really refer to a specific aspect of this - e.g. transient vs steady state, or treatment of margin. This should be replaced throughout for clarity. Consistency of referencing needs checking — e.g. Aðalgeirsdóttir et al. (2014) should be mentioned earlier. The authors often use "primary" and "dominant", which imply "the most important of all choices". They should replace these everywhere with "more important than X" for the comparison being made at that point.

We revised the phrasing through the text as you suggested.

(B009) This is a difficult study to explain, and an important one to get right. I have therefore included many detailed suggestions to clarify and improve the text.

We really appreciate your careful reading. Most of the detailed suggestions are included as follows.

MAIN SCIENTIFIC POINTS

(B010) 1389 Need to also say disadvantage of free geometry here — ice sheet too big.

A text is inserted to explain what you suggest. Ice sheet can be too small also, so only mention that it can deviate from reality.

(B011) 1396/21 Except the SD, which is larger.

Revised to be more accurate.

(B012) /23–27 Why is the bedrock changed only once, not for multiple combinations as for other things? Is this because (a) the effect is small? (b) most models used the later version? (c) it is newer therefore preferred?

All, mainly (a) and (b).

(B013) /10 (and also 1389/16) Language needs clarifying: g-ig spin up and tuning/inversion for basal friction are not mutually exclusive, as they are inferring different state variables. E.g. in Edwards et al. (2014), Elmer/Ice used ice temperatures from a SICOPOLIS glacial-interglacial spin-up then performed inversion for basal friction. And clarify "basal sliding enhancement factors" — does this mean basal sliding coefficients and (SIA and SSA) enhancement factors?

The former. Text is inserted to clarify the point. The latter. Corrected to 'basal sliding coefficients' not to confuse.

(B014) Table 2 caption: columns are not ratios but percentages.

Corrected accordingly.

(B015) Table 2. Given there are compensating errors, please give the sum of the squared residuals with the observed geometry. This will give more information on which is really the best geometry, not only (by accident) the best volume. I think this is crucial information for making preliminary judgements about the most suitable benchmark initialization.

The root mean square of the residuals are appended. Legend and the main text are modified according to the revised table.

(B016) 1400/18–20 Doesn't it show the third largest, not the largest?!

You are right. Text is corrected.

(B017) 1402/1–5 "higher climate scenarios" — for v4, I think the absolute increase from A to C is about the same for C2 and C3, right? And the % increase *decreases* from C1 to C3, which is also relevant. Also worth commenting that v4 makes proportionally less difference in higher climate scenarios, i.e. no longer a near linear response to sliding coefficient as it is for C1.

You are right. Explanation is expanded, thanks.

(B018) /13 "Even under larger basal sliding coefficients" — why "even"? Wouldn't you expect the change in initialisation to have even more effect for these? (because it removes their strong effect in the free spin-up). And in fact the effect is bigger for v4 than v1 so you could say "Especially for" instead.

Right. Replaced as you suggested.

(B019) /18–19 "including the corresponding constant future-climate scenario case C0" — isn't it anomalies with respect to this (as for Fig. 2)?

We are very sorry that the text to describe Fig. 2 was wrong. Your are right. The text is not correct, because C0 is not included in the figure. Text is corrected accordingly, as 'Figure 2 shows the changes in VAF relative to that under the constant climate scenario **C0** obtained by experiments B, F and D, over all the combinations of climate scenarios and sliding coefficients.'

(B020) 1403/1–5 Isn't it worth commenting on that the effect of the non-equilibrium thermal state (D to F) is nonlinear in basal sliding coefficient and climate? i.e. not systematically smaller or larger? I think for v1, C1 decreases, C2 the same and C3 increases, while for v4 it always increases (i.e. I don't think it's just a function of delta_ VAF)

I assumed you mean B and F (this is not your fault but us, not to name the experiment effectively). Comment is inserted as your suggestion, as 'The effect of the non-equilibrium thermal state is not systemically larger (F to B). In the case of **v1** basal sliding, F shows smaller response than B under the **C1** scenario, similar response under the **C2**, larger response under the **C3**, respectively, while in the case of **v4** all F shows larger under the three scenarios.'

(B021) /10–15 I didn't understand this summary — partly because it says observed geometry, when F and F_ s are not fixed to observed. Is it saying that as long as the final geometry is the same, it doesn't make much difference whether the spin-up was transient climate or steady state? Does this mean internal thermal state doesn't matter at all? (i.e. whether it's at equilbrium with geometry, and whether it's derived from 125ka transient or 0ka steady state)? Also — C0 isn't shown.

Yes, that is what we are saying. We revised this part to be clearer. As shown in the second last comment, C0 is not shown because they are all difference relative to C0 results.

(B022) 1404/14–16 "The retreat of the ice-sheet margin over north-western Greenland is not seen in the B' : v4 cases (Fig. 4f)." I can't see a difference in the north-west between B' v1, v2 and v4, only between B and B'.

Corrected. The retreat is not seen in all the B' cases.

(B023) 1405/14–23 This has been cut and pasted from p1402 with only minor edits, and should be deleted because it focuses on comparing initialisation methods (rather than SMB parameterisations) with each other. In my view the points of interest left to discuss are F' vs F and F_ s' to F_ s, which look very similar to B' vs B in absolute changes — i.e. the SMB change seems to be related to B0 (large effect) vs observed geometry (small), and not the transient vs steady state, if I have the experiments correct. Possibly the fractional changes are more similar though?

The former, shortened. The latter: Sorry, this comment is also raised by wrong description of Fig. 2. These are not absolute changes but relative changes from constant climate run. The three experiments F, Fs and B start from an identical topography. Also, three experiments F' Fs' B' start from another identical topography. Since the surface mass balance are ultimately a function of the topography only, the former three and the latter each starts from identical surface mass balances. About fractional changes: figures/tables are added in the supplementary.

***(B024)* 1406/7–8 It's not useful to say that one thing is the biggest increase and another the biggest decrease, because it depends on the order you do things! Changing from fixed obs to free geometry (D to B), is a much bigger enhancement of response than turning sub-melt sliding on..! (Obviously understanding the direction of response is important, and so is ordering by magnitude, but not ordering by signed magnitude).**

Revised to make it clear, as 'Among these four aspects, the inclusion of submelt sliding enhances the ice-sheet response strongest (A to B), but using "fixed-topography" spin-up cancels and even reduces this impact (B to D).'

***(B025)* /10 I disagree that the sensitivity to basal sliding coefficient is a function of delta_ VAF — if that were true, then A and O would always look similar to B, and for example, D' C3 (3 to 3.5) would look similar to B C2 (3–4.5). I think it's a function of free vs fixed geometry (with some enhancement for larger delta_ VAF, but nonlinearly — the C3 range of B v1–v4 is similar to the C2)**

You are right. Removed.

***(B026)* "The spread of the results due to different basal sliding coefficients is slightly larger under the C3 scenario." — as above, to me it looks too similar to C2 to comment on.**

Corrected as your comment.

***(B027)* 1407/5 You can't say you are defining / quantifying the "source of the spread in SeaRISE experiments". You are seeing if you can reproduce the magnitude of variation in delta_ VAF (N.B. not model response, which would include spatial elevation patterns, velocities etc) by changing a subset of the possible configurations (i.e. not all combinations of all parameters/choices that are changed across SeaRISE models) in one model (not all possible model structures). This is a very interesting study, but it is induction not deduction.. Your results point to potential sources of variation, but cannot definitively identify them.**

Yes, we agree. This part no more exists according to other modification.

***(B028)* /12 Is there no drift at all for free spin up? I would have thought model and obs (eg bedrock, GHF) errors would still give some.**

Yes, we do have some, but the drift of free spin-up run is not 'artificial'. Maybe this term is not good because any simulation is more ore less artificial. Rewritten this part without 'artificial'.

***(B029)* 1408/4 Can you please explain this in more detail, as I don't understand what is done.**

This part is revised to: "This 14.5cm effect is about 11 % of the simulated VAF response obtained by D C3:v4 case, and thus the effect of the internal non-equilibrium state is expected to remain minor relative to the total sensitivity."

***(B030)* /5 "Therefore, future-climate experiments...preferred..." — what is the basis for this conclusion? (The volume of the A v4 spin-up is the closest to the observed!). What other information do you have that fixed geometry is better? That it's less sensitive to other perturbations than the free? How do you know that's desirable? Is it because it's easier to spin-up with steady state than transient? It's not clear what the justification is.**

Explanation is inserted, as "In other words, initial topography has more effect on the future projection, *in terms of relative to constant scenario runs*, than the initial internal temperature field." The point is that, if two experiments starts from the identical topography, one with consistent temperature field (free spin-up), the other with inconsistent field (fixed spin-up), and all other model configuration are the same between two, then that simulated volume responses to future warming scenario *relative to those to constant scenario* are similar during five-hundred years.

(B031) /10–15 I don't understand this comparison. Free vs fixed geometry (B–D) is a bigger effect than either of these, so isn't that the "primary source of uncertainties in the simulated short-term future projections of the Greenland ice-sheet". And better to say 500 year time scale, as those focused on 1–200 years won't see this as short-term.

We agree, not the primary. The text is revised.

(B032) 1409/5 Please give the total trend for each run after 500 years — at minimum the range and which are the largest drift runs. It would be useful to separate this for transient and steady state climate runs.

The ranges of the trend (by C0) are inserted.

(B033) /8 "The present paper concludes that such long-term memory has a smaller impact" — this isn't shown

This is concluded by the results that the transient spin-up (which has memory of long-term changes in climate) and the steady-state spin-up (which does not) are almost same. Text is revised to be clear, as 'It is expected that such long-term memory has a smaller impact for the future *changes* in ice-sheet volume at least during next 500 years, compared with the changes due to future surface climate scenarios, because the results of transient spin-up (with long-term memory) and steady-state spin-up (without) show similar responses,'

Discussion section generally:

(B034) Can you give an ordered list (or figure) of the one-at-a-time effects? I think this would bring clarity to the multitude of bars... i.e. for a given v and C, and only for pairs of simulations where one thing is changed, what are the largest to smallest effects of changing that one thing? Fraction might be more useful than absolute.
So 15 pairs, I think — which could be repeated for v1:C1, v:C3, v4:C1, v4:C3? (in Supplementary Material), order by magnitude the fractional changes of:

```
A--O
B--A
D--B
E--D
F--D
D_s -- D
D_s' -- D_s
F_s -- F
F_s' -- F_s
B'--B
D'--D
D_s'--D_s
E'--E
F'--F
F_s'--F_s
```

Or could just show the top 5 out of 15 in each case, maybe.

Sure. We will add such a table to supplementary. Two comparison are duplicated in the list above, and three pairs are added in the paper.

(B035) I would like to see more about why the configurations produce the response they do, and if they are expected — there is some discussion about increasing flow to margins, increasing sensitivity to climate etc — but I think it should be added for each result, even if the reason seems obvious to you.

Such discussion are inserted for each result. This is partly explained by initial condition and partly explained by initial drifts.

(B036) /22 "The results show that the main sources of the spread in the SeaRISE experiments" → no, in this particular set of experiments reproducing possible SeaRISE choices

This part is revised to use the term 'potential'.

(B037) /24 "As already proposed in the SeaRISE papers, and confirmed quantitatively in the present paper, the impacts of these two aspects are of comparable magnitude." — again you need to distinguish these two related but not comparable studies.

The text is deleted.

(B038) 1410/2–3 "temperature is allowed to be evolved according to the surface temperature history..evaluated" — why is this preferred over steady state? It wasn't really evaluated either.

We agree that this is not preferred over steady state. The text is revised.

(B039) /9 "consistent or inconsistent." I don't think this is tested as it requires uncertainty estimates. "Similar or dissimilar" would be OK.

Right. Corrected as you suggested.

(B040) /21 "Here we propose a model intercomparison study " — all of this is new so shouldn't be in the Conclusion but in the Discussion.

This part is completely moved to the bottom of Discussion.

(B041) 1411/1–12 Why choose no advance — why do you think it is better? (it might be, but needs justification). Or is it no better, you just pick it arbitrarily (also OK! but say so).

We cannot say it is either better or not. One thing we expect they choose no advance is from a technical reason: we do not have much constraint for surface melting and/or surface velocity over ice-free grids. If advance is freely allowed, we have to define for example the basal sliding coefficients over those grids, which may have much degree of freedom. Also, we expect some model have a difficulty, although possible, in regeneration of grid system if ice-sheet area is expanded. Such explanation is inserted.

(B042) Need to be clearer why benchmark includes either method — "very heavy full-stokes" should be "computationally expensive Full Stokes".

Explanation inserted.

(B043) /14–18 "entirely" — No! Also resolution, other parameters? Treatment of calving, retreat allowed Are you confident in recommending a benchmark that appears to systematically reduce response? (fixed obs geometry, no advance) Is this purely for model intercomparison or for more realistic projections?

The former: other parameters you mentioned are also included in 'entirely'. This part was revised to be clearer. The latter: this is purely model intercomparison, not for realistic projections. Still many modeling studies (as SeaRISE) separate ice-sheet modeling and other modeling (climate, ocean,...). Realistic projections require realistic scenarios which are also uncertain. SeaRISE presented that even if the 'scenarios' are the same there are variations in the simulated response of Greenland ice sheet. This paper presented, however, that the variations are partly from the structural differences which can be avoided. In other words, uncertainties due to all the aspects except for the surface mass balance (not 'temperature' scenarios) are expected to be extracted. We do not think the benchmark reduce the response. This is just for evaluation of the ice-sheet model uncertainties to the same forcing.

(B044) Where is the SMB from (as above)? Why look at uncertainty due to PDD scheme if all models use the same SMB? (maybe this is clear once we know what the SMB is)

We have no idea what is the best SMB. Although we agree it is another option to use the identical PDD scheme, it is easier to use the SMB field computed externally in advance than to that computed internally in particular for the purpose of the benchmark. The reason is we have to provide not the equations but the subroutine in order to make the SMB really identical among the models, probably in two or more languages. An explanation is inserted as another options, as "or provide an identical surface mass balance *subroutine* (not a scheme to keep it really identical among the models) as well as scenarios,"

CLARIFICATIONS AND SMALLER CHANGES

(B045) 1386/19 "changes, for example, " → "changes such as"

Corrected accordingly.

(B046) 1388/20 Needs a bit more info to explain.

More information is added: "One method applies a Heaviside function at the pressure-melting point of the basal temperature, i.e., the basal sliding is set to zero when below the pressure-melting point. Others apply a smooth sliding transition around the pressure-melting point (Hindmarsh and Le Meur, 2001), i.e., the basal sliding gradually becomes close to zero below the pressure-melting point, partly for numerical stability and partly for physical reasons to introduce sub-grid scale variation of the basal sliding."

(B047) 1389/12 What? I think delete "only"

Deleted.

(B048) /14–28. Confusing structure. Clearer if you write: 19 "The second and third methods are..." and 21–22 "The first of these, "free spinning-up",..."

Revised as you suggested.

(B049) 1390/24 Isn't the "flux-corrected" the same as the "synthetic corrections" in line 10–11 on the same page?

Yes, they are the same in principle, while different in detail. An explanation is inserted.

(B050) /28 Yes it has, e.g. by Goelzer et al. (2013)

Goelzer et al. is mentioned around here.

(B051) 1391/12 Add "only" before "retreat is allowed"

Inserted.

(B052) /16–21 Tech vs physical are not great terms. Is it internal/structural vs inputs? OR dynamics vs SMB? Also "indirect processes" vs "direct impact of the model to response" is unclear; and 19 needs comma after configuration.

Revised.

(B053) 1392/3 brackets wrong for ref

Corrected.

(B054) /6 SD - define - standard deviation? and "short-term statistical air temperature fluctuation" is unclear — is it e.g. Gaussian noise added to parameterised monthly data?

Right, defined.

(B055) /8 ^the^ GrIS

Inserted.

(B056) /10 diversion → divergence / dispersion?

All the term 'diversion' are completely replaced 'dispersion'.

(B057) /11 qualitatively → quantitatively

Corrected.

(B058) 1394/3 Not clear. What is the background temperature field - annual data or annual and summer? Does computation mean lapse rate correction only, or also the interpolation to obtain monthly data? And is this a spatially-varying lapse rate correction?

This part is revised to be clearer. Monthly temperature is computed by an interpolation of two independent parameterization of the annual and summer temperature. The lapse rates are spatially constant.

(B059) /15 "obtained by" → estimated from

Revised.

(B060) 1395/14 ^the mean of^?

Inserted.

(B061) 1396/23–27 Need to mention all experiments (e.g. D_s, F) here. Why no C?

Description of all the experiments are inserted. C is avoided because it is used to specify scenarios C0, C1, C2 and C3.

***(B062) For a big improvement in readability, name experiments using most important change/comparisons, e.g.:
A = NO_SLIDE, B = TRANS_FREE, D = TRANS_FIX, E = TRANS_FIX_NOADV, D_s = SS, E_s = SS_NOADV, F = TRANS_FIXFREE, F_S = SS_FIXFREE
Then use the primes as before.***

There are already not a few comparison patterns among the experiment in this manuscript. Moreover, since you suggest to test multiple combinations of changes not presented in this manuscript, we are afraid that such changes in the naming convention rather confuse the readers. However we agree the manuscript need improvement in readability more or less, so we will try several patterns in the revised manuscript and will choose the optimum pattern. After some trials, we keep the experiment names but every now and then the most important changes are added in the text.

(B063) ***I find the sliding parts a bit confusing to read at first. It feels like more things are being discussed than are! It would be clearer to spell out that the Heaviside step function prevents submelt sliding, the exponential allows it, otherwise it sounds at first reading like two things are varied. And that the v2 and v4 are testing the model tuning, while the SeaRISE experiments vary the same thing but test the effect of increased sliding from climatic forcing. And finally some discussion of how these things interact (basal sliding parameterisation and value(s) of basal friction coefficient).***

This part is revised as your suggestion.

(B064) ***1397/ Suggest for clarity changing "In the first method, similar to the free spinning-up, a steady-state simulation is performed under the climate field at 125 ka with fixed ice-sheet and bedrock topography of the present-day state and only the temperature can evolve. Subsequently, the climate history from 125 to 0 ka is used to force the internal ice-sheet temperature." to: 'The first is identical to the free spinning-up except that the ice sheet and bedrock topographies are fixed to the present day state and only the temperature can evolve". I would also delete "Experiment D uses the same configuration as B except for using this fixed topography transient spinning-up." and similarly line 14–15.***

Revised and deleted.

(B065) ***1398/19–21 Delete (repetition).***

Deleted.

(B066) ***1399/3–8 Seeing as the SD is 5.5K in all experiments, why not just mention it at 1396/21 and not here? i.e. it's not part of the experiment.***

This part is moved to the point you suggested.

(B067) ***/9–11 Delete? — unnecessary.***

Deleted.

(B068) ***/20–24 is confusing. Does "final state" mean just ice temperatures or everything? Does "is adopted for" mean at the start, then spun up? Or used at the end somehow? e.g. temperatures combined with other (non-temperature) fields?***

We agree it confusing a lot. This part is revised.

(B069) ***/25 Suggest editing for clarity: replace "To evaluate... respectively." with "To evaluate...., ^further^ fixed topography ... (experiments F_s and F_s'). Instead of the topography being fixed at the present-day observation, as for D_s and D_s', it is fixed at the final topography of the spin-up phases of experiments B and B', respectively."***

Revised ad suggested with slight modification.

(B070) ***Section 4.6 is generally tricky so a bulleted list would be useful. Something like this?***

```
. B free topography + transient temperature
. F fix to free topography + transient temperature
. D fix to observed topography + steady state temperature
. F_s fix to free topography + steady state temperature
```

I know you have Table 1, but a summary in the main text of how these four relate to each other would help.

A list is appended as you suggested.

(B071) Table 1 and the main text needs to say that E" is the benchmark experiment in the Appendix, and that it uses a different SMB, and what that is. Otherwise the reader is left hanging wondering what it is.

Description is inserted.

(B072) I'd also suggest putting all the prime (') experiments together at the end, as it's harder to keep track of the other configurations. And could the differences from the previous row be put in bold? e.g.

```
O
A JHKP...
B ... sub-melt ...
D ... fixed obs geom ...
E ... no advance
F ... fixed free geom, free margin
```

Then to simplify the table you could just say in the caption that _s means steady state initialization, while prime means switching from T to H melt - a bit like modifiers for katakana and hiragana :) The v1,2,4 and C1, 2, 3 could be in the caption too.

Tables and captions are revised accordingly.

(B073) Table 2 would benefit from a brief recap of v1, v2 and v4 in the caption (as you do for Figure 2).

Descriptions are inserted.

(B074) Figure 1. Can you make each experiment name the same colour as the line? In the caption, I think it would be clearer to write "...obtained by future climate runs under C1 (A1B climate forcing) climate scenario, with "standard" sliding coefficient (v1), in terms of the difference...Each line is a different experimental configuration... "

Good idea. Thanks. Experiment names are also colored. Caption is revised.

(B075) 1400/5 This needs a pointer that other results will be described later, and a clearer separation between discussion of O and others. e.g. move "Simulated responses become larger with enhanced basal sliding coefficient" to 5.2.

Such pointer is inserted. The latter text is kept because it is still the results of O, not B.

(B076) /19 "shows"

This part is revised already.

(B077) Figure 2. Again, I think it's clearer to mention the 3 climate scenarios first, then the experimental configurations. I really like having both VAF and SLE scales, but I think it would be better to put the SLE on the right y axis (with common major grid lines, as they are for C1 and C3).

Caption is reordered. Axis of the figures are modified accordingly.

(B078) 1401/3 Is it +17 cm increase from v1 to v4? Current wording sounds like absolute for v4.

The text is revised to be clear, as "17 cm more than the upper boundary of the original range"

(B079) Figure 4 — Show observed topography too, or show all as anomalies with respect to this, so that differences can be seen clearly.

Difference in the topography from the present-day observation is included in the supplementary.

(B080) /6 → "Simulated VAF responses are ^^ affected by replacing the bed topography of a few regions, ^but^ are less..."

Revised accordingly.

(B081) /20 Not very clear. Suggest: "For O and A, quadrupling the basal sliding coefficient varies the volume by around 5% of observed, but for B by more than 12%."

Revised.

(B082) Figs 3 and 4 appear in the opposite order in the text.

Actually, Fig. 3 is already mentioned (at 1400/21) before the first appearance of Fig. 4 (1401/22). However, since Fig. 3 is not discussed until 1402/16, we exchanged the order of two figures, and modified main text accordingly. Thanks.

(B083) Fig 4 Add "and sub-melt sliding", as O and A are also free.

Inserted.

(B084) 1402/1 greater → more. Add "(comparing B with A)"

Corrected and appended.

(B085) /3 missing bracket

Inserted.

(B086) /4 in the VAF → between B and A

Revised.

(B087) /9 "This is large enough to cancel" → "This more than cancels"

Revised.

(B088) /12 "initialization method" is too broad a term — replace with "whether the geometry is free or fixed to observed" or similar.

Revised accordingly.

(B089) ***/25 "Of all the combinations" Should be "Over all.." and ideally also add "of climate and sliding coefficient" to be clearer.***

Modified and inserted.

(B090) ***/28 "the the"***

Corrected.

(B091) ***1403/1 Again "initialization methods" is too broad — replace with free vs fixed geometry. Also: "when they ^are^ evaluated".***

Corrected.

(B092) ***/3 "Through the elevation-ablation feedback, the impact of the non-equilibrium thermal state is larger in cases of higher sensitivity." — please expand/rephrase, as it's not clear what it means. Is it "The effect of the non-equilibrium thermal state is larger for larger delta_VAF, because the elevation-ablation feedback amplifies the geometry changes"? (but see comment for 1403/1–5 — the picture is not that clear).***

Right. Revised as you suggested.

(B093) ***/6 I'd argue "and B" should be deleted, as you've just compared B and F as being different methods even if the results are very similar. Or should this read "F_s and D_s are equivalent to F and D"?***

Deleted as you suggested.

(B094) ***/20–22 "Thus, under mild climate warming scenarios like C1, the choice of initialization method and the margin treatment has dominant effect on the response of Greenland ice-sheet over 500 years." — what does this mean — compared with the bedrock, sub-melt sliding and basal sliding coefficient? The effect of the margin is smaller than that of the coefficient, at least for some runs. And the SMB has not yet been discussed.***

We compared with bedrock and sub-melt sliding. Text is revised.

(B095) ***1404/21, /25 and /27: "initialization methods" → free vs fixed as before***

Modified accordingly.

(B096) ***/26 ambiguous — assume these numbers are for B to B' not B to D? Better to put them earlier in the sentence.***

Right. Moved to earlier.

(B097) ***1405/4 — I think "large" is better than "dominant", or "similarly large influences... as"***

We modified with the latter suggestion.

(B098) ***/5, /9 and /21 initialization methods → free vs fixed***

Modified accordingly.

(B099) ***/12 60% is indeed a big reduction — so to be fair I think you should also say in Section 5.3 that B to D reduces to around 50% or less.***

Inserted accordingly in the section.

(B100) /26 different initialization → different fixed geometry

Revised accordingly.

(B101) /27 Repetition of first line of paragraph. What is the difference? Looks to me like SMB is more important than which geometry is fixed. You go on to say "Further, of all.." but this should be "Over all..", because it is not "further", it is the point of the paragraph. And if you want to mention steady state, this needs to be in the paragraph start. I think this means comparing not only B' and F with B, but also F_s with B? or maybe with B_s? This paragraph needs expanding.

Right. The repetition is revised and the steady-state is mentioned at the beginning accordingly. Thanks.

(B102) 1406/4 Why isn't F included in this list? Are the "_s" experiments included? What about v1, 2 and v4? Is it everything except C1–3 and SMB? I think there needs to be greater clarity. I'd say SMB parameterisation was technical, but I agree it's helpful to think of it separately from the ice flow.

F is excluded here because of its characteristic: it is an additional configuration just for comparison between B and D. This part is revised to mention v1–4 and C1–3 accordingly. Also, the word 'technical' is removed.

(B103) /19–22 This sentence is confusing and a bit vague. Suggest e.g. "Thus the source of spread in SeaRISE experiments can only partly be explained by variations in the experimental configuration of technical aspects ^of ice flow^." and then something more precise: "The most influential of these is the specification of free or fixed geometry".

Revised accordingly.

(B104) 1407/5 This makes it sound like a third thing was identified as the primary source of spread by SeaRISE. I think you mean something like: "In the series of the experiments in the present paper, the choices that have greatest effect on the response are the method to compute the surface mass balance, and the way to initialize the ice-sheet, which have comparable effect. This is consistent with the discussion [speculation?!] of the possible reasons for spread in the SeaRISE results by Bindschadler et al. (2013) and Nowicki et al. (2013)."

Right. Modified accordingly.

(B105) /7 "may have a certain" → has some

Revised.

(B106) /14–27 I feel this is more repetition..Reword/focus? And need "Over all the" again.

Revised to be focused, accordingly.

(B107) 1408/11 Missing full stop.

Inserted.

(B108) /21 " it may be better" again needs justification

This part is deleted.

(B109) */24 Needs to be clearer whether this is all for transient climate (i.e. only free vs fixed geometry), or if it also apples to / means steady state climate too.*

Both. Modified accordingly.

(B110) */26 "attributed to the difference in the application of the technical methods such as initialization and free evolving margin, and the difference in the surface melting parameterization." — difference with what? Be more specific, e.g. "attributed to the use of a free geometry and margin during spin up"*

Revised to be more specific, as 'the use of a free topography during the spin-up, free evolving margin during the future experiment, and the difference in the surface melting parameterization.'

(B111) */6 "showed the divergence or convergence of..." → something like "showed the degree to which current ice sheet models and modelling choices diverge".*

Revised accordingly.

(B112) */20 "but" → "except", otherwise it sounds like we did do it!*

Corrected.

(B113) *1409/18 identify → "try and understand" or similar. Similarly at 1387/25*

Revised at the two places.

(B114) *1411/1–12 This needs editing and expanding. I'd say temperature is climate, SMB is not. Do you mean SMB from an uncoupled PDD scheme with topography feedback switched off, or SMB from a regional climate model?*

Either PDD or regional climate model is all right, as far as identical among the models. This part is revised.

(B115) *"are less controlled except" → "not specified, except"*

Replaced.

(B116) */14–18 Why choose configuration E'?*

Because among the configuration in this paper this is the closest to the one of ISSM as explained in the next paragraph.

(B117) *"future surface mass balance is imposed using the SeaRISE datasets without any correction." Which SMB dataset? (C1 as below?) Correction for what? (topography, albedo, both?)*

Although most of the models did not use, SeaRISE provided a transient future scenario of SMB computed by a method not explicitly described in the SeaRISE papers. We revised this part, as: "The parameters of the PDD is described on
`http://websrv.cs.umt.edu/isis/index.php/Future_Climate_Data`, where the standard deviation of the short-term statistical air temperature fluctuations is set as 4.5 K, the PDD factor are set as 3 and 8 mm ice equivalent per day per degree for snow and ice, respectively."

(B118) *Contradicts "surface mass balance is imposed ^on^ the SeaRISE datasets without any correction;" → "with?*

Right. Corrected.

(B119) Fixed calving front — is this the same as no margin advance?

This is what is written in Tab. 1 of the SeaRISE paper. We expect that not only advance but also retreat are prohibited. Explanation is inserted.

(B120) List similarities first, then differences.

Reordered accordingly.

(B121) Assuming sub-melt sliding same?

There are no information about sub-melt sliding. Explanation is inserted.

(B122) Anisotropic mesh is a bit jargon-y/unclear — ideally describe it.

Revised to 'numerical grid system'.

(B123) Figure A1 — reduce scale to 1.6 min VAF

Rescaled accordingly.

References

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), J. Glaciol., 59, 195–224, 2013.

Greve, R. and Herzfeld, U. C.: Resolution of ice streams and outlet glaciers in large-scale simulations of the Greenland ice sheet, Ann. Glaciol., 54, 209–220, doi: 10.3189/2013AoG63A085, 2013.

Hindmarsh, R. C. A. and Le Meur, E.: Dynamical processes involved in the retreat of marine ice sheets, J. Glaciol., 47, 271–282, 2001.

Nowicki, S., Bindschadler, R. A., Abe-Ouchi, A., Aschwanden, A., Bueler, E., Choi, H., Fastook, J., Granzow, G., Greve, R., Gutowski, G., Herzfeld, U., Jackson, C., Johnson, J., Khroulev, C., Larour, E., Levermann, A., Lipscomb, W. H., Martin, M. A., Morlighem, M., Parizek, B. R., Pollard, D., Price, S. F., Ren, D., Rignot, E., Saito, F., Sato, T., Seddik, H., Seroussi, H., Takahashi, K., Walker, R., and Wang, W. L.: Insights into spatial sensitivities of ice mass response to environmental change from the SeaRISE ice sheet modeling project II: Greenland, J. Geophys. Res. Earth Surf., 118, 1025–1044, doi: 10.1002/jgrf.20076, 2013.

Manuscript prepared for The Cryosphere
with version 2014/09/16 7.15 Copernicus papers of the LaTeX class copernicus.cls.
Date: 13 November 2015

SeaRISE experiments~~experiment~~ revisited: potential sources of spread in multi-model projections of the Greenland ice sheet

A005 B003

F. Saito[1], A. Abe-Ouchi[2,1], K. Takahashi[1], and H. Blatter[3]

[1]Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan
[2]Atmosphere Ocean Research Institute, Univ. of Tokyo, Kashiwa, Japan
[3]Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland

Correspondence to: F. Saito (saitofuyuki@jamstec.go.jp)

Abstract. The present paper revisits the future surface-climate experiments on the Greenland ice sheet proposed by the Sea-level Response to Ice Sheet Evolution (SeaRISE, Bindschadler et al., 2013) study. The projections of the different SeaRISE participants show dispersion, which has not been examined in detail to date. A series of sensitivity experiments are conducted and analyzed using the Ice-sheet model for Integrated Earth-system Studies (IcIES) by replacing one or more formulations of the model parameters with those adopted in other model(s). The results show that large potential~~the main~~ sources of the dispersion among the projections of the different SeaRISE participants are differences in the initialization methods and in the surface mass balance methods, B008 and both aspects have almost equal impact on the results. The treatment of ice-sheet margins in the simulation has a secondary impact on the dispersion. We conclude that spinning-up the model using fixed topography through the spin-up period while the temperature is allowed to evolve according to the surface temperature history is the preferred representation, at least for the experiment configuration examined in the present paper. A benchmark model experimental set up that most of the numerical models can perform is proposed for future intercomparison projects, in order to evaluate the uncertainties relating to pure ice-sheet model flow characteristics.

1 Introduction

Numerical modeling is an important technique for projecting the response of ice sheets to climate change (e.g. Huybrechts and de Wolde, 1999). Each of the processes simulated in ice-sheet experiments have a degree of uncertainty associated with them, and thus the final output may sometimes have significant dispersion among possible combinations of the methods used to represent them. Multi-model intercomparison over a standardized protocol of numerical experiments is a typical approach for evaluating the uncertainties in model projections. Several intercomparison experiments have been previously performed with focus on various topics, in particular on the behavior of the Greenland ice-sheet under future climate changes.

Typical procedures for investigating the impact of model parameters on the uncertainties in the short-term projection of Greenland ice sheet are parameter studies and sensitivity studies using one numerical model (Huybrechts et al., 1991; Huybrechts and de Wolde, 1999; Graversen et al., 2011; Rogozhina et al., 2011; Seddik et al., 2012; Gillet-Chaulet et al., 2012; Yan et al., 2013; Seroussi et al., 2013; Goelzer et al., 2013).

As numerical models have become increasingly complex, it has become more difficult to examine the sensitivity to all uncertainties in all possible model formulations, both numerical and physical. Multi-model intercomparison is an effective, although not perfect, procedure for evaluation of model uncertainties. Greve and Herzfeld (2013) performed sensitivity studies of 500 year projections of the Greenland ice-sheet under two scenarios: the AR4 climate scenario and doubled basal sliding, using two different numerical ice-sheet models. The models differ not only in the numerical and physical representation of ice-sheet dynamics, but also in the method used to compute the surface mass balance from surface temperatures. Despite the differences, a common result is obtained, showing a larger sensitivity to climate warming than to a doubling of the basal sliding. Herzfeld et al. (2012) studied the sensitivity of Greenland ice sheet projections to the regional updating of the bedrock topography for some glaciers, also using two different numerical ice-sheet models. Both models show significant impact in the response to the doubled sliding scenario by just changing a limited area of bedrock topography. Shannon et al. (2013) used four numerical ice-sheet models to evaluate the effect of enhanced basal sliding driven by surface runoff on 200 years of evolution of the Greenland ice sheet. Edwards et al. (2014) use six numerical ice-sheet models to evaluate three types of modeling uncertainties: climate model input, ice-sheet model choice, and the interaction of the two systems in terms of the surface mass balance-elevation feedback. While some common features from these papers can be extracted, some divergence in the results seems to be unavoidable.

SeaRISE (Sea-level Response to Ice Sheet Evolution) is a multi-model community effort to investigate the likely range of evolution of the Greenland and Antarctic ice sheets over the next few hundred years (Bindschadler et al., 2013). A total of eight models participated for the Greenland experiments (Nowicki et al., 2013). A series of century-scale sensitivity experiments to prescribed changes in surface climate, sub-ice-shelf melting, and basal sliding were performed. The results exhibit a large range in projected changes for the ice-sheet volume: projected Greenland ice-sheet contributions to the global sea level for the future-climate experiment under the A1B scenario range from 5.4 to 38.7 cm at 500 years from the present day. The projected ranges are larger for experiments where future-climate scenarios are amplified by a factor of 2, ranging from~~as~~ 8.5 to

A007

142.6 cm. One of the objectives of the SeaRISE project is to show the possible range of uncertainties in the ice-sheet projection of current ice-sheet models, because no single model can be identified to be the best in every aspect (Bindschadler et al., 2013). The approach of the SeaRISE project is rather unrestricted: some aspects in the experiment protocol are standardized, while many others are left to the individual participants. The former includes part of boundary conditions of the ice-sheet model, such as the present-day surface temperature, surface accumulation and bedrock topography. Scenarios for future surface climate changes such as~~for example,~~ a hundred-year time series of surface temperature, precipitation, and surface melting are provided. *B045* The latter includes structural differences in ice-sheet models such as model numerics or approximation level, and the treatment of some boundary conditions such as the surface mass balance scheme.

Bindschadler et al. (2013) identified differences in the methods to compute the surface mass balance among the participants as the primary source of the dispersion in the results of future-climate experiments on the Greenland ice sheet. Nowicki et al. (2013) further concluded that variations in the initial ice volume, and thus the initialization of the ice-sheet topography, is another source of uncertainty. However, detailed quantitative evaluation of the reasons for the dispersion were beyond the scope of the two papers. The effects of some of the characteristics have already been argued in previous studies. Greve and Herzfeld (2013) compared 500-year future climate experiments with three different grid spacings of 20, 10 and 5 km, and concluded that the sensitivities in the simulated ice sheet volume are insignificant. *A009*

The present paper performs a “one-model” approach to evaluate the relative impact of the various factors on Greenland ice sheet projections under the SeaRISE protocol. The numerical model used in this paper is IcIES (Ice-sheet model for Integrated Earth-system Studies), which also participated in the SeaRISE experiments. There are at least ten characteristics that differ among the ice-sheet models participating in SeaRISE (see Table 2 in Bindschadler et al., 2013), and most have two or more variations.~~As summarized in Table 2 in Bindschadler et al.(2013), there are at least ten characteristics with different implementations among the participating ice-sheet models of SeaRISE, most of which have two or more variations.~~ Some concern numerical aspects, such as grid resolution and time-stepping, and others are physical aspects, such as ice flow mechanics and surface mass balance. *A008*

This paper does not intend to cover the sensitivities of all of the aspects. The initialization methods and the surface mass balance methods, proposed in Bindschadler et al. (2013) as possible sources of variation, and three more characteristics, the bedrock topography boundary conditions, the basal sliding methods, and the treatment of advance/retreat in the ice-sheet margin, are chosen to investigate sensitivities in the present paper. Of the four different sets of future scenarios under the SeaRISE protocol, the surface climate experiment (C1 to C3), the basal sliding experiment (S1 to S3), the ice-shelf melting experiment (M1 to M3), and a combination experiment, the present paper only revisits the surface climate experiment.

In the next section, the five model set-up characteristics of focus in this study are introduced to demonstrate the variety of choices among SeaRISE models used in Bindschadler et al. (2013). In Sect. 3, a model description of IcIES is given to outline the set-up adopted in the submission of Bindschadler et al. (2013). In Sect. 4, we describe the set-up of the five characteristics to replace the IcIES standard configuration in the present experimental design. Results and discussion follow to understand~~identify~~ and compare the possible sources of spread among the results of the SeaRISE models. *B113*

2 Possible sources of spread~~Candidates for sources of spread~~ in SeaRISE projections *A010*

2.1 Bedrock topography

SeaRISE provides several different versions of the present Greenland ice-sheet topography (available at http://websrv.cs.umt.edu/isis/index.php/Present_Day_Greenland). "Greenland Developmental Data Set" (hereafter referred to as *dev1.2*). This data set includes a Jakobshavn trough in the bedrock and bathymetry topography of Bamber et al. (2001) (the second last version in the protocol). For the latest protocol, the bedrock topography including a new compilation of the subglacial troughs over Jakobshavn Isbrae~~Ibsrae~~, Helheim, Kangerlussuaq, and Petermann *A011* glaciers following Herzfeld et al. (2012) is proposed (hereafter referred~~refer~~ to as *JHKP*). *A012* Although the differences between these datasets are localized~~local~~, significant differences in the *A013* simulated global features are possible. Herzfeld et al. (2012) presented a significant difference in the present-day~~the significant difference on the present-day~~ simulated topography and velocity *A014* field by using the JHKP dataset and an older data set without inclusion of the above four glacier troughs (corresponding to a version before dev1.2 in SeaRISE). In addition, significant differences were found in the response of the Greenland ice sheet to doubled-sliding experiments over 500 years, (i.e., equivalent to the S3 experiment in SeaRISE).

2.2 Basal sliding formulation

The available methods to compute basal sliding have several~~some~~ degrees of freedom. One *A015* method applies a Heaviside function at the pressure-melting point of the basal temperature, i.e., the basal sliding is set to zero when below the pressure-melting point. Others apply a smooth sliding transition around the pressure-melting point (Hindmarsh and Le Meur, 2001), i.e., the basal sliding gradually becomes close to zero below the pressure-melting point, partly for numerical stability and partly for physical reasons to introduce sub-grid scale variation of the basal sliding.~~One method applies a Heaviside function at the pressure-melting point of the basal temperature, while others apply a smooth sliding transition around the pressure-melting point Hindmarsh (2001b), partly for numerical stability and partly for physical reasons to introduce sub-grid scale variation of the basal~~

~~sliding.~~ Some models in SeaRISE explicitly document such a smooth transition to implement melting at sub-melting point temperatures. B046

2.3 Initialization method

Obviously, the accuracy of the simulated present-day ice-sheet is crucial for future projections. It is possible that small errors in the simulated present-day state may affect the short-term projections (Arthern and Gudmundsson, 2010; Yan et al., 2013). In addition, since the climate depends on the surface topography and ice extent, present-day climate forcing computed in the simulation may already have some bias. This bias occurs both for simulations with ice-sheet models coupled to sophisticated climate models, but also in simulations using simple climate parameterizations. Some previous studies compute surface temperature by a combination of a reference field obtained from observation-based studies and their perturbation via the lapse rate and changes in surface topography relative to the present-day observed surface topography. This implies that the computed surface temperature field in the model is identical to the observation ~~only~~ when the modeled surface topography is the same as the observation. B047

The choice of initialization method was left to participants in SeaRISE, and three different techniques were applied by the SeaRISE/Greenland participants. One method is called initialization by “tuning” in Bindschadler et al. (2013), which may be better termed ‘inversion’ or ‘optimization’. This method inverts given data fields, e.g.,basal friction coefficients, to adjust present-day observation fields, e.g., surface velocity.~~One method is called initialization by “tuning”, which inverts given data fields, e.g. basal friction coefficients, to adjust present-day observation fields, e.g. surface velocity.~~ Internal temperature fields are usually assumed to be in a steady state with computed velocity fields under the present-day conditions. A016 The second and third methods are~~The second method is~~ called initialization by “spinning-up”, whereby the model is run with the input of climate history of glacial/interglacial cycles, e.g.,derived from the GRIP ice-core record. B048 Although in principle these two initialization methods are not mutually exclusive (e.g. Edwards et al., 2014), the choice of the SeaRISE participants are either of the two. The first of these~~A variation of initialization by “spinning-up”~~ , hereafter referred to as “free spinning-up”, B013 allows the ice-sheet topography to evolve freely under a prescribed climate history. B048 A major disadvantage of “free spinning-up” is that the present-day simulated topography often deviates from reality. The other initialization method is referred to as “fixed topography spinning-up”, where the ice-sheet topography is fixed through the spin-up phase at a slightly smoothed measured B010 present-day topography while ice-sheet temperatures freely evolve. The “fixed topography spinning-up” is a hybrid of the two techniques where the initial topography can be very close to the present-day observation while ice-sheet internal states include the influence of the long-term climate history. One major drawback is that the flow and temperature fields in the initial state are not in equilibrium (Goelzer et al., 2013), which leads to an artificial drift to restore the equilibrium after allowing evolution of the topography.

A number of ~~previous~~ studies have focused on the initialization methods and their impact on the simulation of the Greenland ice sheet. A017 Rogozhina et al. (2011) compare the simulated present-day Greenland ice sheet obtained by several initialization methods including free transient spinning-up. Pollard and DeConto (2012) presented a general and simple method to deduce spatial distribution of basal sliding coefficients to reduce the errors in simulated surface topography that can be applied to any type of ice sheet model. Morlighem et al. (2011) presented another approach in which uncertainties in the bedrock topography were also taken into account in the inversion method. A018 Goelzer et al. (2013) presented a series of Greenland ice sheet simulations with yet another hybrid technique to incorporate the influence of long-term climate history and obtain an initial ice-sheet topography close to the present-day conditions, by adjusting ice-temperature profiles and synthetic corrections over the surface mass balance. They concluded that the uncertainty arising from the surface mass balance methods and scenarios have a larger impact on the sensitivity of short-term projection of the Greenland ice sheet than those from the initialization methods, but the experimental settings were not the same as the SeaRISE experiment. Aðalgeirsdóttir et al. (2014) B008 presented a series of Greenland ice sheet simulations using free transient spinning-up as well as a *flux-corrected* initialization method, in which the surface mass balance during the initialization is modified such that the simulated present-day topography is close to observations (similar in principle to Goelzer et al., 2013 above). They concluded that the initialization methods are an B049 important source of uncertainty. Yan et al. (2013) compared the evolution of the Greenland ice sheet to future climate scenarios between two spin-up methods: free spinning-up under transient and steady-state climate forcing. Both the simulated present-day ice-sheet topography and the simulated surface mass balance were different, thus the impact of the difference in the initialization method includes all of these components. Seroussi et al. (2013) found that the ice-sheet model is far more sensitive to changes in external forcing than its initial temperature for a hundred-year scale experiment, while future-scenario experiments from different initial conditions were not discussed. So far, the influence of the “fixed topography spinning-up” has not been discussed except for (Goelzer et al., 2013) who showed an example in their configuration. This is a main target of the B050 present paper. In addition, although Nowicki et al. (2013) concluded that variation of the initial ice volume may be a source of the uncertainties in the SeaRISE results, the influence of different choices for the initialization methods were not qualitatively evaluated. This paper extends their discussion and shows the relative significance to the short-term projection among other possible methods.

2.4 Treatment of advance of the ice-sheet margin

Precise simulation of the ice-sheet margins (ice-sheet extent) is a challenging issue. When ice-sheet topography and extent are allowed to evolve freely during future-warming experiments, it is possible to obtain sudden jumps in the position of the ice-sheet margin over many regions. Such changes reflect a strong flux imbalance near the margin in the simulated present-day state. Although detailed numerical implementation is not shown in Bindschadler et al. (2013), some participants in SeaRISE describe their methods as either fixing the ice-sheet margin (calving front) or limiting its advance (i.e., only retreat is allowed).~~Some participants in SeaRISE artificially prohibit such cases either by fixing the position of the ice-sheet margin, or by limiting the advance of ice-sheet margin (i.e. retreat is allowed).~~ While this is not necessarily true in reality because speed-up at the margin may result in advance before increased melting, some models just use this assumption. Previous studies have not demonstrated its influence on the sensitivity of the results, and so this issue is explored here.~~This is just an assumption, and previous studies have not demonstrated its influence on the sensitivity of the results, and so this issue is explored here.~~

2.5 Surface mass balance

The four aspects described above involve the structural (internal) rather than external (input) configuration~~the technical rather than physical configuration~~. ~~thus replacement of these four methods may describe the impact of indirect processes in the model to climate warming.~~ The method to compute the surface mass balance to drive ice-sheet models instead affects the external~~the physical~~ configuration, and uncertainty relating to this aspect has a more direct impact on the simulated response of the Greenland ice sheet to climate warming~~describes the direct impact of the model to response of Greenland ice-sheet to climate warming~~. There have been a wide range of methods used to compute surface melting and/or surface mass balance in previous works including SeaRISE.

The method used to compute surface mass balance was left to individual choice in the SeaRISE project, which provided the future scenarios of precipitation, surface temperature, and surface melting, but whether or not to adopt unique parameterization of surface melting using the scenarios of precipitation and surface temperature was left to individual models.

Most participants adopted some forma ~~form~~ of the “positive degree-day” (PDD) scheme (Reeh, 1991) to compute surface melting. Even models using the PDD scheme, however, can vary in one or more parameters used in the scheme, e.g., the conversion coefficients from simulated degree-day to melting, the standard deviation (SD)~~SD~~ of short-term statistical air temperature fluctuation (Gaussian noise added to parameterized monthly data), and so on. Previous~~Some previous~~ studies showed how variation in PDD schemes and their coefficients can influence present-day and future simulation of the Greenland ice sheet (e.g. Stone et al., 2010). Bindschadler et al. (2013)

argued that the variation of the surface mass balance method is the likely primary source of the dispersion in the results of future-climate experiments, although this assertion has not been quantitatively~~qualitatively~~ evaluated. This paper will demonstrate the relative significance of the surface mass balance method on the short-term projection compared to other model settings. *B057*

2.6 Aspects not tested in the present paper

The five aspects mentioned above are a subset of possible sources of the spread. As summarized in Table 2 in Bindschadler et al. (2013), there are at least ten characteristics with different implementations among the participating ice-sheet models of SeaRISE. The remaining aspects are: the numerical method (finite difference or finite element), the horizontal and vertical grid resolutions, the time step, the ice flow mechanics (the shallow ice approximation, full Stokes) and the basal hydrology computation. The dependence on the stress in the basal sliding formulation is also different among the models in addition to the sub-melt sliding formulation. It is possible for there to be other differences in model aspects not in the table, such as the ice enhancement factor, individual numerical schemes and so on. Exploration of these remaining aspects was partly performed in previous studies (e.g. Greve and Herzfeld, 2013), and others are left for future studies.

B005

3 Model description

The time-dependent, three-dimensional and thermodynamically coupled model used in this paper as well as in the SeaRISE project, called IcIES (Ice-sheet model for Integrated Earth-system Studies), is described in Saito and Abe-Ouchi (2005), Greve et al. (2011) and Bindschadler et al. (2013). The model computes the evolution of the ice thickness, bedrock elevation and ice temperature under a history of climate forcing, given in terms of surface mass balance and surface temperature, which may depend on the computed ice-sheet topography. The model parameters are the same as those described in Greve et al. (2011). In the present paper, the model domain spans $1500\,\mathrm{km} \times 2800\,\mathrm{km}$, with ($151 \times 281$ grid-points) corresponding to a horizontal resolution of $10\,\mathrm{km}$.

The evolution of surface elevation is determined by the continuity equation for the local ice thickness with a history of the surface mass balance field. The temperature distribution is calculated by a thermodynamic equation with the surface temperature and geothermal heat flux given at the surface and base, respectively. Changes in the bedrock elevation are calculated by a linear model expressing local isostatic rebound with a prescribed time constant.

The shallow ice approximation is applied (Hutter, 1983) using Glen's flow law with an exponent of $n = 3$ (Paterson, 1994) for the velocity computation. The horizontal velocity vector $\boldsymbol{v}_{\mathrm{H}}$ is calculated for the given surface elevation h and bedrock topography b,

$$\boldsymbol{v}_{\mathrm{H}} = \boldsymbol{v}_{\mathrm{B}} - 2(\rho_{\mathrm{I}} g)^n \left[\left(\frac{\partial h}{\partial x} \right)^2 + \left(\frac{\partial h}{\partial y} \right)^2 \right]^{\frac{n-1}{2}} \int_b^z \mathrm{d}z' \, E A(T) (h - z')^n \times \nabla_H h, \tag{1}$$

where g is the acceleration of gravity, ρ_{I} is the density of ice, and $\boldsymbol{v}_{\mathrm{B}}$ is the basal sliding velocity. The rate factor $A(T)$, through which the velocity and temperature fields are coupled, follows Paterson (1994) and Huybrechts (1992). The formulation in Paterson (1994) is different from the one in Cuffey and Paterson (2010). We use the former in this study for a historical reason, to maintain consistency with the past numerical studies using IcIES including the submission to SeaRISE. Another reason is that the focus of this paper is on sensitivity to different external and technical configurations, but not to "ice-flow" physics. The enhancement factor E in Eq. (1), which controls the softness of ice, implicitly reflects the effect of impurity and/or anisotropy of ice. It is used as a tuning parameter to improve the agreement between the measured and modeled surface topography. In the present paper, the constant value $E = 3$ is adopted in all experiments except where explicitly described.

The basal sliding velocity $\boldsymbol{v}_{\mathrm{B}}$ is computed using the Weertman sliding law, with an allowance for sub-melt sliding following Hindmarsh and Le Meur (2001),

$$\boldsymbol{v}_{\mathrm{B}} = -C_{\mathrm{B}} \frac{{\tau_{\mathrm{B}}}^p}{{N_{\mathrm{B}}}^q} \times f(T'_{\mathrm{B}}), \tag{2}$$

where τ_{B}, N_{B}, and T'_{B} are the basal shear stress, basal normal stress, and basal temperature relative to the pressure-melting point, respectively. The function $f(T'_{\mathrm{B}})$ controls the occurrence of basal sliding (see Sect. 4). Following Huybrechts and de Wolde (1999), the exponents p, q and the coefficients C_{B} are set to 3, 1 and $1.8 \times 10^{-10}\,\mathrm{N}^{-3}\,\mathrm{yr}^{-1}\,\mathrm{m}^8$, respectively, for the standard configuration (**v1**, see Sect. 4).

The computation of the surface temperature follows Fausto et al. (2009): it linearly depends on the surface elevation, longitude and latitude, and an anomaly term that describes the paleo-climate temperature history or future climate-warming scenarios. The annual and summer mean surface temperatures are parameterized separately, and monthly mean temperatures are estimated from interpolation of the two fields using a sinusoidal function.~~The computation of the annual and summer mean surface temperatures follows Fausto et al (2009), which depends on the surface elevation, longitude, latitude and the background temperature field. Monthly mean temperatures are estimated from interpolation of the annual and summer mean fields using a sinusoidal function.~~ *B058,B059*

The surface mass balance field is computed as the sum of the accumulation and ablation fields. The present-day mean annual precipitation (Ettema et al., 2009) is modified by a temperature dependent function following Huybrechts et al. (2002). Conversion from the precipitation to the accumulation rate is computed statistically as in Huybrechts and de Wolde (1999), which is a function of the mean monthly temperature. Ablation (surface melting) is computed using the Positive Degree-Day (PDD) method of Reeh (1991), which relates ablation to both air temperature and snow accumulation. The amount of melting is computed as the product of the number of positive degree days and PDD factors obtained by observations. It considers the possibility for melting even when the average daily temperature is below the freezing point, and different melt rates for melt of snow and ice due to the albedo difference (Braithwaite and Olesen, 1989), and the production of superimposed ice and warming caused by the phase change. This method is adopted in most numerical studies with ice-sheet models (Ritz et al., 1997; Greve, 2000; Huybrechts et al., 2002). Four parameters control the surface melting in the PDD scheme in IcIES, the PDD factor for ice melt, β_{ice}, the PDD factor for snow melt, β_{snow}, the SD of short-term air temperature fluctuation, σ, and the saturation factor for the formation of superimposed ice, P_{max}. The selection of the values of these parameters is described later.

All experiments in the present paper were performed with a newer revision of IcIES than that used for the SeaRISE project. To obtain stable simulations over all the experiments with a unique method, some modifications to the numerical representation were implemented. The physics and the mathematical formulation of the physics were not changed. The difference in the volumes of the simulated Greenland ice sheet for identical configurations varied at most by 0.3 %, which does not affect the conclusions of the present paper. Therefore, although the model itself is slightly modified, the experiment design used for the submission is hereafter referred to as "IcIES" original configuration.

4 Experimental design

Four different future-climate experiments are presented in Bindschadler et al. (2013): the surface climate experiment, the basal sliding experiment, the ice-shelf melting experiment and a combination experiment. The present paper focuses on the surface climate experiment, while the other three experiments are left for future studies. The surface climate experiment leads to less abrupt changes after perturbation is applied than the other three, which is expected to emphasize the differences among various modeling approaches. In this future-climate experiment, changes in the climate conditions on the upper surface of the ice sheet are prescribed. Future scenarios of two fields, surface temperature and precipitation, are provided. The scenarios were calculated from the results of A1B scenario experiments by the mean of 18 climate models used in the Fourth Assessment Report, compiled by Bindschadler et al. (2013). The "A1B climate change" scenario, **C1**, over 500 year is now available, where the first 100 years are obtained from climate model results, and the climate state of the final 400 years is kept constant at the year 100 climate. Two more "enhanced climate change" scenarios, **C2** and **C3**, are defined where the climate change of **C1** with respect to the present day is amplified by factors of 1.5 and 2.0, respectively. In addition, a "constant present day climate" scenario, **C0**, is defined for reference experiments.

One of the major uncertainties relating to ice-sheet dynamics stems from the basal sliding processes because they are poorly understood due to the difficulties in direct observation (e.g. Nowicki et al., 2013). Often, the parameters relating to basal sliding are tuned to match present-day observed features such as ice-sheet topography and/or the surface velocity. Some models adopt spatially homogeneous parameters (e.g. Robinson et al., 2011), while others apply an inversion technique to compute spatially variable parameters (e.g. Seroussi et al., 2013). ~~Although it is important, such fine tuning is beyond the scope of the present paper.~~ In the present paper, the impact of homogeneous changes in the basal sliding coefficients are shown to interpret the results.~~Rather, the impact of homogeneous changes in the basal sliding coefficients are presented to interpret the results of the present paper.~~ Generally, the simulated ice-sheet thickness is too large, especially near the margin (Nowicki et al., 2013), and larger basal sliding coefficients are required to reduce the error. In this paper, the cases of uniform doubled (**v2**) and quadrupled (**v4**) basal sliding coefficients are examined. All of the experiments are repeated using these coefficients throughout the simulation. It is worth mentioning that the enhanced sliding experiments in the present paper differ from the “Basal-sliding experiment” (e.g. S1) presented in SeaRISE. The former keeps the same value for the sliding coefficients over both the spin-up and the future, while the latter changes the coefficients for the future experiment only.

A022

A022

In addition to the experiment using uniform basal sliding coefficients, some experiments are performed with a non-uniform basal sliding coefficient field (case **vm**). Since the case **vm** partly relates to the initialization methods, it is described in detail in Sect. 4.7.

A003

Table 1 summarizes the sensitivity experiments in the present paper. The original IcIES submission, which is referred to as configuration O, adopts the following methods for the five characteristics:

- “Greenland Developmental Data Set” (dev1.2) for the bedrock topography;
- basal sliding following the Weertman law without allowance of submelt sliding;
- “free” spinning-up method to initialize the present-day ice-sheet topography;
- “free” advance/retreat of ice-sheet margin in response to the climate boundary condition;
- positive degree-day method for surface melting using a modification of Tarasov and Peltier (2002), where the standard deviation of the short-term statistical air temperature fluctuations to compute daily temperatures from monthly temperatures is set as 5.5 K in the IcIES original submission, which is slightly larger than the value of 5.2 K in Tarasov and Peltier (2002),

B066

Each of the five characteristics has two or more choices among the SeaRISE models. In the present paper, one method for each characteristic is chosen, to demonstrate structural uncertainties on the projection of Greenland ice sheet. A series of four experiments, A-B-D-E, is the sequence of one-by-one replacement in four methods: bedrock, submelt sliding, initialization and margin advance, starting from the original configuration O. Experiment F is an additional sensitivity

B005

experiment which focuses on the impact of "fixed-topography" transient spin-up (will be described in Sect. 4.6). D, E, and F have variation of "fixed-topography" *steady-state* spin-up, named as $\mathsf{D_s}$, $\mathsf{E_s}$, and $\mathsf{F_s}$, respectively. Configurations B′, D′, E′, F′ $\mathsf{D_s'}$, $\mathsf{E_s'}$ and $\mathsf{F_s'}$ were performed with an additional replacement in the surface mass balance computation. *B061* Finally, configuration $\mathsf{E_s''}$ is an additional experiment shown in the Appendix. The details of these replacements are described below. *B071*

4.1 Bedrock topography (A)

The bedrock topography dev1.2 used in the original configuration O is replaced by the JHKP data set in experiment A. All the procedures are then repeated with the new bedrock data.

4.2 Basal sliding formulation (B)

The original IcIES submission adopts a Heaviside function at the pressure-melting point for the occurrence of basal sliding, which means that submelt sliding is prevented . It corresponds to the use of a binary operator with $f = 1$ if the bottom temperature is at the pressure-melting point and *B063* $f = 0$ otherwise, see Eq. (2). The Heaviside-function switch in A is replaced by an exponential function of the basal temperature to allow the occurrence of submelt sliding following Greve (2005) and Greve et al. (2011), *B063*

$$f(T'_\mathrm{B}) = \exp\left[T'_\mathrm{B}/\gamma\right] \,, \tag{3}$$

where T'_B is the basal temperature relative to the pressure-melting point in °C, the parameter $\gamma = 1$ ~~$\gamma = 1\,^\circ$C~~ is used in the present paper. *A023* Formulation and/or the parameters of submelt sliding inclusion may vary among the SeaRISE models, but in the present paper the formulation above is *A023* chosen for demonstration of submelt sliding. The cases of uniform doubled (**v2**) and quadrupled (**v4**) basal sliding coefficients, which are tests for model tuning and differs from the "Basal-sliding *B005* experiment" presented in SeaRISE, are examined with the allowance of submelt sliding occurrence.

B063

4.3 Initialization method (D and $\mathsf{D_s}$)

For the original submission, IcIES used the "free spinning-up" method. The background temperature history is based on the oxygen isotope record of the GRIP ice-core (Dansgaard et al., 1993; Johnsen et al., 1997), which is provided by SeaRISE as a time series of temperature from 125 ka to the present. At the beginning, a steady-state simulation is performed under the climate field at 125 ka, and from this steady-state condition, the ice thickness and temperature and the bedrock topography are allowed to evolve freely until 0 ka.

Two other methods are tested in the present paper: the "fixed topography *transient* spinning-up" and the "fixed topography *steady-state* spinning-up". The first is identical to the free spinning-up except that the ice sheet and bedrock topographies are fixed to the present day state and only the temperature can evolve.~~In the first method, similar to the free spinning-up, a steady-state simulation is performed under the climate field at 125 ka with fixed ice-sheet and bedrock topography of the present-day state and only the temperature can evolve. Subsequently, the climate history from 125 to 0 ka is used to force the internal ice-sheet temperature.~~ Thus the ice-sheet topography used as the initial condition for the future-climate experiment is identical to the present-day condition. Smoothing of the ice-sheet topography as used in some SeaRISE models is not applied for the present paper, in order to obtain the identical topography among runs with different model parameters. ~~Experiment D uses the same configuration as B except for using this fixed topography *transient* spinning-up.~~

B064

B064

In the "fixed topography *steady-state* spinning-up" method, a steady-state simulation is performed under present-day climate and topography fields with evolving temperature. This initialization method mimics the "tuning" method, where the ice-sheet topography is very close to present-day observations, while the influence of the long-term climate history is excluded. This initialization requires an inversion of, e.g., the coefficients of basal velocity, which is mimicked by different~~which is not implemented in IcIES, but is mimicked by different~~ basal sliding coefficients.~~basal sliding enhancement factors.~~ ~~D_s uses the same configuration as B except for using the above fixed topography *steady-state* spinning-up.~~ In addition, experiments with spatially non-uniform basal sliding coefficients are performed as another mimic of the 'tuning' method, which will be described in the later section.

A003

B013

B064

B005

4.4 Treatment of advance of the ice-sheet margin (E and $\mathsf{E_s}$)

Both advance and retreat of the ice-sheet margin are freely allowed in the original configuration of IcIES. The thickness can be non-zero over the entire model domain during one step in the numerical time integration, but those grids that match a floating condition are immediately cut off. The configuration E ($\mathsf{E_s}$) is equivalent to D ($\mathsf{D_s}$) except that only retreat in the ice-sheet margin is allowed after the present-day simulation. There are some possibilities of how to implement the prohibition of ice-sheet advance numerically. In the present paper, the solution of the ice thickness beyond the present ice-sheet area is set to zero during the time integration. [1] ~~The initialization phase of configuration E is identical to that of D, but the advance in the ice-sheet margin is not allowed under future-climate runs.~~

A019

A019,B005

B065

4.5 Surface mass balance ($\mathsf{B'}$ etc)

In the original IcIES submission, the PDD factor for ice melt is a cubic function of the local mean July surface temperature with a range between a minimum of $8.3\,\mathrm{mm}$ and a maximum of $17.22\,\mathrm{mm}$

[1] Another possibility for implementing the prohibition of the ice-sheet advance is to reset the thickness to zero beyond the present area, after the time integration which allows free evolution.

ice equivalent per day per degree (Tarasov and Peltier, 2002). The factor for snow melt is a linear function of local mean July surface temperature with the range between a minimum of $2.65\,\mathrm{mm}$ and a maximum of $4.3\,\mathrm{mm}$ ice equivalent per day per degree. ~~The SD of the short-term statistical air temperature fluctuations to compute daily temperatures from monthly temperatures is set as 5.5 K in the IcIES original submission, which is slightly larger than the value of 5.2 K in Tarasov and Peltier(2002).~~

Some models in SeaRISE use a PDD scheme with different parameters, and others used other simplified schemes (Bindschadler et al., 2013). One variation of the PDD scheme is chosen in the present paper. Some models adopt constant (temperature-independent) coefficients, such as 3 and $8\,\mathrm{mm}$ ice equivalent per day per degree for snow and ice, respectively, ~~and a SD of air temperature variations of 5.5 K,~~ following Huybrechts and de Wolde (1999). ~~In the present paper, this combination of the PDD parameters is tested to evaluate the impact of the difference in the surface melting methods and especially to compare the relative sensitivity to the four other more technical aspects.~~

B066

B005

B066

B067

4.6 Impact of "fixed-topography" transient spin-up (F etc)

One aspect remaining to be discussed is the impact of non-equilibrium internal states originating from the "fixed-topography" transient spin-up. Since there is a feedback between climate and ice-sheet topography, the difference between "free spin-up" and "fixed topography spin-up" includes both the effect of internal temperature and of the initial topography. One way to minimize the initial discrepancy and to separate the impact of non-equilibrium internal states is to perform a "free spinning-up" simulation that ends with the same topography at the present-day. The impact of the internal non-equilibrium state is evaluated as follows: Experiment F (or F′) is initialized by "fixed-topography" transient spin-up with the topography fixed through $125\,\mathrm{kyr}$ as the final state of the spin-up phase obtained by configuration B (or B′) instead of the present-day topography as D (or D′).~~The final state of the spin-up phase of experiment B (or B′) is adopted for the "fixed-topography" transient spin-up, which is referred to as experiment F (or F′).~~ Thus the difference between experiments B (B′) and F (F′) only stems from the internal thermal state due to the initialization methods, both having an identical initial topography.

B068

A026

To evaluate the impact of "no memory" of the transient past climate, further "fixed-topography" *steady-state* spin-up experiments are performed (F_s and F'_s). Instead of the topography being fixed at the present-day observation, as for configuration D_s and D'_s, it is fixed at the final topography of the spin-up phases of experiments B and B′, respectively.~~To evaluate the impact of "no memory" of the transient past climate, "fixed-topography" *steady-state* spin-up experiments are performed (experiment D_s, D'_s, F_s and F'_s). For the configuration of D_s and D'_s, the topography is fixed at the present-day observation and internal temperature distribution is computed until reaching~~

~~a steady-state under the present-day climate field. For the configuration of $\mathsf{F_s}$ and $\mathsf{F'_s}$, the topography is fixed at the final topography of the spin-up phases of experiments B and B′, respectively.~~ B069

The series of experiments outlined in this section is summarized as follows: B070

- B = free topography + transient temperature,
- F = fix to free topography + transient temperature,
- $\mathsf{F_s}$ = fix to free topography + steady state temperature,
- D = fix to observed topography + transient temperature,
- $\mathsf{D_s}$ = fix to observed topography + steady state temperature.

4.7 Impact of non-uniform basal sliding coefficient (vm, e1:vm)

Another aspect remaining to be discussed is the impact of initialization by "tuning" or inversion. A003 There are three models in the SeaRISE Greenland experiment that use a form of inversion, and these all differ not only in the method and parameter tuned but also in other aspects such as basal sliding formulation and surface mass balance. The results of the three models have already a dispersion as shown in Bindschadler et al. (2013), Fig. 3, due to partial or all combination of difference among the models. An inversion experiment could be performed using the same method as these three models or another method such as Pollard and DeConto (2012). Generally, the inversion depends on the boundary conditions such as surface mass balance as well as the ice flow characteristics in individual models, which are different among the SeaRISE inversion models. Therefore, even if an experiment following one or all of the inversion methods in the SeaRISE is conducted, the many degrees of freedom means that the results may not explain the dispersion in the SeaRISE results. However, 'potential' explanations of the impact of an inversion are worthy of exploration. The essential difference between the inversion models and the others is the application of non-uniform parameter fields such as basal sliding coefficients (with a certain assumption for other fields such as ice temperature and enhancement factors). In order to demonstrate a 'potential' impact of the inversion, we repeat some experiment configurations using a prescribed field of non-uniform basal sliding coefficients kept constant throughout the simulation.

Pollard and DeConto (2012) presented a general method to deduce spatial distribution of basal sliding coefficients to reduce the errors in the simulated surface topography. In this method, the evolution of ice-sheet topography and temperature are computed for a prescribed surface mass balance, periodically adjusting the basal coefficient at each grid point according to the error of local surface elevation compared to the present-day observation. In the present paper, the method is applied with modification for the minimum and maximum limits of the basal sliding coefficient, which are chosen as $10^{-8} \times C_{\mathrm{B},\mathbf{v2}}$ and $10^{4} \times C_{\mathrm{B},\mathbf{v2}}$, respectively (see Eq. 2), after some trials. The same boundary condition as B′ is applied for this computation. As described in the model section, the standard enhancement factor in the present study is 3, but using this value never gives a reasonable coefficient field: even when no sliding is allowed as the lower limit of the coefficients, the interior part of the ice sheet is still lower by more than 400m compared to the present-day observation. Following Pollard and DeConto (2012), we modify the enhancement factor to a smaller value. The enhancement factor set to 1 for this 'inversion' procedure (configuration **e1**). The configuration **vm** is the run with the 'inverted' non-uniform basal sliding coefficient fields that are computed under B′:**C0**:**e1**. In addition, for comparison purposes, a subset of the uniform basal-sliding coefficient runs is repeated with the small enhancement factor $E = 1$.

The non-uniform basal-sliding coefficient cases **vm** are conducted as a variation of the uniform basal-sliding cases. All of the experiments are repeated using these coefficients fixed throughout the simulation, both over the spin-up and the future.

5 Results

Table 2 summarizes the simulated ice-sheet volumes at the end of the initialization phase (or at the beginning of future-climate scenario experiments) compared to the present-day observations, and the root mean square of residuals of the thickness . The results of experiments except for O will be described later in this section. Under configuration O, the overestimation of the ice-sheet volume is within $+6\,\%$ and with increased basal sliding coefficient **v4** within $0.5\,\%$ of the present-day observations. The good match of the simulated volumes can be explained by an overestimation around the ice-sheet margin and an underestimation over the interior regions (e.g. Bindschadler et al., 2013; Yan et al., 2013). The difference in surface elevation relative to the present-day observation is included in the supplementary (Fig. 1). Since generally the simulated thickness over the interior region is larger while that over the margin is smaller than the present-day observation, the root mean square of the residuals is as large as $500\,\mathrm{m}$ even if the total volume is close to the observation, which is a common feature among model studies, in particular using a spatially uniform basal velocity coefficient(e.g. Nowicki et al., 2013).

B015

B075

A027

B015

Bindschadler et al. (2013) presented their results in terms of the simulated time series of volume above flotation (VAF) under future climate warming scenarios, **C1**,**C2** and **C3**, relative to that under the constant climate scenario **C0**. Figure 1 shows the results of the present paper following the SeaRISE analysis under future-climate scenarios **C1** with a standard basal sliding coefficient **v1**. Figure 1 also shows the ranges of the results of the eight SeaRISE participants at 100, 200, 500 years from the present, given in Table 3 of Bindschadler et al. (2013). The result of configuration O, which is a simulation corresponding to the original IcIES submission, is close to the largest response among the SeaRISE participants.~~show the largest response among the experiments.~~

B016, B076, A028

Figure 2 shows simulated changes of VAF at 500 years obtained by a subset of the experiments in the present paper~~Figures 2 and 4 show simulated changes of VAF at 500 years obtained by all experiments in the present paper~~ under the future-climate scenarios **C1**, **C2** and **C3** for the standard (**v1**), doubled (**v2**), and quadrupled basal sliding coefficients (**v4**). B082

The results of configuration O show volume losses of 34.1, 72.1 and 142.8 cm sea level equivalent at the time 500 year under climate scenarios **C1**, **C2** and **C3**, respectively. Standard basal sliding cases **v1** under all future climate scenarios are within the range of original SeaRISE results. Simulated responses become larger with enhanced basal sliding coefficient, and some cases are still within the original range of results, while some are above the range, for example, the simulated VAF response of **C3** : **v4** is 17 cm more than the upper boundary of the original range~~+17 cm~~ . B078

In the following sections, the effects of replacement of the five model aspects are described in turn. The fractional changes of the effects of this series of experiments are summarized in Tab. 1 and Figs. 4–6 in the supplementary. B034

5.1 Bedrock topography

Configuration A is equivalent to O (SeaRISE/IcIES configuration) , except that the bedrock topography dev1.2 is replaced by the JHKP topography. Simulated VAF responses are affected by replacing the bed topography of a few regions, but are~~Simulated VAF responses are already affected by replacing the bed topography of a few regions, however, are~~ less than +2.2 cm under all the combinations of climate and sliding coefficients (Fig. 2). B062 B080

5.2 Basal sliding formulation

Configuration B is equivalent to A (O with JHKP bedrock) , except for the inclusion of sub-melt sliding during both the initialization and future scenario phases. Table 2 shows the simulated volumes at the end of the initialization with configuration B. The introduction of the sub-melt sliding results in a wider sliding area and therefore a smaller ice-sheet volume due to enhanced outward ice flow. The standard basal sliding coefficient case **v1** shows ice-sheet volumes close to present-day observations (1.7 % overestimation). Similar to other configurations, such as O and A, the increase in the basal sliding coefficient leads to smaller present-day ice-sheet volumes. In the case **v4** with four-times coefficients, the resulting present day ice volume underestimates observations by more than 10 %. For O and A, quadrupling the basal sliding coefficient varies the volume by around 5% of observed, but for B by more than 12%.~~Under configurations O and A, the spread of present-day ice-sheet volumes are around 5 % of the observed value among three basal sliding coefficients cases, and lies more than 12 % under B.~~ B062 B081

Figure 3a–c shows simulated present-day ice-sheet topography obtained by B : **v1** to B : **v4** cases, respectively. The supplementary includes a figure showing the difference in the surface elevation relative to the present-day observation (Fig. 2a–c). The interior part of the ice sheet becomes lower B079 with an increasing basal sliding coefficient. In addition, the ice-covered area around the northwest region is much reduced with a higher basal sliding coefficient in particular in the B : **v4** case, which partly contributes to the overall underestimation in the volume.

The submelt sliding treatment affects the VAF response more~~greater~~ for ~~higher climate scenarios and~~ larger sliding coefficients as shown in Fig. 2 (comparing B with A) . For **v4**, the absolute increases in the ΔVAF from A to B are similar between **C2** and **C3** scenarios ($+26.4$ and $+24.9\,\mathrm{cm}$, respectively), and the ratios of the increases in the ΔVAF to the corresponding total ΔVAF become smaller from the lower climate scenario **C1** to the higher **C3**. Also, the case of **v4** has proportionally less difference in the higher climate scenarios when comparing the change between B and A. The **C1** : **v1** case results in a loss of $36.5\,\mathrm{cm}$ at 500 year, (which is about $1\,\mathrm{cm}$ more than in case A) . The largest difference between B and A~~in the ΔVAF~~ is $+26.4\,\mathrm{cm}$ for the **C2** : **v4** case.

5.3 Initialization method

Configuration D is equivalent to B (free transient spin-up) , except that the ice-sheet initial condition is obtained by a fixed topography spin-up given by the present-day observation. Because of the inconsistency in the internal temperature due to fixed topography spin-up, larger drifts are shown even under the constant climate scenario run (**C0**), compared with those of the free spin-up configuration (B). Similar to Bindschadler et al. (2013), no configuration matches the observed rate of present-day volume change. These drifts are subtracted from the results under future climate runs (**C1** to **C3**), in order to isolate the response to the forcing alone. The simulated response of the VAF is $26.0\,\mathrm{cm}$ for D under the **C1** : **v1** case, therefore it has $-10.5\,\mathrm{cm}$ impact relative to B. This more than cancels~~is large enough to cancel~~ the impacts of the treatment of bedrock topography and submelt sliding (Fig. 2). Under the **C2** and **C3** cases, ΔVAF are 52.6 and $111.6\,\mathrm{cm}$, which shows -24.5 and $-39.3\,\mathrm{cm}$ impact, respectively. Thus, the impact of whether the topography is free or fixed within the spin-up to observed~~the replacement of the initialization method~~ reaches around $1/3$ of the range of the original SeaRISE experiments. Especially for~~Even~~ under larger basal sliding coefficients, cases **v2** and **v4**, ΔVAF are significantly reduced due to the different spin-up condition whether free or fixed~~initialization methods~~ , which are large enough to cancel the effect of including submelt sliding. Simulated responses in VAF are reduced to $50\,\%$ or less from B to D.

Figure 4 shows the changes in VAF relative to that under the constant climate scenario **C0** obtained by experiments B (free topography spin-up) , F (fixed topography spin-up as for B) and D(fixed topography spin-up as for the observation) , over all the combinations of climate scenarios and sliding coefficients.~~Figure 4 shows the changes in VAF relative to the corresponding initial condition obtained by experiments B, F and D, over all the combinations of climate scenarios and sliding coefficients, including the corresponding constant future-climate scenario case **C0**.~~

Configuration F is equivalent to B (free transient spin-up) , except that the ice-sheet initial condition is obtained by a fixed topography spinning-up as the final state of configuration B, which means that the initial topography for future-climate runs are identical. Since internal thermal states are not in equilibrium under configuration F due to the artificial prohibition of topography evolution, the thermal conditions drift to restore the equilibrium during the future climate run even under the constant climate simulation. The effect of the non-equilibrium thermal state is not systemically larger from F to B. In the case of **v1** basal sliding, F (fixed topography spin-up) , shows a smaller response than B (free transient spin-up) , under the **C1** scenario, similar response under the **C2**, a larger response under **C3**, respectively, while in the case of **v4** all F show a larger response under the three scenarios. Over all the combinations of climate and sliding coefficient~~Of all the combinations~~ examined in the present paper, the differences in the final states of ΔVAF between B (free topography spin-up) and F (fixed topography spin-up as B) are smaller than the differences in ΔVAF between B and D (fixed topography spin-up as observation) . This means that the model sensitivity of the internal non-equilibrium thermal states is smaller than the sensitivity to ~~the~~ the free or fixed topography options~~the initialization method options~~ , when they are evaluated in terms of changes relative to the constant climate experiment. The effect of the non-equilibrium thermal state is larger for larger ΔVAF, because the elevation-ablation feedback amplifies the geometry changes.~~Through the elevation-ablation feedback, the impact of the non-equilibrium thermal state is larger in cases of higher sensitivity.~~ The maximum impact in the present paper is $+14.5\,\mathrm{cm}$ sea level equivalent for F under the **C3** : **v4** case, which is $10.5\,\%$ of the variability of corresponding D cases.

Configuration $\mathsf{F_s}$ is equivalent to F (fixed topography *transient* spin-up as B) ~~and B~~ except that the initial condition of the ice-sheet is obtained by a fixed topography "steady-state" spinning-up as the final state of configuration B. All the experiments show almost identical sensitivity of VAF between steady-state and transient spin-up, in terms of relative changes in VAF to the corresponding constant climate scenario cases. In other words, as long as the final topography is the same, it does not make much difference whether the spin-up used a transient climate or steady state. Therefore~~Seemingly~~ , if an initial state with free spinning-up methods ends at the observed topography, the time evolution of VAF is expected to come~~comes~~ close to the one obtained by fixed spinning-up methods, both under transient climate scenarios and under the constant present-day climate scenario imposed for the first 500 years.

5.4 Treatment of advance of the ice-sheet margin

The initialization phase of configuration E is identical to that of D (free margin, fixed-topography transient spin-up as observation) , but advance of the ice-sheet margin is not allowed while retreat is freely allowed under future-climate runs. Prohibiting ice-margin advance has a smaller impact than the choice of spin up whether free or fixed~~initialization methods~~ (Fig. 2). The simulated response of VAF is $19.8\,\mathrm{cm}$ in experiment E, $-6.2\,\mathrm{cm}$ relative to D under the **C1** : **v1** case. Thus, under mild climate warming scenarios like **C1**, the choice of spin-up whether free or fixed~~the~~

~~choice of initialization method~~ and the margin treatment has a larger~~dominant~~ effect on the response of Greenland ice sheet over 500 years compared with the effects of bedrock or sub-melt sliding. The impact of replacing the treatment of the margin is affected little by the choice of basal coefficients, but the larger basal coefficients tend to have slightly more impact from the replacement. This reflects the fact that higher velocity at the margin tends to result in more advance in the margin. Under higher climate scenarios such as **C3**, advance in the ice sheet margin is not significant even in the free-margin experiments D, thus less impacts are seen from the replacement of the margin treatment.

5.5 Surface mass balance

Figure 2 shows the simulated changes in VAF under all of the combinations of climate scenarios and basal sliding coefficients by the series of experiment B′ (free topography spin-up), D′ (fixed topography spin-up as observation) and E′ (no advance in the margin). Surface mass balance is replaced from B (PDD of Tarasov and Peltier, 2002) to B′(PDD of Huybrechts and de Wolde, 1999), and after that, the same replacement sequences are followed as B to E (initialization and margin treatment).

Configuration B′ is equivalent to B, except that the surface melting parameterization of Tarasov and Peltier (2002), which was used in the IcIES original submission, is replaced by Huybrechts and de Wolde (1999), which was used by some of the SeaRISE participants. The future-climate runs **C1** and **C0** and the initializations are repeated using the new PDD methods. Table 2 shows the simulated initial volumes under the configuration of the B′ series and Fig. 2 shows the simulated changes in VAF under all of the combination of climate scenarios and basal sliding coefficients by the series of experiment B′, D′ and E′.

With the change of the surface mass balance method, the simulated present-day ice-sheet volumes become larger by about 4 %. Figure 3d–f shows simulated present-day ice-sheet topographies obtained by experiments B′ : **v1** to B′ : **v4**, respectively. The supplementary includes a figure showing the difference in the surface elevation relative to the present-day observation (Fig. 2d–f).

The main difference between B and B′ is found in north-western Greenland. The retreat of the ice-sheet margin over north-western Greenland is not seen in the B′ cases (Fig. 3d–f).~~B′ : **v4** cases (Fig. 3f).~~ Changes over the interior region (around the summit) are small because the change in method primarily influences the ablation area near the ice-sheet margin.

Figure 2 shows a volume loss of 28.2 cm sea level equivalent at 500 year for configuration B′, thus replacing the PDD methods in the **C1** : **v1** case has an impact of ~ -8.3 cm. This impact is slightly smaller than the impact of -10.5 cm by replacing the free vs. fixed topography methods~~the initialization methods~~ from B (free topography spin-up) to D (fixed topography spin-up as observation). The smaller sensitivity partly stems from the overestimation in the present-day topography. Since the simulated initial volume is larger, less surface melting is expected because of the elevation-temperature feedback. Under stronger warming scenarios, the impact of the replacement of the surface melting method from B to B′, which are −21.9 and −50.8 cm under **C2** and **C3**, respectively, is similar or even larger than that of the free vs. fixed topography methods~~the initialization method~~ from B to D.~~D, which are −21.9 and −50.8 cm under **C2** and **C3**, respectively.~~ Similar to the replacement of the free vs. fixed topography methods~~initialization methods~~, the large impact due to different basal-sliding formulation is canceled by the replacement of the surface melting method and the results become closer among the three cases of basal-sliding coefficients under the same climate scenarios. Through all combinations of climate scenarios and basal sliding coefficients, a significant influence in the simulated responses of VAF due to the different surface mass balance methods are shown. As shown in Fig. 2, the difference in the surface melting methods has similarly large influences~~dominant and similar influences~~ on simulated responses as the free vs. fixed topography methods~~the initialization methods~~. Similarly, configurations D′ (fixed topography spin-up as observation) and E′ (no advance in the margin) are equivalent to D, and E, respectively, except for the surface melting parameterization. Under the lower future climate scenario **C1** (Fig. 2a), the influence of the replacement of surface mass parameterization is comparable to that of replacement of both the free vs. fixed topography methods~~the initialization method~~ or the treatment of ice-sheet margin (B′ vs. D; D′ vs. E). Under the higher future-scenario **C3**, the influence of the former becomes even larger than that of the latter. Simulated responses in VAF are reduced to around 60 % of those obtained using the original surface mass balance parameterization (B vs. B′; D vs. D′; E vs. E′) under **C3** future-climate scenario. Similar results to the case of the other surface parameterization are obtained as shown in the comparison of F′ (fixed topography spin-up as B′), F'_s and B′ (free topography spin-up). ~~Configurations F′ and F'_s (Fig. 4), are identical to B′ except that the initial condition of the ice-sheet runs are obtained by a fixed topography “transient” and “steady-state” spinning-up, respectively. In both experiments, the ice-sheet topography is fixed at the final state of configuration B′. Similar results are obtained with both surface mass balance parameterizations. Of all of the combinations in the present paper, the differences in the final states of ΔVAF between B′ and F′ are smaller than the differences between B′ and D′. This means that the impact of the internal non-equilibrium thermal state is smaller than the sensitivity to the initialization methods, with respect to the constant climate experiment. In addition, the influence of non-equilibrium thermal states on the VAF is smaller for both steady-state and transient spin-up.~~

~~The influence of the internal inconsistency and of surface mass balance parameterizations can be compared through the results of F and B′.~~ Comparison between the results of F or F_s (B plus different fixed topography~~different initialization~~) and B′ (B plus different surface mass balance) show the relative influence of the internal inconsistency and the surface mass balance parameterization. Over all~~Further, of all~~ the combinations considered in the present paper, the impact of the internal non-equilibrium thermal state to the simulated sensitivity of VAF is smaller than the impact of the difference in the surface melting methods for both a steady-state and transient spin up.

5.6 Non-uniform basal sliding coefficient field

Figure 5 shows the difference in the simulated surface topography relative to the present-day observation and 'inverted' basal sliding coefficient field. A003 The inversion procedure is performed using the surface mass balance method of Huybrechts and de Wolde (1999), with the ice enhancement factor $E = 1$, and prohibition of advance in the ice-sheet margin. The last constraint is somewhat arbitrary, but is kept for simplicity. The inverted coefficients are smaller than the case **v2** value by some orders of magnitude over the interior region, while larger around the margin. Although not perfect, the overestimation in surface elevation near the margin and the underestimation in the interior part are significantly reduced (see Fig. 2d-f in the supplementary for uniform basal sliding coefficient cases). As mentioned, since the inverted field is a function of other aspects such as surface mass balance, a different distribution should be computed for each configuration. Since the experiment reported in this section is intended to demonstrate non-uniform basal sliding coefficient fields, the same field is used through all the experiment in this section. Among the series of experiments, $\mathsf{E_s}$ and $\mathsf{E'_s}$ (submelt sliding included; fixed topography steady-state spin-up as the present-day observation; no advance in the ice margin) are performed using the inverted field, with default enhancement factors $E = 3$ and $E = 1$.

Figure 6 shows the simulated changes in VAF under all of the combinations of climate scenarios and basal sliding coefficients by the series of experiments $\mathsf{E_s}$ and $\mathsf{E'_s}$. The case $\mathsf{E'_s}$:**e1**:**vm** is the simulation of most optimized present-day state in the present paper. Among the four coefficient cases **v1** to **vm**, under $\mathsf{E'_s}$:**e1** configuration, the non-uniform case **vm** shows smallest changes in VAF under each climate scenario **C1** to **C3**. Similar to the other configuration discussed above, simulated responses become larger with a uniformly enhanced basal sliding coefficient (**e1**:**v1** to **e1**:**v4**), while the case **e1**:**vm** is even smaller than the case **e1**:**v1**. As shown in Fig. 5b, most regions near margins have very large basal sliding coefficients while most of the interior has a very small value (even smaller than the value of **v1**), which leads to larger and smaller changes in VAF over the margin and interior, respectively. Thus totaly smaller change in VAF than **v4** case is shown in the run with $\mathsf{E'_s}$:**e1** configuration. The same holds true for the configuration $\mathsf{E_s}$:**e1** ($E = 1$, PDD following Tarasov and Peltier, 2002). With the default enhancement factor $E = 3$, the relation among four coefficient cases, **v1** to **vm**, varies with experiment: for example, the non-uniform case **vm** has a response between **v2** and **v4** under the $\mathsf{E'_s}$ case. For all the non-uniform basal-sliding coefficient cases, the changes in VAF at 500 years never exceed the changes obtained by **v4** (uniformly quadrupled) case and sometimes become slightly smaller than those obtained by the **v1** case.

6 Discussion

The simulated response of Greenland ice sheet is affected by the method options explored in the experiments presented in this paper, and is partly explained by the difference in the initial state and partly by that in the initial drifts. Replacement of the bedrock topography (O to A) as well as the submelt sliding treatment (A to B) leads to lower elevations in some regions and thus larger responses under future warming scenarios due to the elevation-ablation feedback. Prohibiting ice-margin advance (D to E and so on) refrains ice-sheet growth under the constant future-climate scenario **C0**, and thus the relative responses under warming climate scenarios **C1**–**C3** become smaller. The replacement of initialization method whether free or fixed to the observation (B to D) leads to smaller responses under future warming scenarios, which cannot simply be explained by the difference in the initial volume for some particular cases As shown in Tab. 2, the initial ice sheet volume of B:**v1**, B′:**v1** and B′:**v2** are larger than those with fixed topography spin-up experiments, while the simulated VAF response are larger. This is due to inconsistency in the internal temperature field due to fixed topography spinning-up, which leads to larger drift under the constant climate scenario to approach the steady-state more rapidly, in this case, to larger ice sheet volume and leads to smaller response due to the elevation-ablation feedback.

An ‘inversion’ method following Pollard and DeConto (2012) is applied to compute an optimized *B035* basal coefficient field in order to emulate some of the SeaRISE models initialized with a ‘tuning’ method. Since the inverted non-uniform field depends on all model properties such as bedrock topography, surface mass balance, the basal sliding formulation, and ice-flow mechanics, it is not guaranteed that the result with the non-uniform field in the present paper explains the behavior of the SeaRISE models using a ‘tuning’ method. However, since at least the SeaRISE models with free topography spin-up including IcIES have qualitatively similar results (overestimated thickness around the margin while underestimated in the interior), the computed basal sliding coefficient field in the present paper may capture the general characteristics of the expected inverted basal sliding coefficient field. The inverted field in the present paper generally shows larger values around the margin and smaller in the interior, which leads to a larger response around the margin and a smaller response in the interior, under the future climate scenarios. The total response of Greenland ice sheet is determined how much both responses are compensated. At least throughout the configuration of the present paper, the simulated total responses in VAF do not significantly deviate from the uniform basal sliding coefficient cases.

The four methods examined in the series of transient spin-up, O-A-B-D-E with all cases of the *A003* basal sliding coefficients **v1** to **v4** under all the future climate scenarios **C1** to **C3** (bluish group in *B102* Fig. 2) are related to the ice flow~~technical aspects of the ice flow~~ but do not relate to the model *B102* inputs~~the climate scenarios~~ . Among these four aspects, the inclusion of submelt sliding enhances *B102* *B102* the ice-sheet response strongest (A to B), but using “fixed-topography” spin-up cancels and even *B102* reduces this impact (B to D).~~Among these four aspects, using “fixed-topography” spin-up has a~~

~~major impact on the sensitivity (B and D). The inclusion of submelt sliding has also significant impact in the case of the large coefficients, which can be canceled by the above impact.~~ Prohibition of ice-sheet advance is a secondary influence that can reduce the sensitivity (D to E). B024 ~~The results show generally that as simulated response in VAF is reduced, the spread of the results due to different basal sliding coefficients becomes small.~~ For the lower future-climate scenario case **C1**, the combination of all four aspects (Fig. 2a) affects the volume loss as much as 42 %, B025 which leads to the response of 19.8 cm sea level equivalent in experiment E. This value is very close to the average of SeaRISE participants (19.2 cm sea level equivalent) presented in Bindschadler et al. (2013), regardless of the basal sliding coefficient. For the higher future-climate scenario case **C3** (Fig. 2c), the combination of all four aspects affects the volume loss by as much as 30 % of the total response, which is not enough to explain the large deviation of O from the average. The spread of the results due to different basal sliding coefficients is similar between the **C2** and **C3** scenarios~~slightly larger under the **C3** scenario~~ . Thus the source of spread in SeaRISE experiments can only partly be explained by variations in the experimental configuration of B026 technical aspects of ice flow. The most influential of these is the specification of free or fixed geometry and slightly less, the treatment of the ice-sheet margin evolution.~~Thus the source of spread in SeaRISE experiments can only partly be explained by variations in the experimental configuration of technical aspects, but mostly by the initialization method and slightly less by the treatment of the ice-sheet margin evolution.~~ Using a non-uniform basal-sliding coefficient field and/or smaller enhancement factor have a potential to further reduce the volume loss (Fig. 6). B103 Although significant changes in the volume loss are not shown using the inverted field in the present paper, it is still possible to have larger impacts on the changes using different basal sliding fields. The uncertainty in the methods to compute surface melting can further influence the model A003 sensitivity. Configuration E′ replaces all four technical aspects as well as the surface mass balance compared to the original configuration O. E′ results in a volume loss which is smaller than the average of the SeaRISE experiments for the **C1** future-climate scenario. Even for the highest climate scenario, case **C3**, the volume response is slightly smaller than or close to the average of the SeaRISE experiments, regardless of the basal sliding coefficient (Fig. 2c). Again, significant changes in the volume loss are not shown using the inverted field in the present paper (Fig. 6), but it does not necessarily negate the impact of a non-uniform basal sliding field, and this still has the potential to explain the spread in the SeaRISE results.

A003 In the series of the experiments in the present paper, the choices that have greatest effect on the simulated response are the method to compute the surface mass balance, and the method to initialize the ice-sheet, which have comparable effect. This is consistent with the discussion of the possible reasons for spread in the SeaRISE results by Bindschadler et al. (2013) and Nowicki et al. (2013)~~As shown in the series of the experiments in the present paper, neither the method to compute the surface mass balance, nor the way to initialize the ice-sheet is identified as the primary~~

~~source of the spread in SeaRISE experiments, as already discussed in Bindschadler et al.(2013) and Nowicki et al. (2013)~~ . The variation of the surface mass balance alone (B to B′) has some~~may have a certain~~ influence on the ice-sheet sensitivity, however not enough to completely cancel the large B104 volume response obtained by the IcIES original configuration (i.e., configuration O with **v1** basal B105 sliding). The influence of the initialization methods (whether free or fixed topography) on the short-term ice-sheet sensitivity is comparable to the influence of uncertainties in the surface mass B008 balance methods. Moreover, the influence of the artificial prohibition of the advance of ice-sheet margin, which is not discussed in the papers, is found to be secondary to the main two aspects but not negligible. A006

One drawback when using initialization methods, except for the "free" spin-up, is a drift due to inconsistency in simulated temperature fields. Comparison of the results between B (free topography spin-up) and F (fixed topography spin-up as B) or B′ and F′. where the corresponding pairs have identical topography but different internal states, can show the influence of internal B062 non-equilibrium thermal states. Over all the combinations in the present paper, the difference in the final states of ΔVAF between B (B′) and F (F′) is smaller than the difference in that between B (B′) and D (D′). This implies that, at least in terms of changes relative to the constant climate experiment, the influence of the internal non-equilibrium thermal states to the ice-sheet sensitivity is smaller than the influence of different initial states. ~~One drawback when using initialization methods, except for the "free" spin-up, is an artificial drift due to simulated temperature fields. The "fixed-topography" spin-up leads to non-equilibrium internal states, but the influence of this inconsistency is difficult to evaluate. Since there is a feedback between climate and ice-sheet topography, the difference between "free spin-up" and "fixed topography spin-up" cases includes not only the internal temperature effect but the effect of the initial topography and thus the surface mass balance at the beginning. The influence of internal non-equilibrium thermal states can be estimated indirectly by comparison the results between B and F or B′ and F′, where the corresponding two have identical topography but different internal states. Of all the combinations in the present paper, differences in the final states of ΔVAF between B and F or B′ and F′ are smaller than the differences in those between B and D or B′ and D′, respectively. This implies that, at least in terms of changes relative to the constant climate experiment, the influence of the internal non-equilibrium thermal states to the ice-sheet sensitivity is smaller than the influence of different initial states.~~ B106,B028 The largest difference between B and F is found under the **C3** : **v4** case, which shows a difference of $+14.5\,\mathrm{cm}$ sea level equivalent between the two different internal non-equilibrium B106 thermal states. Since an expected counterpart of the D case, which has the identical topography to the present-day observation without artificial drifts, cannot be easily performed, an indirect evaluation is conducted as follows. This $14.5\,\mathrm{cm}$ effect is about $11\,\%$ of the simulated VAF response obtained by D **C3** : **v4** case, and thus the effect of the internal non-equilibrium state is expected to remain minor relative to the total sensitivity.~~If this effect is also holds for the D case,~~

~~10.5 % of the total sensitivity of the case is estimated to be due to the internal non-equilibrium state.~~ In other words, the initial topography has more effect on the future projection, *in terms of relative to constant scenario runs*, than the initial internal temperature field. B029 Therefore, B030 future-climate experiments initialized by fixed-topography spin-up are considered the preferable approaches for characteristic projections of the ice-sheet evolution by an ice-sheet model. In addition, in terms of changes relative to the constant climate experiment, steady-state and transient spin-up initializations show almost identical sensitivities during 500 year model runs.

Table 3 summarizes simulated changes in VAF of configurations B, F, D, and D′ relative to the corresponding constant future scenario experiments . Except for the lower sensitivity cases such as B107 **C1** : **v1** and **C1** : **v2**, the table shows that the effect of internal non-equilibrium states (B vs. F) is rather small compared to the effect of differences in surface mass balance methods (D vs. D′). Thus, the uncertainties due to surface mass balance must be another potential source~~the primary source~~ B031 of uncertainties in the simulated 500-year scale~~short-term~~ B031 future projections of the Greenland ice sheet, rather than those due to ice flow characteristics.

All A033 the analysis in the present paper is performed using the anomaly relative to the result of the "constant" future climate experiment **C0** ("experiment minus control"), following the discussion of the SeaRISE methods (Bindschadler et al., 2013; Nowicki et al., 2013). In other words, trends in the evolution of the ice-sheet volume at the present-day, whether they are artificial or not, or whether they are consistent with the present-day observation, are excluded from the discussion. Simulated trends vary among the configurations and range from −45 cm (E-**v4**) to +24 cm (D′-**v1**) after 500 years among transient experiments. Steady-state experiments do not deviate much from the corresponding transient experiments. Simulated changes in VAF for some experiments are shown in the supplementary (Fig. 3). B032 In reality, the trends arise as the result of long-term climate history. Since the trend is not necessarily zero, the actual future projection of the Greenland ice sheet should be evaluated as the sum of the trend and the anomalies. It is expected that such long-term memory has a smaller impact for the future *changes* in ice-sheet volume at least during the next 500 years, compared with the changes due to future surface climate scenarios, because the results of transient spin-up (with long-term memory) and steady-state spin-up (without) show similar responses,~~The present paper concludes that such long-term memory has a smaller impact for the future *changes* in ice-sheet volume at least during next 500 years, compared with the changes due to future surface climate scenarios.~~ B033 In the present paper, only a part of the surface climate experiments in SeaRISE have been revisited. The same procedures applied here can be followed for other series of experiments (e.g., basal-sliding experiments), which are left for the next study. A033 Therefore, although it cannot be confirmed, if a *perfect* spin-up (free evolution spin-up under transient climate ending with the present-day observed topography) could be obtained, then it can be expected that the VAF response of such an experiment would be close to that obtained using a fixed-topography spin-up with the present-day topography.~~topography, and also it may be better~~

~~than using a free spin-up under the same configuration.~~ Thus, a future-climate experiment initialized by fixed-topography spin-up (with the present-day topography) under either transient climate history or steady-state climate B108 can be considered a suitable approach for characteristic projection by an ice-sheet model in order to isolate the response to the prescribed climate scenario alone B109 . While it cannot be fully confirmed, the analysis of the series of experiments in the present paper suggests that the large sensitivity of IcIES can be attributed to the use of a free topography during the spin-up, free evolving margin during the future experiment, and the difference in the surface melting parameterization.~~the difference in the application of the technical methods such as initialization and free evolving margin, and the difference in the surface melting parameterization.~~ A033 Sensitivities due to different treatments of the margin advance need to be carefully interpreted, since marine boundaries are present for major Greenland outlet glaciers and thus marine-ice sheet instabilities have been identified in numerical model studies (Nick et al., 2013). It is not mentioned explicitly, but most SeaRISE models determine the grounding line by a floating criterion (set $H = 0$ when the surface falls below flotation height) or fix the grounding line through time. Therefore marine-ice sheet instabilities of the Greenland ice sheet are important in terms of future projection, but SeaRISE models do not have sufficient capability to discuss the marine-ice sheet processes. There are M1, M2, M3 experiments in SeaRISE, which are called ice-shelf melting experiments. Since the SeaRISE Greenland models do not have explicit ice-shelf processes, the implementation of the ‘ice-shelf melting’ varies greatly among the models, that is one of the reason why the spread of these results are very large (larger than C1, C2, C3 spreads presented in this paper). Nowicki et al. (2013) state that: ‘Thus, the current generation of Greenland whole ice sheet models is not yet able to simulate the potential response to a warming ocean, and caution is needed when interpreting the SeaRISE response to this scenario, as the ensemble mean response likely underestimates the true potential response.’ For the same reason, the present paper focuses on climate warming scenarios only, which means that the impact of margin retreat purely due to the surface mass balance is discussed. When marine-ice instability processes are included, the problem of margin advance/retreat may become more significant than those expected in the present paper. B110 Multiple combinations of changes in all of the aspects considered in the present paper (except for the bedrock topography) are tested in order to check for interactions between the uncertainties. ‘One-at-a-time’ effects are summarized in Tab. 1 and Figs. 4–6 in the supplementary. Although the detailed features vary among combinations, the general features in the results discussed in the present paper are also shown. Two aspects, free or fixed topography spin-up and the surface mass balance methods have larger influences than other aspects on the changes in VAF at 500 years over all the future climate scenarios and the basal sliding coefficients. Prohibition of ice-sheet advance has a large influence, in particular when the future climate scenario is mild. The difference of the results by transient spin-up and those by steady-state spin-up are smaller among the other aspects throughout the combinations. Difference of the results by free transient spin-up and those by fixed A004 transient spin-up (as free experiment) are always smaller than the difference of the former and those by fixed transient spin-up (as the observation). Except for **C1**:**v4** and **C2**:**v4** cases, inclusion of submelt sliding has less (or similar) influences than the two aspects of large impact (surface mass balance, fixed-topography spin-up). A large impact of submelt sliding inclusion is found when the surface mass balance follows Tarasov and Peltier (2002) and when the initial topography is the same as free topography spin-up (e.g. B, F). As described in Tab. 2 (see B and **v4**), simulated total volume at the present-day deviates most from the observation among the experiments, and the impact of switching off the submelt sliding inclusion (B to A) is as large as $10\,\%$. Starting from such a small initial condition is considered to be a reason for the large impacts of changes in the submelt sliding formulation, through elevation-ablation feedback.

Since the ice-sheet models will become increasingly more complex, a one-model study such as the present paper cannot cover all possible variations among the existing models. It would be preferable that all participating models perform one common and highly controlled experiment that allows effective identification of the uncertainties due to specific variations in ice-sheet models. Such an experiment would not be an intercomparison for more realistic projections, but rather an abstract test purely for model intercomparison purposes. The intercomparison experiments of the ice2sea projects (e.g. Edwards et al., 2014) mainly focus on model differences, and therefore provide such controlled protocols except~~but~~ for the initialization methods. The experiment in the present paper only covers a small part of the SeaRISE model choices, and thus there is insufficient comparison of the dependence of SeaRISE results on these choices. Nevertheless, it shows that structural and parametric uncertainties are just as important as initialization. In other words, it shows that if all the SeaRISE models repeated this study, the range of the results could widen beyond the current reported spread. Hence, it is important to systematically control and study uncertainties with such designed control experiments.

B002,B023

B040

B004

B112

Here we propose a model intercomparison study to evaluate the uncertainties in modeled response that originate from modeled ice flow characteristics such as ice flow approximation level, basal sliding formulation and model resolution. The proposed experiment set-up, which is referred to as the “benchmark” experiment, consists of a carefully controlled protocol to define the following characteristics:

B005,B006

- Initialization of the present-day condition using either
  - assimilation
  - “fixed-topography” spin-up.
- Prepare “identical” model inputs~~climate forcing~~ in order to extract the influence by difference in ice-flow characteristics only,
  - (easier) not temperature but the spatial/temporal scenario of the surface mass balance with no topography or albedo feedback,

B114

B042

- or provide an identical surface mass balance *subroutine* (not a scheme, in order to keep it really identical among the models) as well as scenarios, B044
- with parameterization such as the PDD scheme, with a regional climate model, or with any methods used for ice-sheet future projections, as far as identical among the models, B114

- Perform two short-term future-climate experiments, a constant climate experiment and a warming climate experiment, in order to subtract the influence of (artificial) drifts, B042
- Advance of the ice-sheet margin must be limited to the present-day (initial) margin. Although the opposite approach is possible, this approach is much easier to implement in some models. Also in this case the treatment of boundary conditions over the ice-free grids does not need to be specified. B041

A demonstration of this type of experiment is presented in Appendix A. Since spinning-up methods are not specified, except~~less controlled except~~ for the ice-sheet topography, most types of ice-sheet B115 models can easily perform this experiment, including computationally expensive Full Stokes models,~~very heavy full-stokes models,~~ models using inversion techniques, and models using free B042 evolution spinning-up over a long climate history. This experiment configuration is a compromise to allow choice of initialization method by individual model, but is, however, still proscribed enough to separate uncertainties and/or some feedbacks. The results of this benchmark would help to address the uncertainties obtained by other intercomparison experiments for more realistic projection with a large variety of model aspects like the SeaRISE experiments. B004

7 Conclusion and prospects

The present paper revisits the future surface-climate experiments on the Greenland ice sheet proposed by the multi-model intercomparison SeaRISE (Bindschadler et al., 2013). A series of sensitivity experiments has been performed, using the ice-sheet model IcIES, to attempt to understand~~identify~~ sources of the spread in the SeaRISE multi-model intercomparison. Five B113 aspects: surface balance parameterization, sliding, margin migration, initialization and bed topography, are chosen to replace the standard formulation of IcIES by those adopted in other models, and all the experiments are conducted from spin-up to the simulation of future evolution. The results show that the difference in the initialization methods as well as in the surface mass balance methods are large potential sources for the spread in the SeaRISE experimental results.~~The results show that the main sources of the spread in the SeaRISE experiments are the difference in the initialization methods and the difference in the surface mass balance methods.~~ ~~As already~~ B036 ~~proposed in the SeaRISE papers, and confirmed quantitatively in the present paper, the impacts of these two aspects are of comparable magnitude.~~ In addition, the treatment of ice-sheet margin B037 migration in the simulations also has a non-negligible impact on the spread among the multi-model projections. Performance of an initialization technique with fixed ice-sheet topography through time while temperature is allowed to evolve according to the surface temperature history or to the present-day condition is indirectly evaluated and found to provide an acceptable initial condition, at least for short-term projections. *B038*

The SeaRISE project, in which several ice-sheet models of different complexity participated to perform similar experiments, showed the degree to which current ice sheet models and modeling choices diverge~~showed the divergence or convergence of current ice-sheet modeling~~ . Furthermore, *B111* Nowicki et al. (2013) show detail and careful analysis of all the results both globally and regionally, to present how and where the models are similar or dissimilar~~consistent or inconsistent~~ . However, *B039* the SeaRISE protocol is not strictly controlled and most experimental configurations are left as the choice of the participants. Therefore, it is difficult to separate the effects of different choices by comparing only the submitted results. The present paper demonstrates that various implementations adopted in individual models can affect the simulated responses and how much they may contribute to the diversity in SeaRISE results. The analysis in the present paper is quite limited in terms of spin-up, and we propose a benchmark experiment to address this. If all models are used to perform a highly controlled experiment, it is easier to analyze the uncertainty due to model spin-up, within the variation of current ice-sheet model structures. *A034*

Appendix A: Demonstration of the "benchmark" experiment *A035*

For a demonstration of the suggested benchmark experiment, configuration E_s'' is performed by IcIES, which is the same as E_s and E_s' except for the future surface mass balance scenarios. Steady-state initialization under fixed present-day topography is performed, and the future surface mass balance is imposed using the SeaRISE datasets without any correction. Although most of the models did not use it, SeaRISE provided a transient future scenario of the surface mass balance computed by a variation of PDD method. The parameters for the PDD are described at http://websrv.cs.umt.edu/isis/index.php/Future_Climate_Data, where the standard deviation of the short-term statistical air temperature fluctuations is set as 4.5 K, the PDD factor are set as 3 and 8 mm ice equivalent per day per degree for snow and ice, respectively. *B117*

Actually, one participant, ISSM, in SeaRISE has a similar configuration to the benchmark: the surface mass balance is imposed with~~on~~ the SeaRISE datasets without any correction; *A036* *B120* initialization is based on inversion which enables initialization with a topography close to that of the present-day; and a fixed calving front is enforced (may correspond to prohibition of both advance/retreat) . There is no explicit information about inclusion of the submelt sliding processes. *B119* The simulated response of VAF for this experiment is 5.4 cm sea-level equivalent at 500 years from the present under **C1** scenario, which is the minimum response among the SeaRISE participants. *B121*

Figure A1 shows the simulated time series of VAF under **C1** scenario with different~~three~~ uniform basal sliding parameters **v1** to **v4**, as well as runs using the inverted non-uniform basal-sliding field (Fig. 5b) with the default enhancement factor (**vm**) and a different enhancement factor $E = 1$ (**e1**:**vm**). The losses in VAF by IcIES are -10.8, -12.0, and $-13.0\,\mathrm{cm}$ sea-level equivalent at 500 years with basal sliding configuration of **v1**, **v2** and **v4**, respectively, thus only $2.2\,\mathrm{cm}$ spread is attributable to the different basal sliding coefficient. Further, using the non-uniform basal sliding coefficient field leads to smaller losses in VAF: -9.0 and $-6.7\,\mathrm{cm}$ sea level equivalent for the **vm** and **e1**:**vm** cases, respectively. The smallest responses in the present paper are obtained under the $\mathsf{E}''_{\mathsf{s}}$ configuration, which is even smaller than configuration E' cases and is only $1.1\,\mathrm{cm}$ sea level equivalent more than~~but still twice as large as~~ the smallest result of SeaRISE participants (ISSM, upper end of the gray bar in Fig. A1). Although the difference is very small, it is still possible that all the model aspects tested in the present paper are not sufficient to explain the SeaRISE spreads under future climate scenarios. There are others differences in the properties such as higher-order physics, the numerical grid system, the basal sliding parameterization, and the distribution of basal sliding coefficient field. Nevertheless, 'net' uncertainties that stem from all the model properties except for those provided by external models (such as the surface mass balance) are expected be evaluated using this type of benchmark experiment.~~The difference of 5 cm sea level equivalent entirely stems from the difference in ice-flow/ice-sheet model characteristics between the two models, higher-order physics, inhomogeneous basal sliding coefficients, anisotropic mesh.~~

A003

A003

A003

A003,B043,B122

Acknowledgements. We thank R. A. Bindschadler, S. Nowicki and others for management of the SeaRISE project. We thank Ralf Greve for support of this study with the SimAnTICS project. We thank Satoru Yamaguchi for support for this study with the Grant for Joint Research Program of the Institute of Low Temperature Science, Hokkaido University. This research is supported by MEXT Japan (Japanese Ministry of Education, Culture, Sports, Science and Technology) through the Green Network of Excellence (GRENE) Arctic Climate Change Research Project, and the Program for Risk Information on Climate Change (SOUSEI project).

References

Aðalgeirsdóttir, G., Aschwanden, A., Khroulev, C., Boberg, F., Mottram, R., Lucas-Picher, P., and Christensen, J.: Role of model initialization for projections of 21st-century Greenland ice sheet mass loss, J. Glaciol., 60, 782–794, doi:10.3189/2014JoG13J202, http://www.ingentaconnect.com/content/igsoc/jog/2014/00000060/00000222/art00016, 2014.

Arthern, R. J. and Gudmundsson, G. H.: Initialization of ice-sheet forecasts viewed as an inverse Robin problem, J. Glaciol., 56, 527–533, doi:10.3189/002214310792447699, http://www.ingentaconnect.com/content/igsoc/jog/2010/00000056/00000197/art00013, 2010.

Bamber, J. L., Layberry, R. L., and Gogenini, S. P.: A new ice thickness and bed data set for the Greenland ice sheet 1: Measurement, data reduction, and errors, J. Geophys. Res., 106, 33 773–33 780, 2001.

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), J. Glaciol., 59, 195–224, http://www.igsoc.org/journal/59/214/j12J125.html, 2013.

Braithwaite, R. J. and Olesen, O. B.: Calculation of glacier ablation from air temperature, West Greenland, in: Glacier fluctuations and climatic change, edited by Oerlemans, J., pp. 219–233, Dordrecht, Kluwer Academic Publishers, 1989.

Cuffey, K. M. and Paterson, W. S. B.: The Physics of Glaciers, Academic Press, fourth edn., 2010.

Dansgaard, W., Johnsen, S. J., Clausen, H. B., Dahl-Jensen, D., Gudestrup, N. S., Hammer, C. U., Hvidberg, C. S., Steffensen, J. P., Sveinbjörnsdottir, A. E., Jouzel, J., and Bond, G.: Evidence for general instability of past climate from a 250-kyr ice-core record, Nature, 364, 218–220, 1993.

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

Ettema, J., van den Broeke, M. R., van Meijgaard, E., van de Berg, W. J., Bamber, J. L., Box, J. E., and Bales, R. C.: Higher surface mass balance of the Greenland ice sheet revealed by high-resolution climate modeling, Geophys. Res. Lett., 36, L12 501, doi:10.1029/2009GL038110, http://dx.doi.org/10.1029/2009GL038110, 2009.

Fausto, R. S., Ahlstrøm, A. P., As, D. V., Bøggild, C. E., and Johnsen, S. J.: A new present-day temperature parameterization for Greenland, J. Glaciol., 55, 95–105, 2009.

Gillet-Chaulet, F., Gagliardini, O., Seddik, H., Nodet, M., Durand, G., Ritz, C., Zwinger, T., Greve, R., and Vaughan, D. G.: Greenland ice sheet contribution to sea-level rise from a new-generation ice-sheet model, The Cryosphere, 6, 1561–1576, doi:10.5194/tc-6-1561-2012, http://www.the-cryosphere.net/6/1561/2012/, 2012.

Goelzer, H., Huybrechts, P., Fürst, J., Nick, F., Andersen, M., Edwards, T., Fettweis, X., Payne, A., and Shannon, S.: Sensitivity of Greenland ice sheet projections to model formulations, J. Glaciol., 59, 733–749, doi:10.3189/2013JoG12J182, http://www.ingentaconnect.com/content/igsoc/jog/2013/00000059/00000216/art00012, 2013.

Graversen, R., Drijfhout, S., Hazeleger, W., van de Wal, R., Bintanja, R., and Helsen, M.: Greenland's contribution to global sea-level rise by the end of the 21st century, Clim. Dyn., 37, 1427–1442, doi:10.1007/s00382-010-0918-8, http://dx.doi.org/10.1007/s00382-010-0918-8, 2011.

Greve, R.: On the response of the Greenland ice sheet to greenhouse climate change, Climate Change, 46, 289–303, 2000.

Greve, R.: Relation of measured basal temperatures and the spatial distribution of the geothermal heat flux for the Greenland ice sheet, Ann. Glaciol., 42, 424–432, 2005.

Greve, R. and Herzfeld, U. C.: Resolution of ice streams and outlet glaciers in large-scale simulations of the Greenland ice sheet, Ann. Glaciol., 54, 209–220, doi:10.3189/2013AoG63A085, http://www.ingentaconnect.com/content/igsoc/agl/2013/00000054/00000063/art00023, 2013.

Greve, R., Saito, F., and Abe-Ouchi, A.: Initial results of the SeaRISE numerical experiments with the models SICOPOLIS and IcIES for the Greenland ice sheet, Ann. Glaciol., 52, 23–30, 2011.

Herzfeld, U. C., Fastook, J., Greve, R., McDonald, B., Wallin, B. F., and Chen, P. A.: On the influence of Greenland outlet glacier bed topography on results from dynamic ice-sheet models, Ann. Glaciol., 53, 281–293, doi:10.3189/2012AoG60A061, http://www.ingentaconnect.com/content/igsoc/agl/2012/00000053/00000060/art00034, 2012.

Hindmarsh, R. C. A. and Le Meur, E.: Dynamical processes involved in the retreat of marine ice sheets, J. Glaciol., 47, 271–282, 2001.

Hutter, K.: Theoretical glaciology; material science of ice and the mechanics of glaciers and ice sheets, Dordrecht, etc., D. Reidel Publishing company/Tokyo, 1983.

Huybrechts, P.: The Antarctic ice sheet and environmental change: a three-dimensional modelling study, Ph.D. thesis, Ber. Polarforsch., 1992.

Huybrechts, P. and de Wolde, J.: The Dynamic Response of the Greenland and Antarctic Ice Sheets to Multiple-Century Climatic Warming, J. Climate, 12, 2169–2188, 1999.

Huybrechts, P., Letréguilly, A., and Reeh, N.: The Greenland ice sheet and greenhouse warming, Palaeogeography, Palaeoclimatology, Palaeoecology, 89, 399–412, 1991.

Huybrechts, P., Janssens, I., Poncin, C., and Fichefet, T.: The response of the Greenland ice sheet to climate changes in the 21st century by interactive coupling of an AOGCM with a thermomechanical ice-sheet model, Ann. Glaciol., 35, 409–415, 2002.

Johnsen, S. J., Clausen, H. B., Dansgaard, W., Gundestrup, N. S., Hammer, C. U., Andersen, U., Andersen, K. K., Hvidberg, C. S., Dahl-Jensen, D., Steffensen, J. P., Shoji, H., Sveinbjornsdottir, A. E., White, J., Jouzel, J., and Fisher, D.: The δ^{18}O record along the Greenland Ice Core Project deep ice core and the problem of possible Eemian climatic instability, J. Geophys. Res., 102, 26 397–26 410, doi:10.1029/97JC00167, http://onlinelibrary.wiley.com/enhanced/doi/10.1029/97JC00167/, 1997.

Morlighem, M., Rignot, E., Seroussi, H., Larour, E., Ben Dhia, H., and Aubry, D.: A mass conservation approach for mapping glacier ice thickness, Geophys. Res. Lett., 38, doi:10.1029/2011GL048659, http://dx.doi.org/10.1029/2011GL048659, l19503, 2011.

Nick, F. M., Vieli, A., Andersen, M. L., Joughin, I., Payne, A., Edwards, T. L., Pattyn, F., and van de Wal, R. S. W.: Future sea-level rise from Greenland/'s main outlet glaciers in a warming climate, Nature, 497, 235–238, doi:10.1038/nature12068, http://dx.doi.org/10.1038/nature12068, 2013.

Nowicki, S., Bindschadler, R. A., Abe-Ouchi, A., Aschwanden, A., Bueler, E., Choi, H., Fastook, J., Granzow, G., Greve, R., Gutowski, G., Herzfeld, U., Jackson, C., Johnson, J., Khroulev, C., Larour, E., Levermann, A., Lipscomb, W. H., Martin, M. A., Morlighem, M., Parizek, B. R., Pollard, D., Price, S. F., Ren, D., Rignot, E., Saito, F., Sato, T., Seddik, H., Seroussi, H., Takahashi, K., Walker, R., and Wang, W. L.: Insights into spatial sensitivities of ice mass response to environmental change from the SeaRISE ice sheet modeling project II: Greenland, J. Geophys. Res. Earth Surf., 118, 1025–1044, doi:10.1002/jgrf.20076, http://dx.doi.org/10.1002/jgrf.20076, 2013.

Paterson, W. S. B.: The Physics of Glaciers, Pergamon, Oxford, third edn., 1994.

Pollard, D. and DeConto, R. M.: A simple inverse method for the distribution of basal sliding coefficients under ice sheets, applied to Antarctica, The Cryosphere, 6, 953–971, doi:10.5194/tc-6-953-2012, http://www.the-cryosphere.net/6/953/2012/, 2012.

Reeh, N.: Parameterization of melt rate and surface temperature on the Greenland ice sheet, Polarforschung, 59, 113–128, 1991.

Ritz, C., Fabre, A., and Letréguilly, A.: Sensitivity of a Greenland ice sheet model to ice flow and ablation parameters: consequences for the evolution through the last climatic cycle, Clim. Dyn., 13, 11–24, http://www.springerlink.com/content/1gf1deewehnq0975/, 1997.

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

Rogozhina, I., Martinec, Z., Hagedoorn, J. M., Thomas, M., and Fleming, K.: On the long-term memory of the Greenland Ice Sheet, J. Geophys. Res. Earth Surf., 116, n/a–n/a, doi:10.1029/2010JF001787, http://dx.doi.org/10.1029/2010JF001787, 2011.

Saito, F. and Abe-Ouchi, A.: Sensitivity of Greenland ice sheet simulation to the numerical procedure employed for ice sheet dynamics, Ann. Glaciol., 42, 331–336, 2005.

Seddik, H., Greve, R., Zwinger, T., Gillet-Chaulet, F., and Gagliardini, O.: Simulations of the Greenland ice sheet 100 years into the future with the full Stokes model Elmer/Ice, J. Glaciol., 58, 427–440, doi:10.3189/2012JoG11J177, http://www.ingentaconnect.com/content/igsoc/jog/2012/00000058/00000209/art00001, 2012.

Seroussi, H., Morlighem, M., Rignot, E., Khazendar, A., Larour, E., and Mouginot, J.: Dependence of century-scale projections of the Greenland ice sheet on its thermal regime, J. Glaciol., 59, 1024–1034, doi:10.3189/2013JoG13J054, http://www.ingentaconnect.com/content/igsoc/jog/2013/00000059/00000218/art00003, 2013.

Shannon, S. R., Payne, A. J., Bartholomew, I. D., van den Broeke, M. R., Edwards, T. L., Fettweis, X., Gagliardini, O., Gillet-Chaulet, F., Goelzer, H., Hoffman, M. J., Huybrechts, P., Mair, D. W. F., Nienow, P. W., Perego, M., Price, S. F., Smeets, C. J. P. P., Sole, A. J., van de Wal, R. S. W., and Zwinger, T.: Enhanced basal lubrication and the contribution of the Greenland ice sheet to future sea-level rise, Proc.

Nat. Acad. Sci. USA, 110, 14 156–14 161, doi:10.1073/pnas.1212647110, http://www.pnas.org/content/110/35/14156.abstract, 2013.

Stone, E. J., Lunt, D. J., Rutt, I. C., and Hanna, E.: Investigating the sensitivity of numerical model simulations of the modern state of the Greenland ice-sheet and its future response to climate change, The Cryosphere, 4, 397–417, doi:10.5194/tc-4-397-2010, 2010.

Tarasov, L. and Peltier, W. R.: Greenland glacial history and local geodynamic consequences, Geophys. J. Int., 150, 198–229, doi:10.1046/j.1365-246X.2002.01702.x, http://dx.doi.org/10.1046/j.1365-246X.2002.01702.x, 2002.

Yan, Q., Zhang, Z., Gao, Y., Wang, H., and Johannessen, O. M.: Sensitivity of the modeled present-day Greenland Ice Sheet to climatic forcing and spin-up methods and its influence on future sea level projections, J. Geophys. Res. Earth Surf., 118, 2174–2189, doi:10.1002/jgrf.20156, 2013.

Table 1. Summary of numerical experiments in this paper. The bedrock column denotes the sources of bedrock topography as a boundary condition (see main text for interpretation of symbols). The column "sub-melt" denotes whether or not to sub-melt basal sliding occurrence based on Eq. (3) is implemented. The initialization columns denotes climate forcing used for initializing the ice-sheet topography, where "125 ky tr" stands for 125 kyr transient forcing based on ice-core record. Thickness columns denotes how the ice thickness is computed during initialization phase, where "free" means that ice-thickness is allowed to evolve freely, "fixed (obs)" means that ice-thickness is kept fixed as the present-day observation through the initialization phase artificially, "fixed (B 0 ka)" means that ice-thickness kept fixed as the simulated topography at 0 ka obtained by experiments with configuration B. The margin column denotes whether the ice margin is allowed to advance freely (free) or limited to the initial condition (no advance) during future-climate experiments. The differences from the previous row are shown in bold. All the configurations are repeated with all the combinations of the basal sliding coefficients (cases **v1**, **v2** and **v4**) and the future climate scenarios (**C0**, **C1**, **C2** and **C3**). The experiment with suffix 's' (e.g., D_s) indicates steady state initialization under the present-day conditions, which is denoted as "0 ka st" in the initialization column. The experiments denoted with prime (like B') means switching the method to compute surface melting from PDD following Tarasov and Peltier (2002) (denoted as "T" in the surface melt column) to PDD of Huybrechts and de Wolde (1999) (denoted as "H"). The table also includes an additional experiment E''_s shown in the Appendix, which uses another method of surface mass balance (indicated by symbol "S"). Details are described in the Appendix.

B071

Exp.	bedrock	sub-melt	initialization	thickness	margin	surface melt
O	dev1.2	n	125 ky tr	free	free	T
A	**JHKP**	n	125 ky tr	free	free	T
B	JHKP	**y**	125 ky tr	free	free	T
D	JHKP	y	125 ky tr	**fixed (obs.)**	free	T
E	JHKP	y	125 ky tr	fixed (obs.)	**no advance**	T
F	JHKP	y	125 ky tr	**fixed (B 0 ka)**	**free**	T
D_s	JHKP	y	0 **ka st**	fixed (obs.)	free	T
E_s	JHKP	y	0 ka st	fixed (obs.)	**no advance**	T
F_s	JHKP	y	0 ka st	**fixed (B 0 ka)**	**free**	T
B'	JHKP	y	125 ky tr	free	free	**H**
D'	JHKP	y	125 ky tr	**fixed (obs.)**	free	H
E'	JHKP	y	125 ky tr	fixed (obs.)	**no advance**	H
F'	JHKP	y	125 ky tr	**fixed (B′ 0 ka)**	**free**	H
D'_s	JHKP	y	0 **ka st**	fixed (obs.)	free	H
E'_s	JHKP	y	0 ka st	fixed (obs.)	**no advance**	H
F'_s	JHKP	y	0 ka st	**fixed (B′ 0 ka)**	**free**	H
E''_s	JHKP	y	0 ka st	fixed (obs.)	no advance	**S**

Table 2. Simulated ice-sheet volume ($\times 10^{15}\,\mathrm{m}^3$), the percentage~~the ratio (%)~~ relative to the present-day observed volume $2.91 \times 10^{15}\,\mathrm{m}^3$, and the root mean square of the difference in the thickness relative to the observation (m) B014 . Configuration correspond to the results for **v1** (using "standard" sliding coefficients), **v2** ($2\times$) and **v4** ($4\times$) are shown. B015 The volumes of other experiments such as D, E etc are identical to the observed value by definition. B073

	v1	(%)	(m)	**v2**	(%)	(m)	**v4**	(%)	(m)
O	3.08	+5.8	455.1	3.00	+3.2	454.9	2.93	+0.5	464.8
A	3.03	+4.2	444.7	2.96	+1.7	450.2	2.89	−0.8	459.6
B F $\mathrm{F_s}$	2.96	+1.7	447.1	2.81	−3.4	476.8	2.60	−10.6	558.3
B′ F′ $\mathrm{F_s'}$	3.08	+5.8	414.1	2.95	+1.3	418.9	2.79	−4.0	442.9

Table 3. Simulated changes in VAF (cm) relative to corresponding constant future climate experiments at 500 years from the present for the configurations B and F and their differences and the two configuration D and D′ and their differences.

	C1 − C0			**C2 − C0**			**C3 − C0**		
Config.	**v1**	**v2**	**v4**	**v1**	**v2**	**v4**	**v1**	**v2**	**v4**
B	−36.5	−41.8	−53.6	−77.1	−90.2	−108.8	−150.9	−169.2	−185.6
F	−32.4	−38.2	−54.7	−76.0	−91.5	−116.8	−156.0	−177.9	−200.1
B − F	−4.1	−3.7	+1.1	−1.1	+1.3	+8.0	+5.1	+8.7	+14.5
D	−26.0	−27.4	−30.3	−52.6	−56.6	−63.6	−111.6	−120.4	−137.9
D′	−19.9	−21.7	−24.8	−39.3	−42.6	−48.6	−74.2	−79.4	−89.3
D − D′	−6.1	−5.7	−5.5	−13.3	−14.0	−15.0	−37.3	−41.1	−48.6

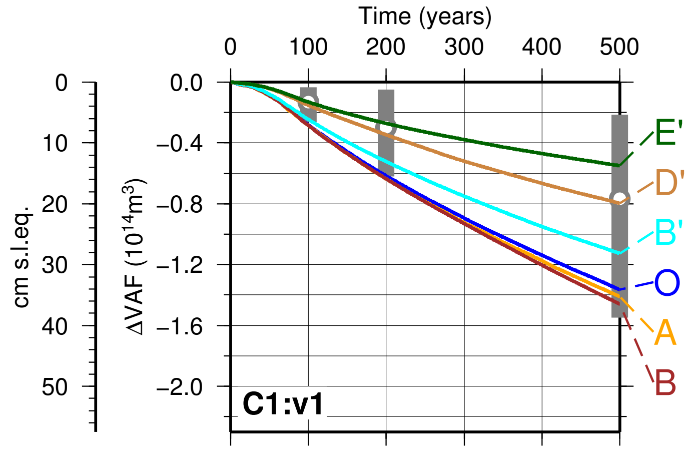

Figure 1. Simulated changes in VAF (volume above flotation, see the main text) obtained by future-climate runs under **C1** (A1B climate forcing), with "standard" sliding coefficient (**v1**), in terms of the difference relative to the result of corresponding constant-climate experiments (**C0**). Each line is a different experimental configuration of O (IcIES SeaRISE compatible), A, B, B′, D′ and E′.~~Simulated changes in VAF (volume above flotation, see the main text) obtained by future-climate runs under experimental configuration of O (IcIES SeaRISE compatible), A, B, B′, D′ and E′, in terms of the difference relative to the result of corresponding constant-climate experiments (C0). The results of C1 (A1B climate forcing) climate scenario, with "standard" sliding coefficient (v1) are shown.~~ The vertical gray bars indicate the range of results summarized in the SeaRISE (Bindschadler et al., 2013, Table 3) at 100, 200 and 500 years. The circles in the gray bars indicate the mean values of all the SeaRISE participants. *B074*

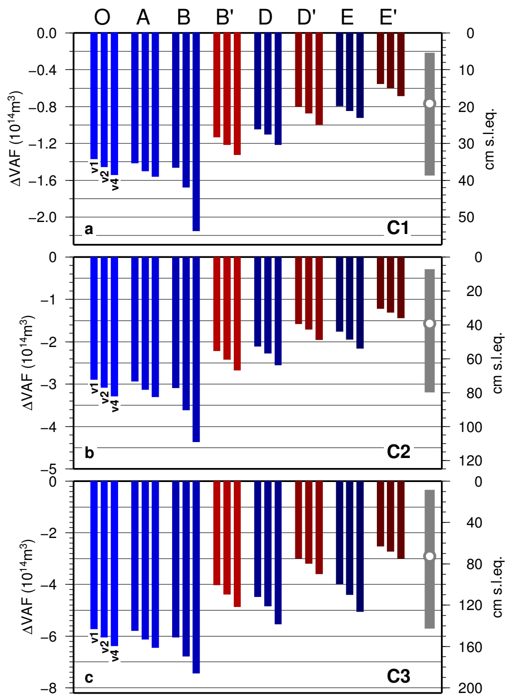

Figure 2. Simulated changes in VAF at 500 years from the present-day obtained by future-climate runs in terms of the difference relative to the result of corresponding constant-climate experiments (**C0**). The top, middle and lower panels are results of **C1** (A1B climate forcing), **C2** (1.5× A1B) and **C3** (2× A1B), respectively. Each panel contains the results of experimental configuration of O (IcIES SeaRISE compatible), A, B, B′, D, D′, E and E′. Three bars from left to right in each configuration correspond to the results for **v1** (using "standard" sliding coefficients), **v2** (2×) and **v4** (4×), respectively.~~Simulated changes in VAF at 500 years from the present-day obtained by future-climate runs under experimental configuration of O (IcIES SeaRISE compatible), in terms of the difference relative to the result of corresponding constant-climate experiments (**C0**), under experimental configuration of O (IcIES SeaRISE compatible), A, B, B′, D, D′, E and E′. Three bars from left to right in each configuration correspond to the results for **v1** (using "standard" sliding coefficients), **v2** (2×) and **v4** (4×), respectively. The top, middle and lower panels are results of run **C1** (A1B climate forcing), **C2** (1.5× A1B) and **C3** (2× A1B), respectively.~~ The vertical gray bars at the right indicate the range of results summarized in SeaRISE (Bindschadler et al., 2013, Table 3) at 500 years. The circles in the gray bars indicate the mean values *B077* of all the SeaRISE participants.

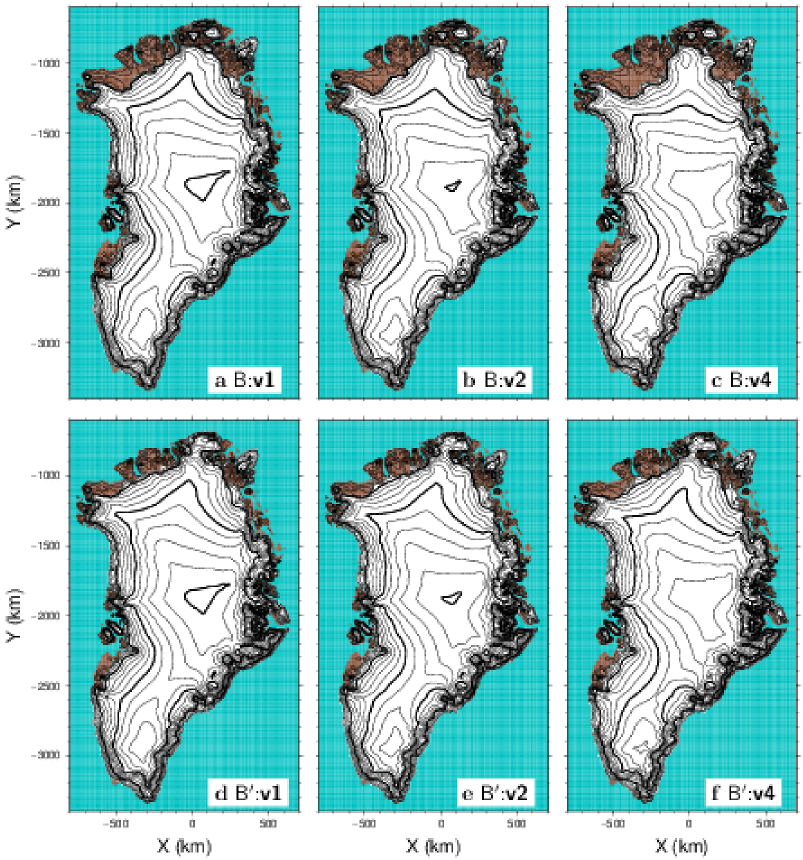

Figure 3. Simulated present-day surface topography obtained by experiments with free spin-up initialization and sub-melt sliding , B (upper panels) and B′ (lower panels). Contour intervals are 200 and 1000 m for thin and thick lines, respectively.

B083

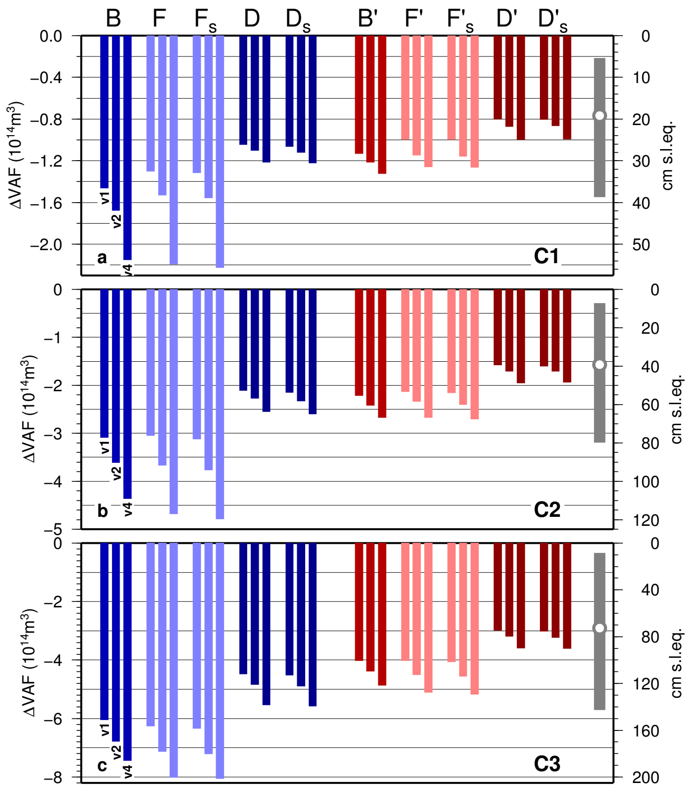

Figure 4. The same figures as Fig. 2 under experimental configuration of B, F, F_s, D, D_s, B′, F′, F'_s, D′, D'_s, respectively. The left five experiments apply Tarasov and Peltier (2002) while the right five apply Huybrechts and de Wolde (1999) for the surface mass balance computation, respectively.

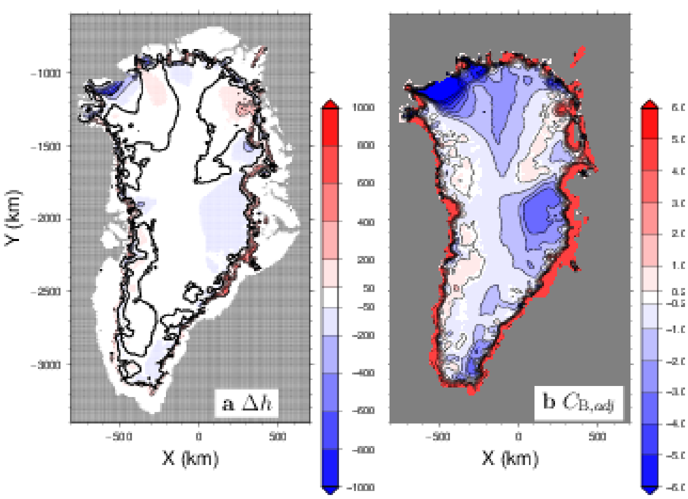

Figure 5. The result of the 'inversion' procedure: (a) difference in the surface elevation (m) relative to the present-day observation (b) 'inverted' basal sliding coefficient field in terms of fraction relative to the value of the case **v2** in logarithmic scale.

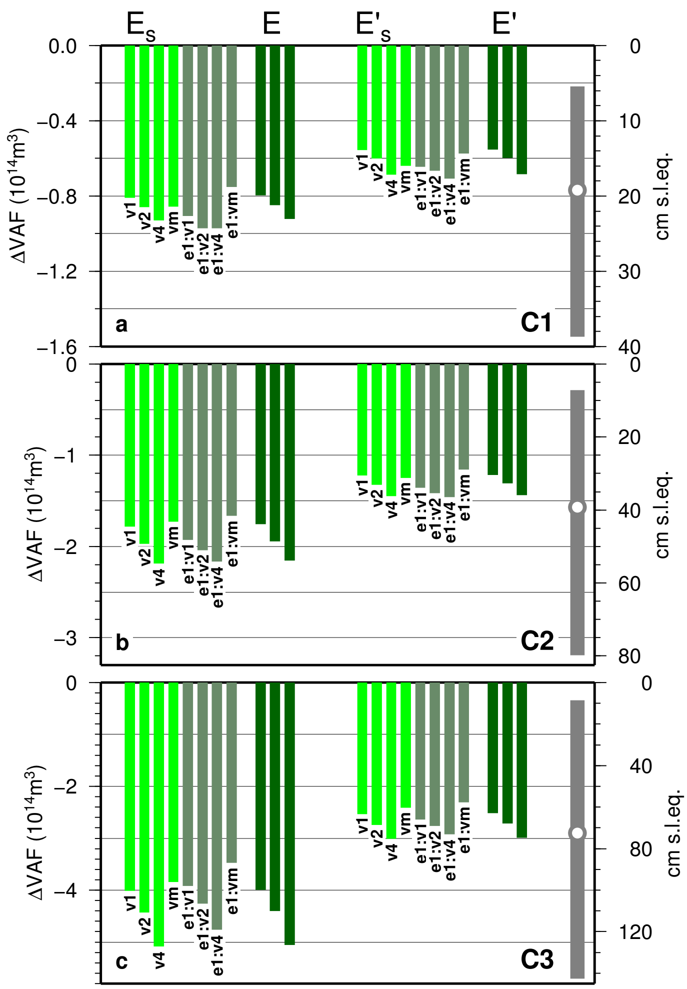

Figure 6. The same figures as Fig. 2 under experimental configuration of $\mathsf{E_s}$, E, $\mathsf{E'_s}$, $\mathsf{E'}$, respectively. The group on the left hand side applies Tarasov and Peltier (2002) while the right hand side applies Huybrechts and de Wolde (1999) for the surface mass balance computation, respectively. The configuration $\mathsf{E_s}$ and $\mathsf{E'_s}$ contain eight different combinations of the basal sliding coefficients (**v1**, **v2**, **v4** and **vm**) and the ice enhancement factor ($E = 3$ as default and $E = 1$ indicated as **e1**).

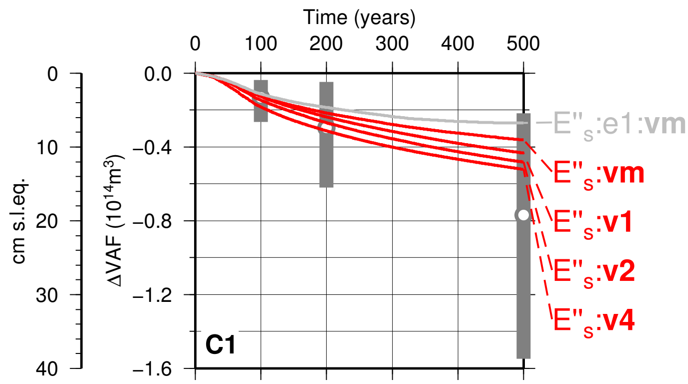

Figure A1. Simulated changes in VAF obtained by future-climate **C1** under experimental configuration of E''_s with uniform sliding coefficient cases **v1**, **v2** and **v4**, with the inverted non-uniform sliding coefficient case **vm**, and that with ice enhancement factor $E = 1$ case **e1**:**vm**, respectively.~~using three different sliding coefficient (**v1**, **v2** and **v4**)~~ .

A003