We have revised our manuscript 'Design and results of the ice sheet model initialisation experiments initMIP-Greenland: an ISMIP6 intercomparison'. We would like to thank the reviewers for their constructive comments that helped to improve the manuscript.

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

Anonymous Referee #1

Summary
This paper summarizes models, methods, and the results of ice sheet model initialization experiments for the Greenland ice sheet, which are (eventually) targeting the ISMIP6 contribution to CMIP6. The broad motivation for the exercise is the recognition – largely motivated by previous, community-endorsed ice sheet model intercomparisons – that decadal and century scale simulations conducted using present-day ice sheet models are keenly sensitive to the model initial conditions (so much so that transients in the initial condition often swamp the ice sheet model response to the prescribed climate forcing of interest). In this paper, the different initialization methods most commonly used by the ice sheet modeling community are discussed, as are the perceived pros and cons of the different approaches. A set of forward model experiments are conducted, which are intended to clearly expose the magnitude and trend of (1) model initialization transients under steady forcing and (2) model transients under idealized climate forcing, here applied in the form of surface mass balance (SMB) anomalies.

While the results of the simulations and paper are not necessarily in themselves scientifically compelling, they serve as an important record and waypoint for the purpose of documenting the current practices and capabilities of different modeling groups, as well as the differences in standard model outputs when applying these different models to the same set of experiments. Therefor, while this paper does not necessarily represent any major scientific breakthroughs, I think it is worthy of publication in TC purely for the purpose of clearly documenting where the ice sheet modeling community stands on these issues at this time. The paper represents the combined and significant efforts of a large number of independent ice sheet modeling groups, including the countless hours spent on model development and testing prior to applying the models to any experiments.
I disagree a bit with the way some of the conclusions for the experiments have been presented or "pitched" here. For one, it's not clear to me that the spread and/or size of the transients in the steady-forcing initialization experiment do actual show improvement over previous efforts. This could be due, in part, to the way the data are presented

(discussed further below). It could also be that a simple quantitative metric from this study, relative to previous studies, needs to be included to support this statement. Further, the fact that the perturbation experiment uses anomalies applied on top of the SMB used for initialization is already an indication that we aren't looking at an apples- to-apples comparison of response between models. For example, if an actual SMB forcing (as opposed to a set of anomalies) was prescribed for the perturbation experiment, the spread in sea-level-equivalent mass loss shown in Fig. 8c would likely be much larger. I don't necessarily disagree with this choice, but the summary statements don't seem entirely accurate.

One obvious place for improvement is in the conclusions, which currently do not provide any clear guidance as to a "path forward", in the sense of what did we learn here and where should the community be working towards in order to address some of the issues and problems discussed in this paper. It seems like one obvious conclusion that could be stated more clearly is that either using data-assimilation OR spin-up approaches in isolation is not a long-term solution. Rather, using some combination of these two approaches is going to be necessary if the goal is to initialize models to have both a realistic initial state while simultaneously minimizing unrealistic transients (good) or representing actual observed ice sheet transients (better). There are some references (noted below) that could be included for these types of approaches, which aren't currently being applied at the whole-ice-sheet scale, but which should be viable for doing so in the near future. This would help to end the paper on a more positive, forward-looking note.

Below, comments are tied to specific points in the submitted text using the key "X, Y", where X refers to the page number and Y refers to the line number.

Major Comments

1,18: I'm not sure I really agree with the last sentence. If the authors really think this is true, then they should back it up quantitatively somewhere in the text. Is the drift referred to here for the init. and steady-forcing experiment? The SMB anomaly experiment? Both?

OK, the sentence has been reformulated. We refer to the drift in the control experiment, where models that can be compared (because they have also participated in the SeaRISE experiments) all show less drift.

2,3: "encapsulates most of the modeling decisions . . ." – I don't entirely agree with this. A major "modeling decision" would be whether or not I choose to use SIA or a Stokes model, but I can imagine using the same init. procedure for both if I chose to do so. It might make more sense here to just point out that the decisions made during the init. process have a very strong impact on any model outputs that follow from using that initial state. I think the point you are trying to make here is simply that these choices are critical as they have very large consequences for "projections".

Yes, agreed, but we also wanted to emphasise that many aspects of the modelling are revealed when looking at initialisation. To follow on the given example, one wouldn't really initialise with the SIA version of a model and then run that state forward with the Stokes version. In other words, many of the modelling decisions have to be made before initialisation. Replaced "encapsulates" by "therefore reveals".

2,28-30: The last sentence here is not really true. For example, there are fairly extensive "internal" constraints available in the form of radar layers, dated at ice core sites and tracked over hundreds of km of the ice sheet. Even though we are not regularly using these data now as constraints, we should be, or could be in the future. Maybe this is a point to make in the conclusions / future directions part of the paper, with appropriate references to some of the work by Joe MacGregor (which is particularly relevant to Greenland)?

OK. We have added a sentence to discuss this additional information in the text. A discussion point on further use of the radar layer data has been added to the conclusions.

3,28-30: "All three methods . . .". Note that these could / can all be combined, and this is probably the future direction we as a community should be moving towards. It might be worth noting that here, even though none of the currently participating models do this (and then discuss this again in the conclusions by pointing to a few papers that are exploring what would truly be called data assimilation – that is, trying to assimilate observations of change (like dh/dt) and/or fields that include a record of change over time (like temperature, layer shapes)).

OK. We have added a point in the conclusions to discuss the combination of methods and assimilation approaches.

3,7-33: In general, I think the major problem being discussed here could be stated a bit more succinctly. That is, the spin-up approach provides an initial condition that has a realistic internal TRANSIENT with respect to some applied external climate forcing, but also generally gives us an initial STATE that is a poor representation of the present day. The current incarnation of optimization approaches does the opposite: we get a good representation of the present-day ice sheet state, but a very bad representation of the internal transients. The solution going forward should be to formally combine these two seemingly at-odds approaches through improved data assimilation approaches.

We discuss this problem in detail in the first two paragraphs of section 5 and have added additional material as an outlook what future research should aim for.

5,2-3: It is probably important to be explicit about the "lineage" of models here. While there are 17 group contributions, more than half of these are from "repeated" models (i.e., 9 of the models listed are either ISSM, PISM, or SICOPOLIS), so in effect, there are only really 11 different models represented here.

OK. Added "There is some overlap between the code bases used by different groups, with ultimately 11 individual ice flow models. However, the same model used by different groups (with varying datasets and initialisation procedures) may lead to very different results".

6,2-23: It might be nice to point out that the division of the three initialization strategies is a bit arbitrary, and not perfect. For example, most of the models that use data assimilation also use some form of spin-up (e.g., for ice temperatures). Also, the "DAs" method is really a sort of "ad hoc" approach to assimilation – instead of using formal methods to iteratively minimize a PDE-constrained, observation-minus-model cost functional, these approaches are minimizing the observation-minus-model difference using some other method (i.e., adjusting the basal traction locally to minimize the mismatch with surface elevations). I appreciate that some categorization needs to be made here to bin these approaches, but it's worth pointing out that the categorization is far from perfect. It's actually quite fuzzy and this is because it's starting to be obvious that some combination of these different methods is required.

Agreed. We have added additional material to clarify that the separation is somewhat arbitrary and that combinations exist and should be further explored.

10,5-21: It's not entirely clear to me what the purpose of this section is. It's missing a clearly motivating intro / closing sentence to make that clear.

The purpose of this section is to evaluate the SMB forcing used by different models and includes figures 3-5. This intent is given in the paragraph just before: "As an important input for the ice sheet simulations, we evaluate the implemented SMB of the different models"

Figure 8: If you are going to keep panel (a) of this figure as is, then I think you also need to show a 2nd figure where you normalize by the initial volume (in SLE). As shown, these trends all look very reasonable but this is because you are showing the rate of absolute, rather than relative change. When normalized by the initial volumes, we would more easily see the volume changes with the more relevant units of cm rather than m. In panels (b) and (d), what time periods are the trends calculated over? In panel (c), the vertical axis label is "mass change". For this, a positive sign would suggest ice sheet growth. Should the wording be changed (e.g., "mass loss") so that it is clear we are looking at mass loss (which is obvious if we are talking about SLR)?

The purpose of panel (a) is primarily to display the range of initial ice mass (vertical scale), but also to give an impression of the overall mass evolution. Since all mass curves in (a) are near constant or monotonically increasing or monotonically decreasing, the information in panel (b) gives a very good idea of the magnitude of mass change (vertical scale in mm!). Normalising by the volume would be a different way of looking at the data that we don't favour for this comparison. E.g. models with too large initial mass and large mass change would in relative terms tend to look 'better' than they are.

We have changed the labels in panels (a,b,c) as suggested and also the sign of the values in b, to match a. Note, the period of mass change (100 years) is already given in the caption.

16,9: "inconsistencies between ice velocity and geometry datasets". The reference to Seroussi et al. won't help the unfamiliar reader here. I suggest you just be explicit about what the problem is: the optimized model velocities, while possibly being consistent with observed surface velocities, conspire with thickness errors to give a flux divergence that is wildly different than and unbalanced by the local SMB. This is where the large and *unrealistic thickness transients come from when conducting a forward run following initialization using a velocity-based-only optimization approach. Note that the uppermost panel in Figure 10 shows this nicely – the very noisy, large amplitude thickness adjustments in the ISSM model are a manifestation of this (relative to the much more subtle thickness transients for the spun-up ICIES2 and PISM models).*

OK. We have included a statement as suggested to name the problem explicitly and added to the discussion of figure 10.

19,16-18: This is left hanging a bit. As noted above in the summary comments, instead of simply pointing out that none of the methods discussed here prove to be optimal for initialization, you could take the opportunity to discuss recent efforts that target these deficiencies (even if they are not yet recognizable at the full-ice sheet scale) and push for their exploration, development, and wider adoption. I'm thinking in particular about formal efforts that attempt to include additional constraints and / or assimilate time dependent observations (for example, Goldberg et al., TC, 7(6), 2013; Perego et al., J. Geophys. Res., 119, 2014).

OK. We have added to the discussion of these points and references, and suggest further exploration of these approaches

19,20: "DAv is the method of choice for short-term projections." I strongly disagree with this statement. Unless you are talking about applying anomaly forcing (as in the perturbation experiment discussed here), this is absolutely not true. Most often, these are going to have the worst and most non-physical thickness transients when stepped forward in time under realistic climate forcing. Only if that climate forcing has been taken into consideration during the optimization process do these have a hope of minimizing non-physical transients. This can clearly be seen in the top left figure of Figure 10 (the ISSM, DAv initialized model has a noisy, large amplitude thickness transient that is very unphysical). In general, this paragraph is not true unless you are talking about anomaly forcing experiments, which I think in general, the community is trying to move away from (for example, an initial condition generated to work well only when applied in an anomaly forcing experiment is of little use for coupling to a climate model, since climate models are generally required to conserve mass, and anomaly forcing does not do that).

Agreed. Reformulated to explicitly limit to cases of anomaly forcing, which is of interest here. This is how we have forced the models and what will very likely be

used for the ISMIP6-CMIP projections, because it is not feasible to initialise to a large number of different GCMs.

20,7-9: I am not yet convinced that this statement – here and in the abstract – is supported by the results shown in this paper. It could be the case, but based on Figure 8a, it is very hard to judge. We would have to see Figure 8a normalized by initial ice sheet volume to be convinced of this. Also, if this statement is going to be supported, it would be nice to do so quantitatively based on previous intercomparison results (e.g. compare the spread from a similar experiment from SeaRISE with that from this study).

OK. We have reformulated this statement. Models that can be compared (because they have also participated in the SeaRISE experiments) all show less drift.

20,11-13: "If this trend continues . . .". While I agree with this statement, I don't think it is for the same reasons as discussed in this paper. If there's any reason this trend will continue to improve, it's that better formal optimization and initialization methods are being developed and applied to ice sheets. That is, methods that take into account not only observational constraints on the current ice sheet state, but also observational constraint on short (i.e. dh/dt) and longer (i.e., temperature profiles) term trends that are inherent to the ice sheet. Again, I feel like there is a bit of a missed opportunity in the conclusions of this paper to point out and promote some of these new directions and methods that should effectively minimize many of the problems highlighted and discussed in this paper.

OK. We have added to the discussion pointing out further directions of research.

Minor / Editorial Comments

Title: Check that the spelling of "initialisation" is correct? Autocorrect seems to prefer "initialization".

In BE both appear to be possible. We prefer "initialisation" in line with the other British spellings.

1,2-3: Should summary refs. for the SeaRISE and Ice2Sea projects be included here? Similarly, should ISMIP6 and CMIP6 efforts here point to some generic reference publications?

Good point, but no references allowed in the abstract. Included in introduction instead.

1,6: ". . . to estimate the associated uncertainties." (in what? Model outputs?)

OK. Added "in modelled mass changes".

1,10: schematic -> idealized ?

OK. Also all other occurrences.

1,13-14: Is there really a wide diversity in the data sets and boundary conditions used? It seems like for the most part, the models are using similar datasets and boundary conditions (for the latter, I mean w.r.t. "observation-based" boundary conditions – I understand that things like basal boundary conditions, which include assumptions about sliding, thermal state, hydrology, etc., probably DO vary widely).

OK. Removed "wide". The intention is to make clear that the diversity that exists in the community is represented here.

1,21-28: The initial reference to EISMINT, followed by a listing of many other non-EISMINT intercomparisons, is confusing. I understand that you only mean to use the categorization that EISMINT suggested, but it could be read as if everything underneath (e.g., ISMIP-HOM, MISMIP, etc.) was also "part of" EISMINT. Suggest rewording this slightly?

OK. Reformulated to "EISMINT and later following comparisons include".

1, general: Do CMIP and ISMIP6 need to be defined here?

Thanks, definitions are included now.

2,10: "removing mass at the margins" – this is a little unclear, as SMB also removes mass inland (although maybe this mass is transferred to the margins, e.g. as melt).

OK. Added "predominantly" to clarify this point.

2,32-34: I would be more emphatic about this point – without very special care, the transient from initialization can entirely dominate the response in decadal / century scale projections.

The wording "are strongly influenced" seems appropriate to us.

2,41: When you say run forward in time here, it might help to add detail about the timescale you are thinking about (e.g., thousands to tens of thousands (more?) years, rather than decades or centuries).

OK. Added "for tens to hundreds of thousands of years".

3, 2: "the model's state is internally consistent" – It isn't clear what you mean by this. The model's internal state is always internally consistent, regardless of the type of spin-up you do. I think what you mean is that models that go through a spin-up are, at any point in time, closer to being in equilibrium with the applied climate forcing, or at least contain internal transients (e.g., in temperature) that are more consistent with external forcing transients. I appreciate this is a subtle difference to try to express.

OK. Reformulated to "the model's state is defined as a consistent response to the forcing". We believe this is the decisive point, while equilibrium with the forcing is not required/ often not desired.

3,10: "by inversion" – be a bit more specific here. I think you mean formal, PDE-constrained optimization?

OK. Reformulated to "by a formal partial differential equations constrained optimisation".

3,16-18: Other "errors" that are forced to be accounted for by optimized parameter fields include observations and model state variables that are entirely ignored in the optimization process. For example, one of the biggest reasons current optimization *approaches lead to such large, unphysical transients is that they are ignoring whether or not the temperature (and hence rheology) is consistent with observations (and as such, all of that uncertainty gets pushed into the basal parameter optimization).*

OK. Reformulated.

3,19-22: Here, I think you need to be explicit in noting that the thing that is being adjusted is the bedrock elevation (i.e., we have good constraints on the ice sheet surface elevation, but much less so with the bedrock elevations. So the thickness is adjusted with the assumption that the uncertainty is the bedrock location, not the upper surface location).

The method discussed here (and in Pollard and DeConto 2012) doesn't involve modifying the bedrock elevation. The models participating in initMIP-Greenland only adjust for the basal friction coefficient in their data assimilation of surface elevation (see also the model descriptions in the appendix).

4,5: "to a large perturbation" – add "in SMB forcing"? or "in climate forcing"?

OK. added "in SMB forcing" .

4,17: ". . . that all boundary conditions AND FORCING remain constant in time." ?

OK.

Table 1: "schematic change of SMB forcing" -> "idealized change in SMB forcing"

OK.

Table 2: Is the list of "contributors" consistent with co-authors on the paper, or is it supposed to be more of a list of co-authors for the respective modeling efforts?

The latter. There is a lot of overlap, but not all contributors are necessarily co-authors on the paper.

6,12-14: Note that SP approaches are generally also favored when the goal is to include an ice sheet model in a coupled climate model?

OK. Included "SP approaches are also generally favoured when including ice sheets in coupled climate models.", before "In two groups …".

6,21: Formally speaking, SMB is not a boundary condition, but rather a source term in the mass conservation equation.

OK. Removed "boundary condition".

7,7: Suggest: ". . . that serve to evaluate the response of these initial states to ..."

Thanks. Reformulated as suggested.

7,10: "boundary conditions and assimilation targets" (plural)

OK.

7,17: ". . . analyzing models WITH RESPECT TO their individual . . ."

OK.

8,8: "prescribe a fixed ice mask" – clarify what you mean here. I think you mean that they just zap away any ice moving past a certain location (e.g., present-day extent)?

OK. Added "and prevent any ice growing outside".

Figure 1 caption: "A complete set of figures . . . IS given . . ."

OK.

9,1: "much smaller than to area." – provide a percentage value here

The volume difference between the two defined areas is 0.3 % while differences in area are 8.2 %. These numbers have been included in the manuscript.

9,1-3: I think the summary point here is that the areal expanse of the modeled ice sheets differs quite a bit w.r.t. observations, but that in terms of overall ice sheet volume, the *differences are smaller (because even if you have an extensive error in the areal coverage, that marginal ice is presumably pretty thin).*

This is true for the observed (see response to last point) but not for the modelled results (15% max error in area and volume alike). Models that overestimate area typically exhibit thicker margins than observed, accommodating additional volume.

9,10: Again, SMB is not really a boundary condition in any formal sense.

OK. Replaced “boundary condition” by “input”.

9,13: RCM = regional climate model? Not yet defined?

This has already been defined at 7,21.

Figure 3: Note whether or not these 3 samples are from the middle of the distribution or if they span the distribution?

OK. Added “spanning the distribution of ice thickness error (see below)”

11,15: “good agreement with the observed” – awkward

OK. Added “SMB”

11,15-16: “. . . is more important . . .” Not clear what “more important” is in reference to here. More important to what?

OK. Added
“to reduce the mismatch with measured SMB”

Figure 5: The units on the axes of figures in panels b and c are hard to read. Enlarge?

OK. The labels have been enlarged. Same for figure 7.

Figure 6 caption (and elsewhere): “Root mean square error (RMSE) ...” (define “RMSE” used in figure axes labels).

OK. Modified here and in three other places.

13,9: "occurring at the margins" – be explicit here that what is important is that these errors are occurring over a fairly small fraction of the total ice sheet area?

OK. Reformulated to
"occurring at the margins over a relatively small fraction of the ice sheet area are weighted less"

13,17: "internal consistency" – this phrase is used fairly often without it being very clear what is meant here. I think in most places, it simply means that the long timescale ice sheet physics (like temperature) are closer to being in equilibrium with the relevant climate forcing (or have a reasonable and realistic transient).

What was meant by "internal consistency" was really that the dynamics of the system are a consistent response to the forcing and not a response to the initialisation. We have removed "internal" in all cases and clarified what is consistent with what in all cases.

14,1: ". . . at the expense of a larger discrepancy with the observed geometry." As noted above, more recent efforts include attempts to improve on this problem by including additional observational constraints beyond velocities (e.g., like the SMB forcing). See additional related discussion in Major Comments above.

This is discussed with additional references included in section 5.

14,9: "for almost any given rheology." – You may need to expand on this point for the non-initiated. What you mean is that you can generally get a good match to observed velocities by simply putting all of the motion into the sliding field and ignoring the fact that you might have the internal rheology entirely wrong.

OK. Added
", as all the uncertainty (including unknown rheology) is compounded in the basal sliding relation."

Figure 7: The "v" and "s" symbols here are very hard to see.

OK. We have increased the font size of the symbols.

15,2: "Recent MODELED mass trends . . ." ?

Yes. Included 'modelled'.

15,9: "which is currently not available" – Realistically though, if the data was available, would most of the models discussed here be able to apply it in a useful way? It's not really just the lack of data availability that is the problem here but also that the models aren't really in the position yet to make good use of these data.

We agree. That is why our original statement implies not only missing data but also missing process understanding and implementation ("realistic outlet glacier dynamics and ocean forcing"). Not changed.

15,10-13: And, the models trying to do hindcasting experiments generally still suffer from the same initialization problems you are focusing on here (either getting the initial ice sheet state right, or the trends right, but not both).

OK. Reformulated to
"suffer the same limitations of observational data sets with short time coverage, uncertainty in external forcing, limited knowledge of processes responsible for dynamic outlet glacier response and the initialisation problems discussed here."

15,20-22: ". . . but more often . . . during initialization (i.e., the trends are dominated by the model's relaxation following an initialization "shock")."

OK. Included, but reformulated to "(i.e., the trends are dominated by the model's response to the initialisation, not to the forcing)". We prefer not to use the term "shock".

16,30: Close with something like: "Simply put, by design a larger ice sheet will be subject to larger rates of mass loss." (note that one could try to correct for this by normalizing rates of mass loss relative to initial ice sheet volumes).

Sentence has been added as suggested.

We are not in favour of normalizing to initial ice sheet volume. It arguably reduces the model spread, but for the wrong reasons.

19[20],8: suggest: ". . . in other words, the models largely agree in their representation of the ice dynamical response to the applied SMB-anomaly forcing."

OK.

19[20],10-11: I don't know if I would call the range of approaches "wide". A more accurate description might be "representative".

OK.

19,20: "at the expense of long-term continuity." I don't follow what this means.

OK. Reformulated to
"at the expense of including long-term processes", which should become clear in context of the sentence before.

19,35: "differences in model ice density". I don't think this was discussed anywhere in the paper up until now.

We have added some additional information on how SLE is calculated (including differences in density) in the description of figure 8, where it already occurred once in caption.

Anonymous Referee #2

Review of Goelzer et al. "Design and results of the ice sheet model initialisation experiments initMIP-Greenland: an ISMIP6 intercomparison":
This manuscript describes the efforts of the ISMIP6 project to summarize various methods for initializing models of the Greenland Ice Sheet (GrIS) in preparation for experiments or projections of change. The impact of initialization is important as evidenced by previous ice sheet model inter-comparison (MIP) efforts, whose results were clouded by the 'uncontrolled-for' use of various initialization techniques. One

impact of this is that initial GrIS conditions for projections across these earlier efforts varied widely, from conditions that (1) were constrained by the data assimilation and inversion techniques to look almost like reality to (2) initial conditions that resulted from long freely-evolving equilibration simulations. This spread had a potentially significant impact on subsequent projections of sea level change.
Because of this issue I place value in this manuscript, which steps back to try and clearly illuminate the types of initialization techniques and their impact on perturbation experiments. I think as a survey of these techniques, this manuscript will be interesting to ice sheet modelers - including those who contributed to this MIP. In the following, my comments (which ignore minor grammar/editorial issues for now) are intended to (hopefully) improve the MIP by deepening analyses and interpretation of inter-model differences in the context of difference model choices (the main point of MIPs). In the few cases where I single out individual model results, be aware that I'm not criticizing these models/results per se, but only trying to use them to motivate a more general analysis. Finally I welcome any counter-arguments, if the authors feel I'm incorrect in any comments I've made.

Comments:

P3L12:"Changes in ice sheet geometry generally cause changes in atmospheric conditions over the ice sheet, and hence changes in SMB." Suggest that the word "feedback" be used here.

Yes, we use 'feedback' in the sentence directly following P3L12.

P3L13: "the most important effect is the height-SMB feedback" -> "an important effect is the height-SMB feedback" (other feedbacks aren't necessarily well-enough explored to make the 'most important' conclusion, in my opinion)

OK, reformulated as suggested.

*P3L17: for non-experts, perhaps also note for context the climatological fraction of total ice flux that comes from surface melt versus marine loss (instead of the fraction of current mass loss *trends* that arises from these two terms)*

Thanks for the clarification. The balance of processes is indeed what we meant to describe. The sentence has been reformulated.

P3L27: "This is a very short period. . .": Suggest adding some interpretation as to why these divergent timescales make things difficult.

OK, added a sentence to clarify that problem.

P3L32: These two subsequent paragraphs (short-term vs. long-term projects) describe an issue that is similar to the difference between weather forecasting (an "initial value problem") and climate prediction (a "boundary value problem"). The difficult intermediate timeframe in the weather/climate context (seasonal->decadal prediction) is similar to the intermediate decadal->centennial timeframe in the ice sheet context. In both intermediate timeframes, it becomes unclear which technique (or blend of techniques) to use. I suggest describing this analogy to place the problem facing ice sheet modelers in the context of similar problems from other fields.

OK, added a sentence to elude to this analogy.

P3L32: suggest reordering this section to more clearly separate discussion of 'long- term' versus 'short-term' simulations and the initialization techniques used for each. As it stands the discussion mixes long and short time scale simulations a bit too much.

We are not really mixing time scales here. The first paragraph P3L32 describes what we want to do: project evolution starting at the present to the (100 year) future. Then follows a description of the two/three predominant approaches used to initialise to the present day, which have different typical time scales attached. We have tried to make that clearer by replacing "used" by "developed" in "Models developed for long-term and paleoclimate simulations".

P4L15: "limitations in observations" -> "uncertainties in observations"?

OK. Reformulated as suggested.

P4L17: "transferred to" -> "masked by alterations to. . ." ..?

Not changed. Important to say that errors are propagated to the optimised parameters.

P4L24: Suggest a brief statement "Given the wide diversity of ice sheet initialization techniques. . ."

Thanks. Included as suggested.

P4L24: "The goal of initMIP-Greenland is to document, compare and improve the techniques used by different groups to initialise their state-of-the-art whole-ice-sheet models to the present day. . .". This implies initialization to a transient ice sheet state (given anthropogenic forcing). For example, it appears that Goelzer et al. (2012) find a ~0.7m GrIS SLR commitment if CO2 concentrations are capped at present day levels. Other studies I am aware of also find similar levels of SLR commitment to present-day climate. This arises from both historical warming relative to the preindustrial Holocene (which is the climate state most consistent with the current GrIS geometry) and also future committed warming, in very roughly equal parts. I think a discussion of this point is critical in order to put the stated goal, of initialization of ice sheets under present-day forcing/assimilation, in context. As one thought experiment: if the above two papers are correct in their commitment estimates, a perfect spin-up to equilibrium under perpetual present-day forcing should probably produce a present-day GrIS that is ~15% smaller than that observed. Another: a perfect DA procedure should result in an initial ice sheet with a transient trend equivalent to the recent historical average trend. Thus: would it be safer to remove "to the present day" from the statement to retain generality with respect to the chosen 'time of initialization'? Or state that initialization to present day is a choice driven largely by availability of observational data, which is required in the case of DA/DAv initialization techniques?

This question has been discussed further below in the manuscript in the section on the transient experiments (P16). We have made clear that matching the observed imbalance is not really possible in the present framework. The period we refer to as 'present-day' is necessarily a bit loosely defined because we wanted to give freedom to the modellers what year to initialise to.

Table 3: Some rows are identical in their entries. For example, DMI-PISM1 and DMI-PISM2. The difference in these types of rows should be identified, so the reader can hopefully identify why they produce different results.

OK. Have included further details for DMI-PISM, and for other models that have identical rows (UAF-PISM 1-3 and 4-6).

P9L5: I think these differences in approaches are very important points. It would be useful to be able to cross-list the initialized states (e.g. in Figure 2) against the amount of 'constraining' that the modeling groups used to obtain that state.

We agree in principle with the idea of providing this information. However, we don't see how the amount of 'constraining' should be quantified in a meaningful way. This is a problem we face with such a diverse ensemble, which we discuss at different places in the manuscript.

Figure comment: several colors in scatterplot figures (e.g. Figure 2) are very similar. For example, ARC-PISM and UAF-PISM3. Even on a good computer screen it is very difficult/impossible to tell the difference. Is there any way to label each dot (or replace each dot with a letter or number, perhaps also associated with a unique color)?

The presentation of the data is always a compromise between showing the ensemble as a whole and showing individual models. Our choice is deliberate and emphasises the ensemble, while still making it possible to trace back information on an individual model if desired. The data in Fig 2, for example, is available in the supplement for readers who want to know the details.

General presentation comment related to above 2x points: allowing users to interactively explore the MIP results would be incredibly useful, if The Cryosphere would allow links to supplementary interactive public online plots (perhaps hosted to/linked via the ISMIP6 website). As just one example: for each online plot, being able to isolate the the DA/DAv/SP contributor 'pools' and allowing an interactive data tip to identify model names upon hover-over, would be fantastic. One reasonably easy way of doing this is Plotly, I'm sure there are others. https://plot.ly/python/line-and-scatter/, "Line and Scatter Plots" example.

Thanks for the suggestion, which we are currently exploring. As stated in the manuscript, the data will be made publically available and users will be able to display the data as desired.

*Suggestion: would the contributors consider providing a mask of grid points on the *terrestrial margins* of their ice sheets that are (unphysical, at steady state) accumulation or (physically consistent) ablation zones? In my experience, it is possible* *for the terrestrial margin points from RCMs to potentially display positive SMB (presumably due to RCM bias). If a significant number of contributors to this MIP are using SMB fields that include these types of unphysical terrestrial margin accumulation zones, an important discussion could be: how these are handled and how the presence of this unphysical margin behavior could affect future simulations.*

It is not entirely clear to us what the reviewer's suggestion is aiming for and how that is related to the manuscript. We interpret the question as largely evolving around the issue of how to use climate model output to force an ice sheet model. From the perspective of this paper, this is an issue that needs to be resolved by individual modellers. In some cases, climate model biases are much larger and need different strategies than in other cases. This question will become very important for ISMIP6 when we design the ice sheet projections, but arguably has been largely circumvented in the present anomaly forcing approach.

P9L15: "Again, a good match with the observed ice extent is more important than the SMB model itself.": this statement, as a value judgement, is unclear to me.

See similar point by reviewer 1. We have added "to reduce the mismatch with measured SMB" to clarify the intention of this sentence,

P13L14: "However, it is noticeable that DA models that have been initialised with one data set show lower errors when comparing with that specific set of observations.": this seems a reflection of a well-known statistical tenet, that one can't use training data as validation data. Perhaps this similarity should be more obviously stated for readers. Put another way: to what extent is comparing against observations useful, when in many cases (DA/DAv) these observations may been already used as part of the initialization procedure?

We believe there are two sides to this issue that are both represented in the manuscript. The first is the point about training and validation data made at P13L8 and P14L9. However, to evaluate the quality of an assimilation process, one should in fact look at how well it can reproduce the training data set.

Figure 4 (and general question): if an ISM is allowed to grow outside of observed boundaries, but receives SMB from an RCM that is limited in extent to the present-day ice ice extent, how is the SMB calculated outside of the present-day ice extent?

This is a well-known problem, but the solution is left to the individual modellers. Typical approaches consist of parameterising the SMB or its components as a function of surface elevation.

Figure 6: Models for which SMB is prescribed to be strongly negative outside the current ice extent will also show low RMSE thickness. I'm aware of at least one participating model that takes this approach. I would be surprised if other well-performing spin-up models did not do the same. Models that take such an approach should be identified so that their good RMSE thickness performance can be judged against the strong constraint of very negative SMBs outside of current ice extent (which will likely, by basic ice dynamics principles, translate into a pretty good ice sheet geometry).

We are definitely aware of this and related questions of 'fairness' for model evaluation and caution the reader in this regard (see e.g. again P13L8). However, a negative SMB is also a very strong condition in the real world for ice not being present in certain places. The model descriptions in Appendix B generally include this information, but approaches are too diverse to allow for a binary flag.

General comment: it is difficult to assess the an unbiased spread of results when a few models are represented by multiple contributions. I'm not sure how one would remedy this, but it leaves the reader a little confused - especially when the difference between some contributions from the same model is not immediately clear (see previous comment).

Being well aware of this problem, we never attempt to present the results as unbiased. Furthermore, the problem runs deeper, because some now separate model families have common ancestors that would need to be revealed.

P16L16: ". . .relatively small mass change for most of them over the course of the 100-year experiment. . .": when contrasted against observed/projected sea level rise rates, I suspect many of these rates of change, even after 100 years, are very large (for example, relative to realistic future GrIS SLR rates). One way to better show ctrl rates of change would be to show the anomaly of each model, relative to the initial volume (which is already represented anyways in Figure 2).

The corresponding numbers are shown in Fig 8 panel b and given as range in the text (~-20 to +25 mm when outliers are removed). We wanted to represent the spread of initial mass in panel a and have complemented that with mass change in panel b. Please also see comment to reviewer 1.

P16L19: ". . .when nine obvious outliers are ignored": it seems that the role of a MIP would be to explain why these outliers exist instead of discarding them. For example, did these models use DA/DAv/SP?

These models (except for one) have already been discussed as outliers in context of figure 4, so this was not repeated here. However, we have added "discussed in context of Figure 4" to remind the reader.

P16L21: "In some cases of the ensemble, the modelled background trend arises from transient forcing of SMB and temperature over the past, but more often it is due to inconsistencies introduced during initialisation." Is it possible to identify which are which (potentially via online plotting technique mentioned above)?

We have reformulated to "In some cases of the ensemble (typically for the SP models)" to identify the models where this should typically be the case. However, any change in the model setup from initialisation to control run can generate a drift and cannot be exclude for any of the models.

Figure8b: at what point in the simulations is the 'mass trend in control' (y-axis) assessed?

Over the 100-year simulation period as described in the caption.

P17L21: "This relation arises because the prescribed SMB anomaly has been optimized for the observed geometry, but has not been limited to the observed ice sheet extent." As I understand, this means that the prescribed SMB anomaly gets larger the farther one goes from the present-day margin (Appendix A). Thus, it seems the strong relationship between initial size (and closely related area) and sea level response is mainly a direct response to a design feature of the MIP, and is not an emergent property of the ISMs themselves. Because of this I question the initial volume/SLR response relationship the authors highlight.

To clarify, the SMB anomaly (as a function of elevation) gets mostly smaller (i.e. more negative) towards the coast of Greenland. This aside, the discussion in this mentioned paragraph indeed clarifies that the relationship seen in Fig8d results to some extent from the experimental design. However, ice sheets with too large ice extent also show large volume losses because they are in balance with an unrealistic SMB. It would be possible to define an experimental design where differences due to different ice extent would be smaller (e.g. anomaly adopted to individual geometries) but we disagree that this would be better/more realistic.

P18L5: I appreciate that a real SLR projection would probably use the 'perturbation minus control' approach to remove drift. However, for the sake of a MIP, I feel that showing the raw results would be very useful, so readers can truly appreciate what each model is actually doing. Conversely, perhaps the authors could make a plot/table showing the ratio of drift to perturbation magnitudes for each model, so readers could better assess how significant the drift actually is (instead of assessing this via visual plot comparisons). For example, this would allow users to assess their favorite rule of thumb for acceptable drift (for example, mine is: drift magnitude must be 1/10 of the expected signal magnitude).

We believe the combination of information from the different panels in figure 8 gives a good overview of the ensemble. Tabled results are available in the supplement for the interested reader.

General: I think the supplementary figures may be of most interest to the participants in this MIP. I really appreciate their inclusion.

Thank you very much.

Figure S3: for models like AWI and ISSM whose elevation is not defined outside of the present-day mask, what happens to ice that flows out of the present day mask? Is it simply set to zero..?

For these models, ice leaves the ice sheet mask only at calving locations, like in the other models. Note that the caption states "where surface elevation is not defined outside of the ice sheet mask", which is typically different from the observed present-day mask.

Figure S3: suggest out lining the ice sheet margin in red, or another obvious color, so bare land vs. ice sheet can be distinguished.

OK. We have added contour lines to delineate the ice sheet mask.

Figure S4: It is clear from this figure which models allow their ice sheets to evolve outside of the present-day volume, and which do not. As above, I'd suggest noting explicitly in a table which models do so and which don't.

Please see response to comment above. Note that ice volume may be constrained during initialisation in some of the models, but never in the forward runs. Area is effectively controlled in some cases, but again, that is difficult to quantify. See also response to comment on figure 6.

Figure S5 (subsetted in Figure 10): A reader will immediately question why the ctrl thickness change for many DA models (AWI-ISSM2,AWI-ISSM1,IGE-ELMER1, IGE-ELMER2, UCIJPL-ISSM, MIROC-ICIES1, ULB-FETISH2) have such major dH/dt artifacts, and why these artifacts won't artificially impact SLR projections (by control-minus-perturbation or absolute change methods). In the MIP spirit, I'd like the underlying reason for this pattern described, and in close conjunction, also why other DAv-based models do NOT exhibit this pattern and why. I think there may be important lessons here. I'd suggest a section of text discussing this.*

We agree that this aspect has not received enough attention in the manuscript before. We have therefore added a further discussion of figure 10, which is summarising results for the different models as far as possible.

Figure S5 (subsetted in Figure 10): Similar to the above comment: several SP models display large ctrl trends (e.g. PISM1-6). This is surprising since the point of a spin-up is generally to remove such trends. Conversely, other SP models have much less of a trend. Along the lines of the previous comment, I'd suggest a section of text discussing why differences in ctrl trends for SP models arise. There could be additional important lessons here.

It is not correct that SP methods attempt to remove trends. Rather, the trends should arise physically consistent from (past) changes in the forcing. Please see

response to the question before. We now discuss the response in experiment ctrl in more detail.

Figures S6/S7: The negative ends of these color ranges indicates (I think) that the SMB forcing is dominant over the dynamic response in these experiments (which exclude potential ocean-driven dynamical forcing). First of all, isolating the dynamic response is a nice addition here. Secondly, this is slightly interesting with respect to the overall MIP, since it indicates that the applied SMB anomaly is a very important player here (especially with respect to initial ice sheet size); ice dynamics are essentially second order. Perhaps if the authors agree with me they could add a discussion to this effect (or provide a counterargument).

Indeed, our results show that the dynamic response to SMB forcing alone (ignoring other forcing mechanism like ocean-induced changes) is a relatively small effect. However, that does not represent a new finding, it was already demonstrated by Huybrechts et al., 2002, which we discussed in the main manuscript and therefore, we do not see the need to re-iterate this here.

P20L20: I think this is a valuable summary paragraph. Suggest again making an analogy to weather forecasts versus climate projections (and/or initial value versus boundary value problems).

Thanks for the suggestion, we believe mentioning this once in the introduction is sufficient.

P20L33: "potential artefacts introduced during interpolation": can the authors possibly provide a quantitative estimate of this source of error?

We have not been able to quantify that error, but think it is nevertheless important to mention it as a possible source of differences between models. We have added a statement to clarify that.

P20L37: "The large ensemble spread in sea-level contribution in the asmb experiment is mostly due to the extra ice in the initial ice sheet geometry." Yes, but as above I'd argue that this relationship is mostly a consequence of the design of the imposed SMB anomaly field. As the authors note, a more realistic anomaly field that takes into account ice sheet geometry bias (e.g. a lapse-rated PDD scheme or an EBM scheme on multiple elevation *classes) would likely show a much less pronounced volume-response relationship. So as stated, it's not clear this is a problem to focus community efforts on exclusively (though, of course the less initial volume bias the better, as long as the bias reduction technique doesn't deleteriously impact subsequent projections).*

The larger ensemble spread is really a combination of models producing too large initial ice sheets and an experimental design that emphasizes this. We disagree that an SMB anomaly "that takes into account ice sheet geometry bias" would be more *realistic*. One could argue that it would effectively represent a work-around for model problems to simulate an ice sheet close to the observed geometry. See also response to comment above.

General: thanks to all the participants/coordinators of this MIP. This was no small effort.

Thanks again for reviewing this paper.

Design and results of the ice sheet model initialisation experiments initMIP-Greenland: an ISMIP6 intercomparison

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Abstract.

Earlier large-scale Greenland ice sheet sea-level projections (e.g., those run during the ice2sea and SeaRISE initiatives) have shown that ice sheet initial conditions have a large effect on the projections and give rise to important uncertainties. The goal of the initMIP-Greenland intercomparison exercise is to compare, evaluate and improve the initialisation techniques used in the ice sheet modelling community and to estimate the associated uncertainties in modelled mass changes initMIP-Greenland is the first in a series of ice sheet model intercomparison activities within ISMIP6 (the Ice Sheet Model Intercomparison Project for CMIP6), which is the primary activity within the Coupled Model Intercomparison Project – phase 6 (CMIP6) focusing on the ice sheets Two experiments for the large-scale Greenland ice sheet have been designed to allow intercomparison between participating models of 1) the initial present-day state of the ice sheet and 2) the response in two idealised forward experiments. The forward experiments serve to evaluate the initialisation in terms of model drift (forward run without additional forcing) and in response to a large perturbation (prescribed surface mass balance anomaly), and should not be interpreted as sea-level projections. We present and discuss results that highlight the diversity of data sets, boundary conditions and initialisation techniques used in the community to generate initial states of the Greenland ice sheet. We find good agreement across the ensemble for the dynamic response to surface mass balance changes in areas where the simulated ice sheets overlap, but differences arising from the initial size of the ice sheet. The model drift in the control experiment is reduced for models that participated in earlier intercomparison exercises.

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1 Introduction

Ice sheet model intercomparison exercises have a long history, going back to the advent of large-scale ice sheet models in the early 1990s. The first intercomparison project (EISMINT, the European Ice Sheet Modelling INiTiative; Huybrechts et al., 1996) defined three levels of possible comparisons that could be distinguished. EISMINT and later following comparisons include (1) schematic experiments with identical model setup and boundary conditions between models (e.g., Huybrechts et al., 1996; Pattyn et al., 2008; Pattyn et al., 2012; Pattyn et al., 2013), (2) experiments allowing individual modelling decisions (e.g., Payne et al., 2000; Calov et al., 2010; Asay-Davis et al., 2016), and (3) experiments of models applied to real ice sheets (e.g., Shannon et al., 2012; Edwards et al., 2014b; Bindschadler et al., 2013, Nowicki et al., 2013a, b). In this genealogy, the present intercomparison is a type 3 experiment with ice sheets models applied to simulate the large-scale present-day Greenland ice sheet. The role of this study is to assess the impact of initialisation on model behaviour; it is a precursor to ice-sheet mass budget projections made using climate forcing for the atmosphere and ocean. The initMIP-Greenland project is the first intercomparison within ISMIP6, the Ice Sheet Model Intercomparison Project for CMIP6 (Nowicki et al., 2016), which is the primary activity within the Coupled Model Intercomparison Project – phase 6 (CMIP6, Eyring et al., 2016) focusing on the ice sheets ISMIP6 is the first ice sheet model intercomparison that is fully integrated within CMIP. This is an improvement to earlier initiatives like ice2sea (Gillet-Chaulet et al., 2012; Shannon et al., 2013; Goelzer et al., 2013; Edwards et al., 2014a; b) and SeaRISE (Sea-level Response to Ice Sheet Evolution; Bindschadler et al., 2013; Nowicki et al., 2013a, b) that were lagging one iteration behind in terms of

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applied climate forcing. More information on ISMIP6 can be found in the description paper (Nowicki et al., 2016) and on the Climate and Cryosphere (CliC) hosted webpage: (http://www.climate-cryosphere.org/activities/targeted/ismip6).

The initialisation of an ice sheet model forms the basis for any prognostic model simulation and therefore reveals most of the modelling decisions that distinguish different approaches (Goelzer et al., 2017). It consists of defining both the initial physical state of the ice sheet and model parameter values. In the context of initMIP-Greenland, we focus on initialisation to the present day as a starting point for centennial time-scale future sea-level change projections (Nowicki et al., 2016). The need for physical ice flow models for such projections lies in the dynamic and highly nonlinear response of ice sheet flow to changes in climatic forcing at the atmospheric and oceanic boundaries. The surface mass balance (SMB) of the ice sheet is governed by the amount of precipitation falling on the surface and by meltwater runoff removing mass predominantly at the margins. Mass is also lost by melting at surfaces in contact with ocean water and by calving of icebergs from marine-terminating outlet glaciers. Changes in ice sheet geometry generally cause changes in atmospheric conditions over the ice sheet, and hence changes in SMB. An important effect is the height-SMB feedback, which causes decreasing SMB with decreasing ice surface elevation and vice versa (e.g., Helsen et al., 2012; Franco et al., 2012; Edwards et al., 2014a; b). An important consequence of the relation between SMB and ice flow is that negative SMB removes ice before it can reach the marine margins and thereby reduces the calving flux (e.g., Gillet-Chaulet et al., 2012; Goelzer et al., 2013; Fürst et al., 2015). An estimate for the recent balance of processes indicates that ablation (i.e., negative SMB) is responsible for two-thirds of the increasing GrIS mass loss in the period 2009-2012, with ice discharge from marine-terminating outlet glaciers accounting for the remaining third (Enderlin et al., 2014). While the relative importance of outlet glacier dynamics for total GrIS mass loss has decreased since 2001 (Enderlin et al., 2014) and is expected to decrease further in the future (e.g., Goelzer et al., 2013; Fürst et al., 2015), it remains an important aspect for projecting future sea-level contributions from the ice sheet on the centennial time scale.

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Observations of ice sheet geometry and surface velocity, which ultimately form the target for any initialisation to the present-day state, exist only since the advent of the satellite era for the last ~25 years (e.g., Mouginot et al., 2015). This is a short period compared to the longer response times of the ice sheet, that can be up to several thousand years (Drewry et al., 1992), and makes it impossible to understand ice sheet changes based on observations alone. While detailed observations mainly cover the ice surface properties, measurements for the ice interior and bed conditions are limited to a handful of deep ice core drilling sites. Radar layers dated at ice core sites can be used to extend the dating over large parts of the Greenland ice sheet (MacGregor et al., 2015), but this information is not well explored by ice sheet modellers so far.

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Projections of ice sheet response on decadal to centennial timescales are strongly influenced by the initial state of the ice sheet model (e.g., Arthern and Gudmundsson, 2010; Nowicki et al., 2013b; Adalgeirsdottir et al., 2014; Saito et al., 2016). The prognostic variables and parameters that need to be defined for the initial state of an ice sheet model at the present day depend to some extent on the complexity of the modelling approach, but typically consist of ice temperature (due to its impact on both ice rheology and basal slip), ice sheet geometry, and boundary conditions at the base of the ice sheet. For this timeframe, ice sheet modellers face an issue similar to the one encountered in the weather/climate community: whether to treat the problem as a “boundary value problem” (climate prediction) or as an “initial value problem” (weather forecasting).

Models developed for long-term and paleoclimate simulations typically use 'spin-up' procedures to determine the initial state, where the ice sheet model is run forward in time for tens to hundreds of thousands of years with (changing) reconstructed or modelled climatic boundary conditions (e.g., Huybrechts and de Wolde, 1999; Saito and Greve, 2012; Aschwanden et al., 2013). This implies that at any time during the simulation (except at the beginning where arbitrary conditions are set), the model’s state is defined as a consistent response to the forcing. Imperfections due to applied physical approximations, limited spatial resolution, and uncertainty in physical parameters and climatic boundary conditions can result in a considerable mismatch between the spun-up state and present-day observations.

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The main alternative to the spin-up approach is to use data assimilation techniques, which leverage high-resolution observations of geometry and velocity to initialise ice sheet models to the present-day state (e.g., Gillet-Chaulet et al., 2012; Seroussi et al., 2013; Arthern et al., 2015). They typically infer poorly constrained basal conditions by a formal partial-differential-equations-constrained optimisation to match observed surface velocities for a given geometry (e.g., Morlighem et al., 2010). This implies that the inferred basal parameters remain constant throughout the simulation, which is limited to the centennial time scale where this is approximately the case. Data assimilation techniques produce an initial state as consistent as possible with observational data, but are affected by inconsistences (e.g., ice temperature not in equilibrium with the stress regime) and by uncertainties in observations (e.g., inconsistencies between different observational datasets (Seroussi et al., 2011)). As data assimilations are designed to best fit observations, errors arising from choices in ice parameters, physical processes, model resolution, observational data sets or from ignoring relevant state variables (e.g. ice rheology) are transferred to basal conditions or other parameters obtained by inversion. An intermediate approach is assimilation of the geometry of the ice sheet, by finding basal conditions that reduce the mismatch with the observed ice sheet surface (Pollard and DeConto, 2012b). This method is typically applied during forward integration of the model and implies a model state in near balance with the forcing, though with a degree of compromise over matching observations. Note that the division of the different initialisation approaches presented here is somewhat arbitrary. Combinations between different approaches (e.g. relaxation after data assimilation) exist and need to be further explored to improve initialisation techniques in the future.

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Given the wide diversity of ice sheet initialisation techniques, the goal of initMIP-Greenland is to document, compare and improve the techniques used by different groups to initialise their state-of-the-art whole-ice-sheet models to the present day as a starting point for centennial time-scale future sea-level change projections. A related goal is to highlight and understand how much of the spread in simulated ice sheet evolution is related to the choices made in the initialisation. All three methods currently used for initialisation of ice sheet models (spin-up, assimilation of velocity, and assimilation

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of surface elevation) and variations thereof are represented in our ensemble. We first describe our approach and experimental setup in Section 2, and present the participating models in Section 3. Section 4 concentrates on the results, with the ice sheet model initial state explored in Section 4.1, and the impact of initialization on ice sheet evolutions analysed in Section 4.2. Discussion and conclusions follow in Section 5.

2 Approach and Experimental setup

In initMIP-Greenland we focus on standalone ice sheet models, i.e., models not coupled to climate models. Although some participating models have the capability to produce their own SMB forcing, this is not a requirement in the present study. We have chosen to leave most of the modelling decisions to the discretion of the participants, which serves to document the current state of the initialisation techniques used in the ice sheet modelling community. Conversely, this implies a relatively heterogeneous ensemble with only incidental overlap of modelling choices between different submissions.

Experiments for the large-scale Greenland ice sheet have been designed to allow intercomparison of the modelled initial present-day states and of the model responses to a large perturbation in SMB forcing (Table 1). Modellers were asked to initialise their model to the present day with the method of their choice (*init*) and then run two forward experiments to evaluate the initialisation in terms of model drift: a control run without any change in the forcing (*ctrl*) and a perturbed run with a large prescribed surface mass balance anomaly (*asmb*). The prescribed SMB anomaly in experiment *asmb* (Appendix A) implies a strongly negative SMB forcing, in line with what may be expected from upper-end climate change scenarios. Nevertheless, the sea-level contribution from these experiments should not be interpreted as a projection, but rather as a diagnostic to evaluate model differences.

Note that the time of initialisation was not strictly defined (in the range 1950-2016), as modellers assign different dates to their initial state according to the data sets used. The participants were also largely free in other modelling decisions, with only the imposed constraint for the forward experiments that all boundary conditions and forcing remain constant in time. In particular, the SMB is not allowed to change (e.g., with surface elevation) other than by the prescribed SMB anomaly. All information and documentation concerning the ISMIP6 initMIP-Greenland experiments can be found on the ISMIP6 wiki (http://www.climate-cryosphere.org/wiki/index.php?title=InitMIP-Greenland).

While modellers were free to use a native model grid of their choice, model output was submitted on a common grid to support a consistent analysis (see Appendix C). This implies that results had to first be interpolated from the native model grid to the output grid, which for state variables has in most cases been done using conservative interpolation (Jones, 1999). In the following we present all results on the output grid with a horizontal resolution of 5x5 km. Furthermore, all ice sheet results have been masked to exclude ice on Ellesmere Island and Iceland.

Table 1 **Summary of the ISMIP6-initMIP-Greenland experiments**

Experiment Title	**Experiment label**	**CMIP6 Label (experiment_id)**	**Experiment Description**	**Duration of the simulation**	**Major Purposes**
Initialisation	*init*	*ism-init-std*	initialisation to present day	n/a	Evaluation
Control	*ctrl*	*ism-ctrl-std*	unforced control experiment	100 yr	Evaluation
SMB anomaly	*asmb*	*ism-asmb-std*	idealised change in SMB forcing	100 yr	Evaluation

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3 Participating groups and models

Participants in initMIP-Greenland from 17 groups and collaborations (Table 2) have provided 35 model submissions. There is some overlap between the code bases used by different groups, with ultimately 11 individual ice flow models. However, the same model used by different groups (with varying datasets and initialisation procedures) may lead to rather different results. These submissions cover a wide spectrum of model resolutions, applied physical approximations, boundary conditions and initialisation techniques, which makes for a heterogeneous ensemble. In some cases, the same group has used two or more different model versions or different initialisation techniques, with several groups running their models at varying horizontal grid resolution. In the following we will refer to each separate submission as a ‘model’, identified by the model ID in the table of general model characteristics (Table 3). A detailed description of the individual models and initialisation techniques can be found in Appendix B.

Table 2 Participants, ice sheet models and modelling groups in ISMIP6-initMIP-Greenland

Contributors	Model	Group ID	Group
Victoria Lee, Stephen L. Cornford, Antony J. Payne, Daniel F. Martin	BISICLES	BGC	Centre for Polar Observation and Modelling, School of Geographical Sciences, University of Bristol, Bristol, UK / Department of Geography, College of Science, Swansea University, Swansea, UK / Computational Research Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA
William H. Lipscomb, Joseph H. Kennedy	CISM	LANL	Los Alamos National Laboratory, Los Alamos, USA / National Center for Atmospheric Research, Boulder, USA / Climate Change Science Institute, Oak Ridge National Laboratory, Oak Ridge, USA / Computational Sciences and Engineering Division, Oak Ridge National Laboratory, Oak Ridge, USA
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Sainan Sun, Frank Pattyn	FETISH	ULB	Laboratoire de Glaciologie, Université Libre de Bruxelles, Brussels, BE
Philippe Huybrechts, Heiko Goelzer	GISM	VUB	Vrije Universiteit Brussel, Brussels, BE
Sébastien Le clec'h	GRISLI	LSCE	LSCE/IPSL, Laboratoire des Sciences du Climat et de l’Environnement, CEA-CNRS-UVSQ, Gif-sur-Yvette, FR
Fuyuki Saito, Ayako Abe-Ouchi	IcIES	MIROC	Japan Agency for Marine-Earth Science and Technology, JP / The University of Tokyo, Tokyo, JP

Heiko Goelzer, Roderik van de Wal	IMAUICE	IMAU	Utrecht University, Institute for Marine and Atmospheric Research (IMAU), Utrecht, NL
Helene Seroussi, Nicole Schlegel	ISSM	JPL	Caltech's Jet Propulsion Laboratory, Pasadena, USA
Helene Seroussi, Mathieu Morlighem	ISSM	UCI_JPL	Caltech's Jet Propulsion Laboratory, Pasadena, USA / University of California Irvine, USA
Martin Rückamp, Angelika Humbert	ISSM	AWI	Alfred Wegener Institute for Polar and Marine Research, DE / University of Bremen, DE
Andy Aschwanden	PISM	UAF	Geophysical Institute, University of Alaska Fairbanks, USA
Nicholas R. Golledge	PISM	ARC	Antarctic Research Centre, Victoria University of Wellington, NZ
Christian Rodehacke	PISM	DMI	Danish Meteorological Institute, DK / Alfred Wegener Institute for Polar and Marine Research, DE
Florian A. Ziemen	PISM	MPIM	Max Planck Institute for Meteorology, DE
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Despite the diversity in modelling approaches (Table 3) and the overlap between different methods, it is useful to distinguish the three main classes of initialisation techniques described before: first, those using a form of data assimilation (DA) to match observed velocities (DAv); second, those that rely solely on model spin-up (SP), and third, the intermediate case of transient assimilation to match surface elevation (DAs). However, even DAv is typically preceded by some form of spin-up (with the same model or a different one) to produce the internal temperature of the ice sheet, and may also be followed by a relaxation run to make the velocities and geometry more consistent. The represented cases of DA infer a spatially varying basal drag coefficient to minimise the mismatch with observations of velocity or geometry. Models using SP use physical parameters and processes to define the basal conditions.

Modelling choices also differ based on model purpose and typical application. Many of the SP models have been built and used for paleo applications for time periods when possible DA targets are very limited and SMB boundary conditions differ from the present. This makes it necessary in those models to parameterise SMB, e.g., by using positive-degree-day (PDD) models (e.g., Huybrechts et al., 1991). SP approaches are also generally favoured when including ice sheets in coupled climate models. In two groups (DMI, MPIM), the ice sheet models and SMB forcing are set up in a similar way as they would be for coupled ice sheet-climate simulations. In contrast, the DAv models are built specifically for centennial time-scale future projections, while DAs again represents an intermediate case of models typically used for long-term simulations, but specifically initialised for the present day. These fundamental differences in modelling approaches have to be kept in mind when comparing the models. The SMB is in many cases taken from regional climate model (RCM) simulations, but arises in some cases from parameterisations based on the modelled ice sheet geometry applying traditional PDD methods.

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Table 3 Model characteristics

Numerical method: FD= Finite difference, FE= Finite element, FV= Finite Volume with adaptive mesh refinement

Ice flow: SIA= Shallow ice approximation, SSA= Shallow shelf approximation, HO= Higher order, HYB= SIA and SSA combined
Initialisation method: DAv= Data Assimilation of velocity, DAs= Data Assimilation of surface elevation, SP= Spin up
Initial SMB: RA1= RACMO2.1, RA3= RACMO2.3, HIR= HIRHAM5, MAR= MAR, BOX= BOX reconstruction (synthesis of simulation and data), PDD= Positive Degree Day Model, EBM= Energy Balance Model (EBM)
Velocity: RM= Rignot and Mouginot, J= Joughin et al.
Bed and surface: M= Morlighem et al., B= Bamber et al., H= Herzfeld et al.
Geothermal Heat Flux (GHF): SR= Shapiro and Ritzwoller, G= Greve, P= Purucker, FM= Fox Maule et al., CST= Constant
Model resolution (Res) in km. In case of heterogeneous grid resolution, the minimum and maximum resolution are given.

Model ID	**Numerics**	**Ice flow**	**Initialisation**	**Initial year(s)**	**Initial SMB**	**Velocity**	**Bed**	**Surface**	**GHF**	**Res min**	**Res max**
ARC-PISM	FD	HYB	SP	2000	RA1		B		SR	5	5
AWI-ISSM1*	FE	HO	DAv	2000	RA3	RM	M		SR	2.5	35
AWI-ISSM2*	FE	HO	DAv	2000	RA3	RM	M		SR	2.5	35
BGC-BISICLES1	FV	SSA	DAv	1997 - 2006	HIR	RM	M			1.2	4.8
BGC-BISICLES2	FV	SSA	DAv	1997 - 2006	HIR	RM	M			2.4	4.8
BGC-BISICLES3	FV	SSA	DAv	1997 - 2006	HIR	RM	M			4.8	4.8
DMI-PISM1+	FD	HYB	SP	2000	PDD		B		SR	5	5
DMI-PISM2+	FD	HYB	SP	2000	PDD		B		SR	5	5
DMI-PISM3+	FD	HYB	SP	2000	PDD		B		SR	5	5
DMI-PISM4+	FD	HYB	SP	2000	PDD		B		SR	5	5
DMI-PISM5+	FD	HYB	SP	2000	PDD		B		SR	5	5
IGE-ELMER1	FE	SSA	DAv	2000 - 2010	MAR	J	M			1.5	45
IGE-ELMER2	FE	SSA	DAv	2000 - 2010	MAR	J	M			1	5
ILTS-SICOPOLIS	FD	SIA	SP	1990	PDD		B		P	5	5
ILTSPIK-SICOPOLIS	FD	SIA	SP	1990	PDD		H		G	5	5
IMAU-IMAUICE1	FD	SIA	SP	1990	RA3		B		SR	5	5
IMAU-IMAUICE2	FD	SIA	SP	1990	RA3		B		SR	10	10
IMAU-IMAUICE3	FD	SIA	SP	1990	RA3		B		SR	20	20
JPL-ISSM	FE	SSA	DAv	2012	BOX	RM	M		SR	1	15
LANL-CISM	FE	HO	SP	1961 - 1990	RA1		M		CST	4	4
LSCE-GRISLI	FD	HYB	DAv	2000	MAR	J	B		FM	5	5
MIROC-ICIES1	FD	SIA	DAs	2004	RA1		B	B		10	10
MIROC-ICIES2	FD	SIA	SP	2004	PDD		B			10	10
MPIM-PISM	FD	HYB	SP	2006	EBM		B		SR	5	5
UAF-PISM1#	FD	HYB	SP	2007	RA1		M		SR	1.5	1.5
UAF-PISM2#	FD	HYB	SP	2007	RA1		M		SR	3	3
UAF-PISM3#	FD	HYB	SP	2007	RA1		M		SR	4.5	4.5
UAF-PISM4#	FD	HYB	SP	2007	RA1		M		SR	1.5	1.5
UAF-PISM5#	FD	HYB	SP	2007	RA1		M		SR	3	3
UAF-PISM6#	FD	HYB	SP	2007	RA1		M		SR	4.5	4.5
UCIJPL-ISSM	FE	HO	DAv	2007	RA1	RM	M		SR	0.5	30
ULB-FETISH1	FD	SIA	DAs	1979 - 2006	MAR		B	B	FM	10	10
ULB-FETISH2	FD	HYB	DAs	1979 - 2006	MAR		B	B	FM	10	10
VUB-GISM1	FD	HO	SP	2005	PDD		B		SR	5	5
VUB-GISM2	FD	SIA	SP	2005	PDD		B		SR	5	5

*AWI-ISSM2 differs from AWI-ISSM1 in the climatic forcing used during temperature spin-up. +DMI-PISM1-5 differ in the melt parameters of the PDD model. #UAF-PISM4-6 differ from UAF-PISM1-3 in the initial geometry.

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4 Results

In this section, we first present results of the *init* experiment, designed to compare the present-day initial state between participating models and against observations. These or similar initial model states would serve as a starting point for physically-based projections of the Greenland ice sheet contribution to future sea-level changes (Nowicki et al., 2016). We then present results for the two forward experiments that serve to further evaluate the response of these initial states to idealised forcing (*ctrl*, *asmb*).

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4.1 Evaluation of the initial state

Because initialisation techniques generally differ in the observational data used as model input, boundary conditions and assimilation targets, we did not prescribe the year(s) of initialisation. The initialisation times in the ensemble (Table 3) therefore represent the time frame(s) of the observations that are used for data assimilation (in case DA) and the simulated SMB used as boundary condition for the individual models. For the comparative analysis, we did not attempt to correct the differences arising from different initialisation times. Compared to the range of modelling uncertainties, this assumption probably holds for the geometry of the ice sheet, but is more questionable for velocity. However, the sparseness and limited temporal resolution of available observations excludes analysing models with respect to their individual reference time frame. Where available, we have used a range of observational data sets to compare against.

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The modelled present-day ice extent (Figure 1) exhibits a large spread among models and ranges from the extent of the observed ice sheet proper (excluding connected glaciers and ice caps) to nearly filling the entire land above sea level (see also supplementary Figure S2 for individual model results). This diversity in the ensemble is representative of the large range of modelling choices and initialisation techniques. For example, the assumption of what should be modelled (only the ice sheet, or including outlying glaciers and ice caps) differs from group to group. Also, models may simulate ice in places where no ice is observed. While some models prescribe a fixed (observed) ice mask and prevent any ice growing outside, most models simulate ice margins that are free to evolve according to the balance of ice flow and SMB. In some cases, modellers have controlled the extent where ice sheets are allowed to grow, e.g., by prescribing a negative SMB over observed ice-free regions.

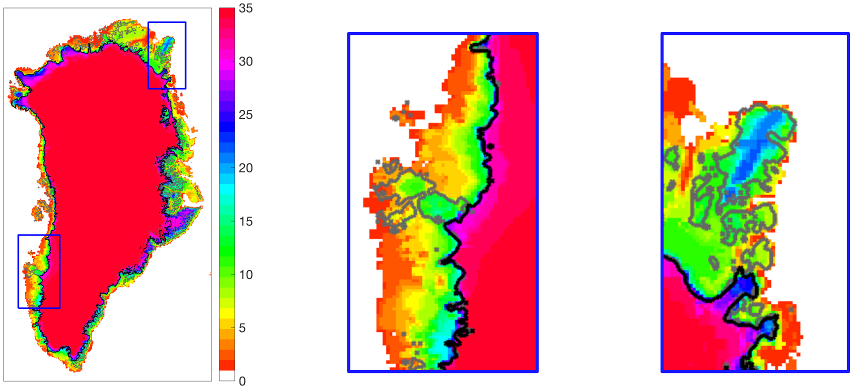

Figure 1 Common ice mask of the ensemble of models in the intercomparison. The colour code indicates the number of models (out of 35 in total) that simulate ice at a given location. Outlines of the observed ice sheet proper (Rastner et al., 2012) and all ice-covered regions (i.e. main ice sheet plus small ice caps and glaciers; Morlighem et al. 2014) are given as black and grey contour lines, respectively. A complete set of figures displaying individual model results is given in the supplementary material.

The diversity of modelling choices equally leads to a large spread in the simulated total ice area and volume at the present day (Figure 2, see supplementary Table S1 for the numbers). In comparison with observations (Morlighem et al., 2014), the initial ice sheet area (horizontal axis in Figure 2) of many models is 'bracketed' by the observed extent (cf. Figure 1) of the ice sheet proper (black diamond) and the extent of the entire ice-covered areas (grey diamond). Differences in observed volume (vertical axis in Figure 2) between these two defined areas are small compared to the ensemble spread, i.e. the proportional change from including ice caps and glaciers surrounding the Greenland ice sheet to volume (0.3 %) is much smaller than to area (8.2 %). An alternative data set (Bamber et al., 2013) provides similar numbers for observed volume and area (not shown). Overestimation of modelled ice sheet area (by up to 15%) is common, and overestimation of volume (up to 15%) is more prevalent than underestimation.

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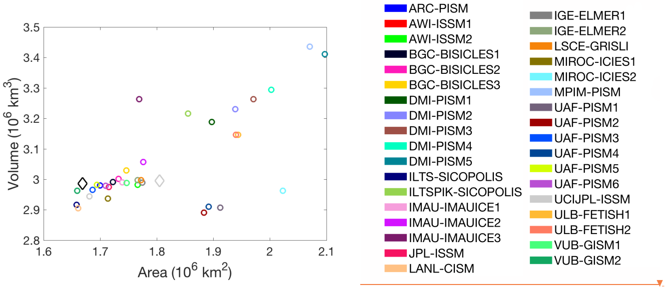

Figure 2 Grounded ice area and grounded volume for all models (circles). Observed values (Morlighem et al. 2014) are given for the entire ice covered region (grey diamond) and for the region of the ice sheet proper (black diamond) according to the mask of Rastner et al. (2012) shown in Figure 1.

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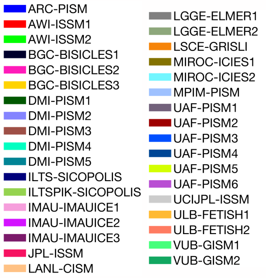

As an important input for the ice sheet simulations, we evaluate the implemented SMB of the different models. Figure 3 shows the typical present-day SMB applied for three of the models spanning the distribution of ice thickness error (see below) while an overview of all models is given in supplementary Figure S2. In the three cases shown, one model applied SMB from a RCM with no modification (AWI-ISSM2), another (MIROC-ICIES) used a PDD method and the last (MPIM-PISM) obtains the SMB from an energy balance model (EBM) designed for coupling of the ice sheet model to a climate model.

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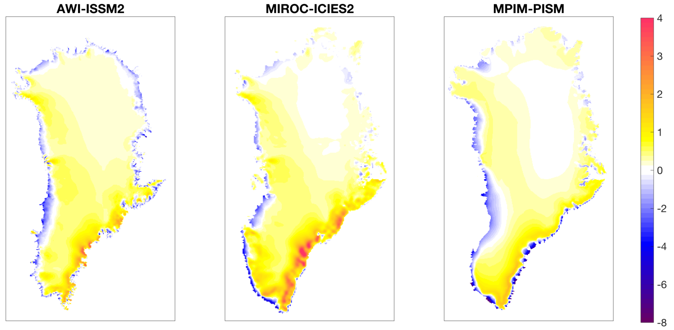

Figure 3 Typical surface mass balance for the initial state for three different models. Note the unequal scaling for positive and negative values.

Because we generally cannot distinguish individual accumulation and ablation processes for the SMB prescribed during initialisation, we separate the assumed SMB into negative and positive regions (i.e., ablation and accumulation zones) for further analysis. Partitioning of mass change processes between SMB and dynamic changes (e.g., van den Broeke et al., 2009; Enderlin et al., 2014) would also be an important diagnostic to analyse. However, the participating models have not incorporated the required mechanisms, and we also lack the necessary forcing, to generate fast dynamical response due to outlet glacier changes in the current experiments. Displaying the SMB magnitude for accumulation and ablation regimes allows us to identify some important outliers (Figure 4a) and frame the model input compared to estimates of total SMB from a range of RCMs (Figure 4b). Apparent outliers are models with small ablation zones and large positive SMB (far right in Figure 4a) and those with a large ablation area (top in Figure 4a). Several of the remaining models cluster around RCM estimates (van Angelen et al., 2014; Fettweis et al., 2017; Noël et al., 2016) for the SMB partitioning, again considering either all ice-covered regions or only the ice sheet proper. This is mostly the case because the models use these or similar products. However, an additional condition required for close agreement with RCM estimates is that the modelled ice sheet is close to the observed extent. Models that lie further from RCM estimates (in Figure 4b) typically have larger ablation zones and consequently larger negative SMB.

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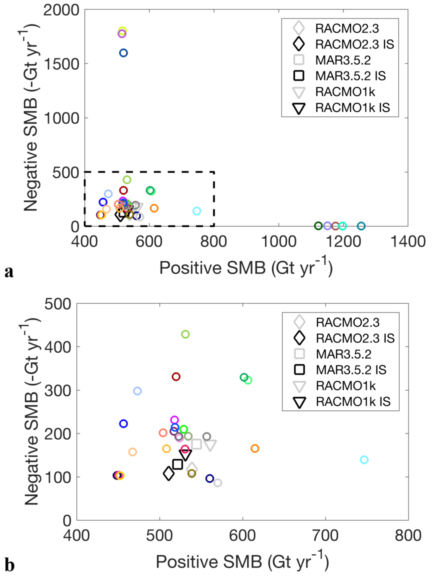


Figure 4 Negative and positive SMB of all models (a) and for the marked inset excluding outliers (b). Diamonds, squares and triangles in (b) give partitioning from average 1979-2000 regional climate model simulations (van Angelen et al., 2014; Fettweis et al., 2017, Noël et al., 2016) with masking to the ice-covered region (grey) and to the ice sheet proper (IS, black) according to the

mask of Rastner et al. (2012). Compare symbol colour to identify individual models with Figures 3-5. Data are available in supplementary Table S1.

We further evaluate the prescribed SMB in comparison to point observations (Figure 5). Available SMB observations (Machguth et al., 2015; Bales et al., 2009) are sparse, especially in the centre of the ice sheet, and have heterogeneous temporal coverage. However, comparison against those observations allows for a first-order evaluation of the SMB inputs chosen or produced by the modellers. Overall, positive SMB is better represented in the chosen SMB datasets than negative SMB. The order-of-magnitude difference in root mean square error (RMSE) between the two measures is partly explained by the relatively low accumulation over a large area in the centre of the ice sheet, compared to relatively high ablation over a narrow marginal zone, which is easily misrepresented in models with too large an ice extent. While the best match with observations in both regions is produced by models using SMB derived from RCMs, good agreement with the observed SMB can also be found for some models using PDD. Again, a good match with the observed ice extent is more important than the SMB model itself to reduce the mismatch with measured SMB.

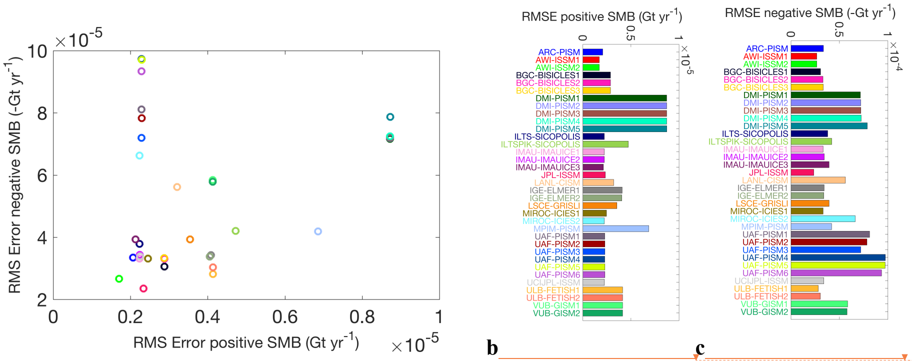
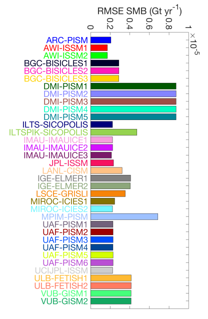


Figure 5 Root mean square error (RMSE) of initial modelled surface mass balance compared to observations for the accumulation zone (b and abscissa in a) and the ablation zone (c and ordinate in a). The observational data sets are from Bales et al. (2009) for the accumulation zone and Machguth et al. (2015) for the ablation zone.

The match of the initial ice sheets with observed geometry (Morlighem et al., 2014) is evaluated as the RMSE between modelled and observed ice thickness (Figure 6). Interpretation of the diagnostics requires distinction between the different initialisation techniques, because the geometry is a prognostic variable in some cases of SP, but a given constraint during initialisation for DA. In some cases of SP, the ice sheet area is effectively confined to the observed, which represents an intermediate case. For models covering a range of horizontal resolutions, accuracy generally decreases with coarser horizontal grid resolution (BISICLES, IMAUICE, ELMER), except for UAF_PISM, where the trend is not clear. Using a different observational data set (Bamber et al., 2013) to calculate the diagnostic gives overall



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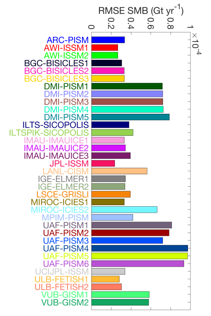

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Deleted: root mean square (RMS) difference similar results (not shown). However, it is noticeable that DA models that have been initialised with one data set show lower errors when comparing with that specific set of observations. This point requires attention, should this diagnostic be used to formally evaluate and score the models at some stage.

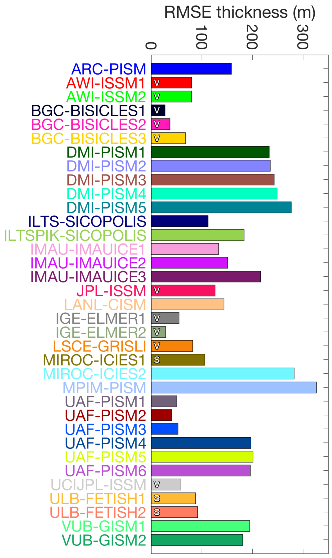

Figure 6 Root mean square error (RMSE) of initial modelled ice thickness compared to observations (Morlighem et al. 2014). The diagnostic has been calculated for subsampled data to reduce spatial correlation, and we show median values for different offsets. Letters in the bars denote assimilation targets for methods DAv and DAs and are left empty for SP.

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To evaluate the match of the models with observed surface ice velocities, we have computed the RMSE between the modelled and observed (Joughin et al., 2016) velocity magnitude (Figure 7a). Calculating the RMSE based on the log of the velocities instead (Figure 7b) results in a slightly different picture, because errors in high velocities typically occurring at the margins over a relatively small fraction of the ice sheet area are weighted less. We note that an alternative choice of metric would be one that accounts for spatial variation in observational uncertainty, such as standardised Euclidean distance. Distinction between models using DAv and the rest is again useful, since velocity is not an independent variable in cases where it enters the inversion calculations. Models using observed velocities in the DAv procedure could in principle be compared with each other to evaluate the success of the inversion technique. However, the comparison would have to take into account that some groups use relaxation after the

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DAv step to get a better consistency between the ice geometry and velocity. This modifies the results depending on the relaxation time. Better consistency for a model can be achieved with longer relaxation time, at the expense of a larger discrepancy with the observed geometry. In any case, not every group uses the same velocity dataset (e.g., Rignot and Mouginot, 2012; Joughin et al., 2016).

It is interesting to note that DAs techniques using only surface elevation as inversion target can have quite low errors in simulated velocities, which implies an overall consistency between geometry and velocity structure of the modelled ice sheets. Although this consistency is expected based on mass conservation, the results confirm that the basic assumptions (e.g., approximation to the force balance and rheology structure) are generally close enough to reality. This is particularly important considering that DAv techniques can match observed velocities well for almost any given rheology, as all the uncertainty (including unknown rheology) is compounded in the basal sliding relation.

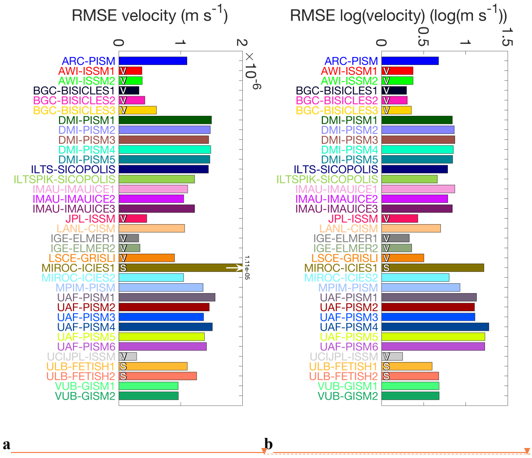

Figure 7 Root mean square error (RMSE) of the horizontal velocity magnitude (a) and the log of the horizontal velocity magnitude (b) compared to observations (Joughin et al., 2016). The diagnostics have been calculated for grid cells subsampled regularly in space to reduce spatial correlation; we show median values for different possible offsets of this sampling.

4.2 Results of the forward experiments

The two experiments *ctrl* and *asmb* have been performed to further test the modelled initial states in terms of their behaviour in typical forward simulations. This is needed to expose model response to changing constraints that were present during initialisation. Furthermore, we evaluate the influence of the initial state and of modelling decisions pertaining to the initialisation on the results of the forward experiments, i.e., the projected ice thickness change and sea-level contribution.

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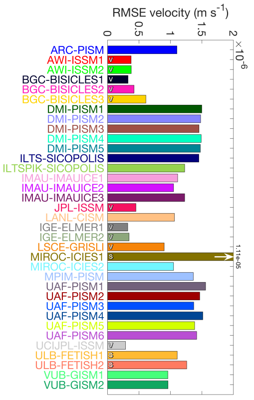

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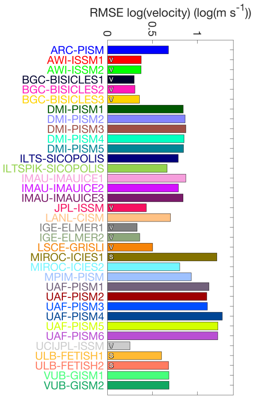

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The experiment *ctrl* serves to evaluate the model response in the absence of additional forcing and is an important step to understand the consequence of modelling choices for forward experiments. Since we have not specified any assumption on the imbalance between SMB and ice flow at the initial state, the ice sheet would ideally exhibit an imbalance that matches observations for a given time interval. Recent modelled mass trends or thickness changes could then in principle be evaluated with existing observational data sets of limited time coverage (e.g., Velicogna et al., 2014). Reproducing recent changes seen by GRACE (mass change) and altimetry (thickness change), however, is hampered by not knowing the ice sheet bedrock and surface elevation well at the time that the satellite started to observe, and would also assess the accuracy of the SMB input (i.e., for many models, a separate RCM). Furthermore, this would require that the experiments aimed for realistic outlet glacier dynamics and ocean forcing (e.g., Nick et al., 2013), which is currently not available (Alexander et al., 2016; Schlegel et al., 2016) and has deliberately not been included in the present experiments. Approaches to validate models using hindcasting techniques (Aschwanden et al., 2013; Larour et al., 2014; 2016; Price et al., 2017) currently suffer the same limitations of observational data sets with short time coverage, uncertainty in external forcing, limited knowledge of processes responsible for dynamic outlet glacier response and the initialisation problems discussed above.

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The simulated ice mass evolution in *ctrl* (Figure 8a) reflects the wide spread of initial ice mass among the models and a relatively small mass change for most of them over the course of the 100-year experiment. This is because a common approach is to attempt initialisation to a steady state with a given SMB forcing, possibly followed by relaxation or by a run with recent SMB forcing. Total mass changes in experiment *ctrl* (Figure 8b) range from ~-20 to +25 mm sea-level equivalent (SLE) when nine obvious outliers (discussed in context of Figure 4) are ignored. Note that the total mass change is not a complete measure of the model drift, since positive and negative trends at different places can compensate. To calculate the SLE contribution for all models consistently, we have masked out ice outside of Greenland (Ellesmere Island and Iceland), considered only the ice mass above floatation, applied a correction to compensate for the map projection error (Snyder 1987) and converted volume to mass using the specific ice densities from each model. In some cases of the ensemble (typically for the SP models), the modelled background trend arises from transient forcing of SMB and temperature over the past, but more often it is due to inconsistencies introduced during initialisation (i.e., the trends are dominated by the model's response to the initialisation, not to the forcing).

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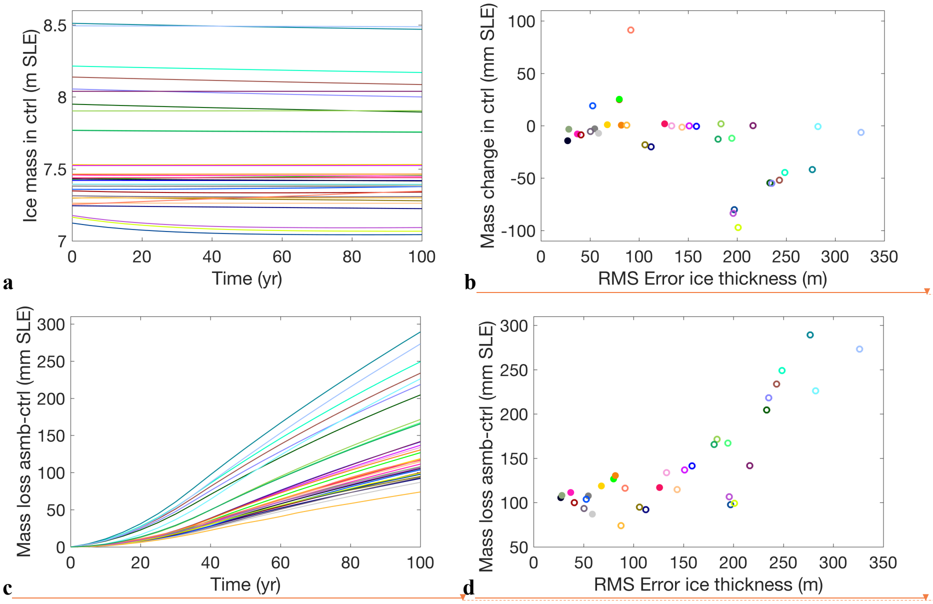

Figure 8 Ice mass evolution in *ctrl* (a) and ice mass loss from *asmb-ctrl* (c). Mass change after 100 years in experiment *ctrl* (b) and from *asmb-ctrl* (d) related to error in initial ice thickness. Ice volume changes have been converted to sea-level equivalent (SLE) assuming an ocean area of 361.8 *10^6 km^2 and the specific ice density from the individual ice sheet models. Filled symbols in (b) and (d) represent DAv models. Data in (b) and (d) is available in supplementary Table S1.

For DAv models (filled symbols in Figure 8b), the mass trend in experiment *ctrl* represents an important diagnostic to complement the measured accuracy of matching the observed geometry, because it will also reflect any inconsistencies between ice velocity and geometry datasets (Seroussi et al., 2011). This can be illustrated by considering a forward model run that is started from an exactly specified geometry as initial state. Optimized model velocities combined with imperfect ice thickness reconstructions may result in a flux divergence that is unbalanced by the local SMB, which leads to large model drift. Conversely, ice sheet models can be relaxed to a steady state when constraints on the target geometry are loosened completely. Match with the observed geometry in the initial state and model drift in the forward experiment are therefore complementary measures that should be considered together. While this is evident for any single model, we only find tentative confirmation amongst the DAv models in our ensemble (filled symbols in Figure 8b), with increasing mass trend for decreasing ice thickness error.

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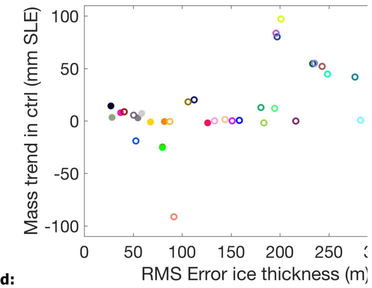

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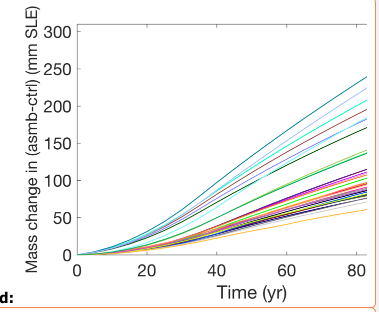

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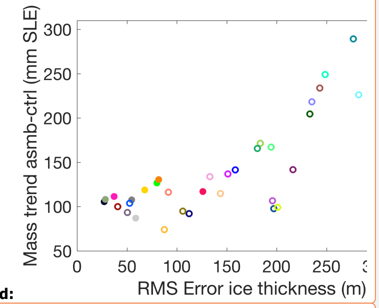

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The simulated sea-level contribution of the models, calculated from the difference in mass change between *asmb* and *ctrl,* shows a large spread of 75 to 290 mm SLE (Figure 8c, d), indicative of the wide range of modelled ice sheet extent (and therefore ice thickness error). This relation arises because the prescribed SMB anomaly has been optimized for the observed geometry, but has not been limited to the observed ice sheet extent. The typical SMB field at the end of experiment *asmb* (illustrated for three different models in Figure 9) is strongly negative along the ice sheet margin, with an ablation zone that covers all of the ice sheet margin and extends several hundred kilometres inland in the southwest and northeast of Greenland. For models with (unrealistically) large initial (present-day) surface areas, the ablation zones are considerably larger (Figure 9b, c), which implies dramatic mass loss. The too large ice sheet area is related to the definition of the ice sheet with respect to outlying glaciers and, more importantly, due to modelled initial conditions further from the present-day. Simply put, by design a larger ice sheet will be subject to larger rates of mass loss.

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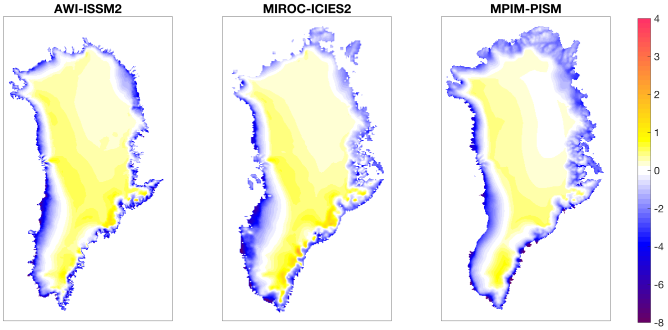

Figure 9 Typical surface mass balance after 100 years in experiment *asmb* for the three models in Figure 3. Note the unequal scaling for positive and negative values.

The spatial patterns of thickness changes in experiment *ctrl* (Figure 10a, b, c and Figure S5) clearly reflect some important differences and similarities between the models and used initialisation techniques. DA models typically exhibit more noise (e.g. Figure 10a) compared to SP models (e.g. Figure 10b, c), which arises from inconsistencies between geometry and velocity for the former as discussed above. Models with identical model setup, but at different horizontal resolution show similar patterns, and the same applies for different versions of one model (DMI-PISM), which differ only by the PDD parameters (Figure S5). In all cases, thickness changes are the largest close to the margin and less pronounced in the interior of the ice sheet, a difference that becomes clearer with longer relaxation time. The patterns also confirm that positive and negative thickness changes at different locations often compensate each other so that the total mass change in experiment *ctrl* (Figure 8c and Table S1) is not a complete measure of the model drift. Because the thickness change in experiment *ctrl* is mostly due to

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unwanted model drift, we have calculated the mass evolution (Figure 8c) and sea-level contribution (Figure 8d) from ice thickness change differences between *asmb* and *ctrl* (Figure 10d, e, f and Figure S6). This is a common workaround to remove model drift and facilitate model comparison, but it also neglects the contribution of any prognostic imbalance and present-day ice sheet evolution in the resulting figures. In the centre of the ice sheet, the modelled thickness change (Figure 10d, e, f) is dominated by the prescribed SMB anomaly and therefore similar between all models (Figure S6), while marginal changes show again much larger differences.

In contrast to the large differences in modelled ice volume changes, which may largely be explained by differences in initial ice sheet extent, we find that models are similar in the dynamic response within the region of overlap, i.e., within most of the observed ice mask. For this analysis, we have calculated the difference between modelled ice thickness changes (*asmb-ctrl*) and the time-integrated SMB anomaly for each individual model (see Figure 10g, h and i for three examples and Figure S7 for all models). This diagnostic, first shown and discussed by Huybrechts et al., (2002), represents ice thickness changes due to the flow of the ice in response to changes in SMB: in other words, the extra information gained by using ice dynamic models over projections of SMB changes alone.

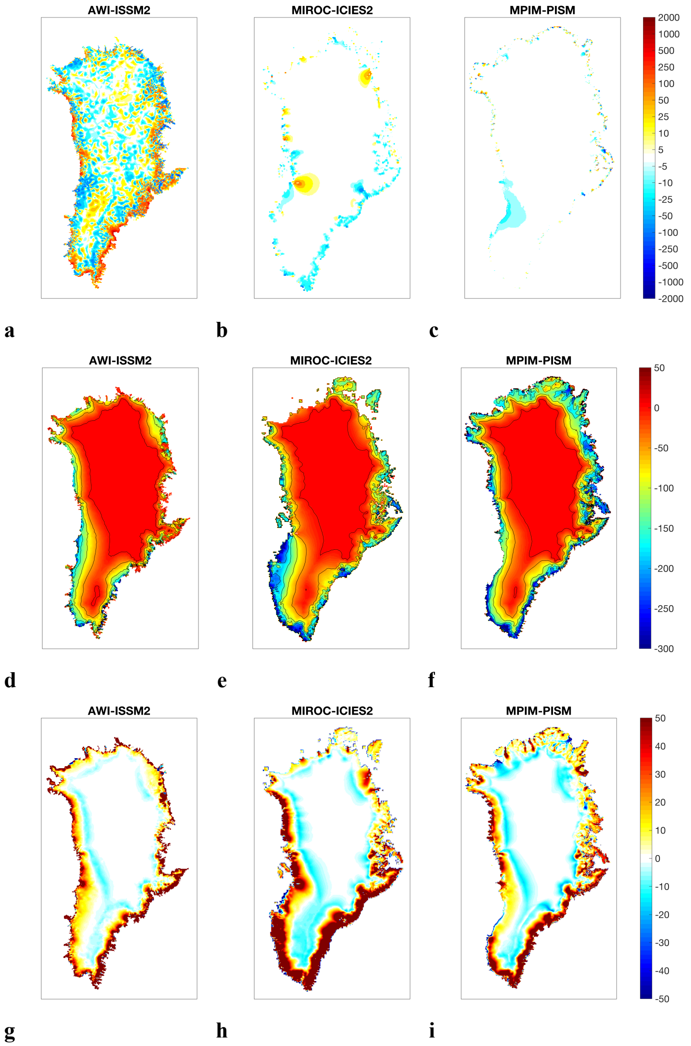
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Figure 10 Ice thickness change in *ctrl* after 100 years (top), difference of ice thickness change (*asmb-ctrl*) after 100 years (middle) and dynamic contribution (bottom) for the three models in Figure 3 and Figure 9. Note the nonlinear contour intervals in the top row.

Dynamic thickening happens in regions of steep gradients in negative SMB anomalies around the margins of the ice sheet. Dynamic thinning occurs across the line separating positive and negative SMB anomalies, close to the equilibrium line. This pattern of dynamic response is reproduced by all models (see Figure S7), and shows strong similarities for the region of overlap across the entire ensemble. In other words, the models largely agree in their representation of the ice dynamical response to the applied SMB-anomaly forcing.

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5 Discussion and conclusion

We have compared different initialisation techniques used in the ice sheet modelling community across a representative spectrum of approaches. While long-term processes and adjustment of internal variables (e.g., ice temperature and rheology) can be incorporated with SP methods, this occurs at the expense of a better match with observations of present-day ice sheet geometry and velocity and hence, the initial dynamic state of the ice sheet. Conversely, the initial states produced by the DAv approach exhibit a much better match with observations, at the expense of including long-term processes. The DAs method and other approaches to incorporate DA elements in SP models and vice versa form an intermediate group. At present, none of the methods is capable of combining both aspects (good match with observations and long-term continuity) sufficiently well that it would render other methods obsolete for all applications.

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DAv is the method of choice for short-term projections with anomaly forcing, and as far as long-term dynamical interactions (e.g., arising from interaction with the basal conditions, the bedrock or from thermo-mechanical coupling) can be neglected. For long-term projections of ice sheet behaviour, where these interactions become important, SP and DAs methods are needed. The range of time-scales where this is the case is not well-defined and may lie anywhere between several decades and several centuries. For the standalone ice sheet projections planned for CMIP6 within ISMIP6 (100 to 200-year time scale), a combination of SP and DA methods may be required to simulate the response of the Greenland ice sheet to future climate change. The challenge remains how to initialise models to closely match the observed dynamical state and at the same time minimise unrealistic transients and incorporate the long-term evolution of thermodynamics and bedrock changes. A promising approach is additionally optimising the basal topography within observational errors as part of the data assimilation procedure (Perego et al., 2014; Mosbeux et al., 2016). Other approaches, based on assimilation of time-series of observed surface velocity (Goldberg et al., 2013) or surface elevations (Larour et al., 2014) exist for smaller scales, but should be further explored to eventually be applied over the entire ice sheet. A so far underexplored possibility is to use existing information from radar layers (MacGregor et al., 2015) as additional constraints in initialisation methods.

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The present ‘come-as-you-are’ approach is well suited to produce an overview of initialisation techniques in the community and to compare individual models against observations. However, we have encountered difficulties in comparing models because of the wide variety of approaches. Differences in the initial ice sheet extent have rendered the locally identical SMB anomaly forcing to be different on the global scale. We have found that estimating mass changes consistently across all models becomes a non-trivial undertaking, considering differences in ice sheet masks, projection errors and differences in model ice density. Additional problems arise from the use of different native grids (unstructured and structured) with potential artefacts introduced by interpolation that we have not been able to quantify.

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The mismatch between observed and modelled ice sheet extent also needs an urgent solution in view of constructing an ensemble of sea-level change projections based on CMIP6 climate model data. The large ensemble spread in sea-level contribution in the *asmb* experiment is mostly due to the “extra” ice in the initial ice sheet geometry. At this stage, it is not clear how to minimize the contribution to sea level change due to this bias introduced solely by the experimental setup. Letting each model estimate its own SMB anomaly relative to the individual ice sheet geometry would likely reduce this problem, but it would complicate any further comparison by removing the constraint of locally identical SMB for all models.

Compared with earlier ice sheet model intercomparison exercises that have initialised ice sheet models for future projections (Bindschadler et al. 2013; Nowicki et al. 2013b), we find considerably less drift in the control experiments (for models that also participated in previous intercomparisons). We attribute this improvement to more attention of modellers on ice sheet initialisation and to an improved understanding of what is needed to achieve that goal, including the development of improved bedrock topography datasets (Morlighem et al., 2014). If this trend continues and initialisation methods get further developed, it is reasonable to expect that the uncertainty in simulated ice sheet model evolution due to initialisation can be reduced for upcoming projections of the future.

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The comparison shows that, despite all the differences, the ice sheet models that took part in this intercomparison agree well in their dynamic response to the SMB forcing for the region of overlap. This is an encouraging sign, given the large diversity of approaches. However, while this good agreement means that all models are able to accurately simulate changes in driving stress, other dynamic forcings (e.g., changes at the marine-terminating glaciers) were not included in the present set of experiments and may lead to a wider variety of responses. To achieve progress in this direction, we need a more complete understanding of the forcings and mechanisms that drive observed ice sheet changes. Aside from SMB, the important questions of how much surface melt water is reaching the bed, how the basal drainage system evolves and, most importantly, how the marine-terminating glaciers interact with the ocean in fjord systems are under active research.

The current 'ensemble of opportunity' approach, just as for GCMs, makes interpretation challenging: in other words, it is difficult to assess which choices in method and which uncertain model inputs have most influence on the results. Ideally, we would have liked to draw firmer conclusions about the influence of modelling choices on the quality of the initialisation and the uncertainty in modelled sea-level contribution. At the present stage, however, the sample size for a given modelling choice is often not sufficient and, more importantly, different model characteristics are not independent from each other. Similar difficulties have been discussed for the CMIP multi-model ensemble and may have led to the IPCC to resort to (slightly arbitrary) expert judgments for some interpretations. Improving the uncertainty analysis and enabling a more rigorous intercomparison and evaluation would require an experimental design that is more controlled and prescriptive. Ice sheet models are well-placed to be used in such a design, being far less computationally expensive than e.g. GCMs, and with far fewer inputs to choose and outputs to evaluate. The effects of changing model structure (such as physics laws and approximations, and resolution) on initialisations and projections is also far easier to evaluate. We therefore envision a second stage of the initMIP-Greenland experiments that performs multiple specific perturbations of the initial states of several models that can be interpreted in a statistically more meaningful way.

Data availability

The model output from the simulations described in this paper will initially be distributed via ftp server and at a later stage be included in the CMIP6 archive through the Earth System Grid Federation (ESGF) with digital object identifiers (DOIs) assigned. In order to document CMIP6's scientific impact and enable ongoing support of CMIP, users are obligated to acknowledge CMIP6, the participating modelling groups, and the ESGF centres (see details on the CMIP Panel website at http://www.wcrp-climate.org/index.php/wgcm-cmip/about-cmip). The forcing datasets are equally initially available through the initMIP-Greenland wiki and in the future through the ESGF with version control and DOIs assigned.

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under the European Community's Seventh Framework Programme (FP7/2007-2013) / ERC grant agreement 610055 as part of the Ice2Ice project as well as the Nordic Center of Excellence eSTICC (eScience Tool for In-vestigating Climate Change in northern high latitudes) funded by Nordforsk (grant 57001). Florian A. Ziemen was supported by the BMBF project PALMOD. Computational resources for MPI-PISM were made available by DKRZ through support from BMBF. IGE-Elmer simulations were performed using the Froggy platform of the CIMENT infrastructure, which is supported by the Rhône-Alpes region (GRANT CPER07_13 CIRA), the OSUG@2020 labex (reference ANR10 LABX56) and the Equip@Meso project (reference ANR-10-EQPX-29-01), and using HPC resources from GENCI-CINES (Grant 2016-016066). Ralf Greve was supported by Japan Society for the Promotion of Science (JSPS) KAKENHI Grant Numbers 16H02224 and 17H06104, and by the Arctic Challenge for Sustainability (ArCS) project of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT). Reinhard Calov was funded by the Leibniz Association grant SAW-2014-PIK-1 and is now funded by the Bundesministerium für Bildung und Forschung (BMBF) grants PalMod-1.1-TP5 and PalMod-1.3-TP4.

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6 Appendix A: SMB anomaly forcing

For the idealised forward experiment that serves to evaluate the initialisation, we have used a parameterisation of SMB anomalies (*dSMB*) as a function of surface elevation and latitude based on the following goals:

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- to capture the first order pattern of the SMB changes that can be expected from the climate models that will be used in ISMIP6 projections
- to provide an idealized forcing, independent of one particular model or modelling choice
- to avoid masking problems by generating a forcing applicable to the whole model domain

The parameterisation has the form *dSMB* = f(sur, lat):

$$dSMB = \min[p_3 * (h - p_2) + p_4 * (\phi - \phi_0), p_1]$$

where *dSMB* is the SMB anomaly, *h* is the surface elevation, ϕ is the latitude and ϕ_0 the reference latitude in degrees. The parameters are the constant SMB anomaly in the accumulation area (p_1), the surface elevation of zero SMB anomaly (p_2), the gradient of SMB anomaly with elevation change (p_3), and the SMB anomaly change per degree latitude (p_4).

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The target *dSMB* is calculated from differences in SMB between the periods 2080-99 AD and 1980-99 AD. We have fitted the parameters independently to output of three models of different complexity (Table 4), one RCM (Fettweis et al., 2017), one general circulation model with elevation classes (GCM, Vizcaino et al., 2015) and one positive-degree-day model in combination with output from an Earth system model of intermediate complexity (EMIC-PDD, Goelzer et al., 2012).

Table 4 Parameters with the best fit to the modelled data for SMB models of different complexity.

Parameter	p_1 (m yr^{-1})	p_2 (m)	p_3 (m yr^{-1} m^{-1})	p_4 (m yr^{-1} deg^{-1})
RCM	0.0720	2248.4	0.0016	0.1011
GCM	0.0549	2438.1	0.0007	0.0568
EMIC-PDD	0.0292	1642.1	0.0023	0.0462

The sensitivity of *dSMB* to elevation changes is around a factor 2 lower in the GCM compared to the RCM and is the highest in EMIC-PDD as can be seen by comparing p_3 in Table 4. We have used the parameter set of medium sensitivity (RCM) for the experiments.

Results for the RCM are shown in Figure 11 with the *dSMB* from the model (a) and from the parameterisation (b) in comparison. While the parameterisation allows for calculating *dSMB* everywhere on the grid, results are masked to the same extent as the modelled data, to facilitate comparison. These results show that the first order pattern is well captured by the parameterisation. The parameterisation works equally well for the two other climate models when proper masking is applied to limit the calculation to ice covered regions (not shown).

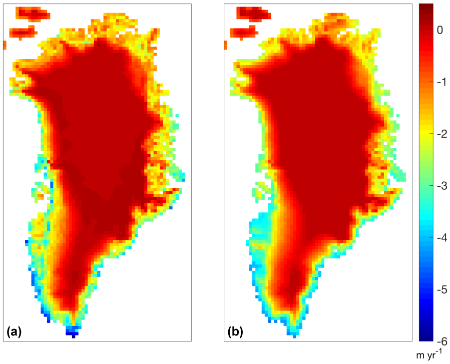

Figure 11: SMB anomaly from a model (a) and reproduced by the parameterisation (b).

For the final ISMIP6 forcing data, the parameterisation was applied to the observed geometry (Bamber et al., 2013) smoothed by a two-dimensional averaging filter (21x21 points). This step serves to produce a smooth forcing field for the range of expected model resolutions. The resulting dSMB on 1 km resolution was used to generate the forcing for other grids and resolutions by conservative interpolation.

For experiment *asmb*, the amplitude of the SMB anomaly was implemented as a time-dependent function, which increases stepwise every full year to 100 % at year 40. The amplitude is then held constant (t > 40 yrs) for prolongation of the experiment until year 100. The forcing is therefore independent of the time step in the individual models.

$$\begin{aligned} SMB(t) &= SMB_{init} + dSMB*(floor(t)/40); && 0 \le t \le 40, \\ SMB(t) &= SMB_{init} + dSMB*1.0; && t \ge 40 \end{aligned}$$

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$SMB(t) = SMB_{init} + dSMB*1.0; \quad t \ge$

where SMB_{init} is the SMB used for the initialisation in each individual model and *dSMB* is the provided SMB anomaly, which is identical for all models. The units of the *dSMB* in the provided data files are (meter ice equivalent/year) with an assumed density of 910 kg/m^3 and 31556926 s yr^{-1}. Note that for models assuming a different ice density, the input data have to converted accordingly.

7 Appendix B: Detailed model description

The models and initialisation methods of the individual models are documented in this section.

7.1 ARC-PISM

A similar approach to that used for previous Antarctic simulations is followed (e.g., Golledge et al., 2014, 2015), but the length of the runs is modified on the basis that GrIS achieves thermal equilibrium faster than e.g. the EAIS. Based on raw input data (Bamber et al., 2001) a 'shallow-ice' only run of 5 years is performed to reduce any spurious steep surface gradients in the data. From the output of this run, a 50 kyr fixed-geometry run is performed, in which the ice sheet is allowed to come into thermal equilibrium with the imposed (present-day) climate. The output from this run is then used for a 15,000 year spinup simulation, in which full model physics are employed, i.e. all model boundaries are allowed to evolve. To minimize drift in this spinup run an initial exploration of parameter space is undertaken to find an optimal combination of values. Parameter tuning is focused on 6 key controls: enhancement factors for the SIA and SSA, maximum and minimum till friction angles, pseudo-plastic exponent 'q', and the fraction of overburden pressure supported by the till. These parameters have been found to exert the primary controls on location and magnitude of sliding and ice flow by deformation, and in doing so most effectively control simulated ice-sheet geometry and volume. To identify an optimal configuration, an initial ensemble of paired parameter simulations is performed, in which the variance between each pair is assessed and all other variables are held constant. Simulations are run at 5 km resolution for 500 years under unforced climatic conditions (i.e. present-day) but with freely-evolving boundaries. Each run is assessed for degree of drift from initialisation. Subsetting from these experiments, a further ensemble of 64 experiments is run, combining all combinations of 2 possible values for each of the 6 parameters. The 'optimal' configuration is chosen based on 1) the lowest deviation from present-day sea-level-equivalent ice volume and 2) the smallest domain-averaged thickness mismatch at the end of the run compared to initialisation. For the latter metric, the standard deviation of the mismatch was assessed, but differences between runs are minimal. These short runs identify the relative control exerted by each parameter over 500 years. To achieve a much longer spinup that deviates least from the starting conditions, a further seven experiments are undertaken until the optimum parameter configuration is found. The final state of the spinup run is then used as the starting point for the prognostic (*ctrl* and *asmb*) experiments.

7.2 AWI-ISSM

The thermo-mechanical coupled Ice Sheet System Model (ISSM, Larour et al., 2012) is used to create an initial condition. For the initialization, a hybrid procedure that combines assimilation and a temperature spin-up over longer periods is setup. The present-day ice sheet geometry (Morlighem et al., 2016) is used and the observed horizontal surface velocities (Rignot and Mouginot., 2012) are assimilated to infer the basal friction coefficient. After an initial relaxation of the ice sheet geometry for 50 years to avoid spurious noise (with no sliding and a constant temperature field), the temperature spin-up is performed on a fixed topography with two different climatic forcings: AWI-ISSM1) present-day climatic and AWI-ISSM2) paleo-climatic conditions. During the inversion, the ice viscosity is kept constant using the enthalpy field from the end of the temperature spin-up. As the higher-order approximation to the Stokes flow is employed, grid refinements are made during the whole initialization procedure (grid sequence 1: hmin=15 km, hmax=50 km; grid sequence 2: hmin=5 km, hmax=50 km, grid sequence 3: hmin 2.5 km, hmax=35 km. In the vertical 17 layers refined to the base are used. AWI-ISSM1 is run for 20 kyr, 40 kyr and 5 kyr in each grid sequence while AWI-ISSM2 is run for 125 kyr, 125 kyr and 25 kyr). Geothermal flux, present day surface temperature and paleo surface temperature anomaly is taken from the SeaRISE webpage (http://websrv.cs.umt.edu/isis/index.php/Present_Day_Greenland). Surface mass balance is an annual mean for the period 1979-2014 from the downscaled RACMO2.3 model (Noël et al., 2016).

7.3 BGC-BISICLES

The initial state is found using data assimilation of velocity followed by relaxation of the surface elevation subject to a constant-in-time SMB (Lee et al, 2015). Merged surface ice velocity from Rignot and Mouginot (2012), is used to infer a 2-D basal traction coefficient and a 2-D stiffening factor multiplying the effective viscosity by solving an inverse problem with fixed ice sheet geometry from Morlighem et al. (2014). The ice surface is evolved by forcing the model using the 2-D parameters with a 1997-2006 mean SMB from HIRHAM5 (Lucas-Picher et al., 2012), subject to fixed calving front boundary conditions. The surface is relaxed in this way for 120 years, which is sufficient for the absolute value of the instantaneous rate of change ice thickness to fall below 0.5 m a-1 in 99 percent of the total area of GrIS. This initialization uses a 3-D, steady-state temperature field generated by a high-order thermomechanical model by Price et al., 2011. For the *ctrl* and *asmb* experiments the fixed calving front is replaced by a calving model (Taylor 2016), where ice calves if water-filled, surface crevasses reach a depth equal to the height of the ice above sea level. A basal melt rate varying between 0 and 4 times ice thickness is also applied in regions where ice is close to fracture.

7.4 DMI-PISM

Spinup over one full glacial cycle (125 kyr BP to present) with the following guidelines: freely evolving run that inherits the climate memory of the last glacial-interglacial cycle and shall represent the currently observed ice sheet state for the contemporary ”year of assignment”. Since we at DMI focus on coupled climate model-ice sheet model simulations, we value a free run that is consistent with the applied forcing higher than a perfect representation of the current observed Greenlandic ice sheet state, such as ice sheet geometry. We have found that this procedure is necessary to avoid strong unnatural drifts in the ice sheet model component after the full coupling between climate model and the ice sheet model is established (Svendsen et al., 2015). The spinup first goes through one complete glacial-interglacial cycle using as base the Era-Interim reanalysis of the period 1979-2012 to determine the surface mass balance (SMB) via positive degree days (PDD). The scaling of the datasets is determined based on the Greenland temperature index in the SeaRISE Greenland Dataset (based on ice core data;

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source SeaRISE Reference data set: Greenland_SeaRISE_dev1.2.nc). Temporal evolution of the sea level is also taken from the same SeaRISE Greenland dataset. The ensemble of runs (PISM1, PISM2, PISM3, PISM4, PISM5) differ in the forcing applied to the Greenland Ice Sheet (GIS). In all cases the forcing source is based on the Era-Interim reanalysis covering the period 1979-2012. The only differences are the applied PDD factors for the determination of the surface mass balance (SMB) via positive degree days (PDD). The following enumeration lists the applied different PDD factors. PISM0: PDD_snow=0.012 m/°C day, PDD_ice=0.018 m/°C day; PISM1: PDD_snow=0.010 m/°C day, PDD_ice=0.016 m/°C day; PISM2: PDD_snow=0.009 m/°C day, PDD_ice=0.014 m/°C day; PISM3: PDD_snow=0.008 m/°C day, PDD_ice=0.012 m/°C day; PISM4 PDD_snow=0.004 m/°C day, PDD_ice=0.008 m/°C day.

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7.5 IGE-ELMER

The model is initialised using a control inverse method as in Gillet-Chaulet et al. (2012). For the momentum equations, we solve the Shelfy-Stream Approximation (SSA). The vertically-averaged viscosity is constant in all simulations and is initialised using the temperature field coming from a paleo spin-up (125ky) of the SICOPOLIS model. The limit of the model domain is fixed and corresponds to the boundary with the ocean: calving front positions are fixed and the calving rate is computed as the opposite of the ice flux through the boundary; land-terminated parts can freely retreat or advance up to the domain limit. The ice-sheet topography is initialised using the IceBridge BedMachine Greenland V1 dataset (Morlighem et al., 2014) where missing values for the bathymetry around Greenland have been filled using data from Bamber et al. (2013). We use a linear basal friction law. The basal friction coefficient is constant in all transient simulations and is initialised with the control method so that the mismatch between observed and modelled velocities is minimum. As observations, we use a composite from the MEaSUREs Greenland Ice Sheet Velocity Map (V1) (Joughin et al., 2010). The ice sheet model is then relaxed for 20 years using a 1989-2008 mean SMB from the regional climate MAR forced with ERA-Interim. The only difference between IGE-ELMER1 and IGE-ELMER2 is the mesh resolution as given in Table 3.

7.6 ILTS-SICOPOLIS

The model is SICOPOLIS version 3.3-dev in SIA mode and with the melting-CTS enthalpy method (ENTM) for ice thermodynamics by Greve and Blatter (2016). The present-day surface temperature parameterization is by Fausto et al. (2009), the present-day precipitation is by Ettema et al. (2009) and the geothermal heat flux is by Greve and Herzfeld (2013) (slightly modified version of the heat flux map by Greve (2005)). A spin-up over the last glacial-interglacial period (125,000 years) is carried out. Except for initial and final 100-year phases with freely evolving surface and bedrock topography, the topography is kept fixed during the spin-up, whereas the temperature evolves freely. This is essentially the method that was used for the SeaRISE experiments (documented in detail by Greve and Herzfeld, 2013). The time-dependent forcing for the spin-up is the GRIP δ^{18}O record (Dansgaard et al., 1993; Johnsen et al., 1997) converted to a purely time-dependent surface temperature anomaly ΔT by the conversion factor 2.4°C/‰ (Huybrechts, 2002).

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7.7 ILTSPIK-SICOPOLIS

The model version, thermodynamics solver and present-day surface temperature parameterization are the same as listed in Section 7.6. The present-day precipitation is by Robinson et al. (2010) and the geothermal heat flux is produced by Purucker (https://core2.gsfc.nasa.gov/research/purucker/heatflux_updates.html) following the technique described in Fox Maule et al. (2005). The ice discharge parameterization by Calov et al. (2015), Eq. (3) therein with the discharge parameter c = 370 m^3 s^{-1}, is applied. A spin-up over the last glacial-interglacial period (135,000 years) with free evolution of all fields (including the ice sheet topography) is carried out. The time-dependent forcing for the spin-up is the GRIP $\delta^{18}O$ record (Dansgaard et al., 1993; Johnsen et al., 1997) on the GICC05 time scale (Svensson et al., 2008), converted to a purely time-dependent surface temperature anomaly ΔT by the conversion factor 2.4°C/‰, and further a 7.3% gain of the precipitation rate for every 1°C increase of ΔT (Huybrechts, 2002).

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7.8 IMAU-IMAUICE

The model (de Boer et al., 2014) is initialised to a thermo-dynamically coupled steady state with constant, present-day boundary conditions for 200 kyr using the average 1960-1990 surface temperature and SMB from RACMO2.3 (van Angelen et al., 2014), extended to outside of the observed ice sheet mask using the SMB gradient method (Helsen et al., 2012). Bedrock data is from Bamber et al. (2013) and geothermal heat flux from Shapiro and Ritzwoller (2004). The model is run in SIA mode with ice sheet margins evolving freely within the observed coast mask, outside of which ice thickness is set to zero.

7.9 JPL-ISSM

The ice sheet configuration is set up using data assimilation of present-day conditions and historical spin-up similar to the study of Schlegel et al. (2013). SSA is used over the entire domain with a resolution varying between 1 km in the fast-flowing areas and along the coast and 15 km in the interior. Grounding line migration is based on hydrostatic equilibrium and a sub-element scheme (Seroussi et al., 2014). Observed surface velocities (Rignot and Mouginot, 2012) are first used to infer unknown basal friction at the base of the ice sheet (Morlighem et al., 2010). Ice temperature is modeled assuming the ice sheet to be in a steady-state thermal equilibrium (Seroussi et al., 2013). A spin up of 50,000 years is then done to relax the ice sheet model (Larour et al., 2012) and reduce the initial unphysical transient behavior due to errors and biases in the datasets (Schlegel et al., 2016) using mean surface mass balance from 1979-1988 (Box, 2013). A historical spin up is then done from 1840 to 2012 using reconstructions of surface mass balance for this period (Box, 2013). Bedrock topography is interpolated from the BedMachine dataset (Morlighem et al., 2014), that combines a mass conservation algorithm for the fast-flowing ice streams and krigging in the interior of the ice sheet. Initial ice thickness is from the GIMP dataset (Howat et al., 2014). Geothermal flux is from Shapiro and Ritzwoller (2004), air temperature from RACMO2 (van Angelen et al., 2014). SMB from a mass balance reconstruction (Box, 2013) averaged over the 2000-2012 period is used in the *ctrl* experiment.

7.10 LANL-CISM

The ice sheet was initialised with present-day geometry and an idealized temperature profile, then spun up for 20,000 years using pre-1990 climatological surface mass balance and surface air temperature from RACMO2. No glacial data were used. The model was spun up for 20,000 years to equilibrate the temperature and geometry with the forcing. The model was initialised (prior to spin-up) with present-day topography and thickness based on the mass-conserving bed method of Morlighem et al. (2011). The surface mass balance (SMB) over the ice sheet was a 1961-1990 climatology from RACMO2. In grid cells where RACMO2 did not provide an SMB, the SMB was set arbitrarily to -2 m yr^{-1}. Surface air temperatures were also from a 20th century RACMO2 climatology (Ettema et al. 2009). The geothermal flux was set spatially uniform to 0.05 W/m2.

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7.11 LSCE-GRISLI

The GRISLI spin-up procedure is based on an iterative data assimilation method to infer the basal drag from the observed surface velocities. The first step consists in a 30 kyr equilibrium simulation of the internal temperature with prescribed ice sheet topography (Bamber et al., 2013), 1979-2005 averaged near surface air temperature (Fettweis et al., 2013), geothermal heat flux (Fox Maule et al. 2009), surface velocities (Joughin at al., 2013) and spatially variating basal drag coefficient from a previous GRISLI experiment (Edwards et al., 2014b). From the resulting internal fields, the 1979-2005 mean SMB and near-surface air temperature (Fettweis et al., 2013) is used to run a succession of eight 220-yr simulations. During the first 20 years, the basal drag coefficient is corrected to limit the deviation from prescribed velocities, and then the basal drag is kept constant for 200 years of surface relaxation. At each iteration, we update the basal drag coefficient with the value computed at the previous iteration. The prescribed velocities are the observed velocities corrected for thickness differences at the end of the 220 years in order to keep the ice flux in GRISLI identical to the observed one. Then, a second temperature equilibrium is run for consistency between the temperature field and the inferred basal drag coefficient. From this, an additional 220-yr simulation is run to optimise the final basal drag coefficient. This basal drag coefficient and associated final ice-sheet conditions are used as initial conditions for all the initMIP GRISLI experiments.

7.12 MIROC-ICIES1

The initialization method as well as other configuration follows Experiment E"s:e1:vm that is presented in Appendix A of Saito et al (2016). The field of basal sliding coefficients are relaxed such that the simulated ice-sheet topography mostly matches the observed geometry using Pollard and Deconto (2012b) method. Using the deduced basal sliding coefficients field, a steady-state spin-up under present-day climate condition with the fixed geometry is performed again.

7.13 MIROC-ICIES2

The initialization method as well as other configuration follows Experiment B':v2 presented in Saito et al. (2016). A free spin-up over 125,000 years is performed following the SeaRISE configuration.

7.14 MPIM-PISM

Spinup over one full glacial cycle (135 kyr BP to present), changed parameters at 20 kyr BP (simply faster starting from a pre-spun up state at 20 kyr BP than re-running the full glacial cycle for each param change). The spinup first goes through one complete glacial cycle using a linear combination of MPI-ESM output. The scaling of the two datasets is determined based on the Greenland temperature index in the SeaRISE Greenland Dataset (based on GRIP data). Sea level changes are also taken from the SeaRISE Greenland Dataset.

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7.15 UAF-PISM

Spin-up over a glacial cycle combined with a short relaxation run. To define the energy state, a “standard” glacial cycle run is performed where the surface can evolve freely, similar to Aschwanden et al. (2013) and Aschwanden et al. (2016). The spin-up starts at 125 kyr BP with the present-day topography from Howat et al. (2014) using a horizontal grid resolution of 9 km. The grid is refined to 6 km, 4.5 km, and 3 km at 25 kyr BP, 20 kyr BP and 15 kyr BP, respectively. We use a positive degree-day scheme to compute the climatic mass balance from surface temperature (Fausto et al., 2009) and model-constrained precipitation (Ettema et al., 2009). The degree-day factors are the same as in Huybrechts (1999). Second, we account for paleo-climatic variations by applying a scalar anomaly term derived from the GRIP ice core oxygen isotope record (Dansgaard et al., 1993) to the temperature field (Huybrechts, 2002). Then we adjust mean annual precipitation in proportion to the mean annual air temperature change (Huybrechts, 2002). Finally, sea level forcing, which determines the land area available for glaciation, is derived from the SPECMAP marine δ^{18}O record (Imbrie et al., 1992). At the end of the spin-up, the computed surface elevation differs from the observed surface elevation. From here we perform two sets of 60-year relaxation simulations using the RACMO 1960-1990 averaged climatic mass balance. In one set (UAF-PISM4-6), we regrid the spun-up state from the 3-km simulation to 1.5 km (UAF-PISM4), 3 km (UAF-PISM5) and 4.5 km (UAF-PISM6) and run a relaxation where the ice sheet is free to evolve. At the end of this relatively short relaxation, the computed surface elevation continues to differ substantially from present-day observation and the model states exhibit a large artificial drift. To reduce the mismatch between observed and simulated surface elevations, we perform a second set, UAF-PISM1-3. Here we regrid the energy state in the ice and in the bedrock from the spun-up state from the 3-km simulation to 1.5 km (UAF-PISM1), 3 km (UAF-PISM2) and 4.5 km (UAF-PISM3) and combine those fields with the present-day topography from Howat et al. (2014) to again run a relaxation where the ice sheet is free to evolve.

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7.16 UCIJPL-ISSM

The ice sheet configuration is set up using data assimilation of present-day conditions (Morlighem et al., 2010). A relaxation of 50 years is then performed to reduce the initial unphysical transient behavior due to errors and biases in the datasets (Seroussi et al., 2011), using mean surface mass balance from 1961-1990 (van Angelen et al., 2014). A Higher-Order model (HO) is used for the entire domain, with 14 vertical layers and a horizontal resolution varying between 0.5 km along the coast and 30 km inland. We perform the inversion of basal friction assuming that the ice is in thermomechanical steady state.

The ice temperature is updated as the basal friction changes and the ice viscosity is changed accordingly. At the end of the inversion, basal friction, ice temperature and stresses are all consistent. After the data assimilation, the model is relaxed for 50 years using the mean surface mass balance of 1961-1990 from RACMO (van Angelen et al., 2014), while keeping the temperature constant. Bed topography is interpolated from the BedMachine Greenland v3 dataset (Morlighem et al., 2017), that combines a mass conservation algorithm for the fast-flowing ice streams and kriging in the interior of the ice sheet. Initial ice surface topography is from the GIMP dataset (Howat et al., 2014). For the thermal model, surface temperatures from Fausto et al. (2009) and geothermal heat flux from Shapiro and Ritzwoller (2004) are used. Mean surface mass balance of 1961-1990 from RACMO (van Angelen et al., 2014) is used in the *ctrl* experiment.

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7.17 ULB-FETISH

Model initialisation is based on the method by Pollard and DeConto (2012b) by optimizing basal sliding coefficients for the grounded ice sheet in an iterative way through minimizing the misfit between observed and modelled surface topography. A regularization term is introduced to smooth high-frequency noise in the basal sliding coefficients (Pattyn, 2017). Initial ice sheet surface and bedrock elevation are taken from Bamber et al. (2013) and geothermal heat flux stems from Fox Maule et al. (2009). The initialisation runs over a period of 50,000 years forced by a constant surface mass balance (Fettweis et al., 2007) and surface temperature (Fausto et al., 2009). During this time, the marine boundaries are kept fixed in space. For the control and forcing runs, the grounded ice margin and grounding line is allowed to move freely, starting from the initialized state. Two model setups were considered: FETISH1 is according to SIA; FETISH2 is a hybrid model (superimposed SSA-SIA) with a flux condition at the grounding line according to Schoof (2007) and Pollard and DeConto (2012a).

7.18 VUB-GISM

The model is initialised with a glacial spin-up over the last two glacial cycles and recent climate forcing data up to the year 2005 (Fürst et al., 2015). For the spin-up, a synthesized temperature record is used based on ice-core data from Dome C, NGRIP, GRIP, and GISP2 (Barker et al., 2011; Andersen et al., 2004; Dansgaard et al., 1993; Kobashi et al., 2011) and precipitation is scaled by 5% per °C. For the period 1958 to 2005, the atmospheric forcing comes from a combination of ECMWF ERA-meteorological reanalysis and ECMWF operational analysis data. Use is made of monthly temperature anomalies and yearly precipitation ratios. The ocean forcing from 1958 to 2005 derives from a CMIP5 model providing temperature anomalies at mid-depth (300-800 m) in 5 surrounding ocean basins with respect to the 1960-1990 period. After the year 2005, atmospheric and oceanic forcings are reset to their 1960-1990 averages in the unforced state. Bedrock elevation and coast mask are based on Bamber et al. (2013), the pattern of surface accumulation for the period 1950-2000 is based on Bales et al. (2009). The higher-order model (GISM1) is initialised with an SIA model (GISM2) to 3 kyr BP. Switching at 3 kyr BP appeared to be sufficiently early to resolve the main effects of including horizontal stress gradients by the present day.

8 Appendix C: Data request

The requested variables (Table 5) serve to evaluate and compare the different models and initialisation techniques.

All 2D data were requested on a regular grid with the following description: Polar stereographic projection with standard parallel at 71° N and a central meridian of 39° W (321° E) on datum WGS84. The lower left corner is at (-800000 m, -3400000 m) and the upper right at (700000 m, -600000 m). This is the same grid (Bamber et al., 2001) as used to provide the SMB anomaly forcing. The output was submitted on a resolution adapted to the resolution of the model and was 10 km or 5 km. The data were conservatively interpolated to 5 km resolution for diagnostic processing.

If interpolation was required in order to transform the SMB forcing (1 km, same as Bamber et al., 2013) to the native model grid, and transform model output to the initMIP output grid (20 km, 10 km, 5 km, 1 km, Bamber et al., 2001), it was requested that conservative interpolation was used. The motivation for using a common method for all models is to minimize model-to-model differences due to the choice of interpolation methods. In most cases this has been followed by the modellers.

We distinguish between state variables (e.g., ice thickness, temperatures and velocities) and flux variables (e.g., SMB). State variables were requested as snapshot information at the end of one-year (scalars) and five-year periods (2D), while flux variables were averaged over the respective periods. For calculation of scalar diagnostics (e.g., total ice mass or ice covered area), it is necessary to correct for the area distortions implicit for a given projection (e.g., Snyder, 1987). Some of the variables may not be applicable for each model, in which case they were omitted.

Table 5 Data request for participation in initMIP-Greenland.

Type: FL= Flux variable, ST= State variable, CST= Constant

Variable name	**Units**	**Type**	**Standard Name (CF)**
Ice Sheet Altitude	m	ST	surface_altitude
Ice Sheet Thickness	m	ST	land_ice_thickness
Bedrock Altitude	m	ST	bedrock_altitude
Bedrock Geothermal Heat Flux	W m^{-2}	CST	upward_geothermal_heat_flux_at_ground_level
Surface mass balance flux	kg m^{-2} s^{-1}	FL	land_ice_surface_specific_mass_balance_flux
Basal mass balance flux	kg m^{-2} s^{-1}	FL	land_ice_basal_specific_mass_balance_flux
Land ice calving flux	kg m^{-2} s^{-1}	FL	land_ice_specific_mass_flux_due_to_calving

Ice thickness imbalance	m s^{-1}	FL	tendency_of_land_ice_thickness
X-component of land ice surface velocity	m s^{-1}	ST	land_ice_surface_x_velocity
Y-component of land ice surface velocity	m s^{-1}	ST	land_ice_ surface_y_velocity
Z-component of land ice surface velocity	m s^{-1}	ST	land_ice_ surface_upward_velocity
X-component of land ice basal velocity	m s^{-1}	ST	land_ice_basal_x_velocity
Y-component of land ice basal velocity	m s^{-1}	ST	land_ice_basal_y_velocity
Z-component of land ice basal velocity	m s^{-1}	ST	land_ice_basal_upward_velocity
X-component of land ice vertical mean velocity	m s^{-1}	ST	land_ice_vertical_mean_x_velocity
Y-component of land ice vertical mean velocity	m s^{-1}	ST	land_ice_vertical_mean_y_velocity
Surface Temperature of Ice Sheet	K	ST	temperature_at_ground_level_in_snow_or_firn
Basal Temperature of Ice Sheet	K	ST	land_ice_basal_temperature
Basal drag	Pa	ST	magnitude_of_land_ice_basal_drag
Land ice area fraction	1	ST	land_ice_area_fraction
Grounded ice area fraction	1	ST	grounded_ice_sheet_area_fraction
Floating ice sheet area fraction	1	ST	floating_ice_sheet_area_fraction
Ice Mass	kg	ST	land_ice_mass
Ice Mass not displacing sea water	kg	ST	land_ice_mass_not_displacing_sea_water
Area covered by grounded ice	m^2	ST	grounded_land_ice_area
Area covered by floating ice	m^2	ST	floating_ice_shelf_area
Total SMB flux	kg s^{-1}	FL	tendency_of_land_ice_mass_due_to_surface_mass_balance
Total BMB flux	kg s^{-1}	FL	tendency_of_land_ice_mass_due_to_basal_mass_balance
Total calving flux	kg s^{-1}	FL	tendency_of_land_ice_mass_due_to_calving

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