September 30, 2016

Prof. Philippe Huybrechts
Geoscientific Model Development

Dear Prof. Huybrechts,

Please find the revisions for the manuscript entitled "Ice Sheet Model Intercomparison Project (ISMIP6) contribution to CMIP6" to be considered for the GMD special issue on the Coupled Model Intercomparison Project Phase 6 (CMIP6) Experimental Design and Organization.

The revised manuscript incorporates all the comments received from the two reviews and three short comments, all of which suggested helpful improvements to the manuscript. The majority of the changes are due to moving text between sections (following the suggestions that we received), clarifying a few aspects of the text, improving the Tables, and the Figures.

Below is a point-by-point response to the reviews and short comment, along with a marked up manuscript version.

Sincerely,

Sophie Nowicki, on behalf of the ISMIP6 steering committee
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Author's response to comments from C Rodehacke (Referee 1)

The manuscript of Nowicki and others describes the foundation and reasoning of the Ice Sheet Model Intercomparison Project (ISMIP6) and its relation the coming CMIP6 exercise.

Under the frame of the Climate and Cryosphere (CliC) and World Climate Research Project (WCRP) model intercomparisons have been and will be a tool to project the future evolution of the earth's climate system. The understanding of how massive land ice masses — such as Antarctica and the Greenland ice sheet — will melt under a changing climate and contribute to an already globally raising sea level is crucial in the context of climate adaptation and mitigation efforts. The manuscript clearly contrasts the difference between various model experiment setups and motivates the usage of these experiments. It also highlights the relationship to former and coming "traditional" CMIP experiments. The manuscript will certainly act as the reference for the described ISMIP6 exercise.

The manuscript is very well written, has a clear structure and all tables and figures are necessary and well prepared. It was a pleasure to review this manuscript. I hope that the manuscript could be published soon, because I will be extremely helpful to have this information for the involved groups as well as the wider CMIP6 audience.

I recommend the publication of the manuscript after few minor corrections.

A detailed list of comments including the text above is given in the attached pdf-file.

We thank the reviewer for the helpful comments. We have now revised our manuscript in light of these and other comments that we have received. A point-by-point reply is given below.

Major Issues
None

Minor Issues
First I give general comments and afterwards specific comments.

General Comments
In the manuscript I prefer a consistent spelling of either "preindustrial" or "pre-industrial".

We have checked the manuscript and used a consistent spelling of "pre-industrial"

Since this manuscript will probably be a reference for the research groups participating, you may add a small table with the essential deadlines to the section 3.4 "Prioritization of experiments and timing". It could act like a "checkbox" table. Please share your thoughts about it.

We thank the reviewer for this idea. However, the dependence of most of the proposed ISMIP6 experiments on model output from climate modeling centers makes it impossible for us to foresee exact timing of the initiatives at this stage.

In the tables A1, A2, and A3 or/and in the appendix A "Variable Request", I would like to see the definition of the flux direction (sign convention). Is ablation (ice loss) a positive or negative flux? Please clarify the text and add (also) please a short remark to the corresponding table captions.

We thank the reviewer for the suggestion. We have added general statements to the table captions to clarify the flux directions.
Table A1: Flux variables are defined positive when the process adds mass or energy to the ice sheet and negative otherwise.
Table A2: Flux variables are defined positive when the process adds mass to the ocean and negative otherwise.
Table A3: Flux variables are defined positive when the process adds mass or energy to the ice sheet and negative otherwise.

Specific comments

In the following specific comments are made, where "P3L23" means line 23 on page 3, for instance.

P4L21: The term ''offline'', may not be known to a general audience. You may rephrase item ii): 'standalone dynamic ice sheet models (ISMs) that are driven by provided forcing fields ("offline").'
We have done the suggested rephrasing.

P4L26: I personally find the suddenly appearing "XXX" confusing. You may add the sub-clause: where XXX stands for different forcing scenarios as described later.
We have added the suggested sub-clause.

P5L16: In the bracket the term "fixed is vague. You may mean "reference ice sheet extent and topography"? If so, please specify a possible reference for illustration.
We believe 'fixed' is the right term here, referring to the prescribed topography and albedo in classic GCM simulations. Referring to a 'reference' instead would add confusion, since there is really only one state of the ice sheets in these simulations.

P5L27: You may add "pre-industrial" to obtain:"… is meant to capture the pre-industrial quasi-equilibrium state of the climate system."
We have done the suggested rephrasing.

P6L25: You state to use the same ice sheet initial condition, which comes from the coupled XXX-withism run, for the XXX-withism and the ism-XXX-self simulations. Since the geometry of the ice sheet could be quite different between the standard AOGCM and the coupled AOGCM-ISM in terms of ice sheet elevation, for instance, the starting conditions and climatic forcing of the standard AOGCM may not be consistent with the XXX-withism ice sheet. Hence the forced ice sheet may show a considerable drift and ultimately this drift overprints the actually wanted impact of the difference between coupled vs uncoupled simulations for simulations of about 150 years. Could be please be so kind and comment.
We agree that there is a danger of a drift dominated by any signal forced by the difference between coupled and uncoupled simulations. We could lessen this drift by using SMB anomalies. However, the potential for a drift is one of the reasons why we are not relying on the coupled modeling for our projections, as we expect the results of the standalone ice sheet modeling to be more robust. The coupled modeling is primarily done so that issues (such as this) created by coupling climate and ice sheet models are exposed, and the community can start to work towards resolving them.

The ism-piControl-self will be used to quantify the drift, which we can subtract from the ism-1pctCO2-self, to get the effect of climate change. However, if the drift is large, this may not be satisfactory. We hope that the AOGCM SMB will be realistic enough and that the spin-up geometry between the standard AOGCM and the coupled AOGCM-ISM is not hugely different, and therefore the drift minimal.

We have restructured the manuscript so that the discussion of the spin-up is now before the coupled experiments. In the new structure, the original first three paragraphs have been left unchanged. The fourth paragraph now discusses the spin-up, and it mainly based on the original sixth paragraph, with any change due to reading flow or needed to address comments about spin-up. The fifth paragraph states the ideal of using actual SMB forcing from the AOGCM, and is the bulk of the old fourth paragraph adapted to address your concerns about initial conditions and drift. The remainder of the section is then unchanged.

The fifth paragraph reads "Ideally, the ice sheet model should be forced with the actual SMB computed by the climate model, rather than an SMB corrected to match observed climatology. We accept that there may be biases in the atmospheric or land models that can lead to an unrealistic SMB, which could result in a steady-state ice sheet geometry that differs substantially from present-day observations. However, correcting for these biases can distort the feedbacks between ice sheets and climate that we seek to investigate. We hope to learn from and ultimately reduce these biases, in the same way that biases elsewhere in the simulated coupled climate system are reduced by greater understanding and improved model design. On the other hand, if the geometry of the spun-up ice sheet is greatly different from observations, then the initial ice sheet may be far from steady state with the SMB forcing from the standard, uncoupled AOGCM. As a result, the *ism-piControl-self* experiment could have a large drift that obscures the climate signal. If this is the case, or in general if the spun-up ice sheet in the coupled system is deemed to be too unrealistic, an alternative spin-up method would be to apply SMB anomalies from the AOGCM, superposed on a climatology that yields more realistic equilibrium ice sheet geometry."

P7L8: I'm unsure if a 'the' is missing:" The choice of the ice sheet model, …. ."
This has been changed as suggested.

P7L14: You may add:" However, any correction… ."
This has been changed as suggested.

P7L22-23: I'm skeptical about the implicit statement that internally computed surface mass balance (SMB) calculations are automatically mass and energy conserving while externally computed SMB are not. A wrong regridding from the probably coarse atmospheric grid to the finer ice sheet model grid could break the conservation (Fischer et al., 2014), regardless if the computation is performed inside or outside the AOGCM. I would like to suggest a more general phrasing such as:"… SMB is obtained from energy based method that conserves mass and energy. It facilitates interpretation of the drivers of SMB variability and change …."
We have done the suggested rephrasing.

P7L29: I guess I understand what is meant by a "realistic" state, but I would claim that this state is uncertain for the pre-industrial era and that an ice sheet state that is consistent with the driving AOGCM climate is more important. Hence you may agree in replacing "… to produce a realistic non-drifting coupled state" with "… to produce a consistent non-drifting coupled state".
We have done the suggested rephrasing.

P7L29: As mentioned above, the pre-industrial state is likely different than the contemporary observed state. Hence you may add the following sub-clause:"... to the pre-industrial (1850) climate, which is different from the contemporary state (Kjeldsen et al., 2015)."
This has been added as suggested.

P10L29: I would like to suggest a slight clarification:" … temperature changes using the relation of Rignot and Jacobs (2002) of 10 yr-1 °C-1 for temperatures above the actual ocean's freezing temperature." Please use "°C" instead of "C".
This has been fixed as suggested.

P11L11: For the first time initMIP is mentioned. Please either introduce it or mention where it is described below.
Following a suggestion of Reviewer 2, we have moved the initMIP description earlier in the text, which solves this problem.

P11L12: I'm sorry, but I do not understand or could not find the referenced section provided in the bracket. Please clarify. In addition this information seems to disagree with the information in the bracket below (P11L22).
Thank you for spotting this, there was a mistake in the referencing. This has been solved along with the changes described in response to the comment before.

P11L23: In my humble opinion a 1% raising atmospheric CO2 concentration has not a linear trend. Hence I suggest:" considers a 1%/year atmospheric CO2 concentration rise until quadrupled concentration and stabilization thereafter."
We have done the suggested rephrasing.

P11L27: Here you may add:" … to pre-industrial conditions, which is probably weaker, constrained than the contemporary state."
This has been added as suggested.

P11L31: Is the leading "to" needed?
This has been kept, as the sentence is "are likely to differ", if the "are" had not been used, we would have indeed removed the "to".

P12L28: You may indicate that some groups have provided longer runs by stating:"… each run for at least one hundred years."
This has been added as suggested.

P13L8/9: I'm not sure but maybe a pronoun is missing:"… geometric changes in these forward experiments." Please check.
Indeed a pronoun was missing and was added as suggested.

P14L31: I would like to suggest to add a more recent citation for the HIRHAM model: (Langen et al., 2015; Lucas-Picher et al., 2012)
This has been added as suggested.

P15L4: For the Greenland ice sheet a very valuable set of observations in the ablation zone comes from the PROMICE network. Therefore I suggest the following change:" … known as the GC-Net (Steffen and Box, 2001), PROMICE network with a focus on the ablation zone (Ahlstrøm et al., 2008)".
This has been added as suggested.

P15L28: In addition to the common glaciological estimates I would like to add the following:" … can be compared with glaciological estimates of ice shelf melting around Antarctica (Rignot et al., 2013; Depoorter et al., 2013) as well as independent tracer-oceanographic estimates (Loose et al., 2009; Rodehacke et al., 2006)."
This has been added as suggested.

P17L27: You may highlight the coupled simulations in the conclusion by extending:"… no dynamic ice sheets, coupled AOGCM-ISM, and standalone…."

This has been added as suggested.

P19L16: Some glaciologists may feel more welcome when instead 'lost' the common term 'ablation' is also used. What do you thing about:" … and ablation to the ocean by either calving or melting."
This has been changed as suggested.

Tables

Here I refer to the table number
Table 2: Please correct the entry for the EC-Earth model. Here the Danish Meteorological Institute (DMI) in Denmark has expressed the interest in the name of the entire consortium.
This has been fixed as suggested.

Table A1, A2, A3: I believe the fractional quantities refer to the total ice covered area. Please clarify and mention it in the table caption.
For a gridded data set, these variables conventionally give the fractional area covered by the quantity in a grid cell. No further clarifications needed.

Table A1, A2, A3: Please indicate in the table caption the sign convention of the fluxes, as already mentioned the general comments section above.
Additional clarifications have been added to the captions. See also reply to general comment above.

Table A2: Please clarify what is the base line of the "Global Average Thermosteric Sea Level Change"? Is it the beginning of each individual simulation or since the historical period started in 1850, for instance?
The data request tables are thought to be universal and would apply equally to e.g. paleo simulations. The standard sea level reference is therefore the beginning of the individual simulation, but may have to be specified for certain cases.

Figures

The figure numbers are given.
Figure A2: Since runoff leaves the snowpack, I would prefer that the arrow points beyond the snowpack.
This has been changed as suggested.

References

Ahlstrøm, A. P., Gravesen, P., Andersen, S. B., van As, D., Citterio, M., Fausto, R. S., Nielsen, S., Jepsen, H. F., Kristensen, S. S., Christensen, E. L., Stenseng, L., Forsberg, R., Hanson, S., Petersen, D. and Team, P. P.: A new programme for monitoring the mass loss of the Greenland ice sheet, Copenhagen, Denmark. [online] Available from: http://www.geus.dk/DK/publications/geol-survey-dk-gl-bull/15/Documents/nr15_p61-64.pdf, 2008.

Fischer, R., Nowicki, S., Kelley, M. and Schmidt, G. A.: A system of conservative regridding for ice–atmosphere coupling in a General Circulation Model (GCM), Geosci. Model Dev., 7(3), 883–907, doi:10.5194/gmd-7-883-2014, 2014.

Kjeldsen, K. K., Korsgaard, N. J., Bjørk, A. A., Khan, S. A., Box, J. E., Funder, S., Larsen, N. K., Bamber, J. L., Colgan, W., van den Broeke, M., Siggaard-Andersen, M.-L., Nuth, C., Schomacker, A., Andresen, C. S., Willerslev, E. and Kjær, K. H.: Spatial and temporal distribution of mass loss from the Greenland Ice Sheet since AD 1900, Nature, 528(7582), 396–400, doi:10.1038/nature16183,

2015.

Langen, P. L., Mottram, R. H., Christensen, J. H., Boberg, F., Rodehacke, C. B., Stendel, M., van As, D., Ahlstrøm, A. P., Mortensen, J., Rysgaard, S., Petersen, D., Svendsen, K. H., A›algeirsdóttir, G. and Cappelen, J.: Quantifying energy and mass fluxes controlling Godthåbsfjord freshwater input in a 5 km simulation (1991-2012), J. Clim., 28(9), 3694–3713, doi:10.1175/JCLI-D-14-00271.1, 2015.

Loose, B., Schlosser, P., Smethie, W. M. and Jacobs, S.: An optimized estimate of glacial melt from the Ross Ice Shelf using noble gases, stable isotopes, and CFC transient tracers, J. Geophys. Res., 114(C8), C08007, doi:10.1029/2008JC005048, 2009.

Lucas-Picher, P., Wulff-Nielsen, M., Christensen, J. H., A›algeirsdóttir, G., Mottram, R. and Simonsen, S. B.: Very high resolution regional climate model simulations over Greenland: Identifying added value, J. Geophys. Res., 117(D02108), 16pp, doi:10.1029/2011JD016267, 2012.

Rodehacke, C. B., Hellmer, H. H., Huhn, O. and Beckmann, A.: Ocean/ice shelf interaction in the southern Weddell Sea: results of a regional numerical helium/neon simulation, Ocean Dyn., 57(1), 1–11, doi:10.1007/s10236-006-0073-2, 2006.

We thank the reviewer for the detailed comments. Most of the references have also been included in the manuscript.

Author's response to comments from X. Asay-Davis (Referee 2)

The manuscript provides a valuable summary of the set of experiments—in coupled climate models both with and without ice-sheet components and in standalone ice-sheet models—and compelling motivation for why these experiments will be useful for exploring the role of Greenland and Antarctic Ice Sheets in the climate system, particularly as related to sea-level change.

We thank the reviewer for the helpful comments. We have now revised our manuscript in light of these and other comments that we have received. A point-by-point reply is given below.

General Comments

The manuscript is well written. Over all, I find the description of the experiments to be quite clear and well thought through. Clearly a commendable effort has gone into designing these experiments. The structure is clear with a few minor exceptions detailed below. The figures provide valuable visual cues to the structure of the experiments as well as the physical processes included in participating models. However, some of the figures are not yet publication quality and could use some additional attention (again, as detailed below).

Thank you for the detailed comments on the figure. They have been cleaned up accordingly.

As my area of expertise is more in ice sheet-ocean coupling and ocean modeling, rather than ice sheet modeling, my most detailed comments relate to ice-ocean interactions. I find that the discussion of potential methods for incorporating melt rates and/or temperature data from the ocean components of AOGCMs as well as the potential used of melt parameterizations needs some further elaboration, as elaborated in the specific comments.

We have altered the manuscript to address your specific comments. However, we are currently not able to be more specific on the way in which the standard ocean forcing will be implemented, as the final choice will depend on the evaluation of CMIP6 ocean runs that have not yet been made by the climate centers. Our goal was therefore to provide a variety of options. This said, ISMIP6 is committed to obtain the best possible forcing for ice sheet models with the help of atmosphere and ocean experts, and in the coming two years, we are organizing a series of workshop to address this issue. The first of these workshops will be held in San Francisco in December 2016, just before AGU.

Some of the discussion of how the time ranges of the "XXX-withism" and "ism-XXX-self" and "ism-XXX-std" differ from those of the standard CMIP6 runs they correspond to was not clear to me. I think this issue applies primarily to the historical runs? As I mention below, perhaps this could be clarified better both in the text and by putting the modified ISM ranges into Table 1, rather than having only the standard CMIP6 ranges.

We have altered the manuscript to clarify why it is challenging for standalone ice sheet models to have the same time range as the standard CMIP6 runs, and by including the modified ISM time range in the Table. Indeed the issue primarily applies to the historical run, which in standard CMIP6 runs start from the pre-industrial spin-up or control run. The reason is that pre-industrial spin-up is challenging for ice sheet models, so ice sheet models generally initialize at present day, or in the late 1990s.

For future Copernicus manuscripts, consider putting the tables and figures inline rather than at the end. This makes the paper much easier to review and is allowed by Copernicus as of January 2016.
This is a great advice! We will do so in future Copernicus manuscripts.

My recommendation is that the manuscript be published with minor corrections.

Specific Comments

p. 3 l. 11: You may wish to define SRES and RCP the first time you refer to them, though these acronyms will be familiar to most readers.

We have now defined SRES and RCP the first time that we refer to them.

p. 4 l. 26: Like Reviewer 1 (Christian Rodehacke), I felt that the XXX convention should be explicitly defined, even though it is likely obvious to the reader.

We used Reviewer 1's suggestion to add the sub-clause "where XXX stands for different forcing scenarios as described later".

p. 5 l. 2: It might be worth mentioning here that you will be discussing the method used to assess and evaluate the AGCM results in Sec. 4 (e.g. "...is to assess and evaluate (using metrics discussed in Sec. 4) CMIP atmosphere..."). During my first reading of the manuscript, I missed that the details of the analysis would come later (though you state it on p. 3 l. 19) and I was expecting at least some sense of what fields, metrics, etc. would be used in this analysis.

Following a comment from V. Eyring, we have now moved up the description of the methods used to assess and evaluate AGCM and AOGCM results (initially in section 4) to this section.

p. 8 l. 14: "The Tier 2 experiments..." You haven't yet introduced the tiers for the different experiments at this point in the text. If you can avoid referring to Tier 2 here by giving those experiments some other descriptor, that would save the awkwardness of needing to introduce the tiers here, rather than later where they seem to fit best.

We have changed the sentence "The Tier 2 experiments" to "Another set of experiments". In addition, following a comment from the CMIP panel, we have now indicated the Tier for each experiment in the experiment tables.

p. 8 l. 30-32: It is not entirely clear what "it" refers to in this sentence, presumably "accurate treatment of ice-ocean interactions"? More importantly, it seems to me that there is little doubt that accurate treatment of ice-ocean interactions requires moving boundaries in the ocean model. Just as parameterizing, rather than explicitly simulation, the circulation in ice-shelf cavities and resulting melt rates leads to inaccuracies, there can be little doubt that ignoring changes in cavity geometry (or parameterizing changes in melt rates) as the ice sheet evolves will lead to inaccuracies. All that is to say that "may" should be replaced with something stronger like "will likely".

We have replaced "It may" by "Accurate treatment of ice-ocean interactions will likely".

p. 9 l. 21-23: I would suggest moving "based on an initial analysis of AOGCM simulation[s] of ice sheet climate" to the beginning of the sentence for clarity. That way, it is hopefully clear that you are identifying the experiments based on the initial analysis, rather than that the ISMs are performing experiments based on the initial analysis. Also, maybe again here you could say that the criteria for determining which AOGCM results are "best" (i.e. chosen for the small subset of experiments) will be discussed in Sec. 4.

We have modified the text as suggested.

p. 10 l. 1-2: "...mismatch in spatial resolution over which SMB varies and that is used by AOGCMs". This phrase is confusing to me. Perhaps "..mismatch between the spatial resolution of AOGCMs and the characteristic length scale of variations in SMB"?

We have modified the text as suggested.

p. 10. l. 8: The use of RCMs as intermediaries between AOGCMs and ice-sheet models also adds ambiguity about which biases are introduced by the AOGCMs and which by the RCMs, does it not?

Indeed, the use of RCMs introduces additional ambiguity about biases, and is a motivation for avoiding the use of RCMs. We have added a sentence to state this.

Paragraph starting at p. 10 l. 26: Presumably, an effective melt parameterization would need to account for both the phenomena you outline in this paragraph (and probably more). It would need to make use of ocean temperature (and probably salinity) as a function of depth somewhere near the calving front each ice shelf and also the depth of the ice draft within the cavity. More sophistication would be nice (e.g. accounting for faster ocean flow with steeper ice-draft slope) but is still a topic of ongoing research.

Indeed, we agree with the reviewer that an ideal effective melt parameterization would be more complex than the ones described in our manuscript. Given that it is still a topic of ongoing research, we are limited in our manuscript to propose solutions that have been used by the community. This said, ISMIP6 is engaging with the ice-ocean community (for example with the upcoming pre-AGU workshop) with the goal of identifying a better way to provide oceanic forcing.

The paragraph on the oceanic forcing has been expanded into four new paragraphs in light of the comments that you make below. The discussion now ends with "Ice-ocean interactions are an active area of research, and more complex parameterizations are being developed (e.g. Asay-Davis et al., 2016). ISMIP6 will organize workshops with the polar ocean community to investigate how to best derive oceanic forcing for ice sheet models, such that by the time the CMIP6 ocean models are evaluated, ISMIP6 may adopt a method that is distinct from those described above."

p. 10 l. 27-28: I do not think that Rignot and Jacobs used surface temperature for their relationship, but rather ocean-bottom temperature close to the calving front. (However, they do not state their method of obtaining the temperature explicitly in their paper, at least as far as I could tell.) Also, this relation is only calibrated for melt rates at the GLs and likely is missing important nonlinearities (Holland et al. 2008).

Thank you for pointing out the mistake of the use "surface" for the ocean temperature and the deficiency of the use of this simple parameterization. Indeed, Rignot and Jacob (2002) sentence "Delta T is the difference between the nearest in situ ocean temperature measurement and the seawater freezing point (*43*) at a depth of 0.88 H_p [Table 1, (*21*)]", which suggests an ocean bottom temperature. We have removed the word "surface" and added a sentence about the problem of using this relationship.

The new text now reads:
One possibility is to calculate melt rate anomalies from changes in the nearest ocean temperature using an observationally derived relation of 10 m yr^{-1} $°C^{-1}$ (Rignot and Jacobs, 2002). However, this linear relation between ocean temperature and melt rates is calibrated for melt rates at the grounding line, and likely missing important non-linearities (Holland et al., 2008).

p. 10 l. 29-30: "...that depends on the ocean temperature at the closest grid cell..." At what depth would the temperature be taken? Hopefully at or near the ocean bottom. Or better yet as a profile of depth.

The parameterizations of Martin et al. (2011), Pollard and DeConto (2012), and DeConto and Pollard (2016) are all fairly similar and based on Beckman and Goose (2003). The oceanic melt rates are linked to ocean temperature using a relationship that takes the form of:

Melt = constant (To – Tf) for Martin et al (2011)

Melt = constant (To – Tf) | To – Tf | for Pollard and DeConto (2012), and DeConto and Pollard (2016)

Where To is a specified ocean temperature and Tf the ocean freezing point temperature at the ice shelf base, and the constant being a combination of density of the ocean water, density of the ice, specific heat capacity of ocean mixed layer, latent heat capacity of ice, thermal exchange velocity…

The specified ocean temperature, To, is different for each studies:

For Martin et al. it is set to -1.7C, a value that correspond to the Ross Ice Shelf from the work of Beckmann and Goose (2003), which according to Beckmann and Goose (2003) correspond to the "average temperature between 200 and 600m depth" for the Ross Ice Shelf.

For Pollard and Deconto (2012): "the ocean temperature To is specified differently for various Antarctic sectors, based on observations but mainly aiming to produce realistic ice shelf extents and grounding line position"

For DeConto and Pollard (2016), To is initially introduced in the method section as "ocean temperature interpolated from the nearest point in an observational (or ocean model) gridded dataset" and later defined as "the 1 degree resolution World Ocean Atlas temperatures at 400m depth"

We have turned the sentence in question into a paragraph to be more specific about the different approaches, and the various definition of ocean temperature. We also agree with the reviewer that ideally the ocean temperature would be a function of depth, and the revised manuscript reflects this.

The paragraph now reads:

"An alternative approach is to parameterize melt rates as proportional to the difference between ocean temperature at the shelf break and the freezing temperature at the ice shelf base. Beckman and Goosse (2003) developed such a scheme for ocean models, and similar schemes have been applied in offline ice sheet model simulations with idealized ocean forcing (e.g. Martin et al., 2011; Pollard and DeConto, 2012; DeConto and Pollard, 2016). In those studies, the ocean temperature is set to the average temperature between 200 and 600 m depth (Martin et al., 2011), or the temperature at 400 m depth (DeConto and Pollard, 2016), or specified differently for specific Antarctic sectors (Pollard and DeConto, 2012). Depending on the evaluation of the CMIP6 models, ISMIP6 may adapt one of these choices, or could prescribe depth-varying profiles of ocean temperature (and possibly salinity). The dependence of melt rates on thermal driving ranges from linear (Martin et al., 2011) to quadratic (Pollard and DeConto, 2012; DeConto and Pollard, 2016). Since the freezing temperature at the ice base decreases with depth, the melt rates in all schemes tend to be higher near grounding lines, as found from observations."

p. 10 l. 30-31: "If none of the CMIP6 ocean models are suitable" Can you be more specific about how "suitable" is defined (or refer to Sec. 4 and make sure you define there how you determine whether ocean results are suitable)?

As mentioned in our earlier responses, the text that described the evaluation of CMIP6 models based on observations and regionally focused ocean models has now been moved ahead of this section. At a minimum, the CMIP6 ocean models will need to capture the broad scale polar ocean characteristics, and the ocean temperatures. However, at this time it is not possible to be more specific on a definition for "suitable", as the field is progressing rapidly, so new metrics may become available and the CMIP6 ocean models may have improved on the CMIP5 ocean models. We have replaced "suitable" by "can accurately capture the broad-scale polar ocean circulation or produce realistic near-shelf temperatures."

p. 10 l. 31-32: "prescribe a melt parameterization that depends simply on the ice shelf draft". I (and

other ocean modelers) feel that this is a poor choice (perhaps very much so) for a couple of reasons: 1) The thermal forcing (or thermal driving – the difference between the freezing point and the "ambient" ocean temperature, however "ambient" is defined) plays at least as important a role as the depth of the ice draft, so that differences between "warm" and "cold" ice shelves cannot be ignored. 2) Such parameterizations have only been used in small regions, where their coefficients have been calibrated to local thermal conditions, not over the whole of Antarctica.
We agree that this is not the ideal choice, and that the difference between cold and warm shelves is important to capture. We have altered the manuscript to stress that if we have to use this method, the parameterization will not be uniform over the whole Antarctic, but will vary from one basin to the next, taking into account warm and cold shelves.

The manuscript now reads:
"If none of the CMIP6 ocean models can accurately capture the broad-scale polar ocean circulation or produce realistic near-shelf temperatures, an alternative is to prescribe a melt rate that simply depends on the ice shelf draft (e.g. Joughin et al., 2010a; Favier et al., 2014). This approach is less satisfactory, however, as it ignores temporal changes in ocean conditions, and typically uses coefficients calibrated to local thermal conditions. If ISMIP6 uses this approach, the provided coefficients would not be uniform, but would take into account that ocean waters reaching ice shelf cavities or fronts differ regionally. In Antarctica, for example, the ice shelves of Pine Island Glacier and Thwaites Glaciers lie in "warm" water, while the Filchner-Ronne or Ross ice shelves reside in "cold" water. Ocean temperatures reflect the dominant water sources, with warm waters dominated by circumpolar deep waters (Jacobs et al., 2011), while cold waters typically correspond to high salinity shelf water (Nichols et al., 2001)."

p. 11 l. 1: "oceanic anomalies (basal mass balance and basal temperatures)" I do not see how these can be generated, independent of ice basal topography (ice draft) if a parameterization is being used. Instead, perhaps coefficients in the parameterization as functions of time could be provided, from which melt rates could be computed given an ice draft.
This is a very good point, and parameterization that varies in time seems like a good idea, except that it might be difficult and time consuming for some groups to implement. At the same time, if our goal is to have all the models apply a similar anomaly (which will never be exactly the same as ice shelf areas vary from one model to the next), we will have to ignore the shelf draft and base it on something like the average depth between all the models, or the observed values. As stated above, the final decision on the oceanic forcing will be made after evaluation of the CMIP6 models, and after community workshops. The goal of the sentence was simply to state that we will distribute the forcing (or how to compute the forcing) via the ISMIP6 website. This sentence is not crucial to the text, so has been removed.

Paragraph starting at p. 11 l. 20: I found this whole paragraph to be very confusing. Perhaps part of it is that initMIP has not yet been described. Maybe you could consider reordering the paper so initMIP has been described already at this point?
We have reordered the manuscript so that initMIP is now already described, and slightly changed the wordings of the paragraph in response to your comments below and additional comments that we have received.

p. 11 l. 21-22: It is not at all clear to me what these two sentences refer to. Is the 1990s to 2014 forcing repeated or is just 2014 repeated? Or something else?
The forcing corresponds to the climate conditions at the end of the present-day initialization method. Present-day is defined differently for each model, and it also dependent on whether the initialization is an interglacial spin-up or whether it is mainly based on data assimilation (when data assimilation is used, present day also depend on what observations have been used). Therefore for one model, present day is year 1990, but for another model, present day will be year 2014. We have altered the manuscript to clarify these sentences.

p. 11 l. 27: Please elaborate on the challenges of initializing ice sheet models to per-industrial conditions and how this presents challenges that do not allow for the typical historical run. This is likely not obvious to all of your readers.

The quantity of accurate, high-resolution data available during the satellite era far exceeds that available for pre-industrial and historical periods. The majority of ice sheet models use these data in sophisticated initialization and assimilation procedures such that the present-day state of the ice sheets is simulated with a very high degree of fidelity. The lack of suitable data means that no such accuracy can be assumed for simulations of the historical periods. This becomes an issue because such inaccuracies are known to have a large effect on projections. For instance, discrepancies between projections can often be attributed to slight differences in the geometry of the ice-sheet margin assumed in a model (e.g., Shannon et al).

We have altered the manuscript to expand the discussion on the challenges of initializing ice sheet models to pre-industrial condition.

p. 11 l 27-29: What does this mean? What period of time is covered? Please consider updating Table 1 so the range of times for the various ism simulations is given separately where they differ from the standard CMIP6 simulations. This would help to clarify the confusing differences in time ranges described in this paragraph compared with those of standard CMIP6.

Because it is not possible for ice sheet models to initialize at a time that correspond to pre-industrial conditions (defined as year 1850 in the CMIP6 climate models) using data assimilation methods, the historical run for ice sheet models cannot start at year 1850. The historical run for ice sheet models can therefore only start from the "present-day" year that the ice sheet model was initialized at, which as clarified in an earlier response could be 1990, but also later. We hope that the rewritten version of this manuscript makes this clearer and we have updated the tables to show the distinctions between the start time of the CMIP6 and ISM runs.

p. 13 l. 3-5: How will the abmb anomaly field be constructed? How will it be made to conform to differences in grounding lines and calving fronts between different models? Similarly, how will the SMB anomaly be made to conform to differences in ice sheet extent between models in asmb?

Because of the difference in ice shelf extent between the different models, the abmb anomaly is prescribed to be constant for each basin. This scalar value is different for each basin, and derived from the mean value of the ice shelf melt observed by Rignot et al. (2014) and Depoorter et al. (2014). The abmb anomaly is applied in the models everywhere where the ice is floating, so that the ice shelf area is the only parameter that impacts the amount of basal melt anomaly applied. For the SMB forcing, the procedure is the same for both Greenland and Antarctica. The schematic SMB anomalies are defined everywhere on the model grid and are therefore applicable for models with varying ice sheet extent.

We have modified the text to include this information.

p. 13 l. 19-20: Why would it be ideal for the ism experiments to follow the AOGCM experiments with a six-month lag? Do you perhaps mean "no more than a six-month lag"? I would think ideally the ISM experiments would follow the AOGCM ones without any lag at all, but a realistic (or perhaps somewhat optimistic) time table would be for a six-month lag.

Indeed, ideally there will be no lag at all. However, we acknowledge that the climate modeling centers will be busy running simulations for other MIPs of CMIP6, hence we expect a time delay. We have however used your suggestion and rephrased so that the sentence now reads "Ideally, the XXX-withism and ism-XXX-self experiments would follow the corresponding AOGCM experiments with no more than a six-month lag."

p. 15 l. 29-30: "regional ocean models (e.g. Timmermann et al. 2012)" FESOM, the model that was the primary focus of this Timmermann paper, is actually a global model with high resolution

focused in Antarctica. Perhaps "regionally focused ocean models" would be more correct?
We have modified the sentence as suggested.

p. 33 Table 1: Please consider putting the actual start and end year for each ISM simulation that used a range different from the default CMIP6 (as requested previously)
The start and end year for each ISM simulations have now been included in the table (now Table 2).

p. 41 Figures A1: I feel this figure need some cleanup before they look professional enough for publication. The curves are not lined up very well (black is peaking out from under green). The blue arrows on the lighter blue surface and green base are not very visible. The giant gray error for freshwater flux should be given adequate room so it doesn't overlap the ice berg. Black lines should be anti-aliased and boundaries of the figure should not be jagged (slanted with respect to the figure caption).
The figure has been cleaned up, and we are confident it is now ready for publication.

p. 42 Figures A2: Blue text (both light and dark) is hard to read on blue background. The phrase "Liquid flux into the snowpack" should ideally either be entirely within or entirely outside the blue region.
The figure has been cleaned up, and we are confident it is now ready for publication.

Typographical Corrections
p. 5 l. 22: "amip" needs to be punctuated differently. Perhaps "The Atmospheric Model Intercomparison Project (amip; Gates et al. 1999) simulation allows..."
We have done the suggested changes.

p. 6. l. 18: "four ISMs simulations" → "four ISM simulations"?
We have corrected the typographical mistake.

p. 9 l. 22: "AOGCM simulation" → "AOGCM simulations"
We have corrected the typographical mistake.

p. 9 l. 28: "...cannot be made however we list..." → "...cannot be made. However, we list..."
We have corrected the typographical mistake.

p 10 l. 5: RCMS → RCMs. Also, a verb is missing in "to SMB", perhaps, "to simulate SMB"?
We have corrected the typographical mistake, and added the missing verb, so it now reads "to simulate SMB".

p. 10 l. 18: "the SMB lapse rate obtained" I would remove the word "obtained". It is not needed.
We have removed the word "obtained" as suggested.

p. 11 l. 8: "the dynamic response output" I would remove the word "output".
We have removed the word "output" as suggested.

p. 11 l. 11: "Ice Sheet-Ocean-Model" → "Ice Sheet-Ocean Model"
We have corrected the typographical mistake.

p. 11 l. 12: "Sect. 3.3).)" there is some extra punctuation here. I think just the one end parenthesis is needed. Also, should this be Sect. 3.3.2?
We have corrected the typographical mistake (cleaned up extra punctuation and changed the mistake in the Sect reference, which should indeed have been 3.3.2).

p. 11 l. 23-24: I would change “our” to “the” at the beginning of both these sentences.
We have done the suggested changes.

p. 11 l. 32: “ice sheets evolution” → “ice sheet evolution”
We have corrected the typographical mistake.

p. 12 l. 1: “at least by 4 meters” → “by at least 4 meters”
We have corrected the typographical mistake.

p. 12 l. 2: “from the ism-lig-std” → “from ism-lig127k-std”
We have corrected the typographical mistake.

p. 12 l. 30: “Antarctic Ice Sheets” → “Antarctic Ice Sheet”
We have corrected the typographical mistake.

p. 15 l. 28: “As regional” → “Just as regional”
We have done the suggested changes.

p. 19 l. 25-26: “not explicitly asked to minimize the data request” → “not specifically requested as an output variable in order to reduce the size of the data files” (or something similar – the original phrasing is not very clear)
We have done the suggested rephrasing.

p. 20 l. 26-39: Note that Asay-Davis et al. has been accepted in GMD so please don’t forget to update the reference when the time comes.
We have done the suggested update.

p. 31 l. 5 and 18: In 2 references, Vizca.no is spelled without the accent mark while in three it is with the accent mark. This may be an issue with the respective journals but it looks strange when these articles are cited close together.
We have done the suggested changes, namely to spell “Vizcaíno” consistently in both the manuscript and references.

Reference

Holland, P. R., Jenkins, A., & Holland, D. M. (2008). The Response of Ice Shelf Basal Melting to Variations in Ocean Temperature. Journal of Climate, 21(11), 2558–2572. http://doi.org/10.1175/2007JCLI1909.1

Author's response to comments from G. Durand (Comment 1)

I enjoyed reading this manuscript clearly describing ISMIP6 initiative. I would however suggest to add a table similar to table 2. I think, it would be appropriate to list the ice sheet models with the corresponding research groups who expressed an interest in participating in this MIP

Thank you very much for having read the manuscript and for your suggestion. We have now added a table similar to table 2, which lists the ice sheet models and the corresponding research groups.

Author's response to comments from V. Eyring (Comment 2)

Comments from CMIP Panel

The CMIP Panel is undertaking a review of the CMIP6 GMD special issue papers to ensure a level of consistency among the invited contributions, also in answering the key questions that were outlined in our request to submit a paper to all co-chairs of CMIP6- Endorsed MIPs. We very much welcome the important contribution from ISMIP6 to the CMIP6 special issue, below are a few comments:

We thanks the CMIP Panel for taking the time to review the ISMIP6 paper and for their leadership of CMIP6. We have revised our manuscript in light of these comments, and other comments that we have received.

Please consistently use the term 'CMIP6-Endorsed MIPs' when you refer to other MIPs that are endorsed by CMIP6.

We have checked the manuscript to ensure a consistent use of the term CMIP6-Endorsed MIPs.

Please ensure consistency of the experiment names and abbreviations with the CMIP6 overview paper (Eyring et al., 2016).

We have checked the manuscript to ensure a consistent use of the experiment names and abbreviations with the CMIP6 overview paper.

Please ensure that all ISMIP6 'experiment_ids' and 'sub_experiment_ids' are consistent with those used in the CMIP6 data request and experiment table, and with the CMIP6 terminology (see email exchange with Karl Taylor).

We have checked the manuscript to ensure that the use of the ISMIP6 experiment_ids and sub_experiment_ids are consistent with those used in the CMIP6 data request, experiment table and terminology, and use the ones from the email exchange with Karl Taylor.

Please ensure that the 'source_id' for the offline models is compliant with CMIP6 terminology.

We have emailed Karl Taylor for a clarification on what the source_id should be for the offline models. The response is that as we are not naming specific models, source_id is not relevant in our manuscript. We will however work with Karl Taylor to obtain source_id for the offline models that are compliant with CMIP6 terminology

p.5,l1ff. Section 3.1

• Is there a more intuitive title that actually describes what is envisaged here? Use seems vague.

We have changed the original title of section 3.1 from "Use of selected AGCM and AOGCM CMIP6 experiments" to "Analysis of experiments with climate models proposed elsewhere in CMIP6 (and not coupled to ISMs)". For consistency in the manuscript, we have also renamed section 3.2 from "Coupled AOGCM-ISM experiments" to "Experiments with climate models coupled to ISMs" and section 3.3 from "Standalone ice sheet model experiments" to "Experiments with ISMs not coupled to climate models".

• The last two paragraphs (l21ff and p6,l1ff) on the definition and explanation of the DECK, CMIP6 historical simulation, ScenarioMIP, and PMIP experiments should be deleted since they are already defined elsewhere in this special issue. It seems sufficient to simply refer to the other papers.

The last two paragraphs of this section are indeed intended to give a brief overview of CMIP, CMIP6, ScenarioMIP and PMIP, for readers that are unfamiliar with these efforts. We do provide reference to these description papers, however, we do not want to delete these two short paragraphs, as they provide the context for the ISMIP6 experiments. In particular, the ice sheet modeling community is not always familiar with the CMIP effort, as it is the first time that there is an ice sheet component in the CMIP effort. Some of the ISMIP6 standalone experiments may appear strange for an ice sheet modeler, who does not know of the CMIP framework/history.

• Would it be possible to list some observations that could be used to assess the models (l15ff)?
The observations that could be used to assess the climate models were discussed in section 4.1. Following a comment of reviewer 2 that he expected to read something about the observations in this section, and your suggestion below that the first paragraph of section 3.1 could be merged with section 4.1, we have now moved the relevant paragraphs of section 4.1 to section 3.1. The moving of paragraphs required some tidying up of the text, which we have also done.

• Possibly merge the first paragraph with Section 4.1 which is on the same subject and seems repetitive as it stands now with bits of information scattered across these two sections.
Done, see comment above.

p7,l19ff: please add to the text that both the downscaling method and the spin-up should be well documented. Also it might be good to expand a bit on the methods used for the spinup.
We have added to the text that downscaling methods and spin-up should be well documented, as you suggested. We have also expanded a little on the methods and challenges for coupled AOGCM-ISM and ISM spin-up.

p8,l8: 'then holds concentrations fixed for an additional two to four centuries.'. This is not how the 1ptCO2 experiment is defined. Note that in contrast to previous definitions, the experiment has been simplified so that the 1% CO2 increase per year is applied throughout the entire simulation rather than keeping it constant after 140 years as in CMIP5, see Section A1.4 in Eyring et al. (2016).
When working with Karl Taylor on the experiment_id (after the paper was submitted) it became clear that the version of the 1pctCO2 experiment that ISMIP6 is using is in line with the CMIP5 version and thus slightly different from the CMIP6 version after 140yrs. We have modified the manuscript to state this.

p8,l21: Here you encourage the extension of the projections until 2300 which is certainly a valid addition when it comes to the assessment of future sea level change. It is however only recommended, whereas in Table 1 this experiment is listed until 2300. Please could you make this consistent, e.g. either make it mandatory or - similar to ScenarioMIP (e.g. SSP5-8.5-Ext) - separate the two simulations in Table 1 into one that goes until 2100 and one that extends to 2300, and additionally list the Tier?
Thank you for pointing this out. We will follow ScenarioMIP and have altered the manuscript to reflect this.

p9,l5ff: Section 3.3: Could you confirm that all the output from the offline and standalone ISM experiments is conform to the output requirements of CMIP6? If ISMIP6 relaxes this requirement on output for some of its offline experiments, then those experiments should be considered not a part of CMIP6 (and therefore not listed in this paper). They could be described elsewhere. Our experience with past MIPs has been that initially the threshold effort required for standardizing data output (CMORization) is perceived as an obstacle by many groups, but time and experience has shown that this effort is well worth it. We have found that only standardized data gets widely used by the community, and the analysis of that data, especially by researchers outside the major modeling centers, has been central to CMIP's success.
We confirm that all the outputs from the offline and standalone ISM experiments will conform to the output requirements of CMIP6. We have worked with Martin Juckes, Denis Nadeau and Karl Taylor to

test that CMOR works for polar stereographic grids. ISMIP6 will also continue to provide help to ice sheet modelers to make their files compliant, a process that started with the initMIP experiments**.**

p9,l13ff: 'A key concern is that ISMIP6 assess uncertainty associated with both emission scenario and the AOGCMs' simulation of these scenarios. To this end, we anticipate identifying a subset of the CMIP6 AOGCM ensemble for use as ISM forcing which captures the full range of potential ice-sheet forcing.' This paragraph is too vague and the sentence seems contradicting - first a subset is selected and this should then be the full range? Please clarify. Please also add more explanation on how this selection process is done and why it is necessary.
ISMIP6 seeks to assess the uncertainty in sea level projections arising from both the ice sheet models and the climate forcing. For a given emission scenario, the AOGCMs simulation of these scenarios will result in a range of atmospheric and oceanic forcings. It is not possible for the standalone ice sheet models to make simulations with the forcings from all AOGCMs. A subset will therefore be selected (rather than doing them all), and the subset will be chosen to represent the range, by using metrics of the SMB and ocean forcing to investigate that range. The manuscript has been modified to explain this.

l18,p15: Data availability:
• Please delete 'the majority' in the first sentence. All CMIP6 simulations will be dis- tributed through the ESGF and non-CMIP6 experiments shouldn't be described in this paper.
We have deleted "the majority" as suggested, and checked that all experiments described in this paper are CMIP6 experiments.

• Could you please add the following additional sentence after the first sentence? '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).'
We have added the suggested sentence.

Table 1: The table lists experiments that are defined by ISMIP6 and experiments that are already defined elsewhere in CMIP6, this is confusing.
• Suggest to remove all experiments that are already defined elsewhere from this table (i.e., please remove the entire row for amip, abrupt-4xCO2, historical, ssp5-8.5, and lig127k).
• The titles of each category could be more specific by for example saying 'ISMIP6 DECK experiments' or something similar.
• Please could you also add a column that shows the Tier for each experiment?
• There could be another category that lists the ISMIP6 offline experiments from Section 3.3 if they are proposed to be part of CMIP6 (in which case the output has to be compliant with CMIP6 standards, see above).
We have removed the rows corresponding to experiments that have already been defined in the CMIP6 description paper or MIP-Endorsed description papers of this special issue, and placed them in a new Table (now Table 1). We feel that this information is important in our manuscript, as it allows readers that are not familiar with CMIP6 to avoid having to read many additional papers to find relevant information.

The new Table 2 now only contains experiments that are ISMIP6 experiments. This table includes your suggested changes: more specific titles, the Tier for each experiments, and the experiments that had been omitted from the original table (and described in the original section 3.3)

Table 2:
• is it possible to add a column with some specifics on the ice sheet models used and a reference if available?
• GFDL and MPI-ESM were two more models that initially indicated interest in participating but

are not listed?

• Except for CanESM that only participates in the diagnostic part of ISMIP6, are all other models listed using fully coupled ice sheet models, or are some of the models listed only contributing with standalone ice sheet models? Maybe this is not fully decided yet?

• Maybe it would be good to also list in a similar manner the standalone ice sheet models?

The new Table 3 now includes the ice sheet models used. We have also added MPI-ESM (the omission had been a mistake on our part). However, GFDL informed us that they no longer wish to take part in ISMIP6 and have asked to be removed.

With the exception of CanESM, all the models listed in Table 3 are planning to participate using fully coupled ice sheet models.

The manuscript now includes a new Table (Table 4) that lists the standalone ice sheet models taking part in ISMIP6 (and their institution).

Tables A1-A3: This is a very helpful overview of the variables requested by ISMIP6 but it would be good to clarify either in the caption or in a separate column from which CMIP6 experiments these variables are requested.
The caption now indicates from which CMIP6 experiments these variables are requested.

Table A2: Some additional information from the models is required to regrid the ocean data to standard grids. OMIP is proposing a weights file that model groups should provide to enable regridding from the native grid to one or two CMIP6 standard grids. Please refer to Griffies et al. (2016) and follow the same procedure for the ISMIP6 Omon requests if regridding is required.
We have modified the manuscript as suggested.

Reference:

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geosci. Model Dev., 9, 1937-1958, doi:10.5194/gmd-9-1937-2016, 2016.

Griffies, S. M., Danabasoglu, G., Durack, P. J., Adcroft, A. J., Balaji, V., Böning, C. W., Chassignet, E. P., Curchitser, E., Deshayes, J., Drange, H., Fox-Kemper, B., Gleckler, P. J., Gregory, J. M., Haak, H., Hallberg, R. W., Hewitt, H. T., Holland, D. M., Ilyina, T., Jungclaus, J. H., Komuro, Y., Krasting, J. P., Large, W. G., Marsland, S. J., Masina, S., McDougall, T. J., Nurser, A. J. G., Orr, J. C., Pirani, A., Qiao, F., Stouffer, R. J., Taylor, K. E., Treguier, A. M., Tsujino, H., Uotila, P., Valdivieso, M., Winton, M., and Yeager, S. G.: Experimental and diagnostic protocol for the physical component of the CMIP6 Ocean Model Intercomparison Project (OMIP), Geosci. Model Dev. Discuss.,doi:10.5194/gmd-2016-77, in review, 2016.

With many thanks for your ongoing efforts in the CMIP6 process.

The CMIP Panel

Author's response to comments from C. Ritz (Comment 3, send by email via Copernicus)

Thank you very much for having read the manuscript and for your suggestions. We have now revised our manuscript in light of these and other comments that we have received. A point-by-point reply is given below.

The main points I have concern the initial state (spinup procedure)
1- As mentionned by reviewer 1 (p6L25) the initial state will be the same for AOGCM-ISM, XXX-withism and ism-XXX-self simulations and this initial state will come from the coupled AOGCM-ISM runs. I am afraid, this choice will prevent the groups that do not have the coupling working at the beginning of the intercomparison, to do XXX-withism and ism-XXX-self. Could you comment?

We would first like to clarify that in our terminology "XXX-withism" stands for a specific AOGCM-ISM experiment. Therefore, we distinguish only two types of experiments (XXX-withism and ism-XXX-self) for the point the reviewer is raising here.

XXX-withism requires the coupled spin-up to be done. If the spin-up and models were perfect, the initial states would be the same (see also response to reviewer 1, p6L25). The ism-XXX-self experiment is only meaningful in combination with a completed XXX-withism with the same combination of climate and ice sheet models, which implies the existence of the coupled initial state. Note also that XXX-withism is an ice sheet only experiment forced by AOGCM output and therefore likely easy to run, once the coupling technology has been developed for XXX-withism.

If a coupled spin-up is not available, we recommend doing the ism-XXX-self with what ever initial ice sheet state is available and repeat the experiment at a later date, starting from the coupled spin-up version. Doing this would in fact be useful to investigate the concern of reviewer 1 (how much difference does the initial state makes). The steering committee had discussed the possibility of including this has an additional experiment. In the end it was decided against, in order to minimize the number of simulations requested from the modeling centers.

2- Do you plan to take advantage of the results of the initMIP project to refine the initial state procedure or simply use these result to quantify the trends related to the spinup procedure

Results of the initMIP project are expected to point to specific aspects of ice sheet initialisation that have a crucial impact on sea-level projections and may be improved. While the initialisation procedures used by the different participating groups are not prescribed by ISMIP6, it is expected that individual groups will take advantage of the initMIP results to improve their initialisation procedures.

We have included a sentence in the manuscript to clarify the intention of initMIP further.

3- I found difficult to follow which initial state will be used in the various simulations, would it be possible to add a column in table 1 to clarify this point?
The manuscript has been rewritten to clarify this, as indirectly asked from reviewers 1 and 2. The experiment description table now includes a column to indicate the initial state for each simulation.

Ice Sheet Model Intercomparison Project (ISMIP6) contribution to CMIP6

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Abstract. Reducing the uncertainty in the past, present and future contribution of ice sheets to sea-level change requires a coordinated effort between the climate and glaciology communities. The Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6) is the primary activity within the Coupled Model Intercomparison Project – phase 6 (CMIP6) focusing on the Greenland and Antarctic Ice Sheets. In this paper, we describe the framework for ISMIP6 and its relationship to other activities within CMIP6. The ISMIP6 experimental design relies on CMIP6 climate models and includes, for the first time within CMIP, coupled ice sheet – climate models as well as standalone ice sheet models. To facilitate analysis of the multi-model ensemble and to generate a set of standard climate inputs for standalone ice sheet models, ISMIP6 defines a protocol for all variables related to ice sheets. ISMIP6 will provide a basis for investigating the feedbacks, impacts, and sea-level changes associated with dynamic ice sheets and for quantifying the uncertainty in ice-sheet-sourced global sea-level change.

1 Introduction

Ice sheets constitute the largest and most uncertain potential source of future sea-level rise (Church et al., 2013, Kopp et al., 2014). The Greenland and Antarctic Ice Sheets currently hold ice equivalent to over 7 and 57 meters of sea-level rise, respectively. Observations indicate that the Greenland and Antarctic Ice Sheets have contributed approximately 7.5 mm and 4 mm of sea-level rise over the 1992-2011 period (Shepherd et al., 2012) and that their contribution to sea-level rise is accelerating (Rignot et al., 2011a). Sea-level change has been identified as a long-lasting consequence of anthropogenic

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climate change, as sea levels will continue to rise even if temperatures are stabilized (Meehl et al., 2012). Therefore, assessing whether the observed rate of mass loss from the ice sheets will continue at the same pace, or accelerate, is crucial for risk assessment and adaptation efforts.

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In addition to their impact on sea-level change, ice sheets influence the Earth's climate through changes in freshwater fluxes, orography, surface albedo and vegetation cover, across multiple spatial and temporal scales (Vizcaíno, 2014). Ice-sheet evolution and iceberg discharge affect ocean freshwater fluxes (e.g., Broecker, 1994), which in turn can affect oceanic circulation (e.g., Weaver et al., 2003), and marine biogeochemistry (Raiswell et al., 2006). Changes in ice sheet orography modify near-surface temperatures by altering atmospheric circulation (Ridley et al., 2005) on both regional and global scales (e.g., Manabe and Broccoli, 1985). Surface albedo and elevation change due to the waxing and waning of ice sheets has played an important role in past interglacial-glacial transitions (e.g., Calov et al., 2009; Abe-Ouchi et al., 2013). Seasonal fluctuations in ice-sheet albedo can also exert considerable influence on local surface energy fluxes (e.g., Box et al., 2012), through both melt and snowfall. Over longer timescales, changes in ice-sheet elevation can cause a positive feedback on surface mass balance, wherein a thinning ice sheet experiences warmer temperatures at lower elevations, which causes further melting and thinning. Ice-sheet elevation changes can also alter the local climate, for instance changing the trajectory of Southern Ocean storms that penetrate onto the Antarctic Plateau (Morse et al., 1998).

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Ice sheets gain mass primarily by accumulation of snowfall, and lose mass through a combination of surface meltwater runoff, surface sublimation, iceberg discharge to the ocean, and basal melting (under both grounded ice and floating ice shelves). The Antarctic Ice Sheet experiences minimal surface melt and thus loses mass primarily through basal melting and iceberg calving. Most basal mass loss in Antarctica occurs under ice shelves (e.g. Joughin et al., 2003; Pritchard et al., 2012), but sub-ice-sheet meltwater is also produced over large areas (Fricker et al., 2007). Together, basal melting and iceberg calving currently outweigh snowfall accumulation to the Antarctic Ice Sheet (Rignot et al., 2013; Depoorter et al., 2013). The Greenland Ice Sheet is also currently losing mass overall; this occurs primarily through iceberg calving and surface runoff. Surface mass balance changes have recently surpassed iceberg calving changes as the dominant contributor to Greenland mass loss (van den Broeke et al., 2009), with increased surface runoff now contributing 60% of the mass loss (Enderlin et al., 2014). Due to the long response time of ice sheets, mass changes observed at present are a complex combination of the response to present climate changes, as well as past climate changes as far back as several tens of thousands of years. These integrating effects of ice sheets and the vastly different time scales on which ice sheet models and climate models operate have historically inhibited efforts to interface these two components of the Earth system.

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Previously, ice sheets were not explicitly included in the CMIP process, and separate modeling studies were used to make projections of their future contributions to sea level. This has often led to mismatches between the climate data used to force these models and the contemporary version of the CMIP projections. This mismatch was perhaps acceptable when ice sheets

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were regarded as passive elements of the climate system on sub-millennial time scales (e.g., Church and Gregory, 2001). Observations of rapid mass loss associated with dynamic change in the ice sheets, however, have highlighted the need to couple ice sheets to the rest of the climate system. At one stage, this mismatch was such that little confidence could be placed in the projections of ice-sheet models, which were felt to omit the key processes responsible for observed changes (e.g., Meehl et al., 2007). With subsequent developments in ice-sheet modeling, many of the processes thought to affect ice-sheet dynamics on sub-centennial time scales (such as grounding-line migration, changes in basal lubrication and to some extent iceberg calving) can be simulated with some confidence (e.g., Church et al., 2013). Previous ice sheet model inter-comparison exercises have played a crucial role in this development. An excellent example is the ongoing series of inter-comparisons aimed at understanding issues associated with the numerical modeling of grounding-line motion (e.g., Pattyn et al., 2012, 2013). Two previous international efforts, the SeaRISE and ice2sea initiatives, supplied projections on which the assessments of Church et al. (2013) were based. A major criticism of both efforts, however, was that they were based on forcing from the Special Report on Emissions Scenarios (SRES, Nakićenović et al., 2000) rather than the current Representative Concentration Pathway (RCP, van Vuuren et al., 2011) framework. The Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6) is explicitly designed to ensure that ice sheet (hence sea-level) projections are fully compatible with the CMIP6 process.

ISMIP6 brings together for the first time a consortium of international ice sheet models and coupled ice sheet – climate models. This effort will thoroughly explore the sea-level contribution from the Greenland and Antarctic Ice Sheets in a changing climate and assess the impact of large ice sheets on the climate system. In this paper, we provide an overview of the ISMIP6 effort and present the ISMIP6 framework. We begin by explaining the objectives and approach for ISMIP6 (Sect. 2), and describe the experimental design (Sect. 3). We next present an evaluation and analysis plan (Sect. 4) and finally discuss the expected outcome and impact of ISMIP6 (Sect. 5).

2 Objectives and Approach

ISMIP6 was initiated with the help of the Climate and Cryosphere (CliC) effort of the World Climate Research Project (WCRP) and is now a targeted activity of CliC. The main goal is to better integrate ice sheet models in climate research in general, and in the CMIP initiative in particular. ISMIP6 offers the exciting opportunity of widening the current CMIP definition of the Earth System to include ice sheets. Together with the CliC targeted activity on glacier modeling (GlacierMIP) and existing models for thermal expansion within the CMIP framework, output from ISMIP6 will add sea level to the family of variables for which CMIP can provide routine IPCC-style projections. ISMIP6 is primarily focused on the CMIP6 scientific question "How does the Earth System respond to forcing?", but will also contribute to answering the question "How can we assess future climate change given climate variability, climate predictability and uncertainty in climate scenarios?" for scenarios involving the mass budget of the ice sheets and its impact on global sea level.

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ISMIP6 targets two Grand Science Challenges (GCs) of the WRCP: "Melting Ice and Global Consequences" and "Regional Sea-level Change and Coastal Impacts". Specifically, the primary goal of the ISMIP6 effort is to improve our understanding of the evolution of the Greenland and Antarctic Ice Sheets under a changing climate. A related goal is to quantify past and future sea-level contributions from ice sheets, including the associated uncertainties. These uncertainties arise from uncertainties in both the climate input and the response of the ice sheets. A secondary goal is to investigate the role of feedbacks between ice sheets and climate in order to gain insight into how changes in the ice sheets will affect the Earth climate system.

These goals require an experimental framework that can address the following objectives:

- Develop better models of climate and ice sheets, as both coupled systems and individual components
- Improve understanding of how ice sheets respond to climate on various timescales, both in the past and in the future
- Improve understanding of how ice sheets affect local and global climate, and explore ice sheet-climate feedbacks
- Improve simulation of sea-level change, especially projections for the 21st century and over the next 300 years

As depicted in Fig. 1, our goals and objectives rely on three distinct modeling efforts: i) traditional CMIP atmosphere – ocean general circulation models (AOGCM/AGCMs) without dynamic ice sheets, ii) standalone dynamic ice sheet models (ISMs) that are driven by provided forcing fields ("offline"), and iii) atmosphere-ocean climate models coupled to dynamic ice sheets (AOGCM-ISMs), which, as described in the following sections, can be combined to form an integrated framework.

3 ISMIP6 Experimental Design

Following the CMIP6 protocol, the ISMIP6 experiments both use and augment the CMIP6-DECK (Diagnostic Evaluation and Characterization of Klima) and Historical simulations (Meehl et al., 2014; Eyring et al., 2016). In addition, ISMIP6 collaborates with the CMIP6-Endorsed Paleoclimate Model Intercomparison effort (PMIP4, Kageyama et al., 2016) and builds on the CMIP6-Endorsed ScenarioMIP (O'Neill et al., 2016) that focuses on future climate experiments for CMIP6. For a selected number of AGCM/AOGCM experiments that are already part of CMIP6 (Table 1 and described in Sect. 3.1), three additional model configurations are proposed: "*XXX-withism*", *"ism-XXX-self"* and "*ism-XXX-std"*, where XXX stands for different forcing scenarios as described later and shown in Table 2. The first case, "*XXX-withism*", indicates that the ice sheet model is run interactively with the climate model (the AOGCM-ISM configuration described in Sect. 3.2). The other two cases describe an offline, or "standalone", ice sheet model that is driven by outputs from either an uncoupled AOGCM "*ism-XXX-self*" (the ISM configuration described in Sect. 3.2) or from a standard ISMIP6 dataset *"ism-XXX-std"* that will be provided for the glaciology community (the ISM configuration described in Sect. 3.3). The goal of the *ism-XXX-self*

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simulations is to obtain an ice sheet evolution and sea-level contribution that can be compared to the AOGCM-only and the AOGCM-ISM experiments in order to gain insight into the feedbacks between ice sheets and climate. Differences between the *ism-XXX-self* runs and AOGCM-ISM runs will be attributable to ice-sheet feedbacks on other climate components. The *ism-XXX-std* experiments will complement the AOGCM and AOGCM-ISM experiments by using ice sheet configurations and forcing data sets that are as realistic as possible, aiming to minimize the effects of AOGCM biases. The *ism-XXX-std* simulations target mainly the glaciology community and aim to simulate realistic ice-sheet evolution for sea-level estimates. A related set of standalone experiments, called initMIP, will explore uncertainties associated with the initialization of ice sheet models for Greenland and Antarctica.

3.1 Analysis of experiments with climate models proposed elsewhere in CMIP6 (and not coupled to ISMs)

A first component of the ISMIP6 effort is to assess and evaluate CMIP atmosphere general circulation models (AGCMs) and coupled atmosphere – ocean general circulation models (AOGCMs) over and surrounding the polar ice sheets. This part of ISMIP6 can be viewed as diagnostic in the sense that all climate models that participate in CMIP6 will be included in this assessment without requiring extra work from the climate modeling centers. These experiments do not include dynamic ice sheets, and as explained in the CMIP6 protocol (Eyring et al., 2016), climate modeling centers that contribute to CMIP6 are required to submit simulations for the DECK and CMIP6 Historical runs. Our goals are to establish the suitability of the CMIP models for producing climate input for ice sheet models and to assess the uncertainty in projections of sea-level change arising from such climate input. As described in Sect. 4, an additional goal is to assess past and projected changes in surface forcing (here for a fixed ice-sheet extent and topography), along with the resulting sea-level contribution from both ice sheets due to changes in surface freshwater flux alone. The largest uncertainty in century-scale sea-level projections, however, remains the dynamic ice sheet response to changes in atmospheric and oceanic conditions, which will be addressed by the other components of ISMIP6 (Sect. 3.2 and 3.3).

The experiments with climate models not coupled to ISMs, listed in Table 1, are central to ISMIP6 and thus briefly introduced. These AGCM/AOGCM experiments are already part of CMIP6, such that more detailed information on the experimental protocol is available elsewhere in this special issue. ISMIP6 uses three of the four DECK experiments described in Eyring et al. (2016). The Atmospheric Model Intercomparison Project (*amip*, Gates et al., 1999) simulation allows the evaluation of the atmospheric component of climate models given prescribed sea-surface temperatures and sea ice conditions. These oceanic forcings are based on observations and range from January 1979 to December 2014 for CMIP6 (see Appendix A1.1 of Eyring et al., 2016). The pre-industrial control, *piControl*, is a coupled atmospheric and oceanic simulation with constant conditions, chosen to represent pre-industrial values (with 1850 as the reference year, see Appendix A1.2 of Eyring et al., 2016). *piControl* serves as the starting point for many simulations and is meant to capture the pre-industrial quasi-equilibrium state of the climate system. It allows an evaluation of model drift and provides insight into the

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unforced internal variability. The DECK also contains two idealized "climate change" experiments, in which the CO_2 concentration is varied to gain insight into the Earth system response to basic greenhouse gas forcing. ISMIP6 will focus on a *1pctCO2to4x* simulation, a slightly modified version of the DECK *1pctCO2* simulation. The *1pctCO2* simulation is 150 years long, starting from the *piControl*, with a 1% per year increase in atmospheric CO_2 concentration. The *1pctCO2to4x* simulation is identical to *1pctCO2* for the first 140 years, at which point the CO_2 concentration reaches four times the initial value. At this point, *1pctCO2to4x* branches from *1pctCO2* and continues with constant quadrupled CO_2. (Note that the *1pctCO2to4x* scenario was called *1pctCO2* in CMIP5 (Taylor et al., 2012) and *1pctto4x* in CMIP3.) Groups participating in ISMIP6 with a coupled AOGCM-ISM should carry out the *1pctCO2to4x* simulation, starting from year 140 of their *1pctCO2* simulation, in order to produce boundary conditions for their *ism-1pctCO2to4x-self* simulation.

The CMIP6 Historical simulation, *historical,* tests the capability of AOGCMs to simulate the historical period, defined as 1850 to 2014. The forcing is derived from observations of solar variability and changes in atmospheric composition, including both anthropogenic and volcanic sources (see Appendix A2 of Eyring et al., 2016). The more distant past is the focus of PMIP4, which designs paleoclimate experiments (Kageyama et al., 2016; Otto-Bliesner et al., 2016). ISMIP6 collaborates with PMIP4 for experiment *lig127k*, a simulated time slice of the Last Interglacial (LIG); the warm period from 129,000 to 116,000 years ago when global mean sea level was 5–10 m higher than present (Masson-Delmott et al., 2013). The future in CMIP6 falls under the guidance of ScenarioMIP (O'Neill et al., 2016) and ISMIP6 will focus on the high-emission scenario *ssp585* that produces a radiative forcing of 8.5 W m^{-2} in 2100 and *ssp585ext* its extension to 2300, to evaluate climate and ice sheet changes in response to a large forcing. If time permits, lower-emission mitigation scenarios will also be included in the ISMIP6 standalone ice sheet framework.

Evaluation of the climate over and surrounding the ice sheets is necessary both to establish the suitability of current climate models to provide forcing for ice sheet models, and to gain insight into sea-level uncertainty arising from uncertainty in atmospheric and oceanic climate forcings. Of particular interest is the surface climate over the ice sheets, with a focus on temperature and surface mass balance (SMB). SMB is defined as total precipitation minus evaporation, sublimation and surface runoff, where runoff is meltwater less any refreezing within the snowpack. Because the ocean condition is prescribed for the *amip* simulation but not for the *historical* simulation, we expect that the temperature and SMB provided by the two simulations over the same time period will differ. We will explore our second interest, the capability of climate models to reproduce the oceanic state in the vicinity of the ice sheets, using the *historical* simulation.

The general approach for evaluating the atmospheric component of climate models over the ice sheets (e.g., Yoshimori and Abe-Ouchi, 2012; Fettweis et al., 2013; Vizcaíno et al., 2013; Cullather et al., 2014; Lenaerts et al., 2016) is to compare the large-scale atmospheric state over the polar regions, the local climate, and processes at the ice-sheet surface. The latter

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focuses on whether the climate model can simulate snow processes, including albedo evolution and refreezing, at a horizontal resolution that captures the SMB gradients at ice sheet margins. Both the atmospheric components and factors that can affect atmospheric processes are often evaluated. One example is determining whether sea ice conditions are adequately captured in *historical* simulations (e.g., Lenaerts et al., 2016), as sea ice can influence moisture availability and therefore precipitation. However, adequate modeling of precipitation also requires well-resolved ice sheet topography (orographic forcing), which remains challenging for coarse-resolution climate models (Vizcaíno, 2014).

The large-scale atmospheric state over the polar regions is often assessed by comparing the modeled atmospheric flow at 500 hPa to atmospheric reanalysis values. For the local climate, near-surface winds and near-surface temperatures can be compared to regional climate models (RCM) such as RACMO2 (van Meijgaard et al., 2008; Lenaerts et al., 2012; van Angelen et al., 2014), MAR (Fettweis, 2007; Fettweis et al., 2011), or HIRHAM (Langen et al., 2015; Lucas-Picher et al., 2012), reanalysis (e.g., Agosta et al., 2015), and observations where available. RCMs are also used to evaluate the spatial pattern of surface mass balance and its components (precipitation, sublimation, and surface melt) computed by global circulation models. The surface energy budget, particularly the seasonal cycle of net shortwave and longwave radiation and the sensible and latent heat fluxes, can be evaluated against measurements taken by automatic weather stations on the ice sheet surface. Such stations include, for example, the 15 Greenland stations known as the GC–Net (Steffen and Box, 2001), the Greenland PROMICE network with a focus on the ablation zone (Ahlstrom et al., 2008), and in Antarctica the Neumayer Base (Lenaerts et al., 2010). These stations also record winds and temperatures. The surface temperature over the ice sheets may also be evaluated from satellite observations, using, for example, data derived from the Moderate Resolution Imaging Spectroradiometer (MODIS, Hall et al., 2012). These remotely sensed temperature products show the onset and/or spatial extent of surface melt (e.g., Mote et al., 1993; Hall et al., 2013), which can then be used to assess whether the climate models capture the relevant processes at the ice sheet surface (e.g., Fettweis et al., 2011; Cullather et al., 2016). However, a full understanding of why surface melt varies from model to model may require investigations that include cloud properties (van Tricht et al., 2016).

The current generation of climate models participating in CMIP6 is unlikely to simulate ocean circulation in ice shelf cavities or within fjords. Thus, evaluation of the ocean state around the ice sheets involves first establishing that the climate models can reproduce certain properties of the key water masses. Ocean circulation around the Greenland Ice Sheet involves a complex interaction between polar waters of Arctic origin and Atlantic waters from the subtropical North Atlantic (Straneo et al., 2012). The mechanisms that transport warm water through fjords and toward the ice fronts remain an active area of research (Wilson and Straneo, 2015; Straneo and Cenedese, 2015). In the Southern Ocean, important water masses include Antarctic Bottom Water and Antarctic Intermediate Waters. In the coastal regions, Circumpolar Deep Water, Antarctic Surface Water, and High Salinity Shelf Water are the primary oceanic influences on ice sheets (Bracegirdle et al., 2016). Given the difficulty many CMIP5 models had in capturing high-latitude ocean properties, CMIP6 models should be evaluated using existing datasets (Bracegirdle et al., 2016). These datasets include Argo, expendable bathythermograph (XBT) and conductivity/temperature/depth (CTD) vertical temperature and salinity profiles (e.g., Dong et al., 2008), sea ice extent products sourced from passive microwave instruments (e.g., Bjorgo et al., 1997; Cavalieri and Parkinson, 2012; Parkinson and Cavalieri, 2012), sea surface temperature (SST) from WindSat and AMSR-E over the open ocean, satellite altimetry (Jason-1 and Jason-2) over the open ocean, and World Ocean Atlas 2009 climatological temperatures. For ocean models that include ice-shelf cavities and ice/ocean interactions, sub-ice-shelf basal melting can be compared with glaciological estimates of ice-shelf melting around Antarctica (Rignot et al., 2013; Depoorter et al., 2013) derived from remote-sensing observations, as well as independent tracer-oceanographic estimates (Loose et al., 2009; Rodehacke et al., 2006). Just as regional atmospheric models will be key for evaluating the atmospheric component of climate models, regionally focused ocean models (e.g., Timmermann et al., 2012) and ocean reanalysis products are likely to provide valuable insight for evaluating CMIP ocean models.

3.2 Experiments with climate models coupled to ISMs

The second component of ISMIP6 is a suite of experiments designed to assess the impacts of dynamic ice sheets on climate and to better understand feedbacks between ice sheets and climate. We also aim to obtain an ensemble of sea-level projections from fully coupled atmosphere – ocean – ice sheet frameworks, which can later be compared to projections from standalone ice sheet models (Sect. 3.3). The experiments should be identical to the corresponding standard CMIP AOGCM experiments except for the treatment of ice sheets, so that any observed feedbacks and impacts can be attributed to dynamic ice sheets and not to other sources. As indicated in Table 2, five coupled AOGCM-ISM simulations are proposed, whose experiment IDs are *piControl-withism*, *1pctCO2to4x-withism*, *historical-withism*, *ssp585-withism* and *ssp585ext-withism*. These simulations are complemented by five ISM simulations: *ism-piControl-self*, *ism-1pctCO2to4x-self*, *ism-historical-self*, *ism-ssp585-self* and *ism-ssp585ext-self*.

In the *XXX-withism* setup, the ice sheet model is run interactively with the AOGCM: the climate model sends a surface forcing (SMB at a minimum) to the ice sheet model, and receives changes in ice sheet geometry. The land surface type and surface elevation in the climate model are dynamic, allowing, for example, a reduced albedo if the land surface changes from glaciated to unglaciated. Changes in the ice sheet mass should also affect the ocean temperature and salinity, as freshwater fluxes (liquid and/or solid) and energy fluxes are routed to the ocean. Liquid fluxes can originate from surface runoff, subglacial drainage systems, or basal melting of the ice in contact with the ocean. Solid fluxes come from iceberg calving, which may be computed with calving laws whose details are left to the discretion of the modeling groups. Explicit iceberg models are not required. Similarly, ocean melting of ice shelves can be handled as desired, as long as the net freshwater flux and latent heat flux are routed consistently to the ocean model.

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The *ism-XXX-self* configuration denotes runs of an uncoupled ice sheet model driven by the outputs of the AOGCM-only simulation (Sect. 3.1). The *ism-XXX-self* experiment is only meaningful in combination with a completed *XXX-withism*, and with the same combination of climate and ice sheet models. In this configuration, changes in the ice sheet do not affect the climate model, and therefore the climate inputs passed to the ice sheet model differ from those in the AOGCM-ISM experiment. The ice sheet model should, however, be configured with the same settings as for the AOGCM-ISM runs and should use the same initial conditions (i.e., the outcome of the spin-up carried out with the coupled AOGCM-ISM).

Initial conditions for both the *ism-XXX-self* experiments and the *XXX-withism* experiments will be generated by running the coupled AOGCM-ISM to a quasi-equilibrium state with pre-industrial forcing that represent year 1850. Pre-industrial AOGCM-ISM spin-up is an area of active research (e.g., Fyke et al. 2014) that seeks to produce a consistent non-drifting coupled state corresponding to the pre-industrial climate, which is different from the contemporary state (Kjeldsen et al., 2015). The challenge is that ice sheets reach quasi-equilibrium on timescales of many millennia, more slowly than the oceans, which typically have been the slowest components of AOGCMs. To reach steady state, the ice sheet model may have to be run for ~10,000 years or longer. Since runs of this length are impractical for a complex climate model, the coupling between the ice sheet model and the climate model will likely have to be asynchronous for at least part of the spin-up. In this case, once the ice sheet model has reached steady state, the coupled system should be run synchronously for an additional period before starting the experiments. ISMIP6 will not dictate spin-up procedures for obtaining pre-industrial initial ice-sheet conditions, but the procedure should be documented.

Ideally, the ice sheet model should be forced with the actual SMB computed by the climate model, rather than an SMB corrected to match observed climatology. We accept that there may be biases in the atmospheric or land models that can lead to an unrealistic SMB, which could result in a steady-state ice sheet geometry that differs substantially from present-day observations. However, correcting for these biases can distort the feedbacks between ice sheets and climate that we seek to investigate. We hope to learn from and ultimately reduce these biases, in the same way that biases elsewhere in the simulated coupled climate system are reduced by greater understanding and improved model design. On the other hand, if the geometry of the spun-up ice sheet is greatly different from observations, then the initial ice sheet for the *ism-XXX-self* experiments may be far from steady state with the SMB forcing from the standard, uncoupled AOGCM. As a result, the *ism-XXX-self* experiment could have a large drift that obscures the climate signal. The drift will be quantified from the control experiments. In case of a large drift, or if the spun-up ice sheet in the coupled system is deemed to be too unrealistic, an alternative spin-up method would be to apply SMB anomalies from the AOGCM, superposed on a climatology that yields more realistic equilibrium ice sheet geometry.

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The method used to downscale SMB (as well as oceanic forcing) from the coarse climate model grid to the finer ice sheet model grid is left to the discretion of each group, but should be well documented. The data request for ISMIP6 in Appendix A asks modelers to report certain fields on both the atmospheric and ice sheet grids to allow for an evaluation of the downscaling procedure. Also, ISMIP6 prefers that the surface-melt component of SMB is obtained from an energy-based method that conserves mass and energy, to facilitate interpretation of the drivers of SMB variability and change (e.g. Vizcaíno, 2014). Highly parameterized methods of computing surface melt, such as positive-degree-day (PDD) methods (e.g. Reeh, 1991; Bougamont et al., 2007), should be avoided. The choice of the ice sheet model, its complexity in approximating ice flow, and ice-sheet-relevant boundary conditions (e.g., geothermal flux) are left to the modelers' discretion. In all experiments, however, the ice sheets should not be forced to terminate at the present-day ice margin if the simulated SMB and/or the ice sheet dynamics cause a margin advance.

Regardless of the spin-up method, the first ISMIP6 experiment to be performed with the coupled AOGCM–ISM is the pre-industrial control, *piControl-withism*. This is a multi-century (500 years suggested) control run aiming to assess model drift and systematic bias and to capture unforced natural variability. The drift in the standalone ISM experiments *ism-XXX-self* will be quantified with a control run (*ism-piControl-self*). The core ISMIP6 prognostic climate change experiment is *1pctCO2to4x-withism*, which applies a 1% per year increase in CO_2 concentrations over 140 years until levels are quadrupled, then holds concentrations fixed for an additional two to four centuries. The *1pctCO2to4x-withism* will be compared to the AOGCM simulation *1pctCO2to4x*, and the standalone ISM forced by the AOGCM surface mass balance and temperature (*ism-1pctCO2to4x-self*). The duration of these three experiments should be the same. It is suggested that the experiments be run for at least 350 years, and if possible for 500 years, because previous studies (e.g., Ridley et al., 2005; Vizcaíno et al., 2008; 2010) indicate that coupled AOGCM–ISM runs start to clearly diverge from uncoupled runs after about 250–300 years of simulation.

Another set of experiments repeats the CMIP6 *historical* *ssp585* and *ssp585ext* simulations with a coupled AOGCM-ISM. The *historical-withism* simulation begins at year 1850 from the pre-industrial spin-up and finishes at the end of 2014. This simulation is followed by *ssp585-withism* and *ssp585ext-withism*, with experimental settings and forcings as described in O'Neill et al. (2016). The *ssp585-withism* begins in January 2015 and is initiated from the December 2014 results of the *historical-withism* simulation. The *ssp585-withism* experiment is run for the 21st century and its extension to the end of the 23rd century. For completeness, these experiments are to be repeated with standalone ISM simulations *ism-historical-self* *ism-ssp585-self* and *ism-ssp585ext-self*. We accept that with this protocol, the 2015 ice sheet is likely to be distinct from the observed ice sheet due to model drift from the Historical run, and that this will have implications for projected ice sheet evolution (e.g., Stone et al., 2010).

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Based on community feedback, we expect that several AOGCM–ISMs will be ready to participate in coupled climate experiments for CMIP6. Table 3 shows climate modeling centers that have expressed interest in participating in ISMIP6. The primary focus is coupled ice sheet atmosphere simulation for the Greenland Ice Sheet, but some groups have indicated participation only in the diagnostic aspect of ISMIP6 (where the goal is to provide climate data for the standalone ice sheet work). Full coupling of ice sheet models to climate models remains challenging, especially for interactions with the ocean. Accurate treatment of ice-ocean interactions requires ISMs that can simulate grounding line migration (which demands fine grid resolution) and iceberg calving, and ocean models that can simulate circulation in the cavities below ice shelves and the consequent melting or accretion of ice on the undersides of the shelves. Accurate treatment of ice-ocean interactions will likely also require ocean models to alter their domain (both vertically and horizontally) as the calving front migrates and as sub-ice-shelf ocean cavities evolve in space and time. For the Greenland Ice Sheet, ocean models may need to capture fjord dynamics on smaller spatial scales (~1 km) than are currently resolved by global ocean models. In addition, credible ice-ocean coupling requires accurate knowledge of the bathymetry beneath ice shelves and ice sheets, where data are sparse. Because of these challenges, we do not expect a realistic treatment of the Antarctic Ice Sheet in the ISMIP6 coupled AOGCM-ISM experiments. Antarctica is included, however, in the standalone experiments described in the next section.

3.3 Experiments with ISMs not coupled to climate models

The final set of ISMIP6 experiments will use standalone ice sheet models driven by climate model output and other datasets. Groups and models that have expressed an interest in participating in this aspect of ISMIP6 are listed in Table 4. The models participating in this effort will likely be configured differently from those in the *ism-XXX-self* simulations described in Sect. 3.2. For example, an ice sheet model that is spun up to quasi-equilibrium with a climate model will likely have a thickness and extent that differ appreciably from observed values, whereas standalone models can be initialized more realistically. Also, an ISM in a climate model might use a coarse resolution or a simple approximation of ice dynamics in order to be more computationally efficient, while the same model used strictly for projections would likely have a finer resolution, at least in regions of fast flow (e.g. Aschwanden et al., 2016), and could incorporate more complex ice flow dynamics. Similarly, ice sheet models that are used for paleoclimate studies are often distinct from those used for projections of a few hundred years.

3.3.1 initMIP

The initMIP ice sheet experiments are designed to explore uncertainties in sea-level projections associated with model initialization and spin-up. Such uncertainties have been identified by previous model intercomparison efforts (e.g., Bindschadler et al., 2012; Nowicki et al., 2013a, b; Edwards et al., 2014a, Shannon et al., 2013; Goelzer et al., 2013; Gillet-Chaulet et al., 2012) and include the impacts of model initial conditions, sub-grid scale processes, and poorly known parameters. The initMIP project aims to evaluate initialization procedures, to estimate trends caused by model initializations and to investigate the impact of choices in numerical and physical parameters (e.g., stress balance approximation or model

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resolution). Results of the initMIP project are expected to point to specific aspects of ice sheet initialization that have a crucial impact on sea-level projections and may be improved.

ISM initialization methods to present-day conditions range from running paleo-climate spin-up for thousands of years (e.g., Martin et al., 2011; Sato and Greve, 2012; Aschwanden et al., 2013; Fürst et al., 2015; Saito et al., 2016) to assimilating present-day observations (e.g., Morlighem et al., 2010; Gillet-Chaulet et al., 2012; Seroussi et al., 2013, Arthern et al., 2015). The choices made in this procedure affect ice sheet extent, flow rates, volume, and volume trends, which can have substantial effects on estimates of ice sheet contribution to sea-level rise, as (e.g. Aðalgeirsdóttir et al., 2014). Improving ISM initial conditions is an active area of research and a multidisciplinary effort. It requires acquisition of additional data with high spatial coverage over entire ice sheets and at increased resolution (e.g., Bamber et al., 2013; Rignot et al., 2011b; Joughin et al., 2010a; Howat et al., 2014). Ideally, all datasets used in the data assimilation are from the same period, as initializing an ice sheet model with datasets taken at different times can cause the ice flow model to artificially redistribute the glacier mass in unrealistic ways that serve only to reconcile these inconsistencies (Seroussi et al., 2011). This also implies that the date the initial state is associated with can differ between models on grounds of the used data sets. New algorithms that reconcile initialization datasets are being developed, most notably for bedrock elevation (e.g., Morlighem et al., 2011; Morlighem et al., 2014), which is notoriously poorly constrained.

The initMIP project consists of a Greenland component and an Antarctic component. Following initialization, there is a set of two forward experiments for the Greenland Ice Sheet and three forward experiments for the Antarctic Ice Sheet, each run for at least 100 years: i) a control run (*ctrl*), ii) a surface mass balance anomaly run (*asmb*) and iii) a basal melt anomaly run (*abmb*) in which anomalous melt is applied beneath the floating portion of the Antarctic Ice Sheet. All other model parameters and forcing in the forward runs are the same as those used for initialization. The *ctrl* is an unforced forward experiment designed to evaluate the initialization procedure and characterize model drift, the surface mass balance remaining identical to the one used during the initialization procedure. In *asmb*, a prescribed SMB anomaly is applied to test the model response to a large perturbation. The schematic perturbation anomaly mimics outputs of several SMB models of different complexity between the end of the 20th century and the end of the 21st century, and is designed to capture the first-order pattern of SMB changes expected from climate models. The schematic SMB anomalies are defined everywhere on the model grid, and are therefore applicable for models with varying ice sheet extent. In *abmb*, a prescribed anomaly of basal melting rate under floating ice is applied while SMB is kept the same as in *ctrl*. Because of the difference in ice shelf extent between the different models, the basal melt anomaly is prescribed to be constant for each basin. This scalar value is different for each basin and derived from the mean values of the ice shelf melt observed by Rignot et al. (2013) and Depoorter et al. (2013). The applied anomaly simulates a doubling of sub-ice shelf melting after 40 years of simulation for models with initial melting rates close to today's observations.

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Since these experiments are designed to allow comparison among the different models, some simplifications are imposed. Neither SMB nor bedrock topography should be adjusted in response to ice-sheet geometric changes in these forward experiments. However, to sample the uncertainty in sea-level due to initialization, groups are encouraged to submit multiple variations of the experiment, for example by changing the sliding law, stress balance approximation, model resolution, or datasets (such as using different bedrocks). While the initialization procedures used by the different participating groups are not prescribed by ISMIP6, it is expected that individual groups will take advantage of the initMIP results to improve their initialization procedures. initMIP is also intended to give ice sheet modelers an opportunity to get involved in ISMIP6 at an early stage, before outputs of CMIP6 AOGCM become available; hence our prescription of simplified anomalies. We refer interested readers to the initMIP webpage (http://www.climate-cryosphere.org/wiki/index.php?title=InitMIP) for more information.

3.3.2 ism-XXX-std configuration

The *ism-XXX-std* experiments target primarily the glaciology community and seek to obtain realistic ice sheet evolution to inform estimates of past, present and future sea level. ISMIP6 will supply forcing data from CMIP6 that allows standalone ISMs to simulate the evolution of both the Greenland and Antarctic Ice Sheets. ISMIP6 seeks to assess the uncertainty in sea-level change arising from both the ice sheet models and the climate forcing. A key concern is that ISMIP6 assess uncertainty associated with emission scenario and the AOGCMs' simulation of these scenarios: for a given emission scenario, the AOGCMs simulation of this scenario will result in a range of atmospheric and oceanic forcings. Clearly, there is a tension between the range of potential ice sheet forcing, the need to explore uncertainty associated purely with ISMs (e.g., related to initial conditions, bedrock topography and parametric uncertainty), and the computing requirements of specific ISMs (some of which may only be able to perform a small number of experiments). To this end, we anticipate identifying a subset of forcing from the CMIP6 AOGCM ensemble based on the analysis of AOGCM simulations of ice-sheet climate (Sect. 3.1). The subset will be chosen to capture the full range of potential ice sheet forcing for a given emission scenario, using metrics of the SMB and ocean forcing to investigate that range. Within the selected subset of forcing, we plan to identify a small number of simulations that all ISMs must perform. Groups that are able to perform numerous simulations will be encouraged to participate in all experiments. Shannon et al. (2013) is an example of this approach.

The forcing data can naturally be divided into atmospheric and oceanic forcing. Central to the former is the means to determine SMB associated with a particular CMIP6 experiment. Several methods have previously been employed to do this. Until we can assess the quality of the climate simulated by CMIP6 AOGCMs above and around the ice sheets (after the

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analysis of the CMIP6 DECK and Historical simulations), a definitive choice cannot be made. However, we list the options in order of preference:

1. Use the SMB calculated by the AOGCM directly. This has the advantage that the SMB will be entirely consistent with other parts of that AOGCM's simulation of climate. There is concern, however, that the quality of the SMB computed by the AOGCMs will make this approach unrealistic due primarily to the mismatch between the spatial resolution of AOGCMs and the characteristic length scale of variations in SMB. Several groups have, however, made recent progress in this area (e.g., Vizcaíno et al., 2013; Lipscomb et al., 2013). The use of anomalies should also be considered in this context.
2. In the event that AOGCM-determined SMB is shown to be inadequate, an intermediate step is required. Previously, this has been the use of Regional Climate Models (RCMs) to simulate SMB. For example, the ice2sea effort chose to generate SMB from an RCM (Edwards et al., 2014a,b; Fettweis et al., 2013). This approach, however, introduces a further link into the processing chain that may lead to delay in the production of sea-level projections. It also introduces the issue of choice of RCM and whether results from a number of RCMs should be used (further complicating the design of the ISM ensemble). Furthermore, the use of RCMs as intermediaries between AOGCMs and ISMs adds ambiguity about which biases are introduced by the AOGCMs and which biases are the result of the RCMs.
3. Use a parameterization or simplified process model to simulate SMB by downscaling atmospheric forcing over the ice sheet from an AOGCM. This approach was used by SeaRISE (Bindschadler et al., 2013), where the precipitation and surface temperature from 18 AOGCMs models taking part in the A1B scenario were combined to generate monthly mean values. These mean precipitation and temperature values where then passed to the SMB scheme of the ice sheet model (generally a PDD method that accounted for the temperature aspect of the SMB-elevation feedback) to obtain SMB anomalies that were added to the ice sheet surface conditions at initialization.

A further consideration is that the AOGCM models assume a fixed ice sheet elevation, i.e. they neglect the effect of ice sheet elevation change on the atmosphere and hence omit the SMB-elevation feedback. Standalone ISMs will need to include this effect by parameterizing the SMB lapse rate (Edwards et al., 2014a,b; Fettweis et al., 2013; Goelzer et al., 2013). This approach may be less of an issue for method 3 above because SMB is determined interactively within the ISM rather than being prescribed as forcing.

A second way in which the atmosphere could force dynamic change in ice sheets is through the production of large quantities of melt water. Mechanisms have been proposed that link melt water to both ice shelf collapse (Banwell et al., 2013) and enhanced lubrication of ice flow (Zwally et al., 2002) (although recent modeling studies suggest a minor influence of the latter on large-scale ice flow (e.g., Shannon et al., 2013)). Surface air temperature and runoff forcing will therefore also be made available.

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Both Antarctica and Greenland are thought to respond to changes in proximal ocean temperatures, which affect the melt rates of floating ice shelves and the vertical faces of outlet glaciers. Obtaining suitable oceanic forcing from CMIP6 climate models will be a major challenge. Few CMIP6 models will calculate the appropriate melt rates, and even these results are likely to be inaccurate because of issues of model resolution and the unique physics of ocean circulation adjacent to melting ice. Melt rates will therefore need to be determined outside the climate model using an index for proximal ocean temperature. This index is most likely to be water temperature (and salinity) at the continental shelf break at an intermediate range of depths (equivalent to the base of ice shelves or the depth of ice grounded on bedrock). This quantity will be included in our evaluation of CMIP6 forcing (see Sect. 3.1).

A wide range of approaches has been used to calculate the required melt rate from prescribed ocean-temperature forcing. The simplest method is to calculate melt rate anomalies from changes in the nearest ocean temperature using an observationally derived relation of 10 m yr^{-1} $°C^{-1}$ (Rignot and Jacobs, 2002). However, this linear relation between ocean temperature and melt rates is calibrated for melt rates at the grounding line, and likely is missing important non-linearities (Holland et al., 2008). An alternative approach is to parameterize melt rates as proportional to the difference between ocean temperature at the shelf break and the freezing temperature at the ice shelf base. Beckman and Goosse (2003) developed such a scheme for ocean models, and similar schemes have been applied in offline ice sheet model simulations with idealized ocean forcing (e.g., Martin et al., 2011; Pollard and DeConto, 2012; DeConto and Pollard, 2016). In those studies, the ocean temperature is set to the average temperature between 200 and 600 m depth (Martin et al., 2011), or the temperature at 400 m depth (DeConto and Pollard, 2016), or specified differently for specific Antarctic sectors (Pollard and DeConto, 2012). Depending on the evaluation of the CMIP6 models, ISMIP6 may adapt one of these choices, or could prescribe depth-varying profiles of ocean temperature (and possibly salinity). The dependence of melt rates on thermal driving ranges from linear (Martin et al., 2011) to quadratic (Pollard and DeConto, 2012; DeConto and Pollard, 2016). Since the freezing temperature at the ice base decreases with depth, the melt rates in all schemes tend to be higher near grounding lines, as found from observations.

If none of the CMIP6 ocean models can accurately capture the broad-scale polar ocean circulation or produce realistic near-shelf temperatures, an alternative is to prescribe a melt rate that simply depends on the ice shelf draft (e.g. Joughin et al., 2010b; Favier et al., 2014). This approach is less satisfactory, however, as it ignores temporal changes in ocean conditions, and typically uses coefficients calibrated to local thermal conditions. If ISMIP6 uses this approach, the provided coefficients would not be uniform, but would take into account that ocean waters reaching ice shelf cavities or fronts differ regionally. In Antarctica, for example, the ice shelves of Pine Island Glacier and Thwaites Glaciers lie in "warm" water, while the Filchner-Ronne or Ross ice shelves reside in "cold" water. Ocean temperatures reflect the dominant water sources, with

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warm waters dominated by circumpolar deep waters (Jacobs et al., 2011), while cold waters typically correspond to high-salinity shelf water (Nichols et al., 2001).

Ice-ocean interactions are an active area of research, and more sophisticated parameterizations of melt are becoming available (e.g., Jenkins, 2016; Asay-Davis et al., 2016). Simplified models of the system could be used (e.g., Payne et al., 2007), as could high-resolution ocean models that resolve ice-shelf cavities and fjords. Given this wide range of methods, ISMIP6 will leave the detailed choice of the parameterization to individual ice-sheet modelers, but will issue guidance on what constitutes an acceptable parameterization. We will organize workshops with the polar ocean community to investigate how to best derive oceanic forcing for ice sheet models, so that by the time the CMIP6 ocean models are evaluated, a clearer protocol is in place. The calculated melt rate will be part of the standard data request for ice sheet models (see Appendix A), and part of our evaluation will be to determine how well the applied forcing compares to observed melt rates of Rignot et al. (2014) and Depoorter et al. (2014).

ISMIP6 will not dictate the choice of ice sheet model complexity in terms of the ice flow approximation, the basal sliding law, the treatment of grounding lines, the calving law, the ice-sheet-specific boundary conditions (e.g., bedrock topography), or the initialization method. An exception is that models of the Antarctic Ice Sheet should include floating ice shelves and grounding line migration. The spatial resolution of the ISM in the vicinity of fast-flowing ice streams and the grounding line affects the dynamic response (Durand et al., 2009; Pattyn et al., 2012, 2013), and the model resolution must be fine enough to capture this response accurately. To this end, participating models are encouraged to take part in model intercomparison efforts that target specific aspects of ice sheet modeling, such as the current MISOMIP (Marine Ice Sheet Ocean Model Intercomparison Project; Asay-Davis et al., 2016) and are required to take part in initMIP (initialization-focused experiments that compare and evaluate the simulated present-day state; Sect. 3.3.1). The lack of a stricter protocol is a reflection of the challenges in identifying which factors are the most important when making projections, which datasets are most accurate, and how to best capture and parameterize certain ice-sheet processes. For example, although the choice of bedrock topography affects mass transport and is thus likely to influence a projection, it is currently not possible to identify a best dataset due to the difficulty in obtaining bedrock measurements. Groups are encouraged to repeat the experiments with a variety of perturbations of weakly-constrained parameters, boundary conditions, etc. in order to test the sensitivity of projections to these choices.

Unlike the protocol for climate models, the *ism-XXX-std* simulations cannot be initiated from a spin-up corresponding to year 1850. This is due to the challenge of initializing ice sheet models to pre-industrial conditions, which are constrained more weakly than the contemporary state: the quantity of accurate, high-resolution data available during the satellite era far exceeds that available for pre-industrial and historical periods. The majority of ice sheet models use these data in

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sophisticated initialization and assimilation procedures, such that the present-day state of the ice sheet is simulated with high fidelity. The lack of suitable data before the satellite era means that no such accuracy can be assumed for simulations of the historical periods. Such inaccuracies are known to have a large effect on projections. For instance, discrepancies between projections can often be attributed to slight differences in the geometry (e.g., Shannon et al. 2013). The *ism-XXX-std* simulations will thus be initiated from a present-day spin-up.

The first *ism-XXX-std* simulation is *ism-pdControl-std*, the ice sheet present-day control with constant forcing needed to evaluate model drift. This constant forcing is based on the climate at the end of the initialization procedure. For many models, the forcing and simulation will be the same as the "*ctrl*" in the initMIP experiment (Sect. 3.3.1), unless a change has been made in the initialization. The idealized climate change experiment, *ism-1pctCO2to4x-std*, considers a 1% per year atmospheric CO_2 concentration rise until quadrupled concentrations and stabilization thereafter. The *ism-historical-std* will be an abbreviated simulation for the historical period (as it begins from the present-day spin-up) and, following the CMIP6 protocol, ends in December 2014. The *ism-amip-std* is a simulation for the last few decades to understand the well-observed record of ice sheet changes. The results from the *ism-amip-std* and *ism-historical-std* are likely to differ, and the comparison will provide some insight into the relative importance of biases, climate variability and climate change. The main simulation for projecting 21st century sea-level rise is the *ism-ssp585-std*, which is initiated from the *ism-historical-std* simulation. (As mentioned previously, other scenarios will be considered if time permits.) If possible, projections should continue to the end of the 23rd century with the extension scenario *ism-ssp585ext-std*.

We complement the experiments for the recent past and future with one paleo experiment (*ism-lig-std*), to simulate Greenland ice-sheet evolution during the Last Interglacial. The transient simulation will span the period 135 kyr to 115 kyr to include transitions from the preceding and to the following cold periods. The climate forcing for *ism-lig-std* will be derived from the PMIP4-CMIP6 experiment *lig127k* and other (transient) LIG climate simulations (cf. Bakker et al., 2012; Lunt et al., 2013) that will be performed by PMIP4 (Otto-Bliesner et al., 2016). The proposed experiment builds on past efforts to study Greenland ice-sheet stability and evolution during the LIG and constrain the Greenland contribution to the LIG sea-level highstand (e.g. Robinson et al., 2011; Born and Nisancioglu, 2012; Helsen et al., 2013).

3.4 Prioritization of experiments and timing

The ISMIP6 experiments listed in Table 2 are divided into three "Tiers" to indicate prioritization. Tier 1 denotes experiments that are to be completed by the ISMIP6 participants. Tier 2 experiments are highly encouraged, while Tier 3 experiments are optional.

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For the coupled AOGCM-ISM experiments, the Tier 1 experiments *piControl-withism* and *1pctCO2to4x-withism* should be performed first. These experiments have already been performed by many climate modeling groups, and their idealized settings allow for an easier evaluation of the ice-climate feedback. The Tier 2 experiments, *historical-withism, ssp585-withism* and *ssp585ext-withism*, are more relevant to our goal of producing sea-level projections concurrent with the CMIP6 future climate. Ideally, the *XXX-withism* and *ism-XXX-self* experiments would follow the corresponding AOGCM experiments with no more than a six-month lag.

For the standalone *ism-XXX-std* experiments, ISMIP6 is constrained by the timing of the AOGCM runs that will be used to derive forcings for ice sheets. We anticipate that the DECK simulations will be completed by the spring of 2017, which implies that climate models cannot be evaluated rigorously before summer 2017, and in turn that the ISM Tier 1 experiments based on CMIP6 DECK forcing would begin in 2018. As soon as suitable forcings are available from the SSP5-8.5 experiments (CMIP6-Endorsed ScenarioMIP, Tier 1), the *ism-ssp585-std* and *ism-ssp585ext-std* will be the focus of the standalone ISM work. To allow ice-sheet modeling groups the necessary time to perform the simulations, we plan to begin *ism-ssp585-std* and *ism-ssp585ext-std* in early 2019. Similarly, the *ism-lig-std* cannot proceed until the PMIP participants have completed the CMIP6-Endorsed PMIP4 Tier 1 experiment and other transient PMIP4 experiments. In the meantime, ISMIP6 standalone ice sheet models will focus on initMIP, with the goal of finishing this suite of experiments by the end of 2016 for Greenland and by the end of 2017 for Antarctica.

4 Evaluation and Analysis

The framework described in this paper entails an evaluation of the climate system, with a particular focus on the polar regions. This framework works toward the goals of i) assessing the effect of including dynamic ice sheets in climate models and ii) improving confidence in projections of sea-level rise associated with mass loss from the Greenland and Antarctic Ice Sheets. Our evaluation and analysis will be based on key model output variables for the atmosphere, ocean and ice sheets that form the ISMIP6 data request summarized in Appendix A.

4.1 Evaluation of ice sheet models

Ice sheet models will be evaluated using methodologies already in use by the ice-sheet modeling community. These metrics typically begin by assessing whether the volume and area of the modeled present-day ice sheet are comparable to observed values. The next step evaluates the spatial patterns of surface elevation, ice sheet thickness, surface velocities, and positions of the ice front and grounding line. Some ice sheet models are initialized using data assimilation methods, which precludes the use of certain observations in the evaluation. Evaluation of these models can be done by hindcasting, a method that evaluates whether recent observed trends are captured (Aschwanden et al., 2013). Examples include comparison against the gravimetry (GRACE) time series from 2003 onwards, which provides an integrated set of measurements for mass changes in

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Greenland and Antarctica. This approach will also enable a direct comparison between predicted sea-level rise from ISMs and the change in ocean mass observed by GRACE. The recent IMBIE effort (Ice Sheet Mass Balance Inter-comparison Exercise, Shepherd et al., 2012) facilitates this comparison by combining observations from gravimetry, altimetry and velocity changes between 1992-2012 into a single dataset of annual mass budget for each ice sheet. The follow-on effort, IMBIE2 (Shepherd, personal communication), will extend the record in time and plans to separate the observed mass change into SMB and dynamic components.

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4.2 Effects of dynamic ice sheets on climate

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The combination of coupled AOGCM-ISM simulations (*XXX-withism*) and standalone ice sheet simulations (*ism-XXX-self*) will support a clean analysis of ice-sheet feedbacks on the climate system, which can further affect ice-sheet evolution (e.g., Driesschaert et al., 2007; Goelzer et al., 2011; Vizcaíno et al., 2008, 2010, 2015). A limited number of feedbacks can be studied in an AOGCM without a dynamic ISM. For instance, because AOGCMs generally compute ice-sheet SMB through a land model coupled on hourly time scales to the atmospheric model, the albedo-melt feedback can be studied in an AOGCM alone. Other important feedbacks, however, are present only if the ice sheet is dynamic:

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- As ice sheets thin, the lower elevation leads to warmer surface temperatures that increase melting. This ice-elevation feedback is small on sub-century time scales (Edwards et al., 2014b), but over longer time scales, it can drive ice sheets to a point of no return, where retreat would continue unabated even if the climate returned to an unperturbed state.
- Changes in ice sheet elevation modify the regional atmospheric circulation (e.g., Ridley et al., 2005), which can either enhance or slow the rate of retreat.
- Changes in land surface cover (e.g., from glaciated to vegetated) can darken and warm the surface, promoting atmospheric warming and further melting.
- Increased freshwater fluxes (both solid and liquid) from retreating ice sheets can modify the density structure of the ocean, which may be strong enough to suppress convection and weaken the Atlantic meridional overturning circulation. Although some studies (e.g., Hu et al., 2009) find that this is a small effect, others suggest that increased runoff from the Greenland Ice Sheet has already reduced deep convection in the Labrador Sea (Yang et al., 2016).
- The buoyancy of fresh glacial meltwater from sub-ice-shelf melting can modify the ocean circulation that drives the melting. On longer time scales, changes in the size and shape of sub-shelf cavities may also alter the circulation.

The ISMIP6 experiments will be performed on climate model runs lasting several centuries, long enough to allow a detailed analysis of at least the first four of these feedbacks. Ocean cavity feedbacks, however, may require further development of ocean models that can adjust their boundaries dynamically as marine ice sheets advance and retreat.

4.3 Sea-level change

The SMB over the Greenland Ice Sheet is currently becoming less positive, thus resulting in an increasing contribution to sea-level rise due to increased surface runoff (van Angelen et al., 2014; Fettweis et al., 2011). This trend is expected to continue (Fettweis et al., 2013; Rae et al., 2012), although there is a large spread in AOGCMs (Yoshimori and Abe-Ouchi, 2012). The picture is less clear for the Antarctic Ice Sheet, where both accumulation and surface melt are projected to increase (Lenaerts et al., 2016). The multi-model ensemble of the surface freshwater flux from AOGCM simulation will provide insight into the resulting contribution of past and future sea level due to changes in SMB alone.

The largest uncertainty in sea level, however, remains the contribution from the ice sheets. ISMIP6 targets the contribution of dynamic ice sheets to global sea level, via multi-model ensemble analysis of standalone ice sheet models (*ism-XXX-std*). For a number of experiments, the multi-model ensemble from the *ism-XXX-std* will be contrasted to the multi-model ensemble resulting from coupled AOGCM-ISM simulations (*ism-XXX-withism*). We expect the results of the standalone modeling (*ism-ssp585-std* and *ism-ssp585ext-std*) to be more robust for projections, as we anticipate that the spun-up ice sheet from the coupled historical simulation (*historical-withism*) will differ substantially from present-day observations, and these differences will alter the projected ice sheet evolution (e.g. Stone et al., 2010; Shannon et al., 2013). The projections from *ssp585-withism* and *ssp585ext-withism* will likely expose issues resulting from coupling dynamic ice sheet models to climate models, motivating the community to begin resolving them.

We also aim to quantify the uncertainty in sea level arising from uncertainties in both the ice sheet models and the climate input, hence the need to sample across scenarios and models. For example, the ongoing initMIP project will provide insight into sea-level uncertainties resulting from ice sheet model initialization. By repeating model runs with different datasets, sliding laws, model resolutions, etc., initMIP will allow us to constrain the sea-level contribution associated with these choices. Ice sheet evolution will also depend on climatic drivers. For instance, given a certain number of AOGCMs that simulate present-day ice-sheet SMB reasonably well, comparing their SMB results under various climate-change simulations will allow us to quantify climate-model-driven uncertainty in SMB. If relationships between large-scale climate drivers (e.g., regional temperature and precipitation) and ice-sheet area-integral SMB can be established (e.g., Gregory and Huybrechts, 2006; Fettweis et al., 2013), this would allow estimation of SMB from AOGCM experiments for other climate scenarios. If possible, synergies with other CMIP6 efforts will allow us to further investigate the uncertainty in climate input. For example, the CMIP6-Endorsed High Resolution Model Intercomparison Project (HighResMIP, Haarsma et al., 2016) and Coordinated Regional Climate Downscaling Experiment (CORDEX, Gutowski et al., 2016) may allow us to quantify the impacts of increased resolution on SMB.

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5 Discussion and conclusion

ISMIP6 has an experimental protocol and a diagnostic protocol. The experimental design uses and builds upon the core DECK and CMIP6 Historical simulations, along with selected CMIP6-Endorsed PMIP4 and ScenarioMIP simulations. The suite of ISMIP6 experiments involves three types of models: AOGCM/AGCM with no dynamic ice sheets, coupled AOGCM-ISM, and standalone ISM. The diagnostic protocol is based on ice-sheet-related model outputs, many of which are already present in the CMIP6 atmosphere and ocean diagnostics. The evaluation of the climate in the polar regions from AOGCM and AOGCM-ISM simulations will guide recommendations for existing and new ice-sheet–climate coupling efforts. ISMIP6 promotes the development of the ice sheet component of climate models in an effort to bring both climate and ice-sheet models to greater maturity. ISMIP6 targets two of the WCRP Grand Science Challenges: "Melting Ice and Global Consequences" and "Regional Sea-level Change and Coastal Impacts". Given the current rapid changes in the Greenland and Antarctic Ice Sheets, ice sheets cannot be considered passive players in the climate system anymore. Their contributions to future sea level will likely have considerable human and environmental impacts, and ISMIP6 will facilitate research in this critical area.

ISMIP6 will coordinate simulation and analysis of ice sheet evolution in a changing climate. Inclusion of ice sheet models is unique in CMIP history and is necessary to advance understanding of the sea-level contribution from the Greenland and Antarctic Ice Sheets, the climate system response to ice-sheet changes, and the feedbacks between ice sheets and climate. ISMIP6 is thus an important step in closing the gap between the climate and ice-sheet modeling communities. Our key output, the sea-level contribution from ice sheets, complements the projections of ocean thermal expansion that already sit within the CMIP framework. This improvement will help sea level join the family of variables for which CMIP can provide routine IPCC-style projections. Ultimately, the success of ISMIP6 relies on the broad participation of the CMIP6 modeling centers, standalone ice sheet modeling groups, and analysts of the atmosphere, ocean and ice sheets.

Data availability

The model output from the simulations described in this paper will be distributed 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 modeling groups, and the ESGF centers (see details on the CMIP Panel website at http://www.wcrp-climate.org/index.php/wgcm-cmip/about-cmip). Datasets for natural and anthropogenic forcings are required to run the experiments; these datasets are described in separate invited contributions to this Special Issue. The forcing datasets will be made available through the ESGF with version control and DOIs assigned. Exceptions in the distribution method will be made for the forcing for the initMIP Greenland and Antarctic efforts that specifically target standalone ice sheet models. Instruction of how to obtain forcing datasets not available through ESGF will be posted on the ISMIP6 website (http://www.climate-cryosphere.org/activities/targeted/ismip6).

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6 Appendix A: Variable Request

This special issue includes a manuscript that is dedicated to the CMIP6 data request. The majority of our data request is based on the CMIP5 CMOR tables Amon (Monthly Mean Atmopsheric Fields), Omon (Monthly Mean Ocean Fields), LImon (Monthly Mean Land Cryosphere Fields), and OImon (Monthly Mean Ocean Cryosphere Fields), which already contained many of the output required to diagnose and intercompare the climate over land ice/ice sheets and to derive forcing for the ice sheets. In the CF convention, 'land ice' comprises grounded ice sheets, floating ice shelves, glaciers and ice caps, while 'ice sheet' refers to grounded ice sheets and floating ice shelves. A few additional variables are needed to properly derive the forcings for ice sheets from AOGCMs, and to record outputs from the evolving ice sheets in the coupled AOGCM-ISMs experiments (such as ice elevation change), or from the standalone ice sheet simulations. In this Appendix, we briefly outline the ISMIP6 data request on the atmosphere grid (Table A1), ocean grid (Table A2), and ice sheet grid (Table A3), and provide some context for key new variables.

The mass change of ice sheets (see Fig. A1) is a result of the surface mass balance (SMB), ice melt (or refreeze) at the base of the grounded ice sheet (BMB), and mass exchange with the ocean. The latter can be further split into frontal mass balance (FMB, defined as iceberg calving and melt (or refreeze) at the ice shelf font) and melt (or refreeze) at the base of ice shelves (BMB). All fluxes are defined as positive when the process adds mass to the ice sheet and negative otherwise. The thermal

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state of the ice sheet models is documented by the basal temperature and by the temperature at the ice sheet-snowpack interface. Note that BMB and basal temperature are computed differently depending on whether the ice is grounded or floating, requiring the use of distinct Long Names, but same Standard Names in Table A3.

Climate models will be evaluated primarily based on how well they can simulate SMB over the ice sheets. This quantity (see Vizcaíno (2014) and Fig. A2) can be defined as precipitation minus runoff minus evaporation (which in our context includes any sublimation, a small term over ice sheets), where precipitation is the sum of snowfall and rainfall. Runoff is the liquid water that escapes the ice sheet, while some of the water may be retained in the snow pack and possibly refreezes. The evaluation of climate models also benefits from analysis of energy fluxes, key temperatures, and area fraction of land ice, grounded ice sheet (excludes ice shelf) and snow over the land ice. Note that some variables, such as SMB, are present in both Table A1 and Table A3, since in a coupled AOGCM-ISM simulation, the two will differ due to downscaling to the ice sheet grid. The data request for the ocean serves primarily as input to construct oceanic forcing for ice sheet models off-line. It is not as extensive as the data request for the atmosphere, because marine boundary conditions for outlet glaciers and ice shelves are not routinely generated by AOGCMs. It is therefore premature to set diagnostic protocols at this stage. However, participants are asked to follow the protocols of the CMIP6-Endorsed Ocean Model Intercomparison Project (OMIP, Griffies et al., 2016) when preparing the data listed in Table A2, in particular when regridding the ocean data from a native grid to the CMIP6 standard grids. The ice sheet data request contains key characteristics needed to evaluate the ice sheet geometry, and ice sheet flow. It also contains key ice sheet specific boundary conditions that may differ between models and a record of the forcing applied to the ice sheet model. To facilitate the analysis of the ice sheet contribution to sea level, a number of integrated measures (for example, ice sheet mass) are also requested.

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8 Tables and Figures

Table 1: Overview of the experiments with climate models not coupled with ice sheet models that are to be used by ISMIP6. All experiments are started on 1 January and end on 31 December of the specified years.

Experiment	**CMIP6 label (experiment_id)**	**Experiment description**	**Start year**	**End year**	**Minimum no. years per simulation**	**Major purposes**
DECK experiments						
AMIP	*amip*	Observed SSTs and SICs prescribed	1979	2014	36	Evaluation, variability
Pre-industrial control	*piControl*	Coupled atmosphere-ocean pre-industrial control	n/a	n/a	500	Evaluation, unforced variability
1% yr^{-1} CO_2 concentration increase	*1pctCO2*	CO_2 concentration prescribed to increase at 1% yr^{-1}	n/a	n/a	150	Climate sensitivity, feedbacks, idealized benchmark
Modified DECK experiment						
1% yr^{-1} CO_2 concentration increase to 4 time CO_2	*1pctCO2to4x*	CO_2 concentration prescribed to increase at 1% yr^{-1} and then held constant to quadruple levels	n/a	n/a	350	Climate sensitivity, feedbacks, idealized benchmark
CMIP6 historical simulation						
Past ~ 1.5 centuries	*historical*	Simulation of the recent past	1850	2014	165	Evaluation
CMIP6-Endorsed ScenarioMIP simulations						
SSP5-8.5	*ssp585*	Future scenario with high radiative forcing by the end of the century	2015	2100	86	Climate sensitivity
SSP5-8.5ext	*ssp585ext*	Extension of high radiative forcing future scenario	2101	2300	200	Climate sensitivity
CMIP6-Endorsed PMIP4 simulation						
PMIP4 last interglacial	*lig127k*	Equilibrium simulation of the peak of the last interglacial period	127ka	n/a	100	Climate sensitivity, feedbacks, long responses

Table 2: Overview of the ISMIP6 experiments with dynamic ice sheets that are either coupled to climate models (AOGCM-ISM, *XXX-withism*) or run offline (ISM, *ism-XXX-self* and *ism-XXX-std*). All experiments are started on 1 January and end on 31 December of the specified years. PD indicates that the start date correspond to the date of the present-day ISM spin-up.

Experiment	**CMIP6 label (experiment_id)**	**Experiment description**	**Start year**	**End year**	**Minimum no. years per simulation**	**Starting conditions**	**Tier**
Repeat of DECK experiments with dynamic ice sheets							
AMIP	*ism-amip-std*	Offline ISM forced by ISMIP6-specified AGCM *amip* output	PD	2014	n/a	ISM spinup	2
Pre-industrial control	*piControl-withism*	Pre-industrial control with interactive ice sheet	n/a	n/a	500	AOGCM-ISM spinup	1
	ism-piControl-self	Offline ISM forced by own AOGCM *piControl* output	n/a	n/a	500	AOGCM-ISM spinup	1
Present-day control	*ism-pdControl-std*	Offline ISM forced by end of present-day spinup conditions	n/a	n/a	100	ISM spinup	1
Repeat of 1pctCO2to4x with dynamic ice sheets							
1% yr^{-1} CO_2 concentration increase to 4 time CO_2	*1pctCO2to4x-withism*	Simulation with interactive ice sheet forced by 1% yr^{-1} CO_2 increase to 4x CO_2 (subsequently held constant to quadruple levels)	n/a	n/a	350	AOGCM-ISM spinup	1
	ism-1pctCO2to4x-self	Offline ISM forced by own AOGCM *1pctCO2to4x* output	n/a	n/a	350	AOGCM-ISM spinup	1
	ism-1pctCO2to4x-std	Offline ISM forced by ISMIP6-specified AOGCM *1pctCO2to4x* output	n/a	n/a	350	ISM spinup	1
Repeat of CMIP6 historical simulation with dynamic ice sheets							
Past ~ 1.5 centuries	*historical-withism*	Historical simulation with interactive ice sheets	1850	2014	165	AOGCM-ISM spinup	2
	ism-historical-self	Offline ISM forced by own AOGCM *historical* output	1850	2014	165	AOGCM-ISM spinup	2
	ism-historial-std	Offline ISM forced by ISMIP6-specified AOGCM *historical* output	PD	2014	n/a	ISM spinup	2
Repeat of CMIP6-Endorsed ScenarioMIP simulations with dynamic ice sheets							
High radiative forcing future emission scenario (SSP5-8.5)	*ssp585-withism*	SSP5-8.5 simulation with interactive ice sheet	2015	2100	86	*historical-withism*	2
	ism-ssp585-self	Offline ISM forced by own AOGCM *ssp585* output	2015	2100	86	*ism-historical-self*	2
	ism-ssp585-std	Offline ISM forced by ISMIP6-specified AOGCM *ssp585* output	2015	2100	86	*ism-historical-std*	2
Extension of high radiative forcing future scenario (SSP5-8.5ext)	*ssp585ext-withism*	Extension of SSP5-8.5 simulation with interactive ice sheet	2101	2300	200	*ssp585-withism*	3
	ism-ssp585ext-self	Offline ISM forced by own AOGCM *ssp585ext* output	2101	2300	200	*ism-ssp585-self*	3
	ism-ssp585ext-std	Offline ISM forced by ISMIP6-specified AOGCM *ssp585ext* output	2101	2300	200	*ism-ssp585-std*	3
Last interglacial simulation based on PMIP4 simulations with standalone ice sheet only							
Last interglacial	*ism-lig-std*	Last interglacial simulation forced by *lig127k* and other PMIP experiments.	135ka	115ka	20000	ISM spinup	3
initMIP Greenland and Antarctic simulations with standalone ice sheet only							
Present-day control	*ctrl*	Present-day control	n/a	n/a	100	ISM spinup	1
Surface mass balance	*asmb*	Surface mass balance anomaly prescribed	n/a	n/a	100	ISM spinup	1
Basal melt	*bsmb*	Basal melt anomaly under floating ice prescribed (Antarctica only)	n/a	n/a	100	ISM spinup	1

Table 3: Climate Modeling Centers that have expressed an interest in ISMIP6. *Indicates only an interest in the diagnostic component (no AOGCM-ISM participation anticipated).

Climate Model	Ice Sheet Model	Institute/Country
CanESM*	None	CCCma/CA
CESM	CISM	NCAR-COLA/USA
CNRM-CM	GRISLI	CNRM-CERFACS/FR
EC-Earth	GrIS	DMI/DK
GISS	PISM	NASA-GISS/USA
INMCM	VUB	INM/RU
IPSL-CM6	GRISLI	IPSL/FR
MIROC-ESM	IcIES	AORI-UT-JAMSTEC-NIES/JP
MPI-ESM	PISM	MPI/DE
UKESM	BISICLES	MetOffice/UK

Table 4: Ice sheet modeling groups that have expressed an interest in ISMIP6.
x Indicates planned contribution.

Ice Sheet Model	Greenland	Antarctica	Institute/Country
BISICLES	x		BGC/UK
CISM	x		LANL/USA
Elmer/Ice	x	x	LGGE/FR
f.ETISH		x	ULB/BE
GISM	x		VUB/BE
GRISLI	x		LSCE/FR
IcIES	x	x	MIROC/JP
IMAUICE	x	x	IMAU/NL
ISSM	x	x	JPL/USA
ISSM	x		AWI/DE
MPAS-LI		x	LANL/USA
MPAS-LI		x	ORNL/USA
PennState3D		x	PSU/USA
PISM	x		UAF/USA
PISM	x	x	ARC/NZ
PISM	x		DMI/DK
PISM	x		MPIM/DE
SICOPOLIS	x	x	ILTS/JP
Úa		x	BAS/UK
WAVI		x	BAS/UK

Table A1: Data in the LImon Table (Monthly Mean Land Cryosphere Fields) and/or Amon Table (Monthly Mean Atmospheric Fields) needed to capture the glaciated/ice sheet surface realm. These fields are saved on the atmosphere grid and contain monthly output. Tier indicate priority of variable: Mandatory (1), Desirable (2), Experimental (3). These variables are requested for climate models participating in the diagnostic component of ISMIP6 (Table 1), and for the *XXX-withism* experiments (Table 2). Flux variables are defined positive when the process adds mass or energy to the ice sheet and negative otherwise.

Long name (netCDF)	Units	Standard name (CF)	Tier
Near surface air temperature (2m)	K	air_temperature	1
Surface temperature	K	surface_temperature	1
Snow internal temperature	K	temperature_in_surface_snow	2
Temperature at the interface between ice sheet and snow	K	land_ice_temperature_at_snow_base	2
Surface mass balance flux	kg m^{-2} s^{-1}	land_ice_surface_specific_mass_balance_flux	2
Precipitation	kg m^{-2} s^{-1}	precipitation_flux	1
Snowfall flux	kg m^{-2} s^{-1}	snowfall_flux	1
Rainfall flux	kg m^{-2} s^{-1}	rainfall_flux	2
Surface snow and ice sublimation flux	kg m^{-2} s^{-1}	surface_snow_and_ice_sublimation_flux	2
Surface snow and ice melt flux	kg m^{-2} s^{-1}	surface_snow_and_ice_melt_flux	2
Surface snow melt flux	kg m^{-2} s^{-1}	surface_snow_melt_flux	3
Surface ice melt flux	kg m^{-2} s^{-1}	surface_ice_melt_flux	3
Surface snow and ice refreezing flux	kg m^{-2} s^{-1}	surface_snow_and_ice_refreezing_flux	3
Land ice runoff	kg m^{-2} s^{-1}	land_ice_runoff_flux	2
Snow area fraction	1	surface_snow_area_fraction	1
Land ice area fraction	1	land_ice_area_fraction	1
Grounded ice area fraction	1	grounded_ice_area_fraction	1

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Land ice altitude	m	surface_altitude	1
Net latent heat flux over land ice	W m^{-2}	surface_upward_latent_heat_flux	1
Sensible heat flux over land ice	W m^{-2}	surface_upward_sensible_heat_flux	1
Downwelling shortwave	W m^{-2}	surface_downwelling_shortwave_flux_in_air	1
Upward shortwave over land ice	W m^{-2}	surface_upwelling_shortwave_flux_in_air	1
Downwelling longwave	W m^{-2}	surface_downwelling_longwave_flux_in_air	1
Upward longwave over land ice	W m^{-2}	surface_upwelling_longwave_flux_in_air	1
Albedo over land ice	1	surface_albedo	2

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Table A2: Data on the Omon Tables (Monthly Mean Ocean Fields) needed to capture the glaciated/ice sheet surface realm or for intercomparison of the model simulations. These fields are saved on the ocean grid and contain monthly output. Data preparation should follow the CMIP6-Endorsed OMIP protocol. Tier indicates priority of variable: Mandatory (1), Desirable (2), Experimental (3). These variables are requested for climate models participating in the diagnostic component of ISMIP6 (Table 1), and for the *XXX-withism* experiments (Table 2). Flux variables are defined positive when the process adds mass to the ocean and negative otherwise.

Long name (netCDF)	Units	Standard name (CF)	Tier
Global surface height above geoid	m	sea_surface_height_above_geoid	1
Global average thermosteric sea-level change	m	global_average_thermosteric_sea_level_change	1
Sea water potential temperature	^{o}C	sea_water_potential_temperature	1
Sea surface temperature	^{o}C	sea_surface_temperature	2
Sea water salinity	Psu	sea_water_salinity	1
Water flux into sea water from iceberg	kg m^{-2} s^{-1}	water_flux_into_sea_water_from_icebergs	2
Water flux into sea water from ice sheets	kg m^{-2} s^{-1}	water_flux_into_sea_water_from_land_ice	3

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Table A3: Data on the Icesheetmon or Icesheetyear Tables needed to capture the dynamical ice sheet model realm. These fields are saved on the ice sheet grid and contain monthly or yearly output. Tier indicate priority of variable: Mandatory (1), Desirable (2), Experimental (3). These variables are requested for models participating in the *XXX-withism, ism-XXX-self* and *ism-XXX-std* experiments (Table 2). Flux variables are defined positive when the process adds mass or energy to the ice sheet and negative otherwise.

Long name (netCDF)	Units	Standard name (CF)	Tier
Ice sheet altitude	m	surface_altitude	1
Ice sheet thickness	m	land_ice_thickness	1
Bedrock altitude	m	bedrock_altitude	1
Bedrock geothermal heat flux	W m^{-2}	upward_geothermal_heat_flux_at_ground_level	3
Land ice calving flux	kg m^{-2} s^{-1}	land_ice_specific_mass_flux_due_to_calving	3
Land ice vertical front mass balance flux	kg m^{-2} s^{-1}	land_ice_specific_mass_flux_due_to_calving_and_ice_front_melting	2
Surface mass balance and its components	kg m^{-2} s^{-1}	see Table A1	1
Basal mass balance of grounded ice sheet	kg m^{-2} s^{-1}	land_ice_basal_specific_mass_balance_flux	2
Basal mass balance of floating ice shelf	kg m^{-2} s^{-1}	land_ice_basal_specific_mass_balance_flux	2
X-component of land ice surface velocity	m yr^{-1}	land_ice_surface_x_velocity	1
Y-component of land ice surface velocity	m yr^{-1}	land_ice_ surface_y_velocity	1
Z-component of land ice surface velocity	m yr^{-1}	land_ice_ surface_upward_velocity	2
X-component of land ice basal velocity	m yr^{-1}	land_ice_basal_x_velocity	1
Y-component of land ice basal velocity	m yr^{-1}	land_ice_basal_y_velocity	1
Z-component of land ice basal velocity	m yr^{-1}	land_ice_basal_upward_velocity	2
X-component of land ice vertical mean velocity	m yr^{-1}	land_ice_vertical_mean_x_velocity	2
Y-component of land ice vertical mean velocity	m yr^{-1}	land_ice_vertical_mean_y_velocity	2
Land ice basal drag	Pa	magnitude_of_land_ice_basal_drag	3

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Surface temperature	K	surface_temperature	1
Temperature at the interface between ice sheet and snow	K	land_ice_temperature_at_snow_base	1
Basal temperature of grounded ice sheet	K	land_ice_basal_temperature	1
Basal temperature of floating ice shelf	K	land_ice_basal_temperature	1
Land ice area fraction	1	land_ice_area_fraction	1
Grounded ice area fraction	1	grounded_ice_sheet_area_fraction	1
Floating ice sheet area fraction	1	floating_ice_sheet_area_fraction	1
Surface snow area fraction	1	surface_snow_area_fraction	2
Scalar outputs / Integrated measures			
Ice mass	kg	land_ice_mass	2
Ice mass not displacing sea water	kg	land_ice_mass_not_displacing_sea_water	2
Area covered by grounded ice	m^2	land_ice_area_grounded	3
Area covered by floating ice	m^2	land_ice_area_floating	3
Total SMB flux	kg s^{-1}	tendency_of_land_ice_mass_due_to_surface_mass_balance	3
Total BMB flux	kg s^{-1}	tendency_of_land_ice_mass_due_to_basal_mass_balance	3
Total calving flux	kg s^{-1}	tendency_of_land_ice_mass_due_to_calving	3

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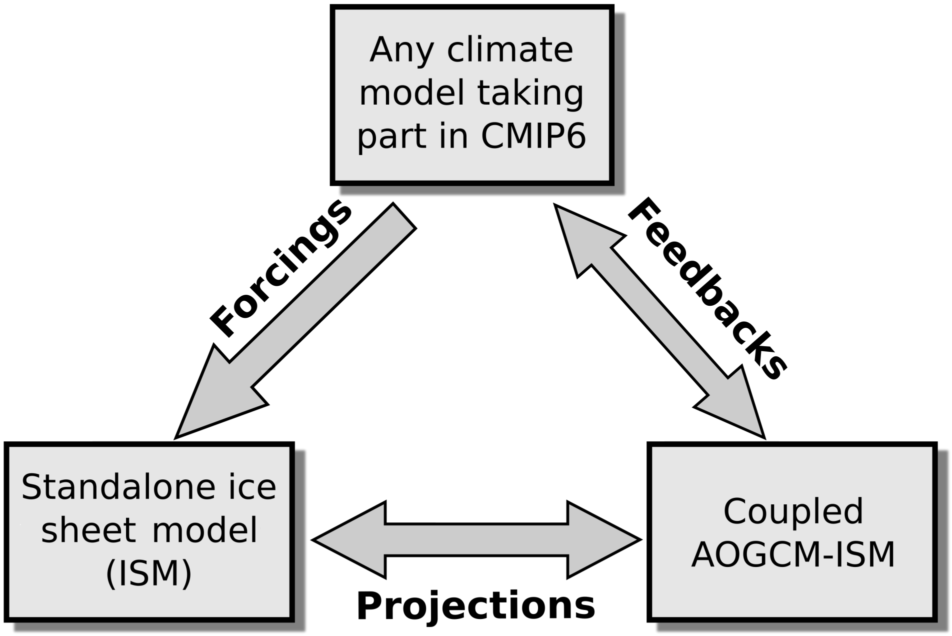

Figure 1: Overview of the ISMIP6 effort designed to obtain forcing from climate models, project sea-level contributions using ice sheet models, and explore ice sheet-climate feedbacks.

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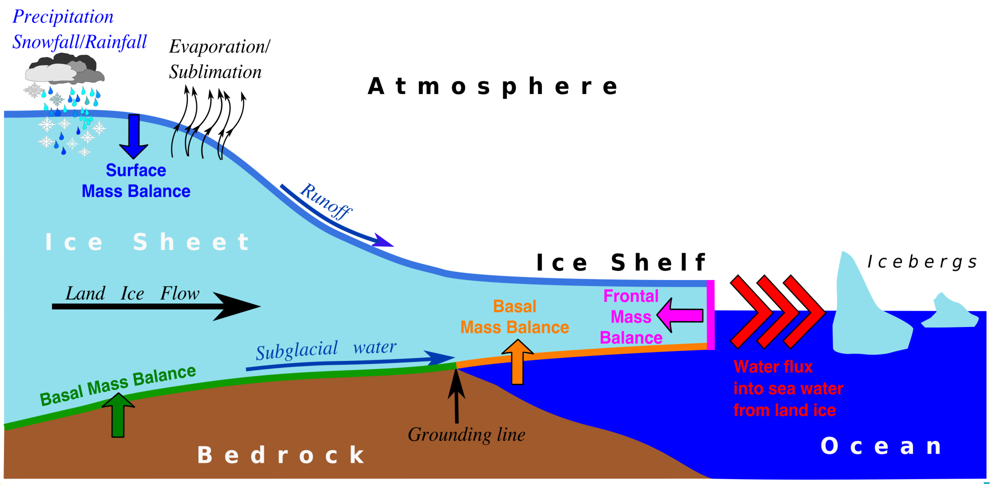

Figure A1: Illustration of the mass change of ice sheets and key data request that are specific to ice sheet model evaluation or forcing. See text for details.

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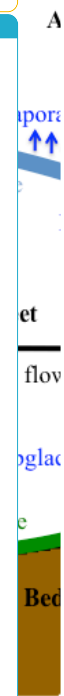

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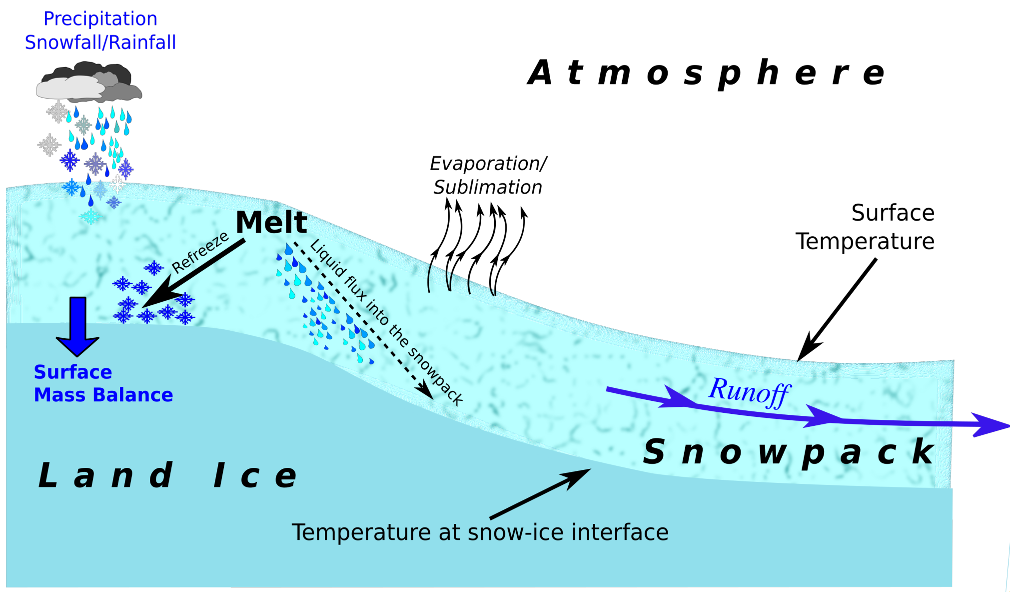

Figure A2: Illustration of key processes needed to compute atmospheric forcing for ice sheet models, and to evaluate the surface mass balance simulated by climate models.

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