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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 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.

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 (Vizcaino, 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).

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., 2004; 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.

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 were regarded as passive elements of the climate system on time scales less than a millennium (e.g., Church and Gregory, 2001). Observations of rapid mass loss associated with dynamic change in the ice sheets have however brought the need to couple ice sheets to the rest of the climate system into sharper focus. 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 of observed changes (e.g., Meehl and Stocker, 2007). Subsequent developments in ice-sheet modeling have meant that 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 on-going 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 supplied projections on which the assessments of Church et al. (2013) were based. These were the SeaRISE and ice2sea initiatives. A major criticism of both was, however, that they were still based on forcing from SRES emission scenarios rather than the current RCP 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 our 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), then 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, key 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

Following the CMIP6 protocol, the ISMIP6 experiments both use and augment the CMIP6-DECK (Diagnostic Evaluation and Characterization of Klima) and Historical (1850 – present day) simulations (Meehl et al., 2014; Eyring et al., 2015). In addition, ISMIP6 collaborates with the well-established Paleoclimate Model Intercomparison effort (PMIP) and builds on the new ScenarioMIP that focuses on future climate experiments for CMIP6, which are both also described in this special CMIP6 issue. 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) dynamic ice sheet models (ISMs) that are driven "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

Table 1 summarizes the experimental framework for ISMIP6, and this section describes the specifics. For a selected number of experiments shown in Table 1, three additional model configurations are proposed in addition to the standard CMIP6 GCM configuration described in Sect. 3.1: "*XXX-withism*", "*ism-XXX-self*" and "*ism-XXX-std*". 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 the standard ISMIP6 dataset *"ism-XXX-std"* that will be provided for the glaciology community (the ISM configuration described in Sect. 3.3).

3.1 Use of selected AGCM & AOGCM CMIP6 experiments

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. This is because these experiments do not include dynamic ice sheets, and as explained in the CMIP6 protocol, 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. Of particular interest are surface forcings for ice sheets, namely 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. 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., 2013; Fettweis et al., 2011), and 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). We seek to assess past and projected changes in SMB (here for a fixed ice sheet extent and topography), along with the resulting sea level contribution from both ice sheets due to changes in SMB alone. The largest uncertainty in century-scale sea level projections, however, remains the dynamical ice sheet response to changes in atmospheric and oceanic conditions, which will be addressed within the other components of ISMIP6.

Eyring et al. (2015) describe the CMIP6 DECK experimental setup. DECK comprises a suite of four experiments, which we briefly introduce. The Atmospheric Model Intercomparison Project (Gates et al., 1999) *amip* 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. 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). *piControl* serves as the starting point for many simulations and is meant to capture the near-equilibrium state of the climate system. It allows an evaluation of model drift and provides insight into the 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. The *abrupt4xCO2* simulation imposes an instantaneous quadrupling of CO_2 concentration, while the *1pctCO2* considers a gradual 1% per year increase in CO_2 until levels reach four times the initial value. Both experiments provide insight into the response time of the system, with the latter being a benchmark for studying transient climate response.

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., 2015). The more distant past is the focus of PMIP, which designs paleoclimate experiments (Braconnot et al., 2012; Abe-Ouchi et al., 2015). ISMIP6 collaborates with PMIP for simulation of the Last Interglacial, *lastinterglacial,* a warm period from 129,000 to 116,000 years ago when sea level reached 5–10 m above present-day heights (Masson-Delmott et al., 2013). The future in CMIP6 falls under the guidance of ScenarioMIP (O'Neill et al., 2016); ISMIP6 has chosen the high-emission scenario *ssp5-8.5* to evaluate climate and ice sheet changes in response to a large forcing, as a primary focus. If time permits, other scenarios -such as mitigation scenarios- will also be included in the ISMIP6 standalone ice sheet framework.

3.2 Coupled AOGCM-ISM experiments

The first suite of ISMIP6 experiments is 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 1, four coupled AOGCM-ISMs simulations are proposed, whose experiment ID are: *piControl-withism*, *1pctCO2-withism*, *historical-withism*, and *ssp5-8.5-withism*. These simulations are complemented by four ISMs simulations, whose experiment ID are: *ism-piControl-self*, *ism-1pctCO2-self, ism-historical-self* and *ism-ssp5-8.5-self.*

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). 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 exactly 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). The goal 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 therefore be attributable to ice-sheet feedbacks on other climate components.

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. Therefore, the land surface type and surface elevation in the climate model are dynamic, allowing, for example, a change in albedo if the land surface type 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 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.

The choice of 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. However, in all experiments, 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. 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, correction for these biases would distort the feedbacks between ice sheets and climate that we seek to investigate. Bias corrections are thus discouraged. 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.

The method used to downscale SMB (and indeed oceanic forcing) from the coarse climate model grid to the finer ice sheet model grid is left to the discretion of each group. The data request for ISMIP6 in Appendix A, however, asks modelers to report certain fields on both the atmospheric and ice sheet grids to allow for an evaluation of the downscaling procedure. Additionally, ISMIP6 prefers that the surface-melt component of SMB is obtained from an energy-based method. In order to guarantee conservation of mass and energy within the AOGCM, and facilitate interpretation of the drivers of SMB variability and change (e.g. Vizcaino, 2014), other methods like the positive-degree-day (PDD) method to determine surface melt (e.g. Reeh, 1991) should be avoided.

ISMIP6 will not dictate any spin-up procedures for obtaining preindustrial initial ice-sheet conditions for the coupled AOGCM–ISM that represent year 1850. Preindustrial spin-up is an area of active research (e.g., Fyke et al. 2014) that seeks to produce a realistic non-drifting coupled state that corresponds to the preindustrial (1850) climate. The challenge is that ice sheets reach quasi-equilibrium on timescales of many millennia, which is slower 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 simulation. In this case, once the ice sheet model has reached steady state, the coupled system should be run synchronously for an additional period, prior to starting the experiments.

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 core ISMIP6 prognostic climate change experiment is *1pctCO2-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 *1pctCO2-withism* will be compared to the AOGCM DECK simulation *1pctCO2*, and the standalone ISM forced by the AOGCM DECK (*ism-1pctCO2-self*). The duration of the experiment 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; Vizcaino et al., 2008; 2010) indicate that coupled AOGCM–ISM runs start to clearly diverge from uncoupled runs after about 250–300 years of simulation.

The Tier 2 experiments repeat the CMIP6 Historical simulation and the ScenarioMIP SSP5-8.5 experiments with a coupled AOGCM-ISM setting. The Historical simulation, *historical-withism*, begins at year 1850 from the pre-industrial spin up and terminates at the end of December 2014. The experimental settings and forcings for *ssp5-8.5-withism* follow the protocol described in O'Neill et al. (2016). In particular, the future in CMIP6 begins in January 2015 and is initiated from the December 2014 results of the CMIP6 Historical simulation. 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 the projected ice sheet evolution (e.g. Stone et al., 2010). The *ssp5-8.5-withism* experiment is run for the 21st century and preferably runs to the 23rd century.

Based on community feedback, we expect that several AOGCM–ISMs will be ready to participate in coupled climate experiments for CMIP6. Table 2 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 only indicated participation 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. It may 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 much 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, ISMIP6 incorporates not only coupled AOGCM–ISMs but also standalone ice sheet models driven offline by output from CMIP6 climate models (Sect 3.3). The primary goal of the AOGCM-ISMs experiments is to investigate ice sheet-climate feedbacks, and to improve the development of AOGCM-ISMs for use in future CMIP efforts.

3.3 Standalone ice sheet model experiments

The participating models in this effort are likely to differ from the "*ism-XXX-self"* configuration described in Sect 3.2. For example, an ice sheet model that is run "within" 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 be used with a finer resolution (at least in regions of fast flow (e.g. Aschwanden et al., 2016)) and incorporate more complex ice flow dynamics. Similarly, ice sheet models that are used for paleoclimate studies are often distinct from those used for projections on the order of a few hundred years.

3.3.1 ism-XXX-std configuration

The *ism-XXX-std* experiments target primarily the glaciology community and seek to obtain realistic ice sheet evolution that 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. 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. Clearly, there is a tension between the size of this subset, the need to explore uncertainty associated purely with ISMs (related to, for instance, 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). Our intention is to identify a small number of experiments that all ISMs must perform based on an initial analysis of AOGCM simulation of ice-sheet climate but also to provide forcing for a far larger number of experiments for those groups that are able to perform numerous simulations (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 an assessment of the quality of CMIP6 AOGCMs of the climate above and around the ice sheets can be made (after the analysis of the CMIP6 DECK and Historical simulations), a definitive choice cannot be made however we list the options below in order of preference:

1. Using 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, however, concern that the quality of the SMB determined

within the AOGCMs will make this approach unrealistic due primarily to the mismatch in spatial resolution over which SMB varies and that is used by AOGCMs. 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 SMB, and the ice2sea effort chose to generate SMB from a RCM. This approaches does, however, introduce 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 employed (further complicating the design of the ISM ensemble).
3. Employ 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 therefore need to include this effect by parameterizing the SMB lapse rate obtained (Edwards et al., 2014a,b; Fettweis et al., 2013, Goelzer et al., 2013). This approach may be less of an issue for Methods 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 occurrence of large quantities of melt water, and 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). Surface air temperature and runoff forcing will therefore also be made available.

Obtaining oceanic forcings from the CMIP6 ocean models is even more challenging, as ice shelf basal melt rates are needed. One possibility is to calculate melt rate anomalies from ocean surface temperature changes using the relation of Rignot and Jacobs (2002) of 10 m yr^{-1} C^{-1}. An alternative approach is to use a melt parameterization that depends on the ocean temperature at the closest grid cell (e.g., Martin et al., 2011; Pollard and DeConto, 2012; DeConto and Pollard, 2016). If none of the CMIP6 ocean models are suitable, a solution could be to prescribe a melt parameterization that depends simply on the ice shelf draft (e.g., Joughin et al., 2010a; Favier et al., 2014). When the set of standardized atmospheric anomalies

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(surface mass balance and surface temperature) and oceanic anomalies (basal mass balance and basal temperatures) have been generated, it will be announced on the ISMIP6 website (http://www.climate-cryosphere.org/ismip6).

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 ice sheet model near the fast-flowing ice streams and in the vicinity of the grounding line affects the dynamic response output (Durand et al., 2009; Pattyn et al., 2012, 2013); thus, using the smallest possible grid resolution is recommended in these regions. Finally, 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., 2015) and are required to take part in initMIP (initialization-focused; Sect. 3.3).) to compare and evaluate the simulated present-day state. 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 will be 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.

The first simulation is the *ism-pdControl-std*, the ice sheet present-day control with constant forcing needed to evaluate model drift. The forcings are set to the end of the initialization procedure, which ranges from the 1990s to 2014. For many models, it will be the same as the "*ctrl*" in the initMIP experiment (Sect. 3.3.2), unless a change has been made in the initialization. Our idealized climate change experiment, *ism-1pctCO2-std*, considers a linear increase in CO_2 levels to quadrupled levels, followed by fixed quadrupled CO_2. Our main simulation for projecting 21st century sea level is the *ism-ssp5-8.5-std* (as mentioned previously, if time permits other scenarios will be considered). If possible, projections should continue up to the 23rd century. Unlike the protocol for climate models, *ism-ssp5-8.5-std* cannot be initiated from a historical run that begins in 1850. This is due to the challenge of initializing ice sheet models to pre-industrial conditions. The *ism-historical-std* will therefore be an abbreviated simulation for the historical period, which begins from the present-day control 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 simulation of ice sheets evolution for the Last Interglacial period (Lunt et al, 2013), *ism-lig127k-std,* is forced by the climatic forcing derived from PMIP4 Last Interglacial experiment, *lig127k*. This is a period where the sea level was higher than present day at least by 4 meters, with uncertain contribution from both Greenland and Antarctic ice sheets (Masson-Delmotte et al, 2013). The results from the *ism-lig-std* will provide information on the tendency of the long term response of the current climate and ice sheet model.

3.3.2 Additional experiments

Additional ISM experiments are designed to assess the uncertainty in sea level projections stemming from weakly constrained boundary conditions and biases and limitations in ice flow models. Such uncertainties have been identified in the framework of previous model intercomparison efforts (e.g., Bindschadler et al., 2012; Nowicki et al., 2013a, b; Edwards et al., 2014b, 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 objectives of these additional ISM experiments are to i) estimate any trends caused by model initializations and ii) investigate the impact of choices in numerical and physical parameters (e.g., stress balance approximation, model resolution).

ISM initialization methods range from running paleo-climate spin-up for thousands of year (e.g., Martin et al., 2011; Sato and Greve, 2012; Aschwanden et al., 2013; Fürst et al., 2015; Saito et al., 2015) to assimilating present-day observations (e.g., Morlighem et al., 2010; Gillet-Chaulet et al., 2012; Seroussi et al., 2012, Arthern et al., 2015). The choices made in this procedure affect ice sheet configuration, flow, initial volume, and volume trends, which can have substantial effects on estimations of ice sheet contribution to sea level rise, as described by Aðalgeirsdóttir et al. (2014). Improving ice sheet model initial conditions is an active area of research and a multidisciplinary effort. It requires acquisition of additional data with high spatial coverage (full ice sheet) and increased resolution (e.g., Bamber et al., 2013; Rignot et al., 2011b; Joughin et al., 2010; Howat et al., 2014). Ideally, all datasets 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). 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 on-going initMIP project is a precursor to ISMIP6 and is designed to explore uncertainty associated with model initialization and spin-up and to evaluate initialization procedures. It consists of a set of two forward experiments for the Greenland Ice Sheet and three forward experiments for the Antarctic Ice Sheets that are each run for one hundred years: i) a control run (*ctrl*), ii) a surface mass balance anomaly run (*asmb*) and iii) a basal melt anomaly applied under the floating ice (*abmb*) of the Antarctic Ice Sheets. All other model parameters are the same as those used for the initialization procedure. The *ctrl* is an unforced forward experiment designed to evaluate the initialization procedure and characterize model drift; the surface mass balance should remain similar to the initialization procedure. In *asmb*, a prescribed surface mass balance

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anomaly is applied to test the model response to a large perturbation. The schematic perturbation anomaly mimics outputs of several surface mass balance models of different complexity for the periods 1980–1999 and 2080–2099 and is designed to capture the first-order pattern of SMB changes expected from climate models. In *abmb*, a prescribed anomaly of basal melting rate under floating ice is applied while surface mass balance is kept the same as in *ctrl*. The basal melt anomaly is designed to simulate possible changes in ocean circulation and their impact on ice dynamics.

These experiments are designed to allow comparison between the different models, so some simplifications are imposed. Neither surface mass balance nor bedrock topography should be adjusted in response to ice-sheet geometric changes in forward experiments. However, to sample the uncertainty in sea level due to initialization, groups are encouraged to submit as many variations of the experiment as possible, for example by changing the sliding law, stress balance approximation, model resolution, or datasets (such as using different bedrocks). initMIP is also intended to give ISMs 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.

3.4 Prioritization of experiments and timing

For the coupled AOGCM-ISM experiments, the Tier 1 experiments *piControl-withism* and *1pctCO2-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. Our Tier 2 experiments, *historical-withism* and *ssp5-8.5-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 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 rigorous evaluation of climate models cannot occur prior to 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 SSP-5-8.5 experiment (ScenarioMIP, Tier 1), the *ism-ssp5-8.5-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-ssp5-8.5* in early 2019. Similarly, the *ism-lig127-std* cannot proceed until the PMIP Tier 1 experiment has been completed by the PMIP participants. 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 mid 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 climate and ice sheet models

Evaluation of the climate over and surrounding the ice sheets is necessary both to establish the suitability of the current generation of climate models to provide forcing for ice sheet models, and to gain insight into sea level uncertainty arising from uncertainty in climate forcings. The first models to be evaluated will be the AGCMs and AOGCMs of all groups participating in the CMIP6 initiative, with primary focus on the *amip* and *historical* simulations. Of particular interest is the surface climate over the ice sheets. Because the ocean condition is prescribed for the *amip* simulation but not for the *historical* simulation, we expect that the 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 evaluation of the coupled AOGCM-ISMs will be based on the *historical-withism* 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; Vizcaino 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 focuses on whether the climate model can simulate snow processes, including albedo evolution and refreezing, at a horizontal resolution that is suitable to capture the SMB gradients that occur at ice sheet margins. Both the atmospheric components and factors that can affect atmospheric processes are often evaluated. One example is determining whether the 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 (Vizcaino, 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., 2010; van Angelen et al., 2014), MAR (Fettweis, 2007; Fettweis et al., 2011), or HIRHAM (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, tend to be evaluated against measurements taken by automatic weather stations on the ice sheet surface. Such stations include, for example, in Greenland the 15 stations known as the GC–Net (Steffen and Box, 2001) 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 provide an indication of 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 front remain an active area of research (Wilson and Straneo, 2015; Straneo and Cenedese, 2015). In the Southern Ocean, the important water masses are the Antarctic Bottom Water and the 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., 2015). 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). As regional atmospheric models will be key for the evaluation of the atmospheric component of climate models, regional ocean models (e.g., Timmermann et al., 2012) and ocean reanalysis products are likely to provide valuable insight for evaluating CMIP ocean 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 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 extent the record in time and plans to separate the observed mass change into SMB and dynamic components.

4.2 Effects of dynamic ice sheets on climate

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; Vizcaino 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:

- 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., 2014), 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

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*). In addition, the multi-model ensemble of the surface freshwater flux from AOGCM simulations will suggest how much sea level change is overlooked when dynamic ice sheets are not included in climate models.

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 on-going initMIP project (which understand the impact of uncertainties in ISM initialization on their projection) will provide insight into the sea level trends resulting from ice sheet model initialization. By repeating model runs with different datasets, sliding laws, model resolutions, etc., initMIP will allow us to put constraints on 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 High Resolution Model Intercomparison Project (HighResMIP), or the Coordinated Regional Climate Downscaling Experiment (CORDEX) efforts, may allow us to quantify the impacts of increased resolution on SMB.

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 PMIP and ScenarioMIP simulations. Our suite of experiments involves three types of models: AOGCM/AGCM with no dynamic ice sheets, AOGCM-ISM, and standalone ISM. The diagnostic protocol is based on ice-sheet-related model outputs, many of which are already present in the CMIP5 atmosphere and ocean diagnostics. The evaluation of the climate in the polar regions from AOGCM and AOGCM-ISM will identify a set of 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 higher levels of maturity. ISMIP6 targets two of the WCRP Grand Science Challenges, namely "Melting Ice and Global Consequences" and "Regional Sea Level Change and Costal Impacts". Given the current rapid changes in the Greenland and Antarctic Ice Sheets, ice sheets cannot be considered passive players in the climate system. Their potential contributions to future sea level have considerable societal impacts, and we expect that 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 ice sheets, how the climate system responds to changes in the Greenland and Antarctic Ice Sheets, 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 be a step forward for sea level to 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 majority of the simulations described in this paper will be distributed through the Earth System Grid Federation (ESGF) with digital object identifiers (DOIs) assigned. 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 outputs from the initMIP Greenland and Antarctic efforts and for forcing datasets derived from CMIP6 model simulations that specifically target standalone ice sheet models. Instruction of how to obtain model outputs or forcing datasets not available through ESGF will be posted on the ISMIP6 website (http://www.climate-cryosphere.org/activities/targeted/ismip6). As in CMIP5 and other MIPs participating in CMIP6, the model outputs from ISMIP6 will be freely accessible. Users are obligated to acknowledge CMIP6, ISMIP6, the participating modeling groups providing the data, and the ESGF centers.

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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 is defined as grounded ice sheet, floating ice shelf, glacier and ice caps, while ice sheet includes grounded ice sheet and floating ice shelf. 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 (Tables 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 surface mass balance (SMB), ice melt at the base of the grounded ice sheet (BMB), and ice discharged or lost to the ocean. The later includes frontal mass balance (FMB, defined as iceberg calving and melt at the ice shelf font) and melt at the base of ice shelves (BMB). Temperatures used to drive ice sheet models are the basal temperature and temperature at the ice sheet-snowpack interface. Note that basal mass balance and basal temperature are computed differently depending on whether the ice flows over bedrock or ocean, requiring the use of distinct Long Names, but same Standard Names in Table A3.

Climate models will be evaluated primarily on whether they can simulate SMB over the ice sheets. This quantity (see Vizcaino (2014) and Fig A2) can be defined as precipitation less runoff less evaporation (which in our context includes any sublimation, as this term is small over ice sheets). In turn, precipitation is the sum of snowfall and rainfall. Runoff is the available liquid water minus any refreezing that takes place. Finally, the available liquid water (not explicitly asked to minimize the data request) consist of rainfall, melt of snow and ice, less the liquid flux in the snowpack. The evaluation of climate model also benefit 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. In a coupled AOGCM-ISM simulation, the two will differ due to downscaling to the ice sheet grid. The data request for the ocean is primarily to obtain forcing for ice sheet, and is not as extensive as the data request for the atmosphere because ice-ocean interaction remains challenging for AOGCMs. It is therefore premature to set diagnostic protocols at this stage. 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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Tables and Figures

Table 1: Summary of the ISMIP6 experiments.

Experiment Title	CMIP6 Label (experiment_id)	Experiment Description	Start Year	End Year	Minimum # Years Per Simulation	Major Purposes
DECK Experiments						
AMIP	*amip* *ism-amip-std*	observed SSTs and SICs prescribed	1979	2014	36	evaluation, variability
pre-industrial or present day control	*piControl* *piControl-withism* *ism-piControl-self* *ism-pdControl-std*	pre-industrial (pi) conditions imposed with CO_2 concentration fixed, or present day (pd) condition imposed	n/a	n/a	500	evaluation, unforced variability
abrupt quadrupling of CO2	*abrupt-4xCO2*	atmospheric CO_2 concentration abruptly quadrupled and then held constant	n/a	n/a	150	climate sensitivity, feedbacks, fast responses
1% per year CO_2 increase	*1pctCO2* *1pctCO2-withism* *ism-1pctCO2-self* *ism-1pctCO2-std*	atmospheric CO_2 concentration prescribed to increase at 1% yr^{-1} and then held constant to quadruple levels	n/a	n/a	150	climate sensitivity, feedbacks, idealized benchmark
CMIP6 *historical* Simulations						
CMIP6 historical	*historical* *historical-withism* *ism-historical-self* *ism-historical-std*	simulation of the recent past with CO2 concentration prescribed	1850	2014	165	evaluation
CMIP6 ScenarioMIP Simulations						
ScenarioMIP	*ssp5-8.5* *ssp5-8.5-withism* *ism-ssp5-8.5-self* *ism-ssp5-8.5-std*	future scenario with high radiative forcing by the end of the century	2015	2300	286	climate sensitivity
CMIP6 PMIP Simulations						
PMIP last interglacial	*lig127k* *ism- lig127k -std*	simulation of the last interglacial	n/a	n/a	3000	climate sensitivity, feedbacks, long responses

Table 2: Climate Modeling Centers that have expressed an interest in ISMIP6. *Indicates only an interest in the diagnostic component (no AOGCM-ISM participation anticipated).

Model	Institute/Country
CanESM*	CCCma/Canada
CESM	NCAR-COLA/USA
CNRM-CM	CNRM-CERFACS/France
EC-Earth	SMHI and 26 institutes/Sweden and 9 EU countries
GISS	NASA-GISS/USA
INM	Institute of Numerical Mathematics/Russia
IPSL-CM6	IPSL/France
MIROC-ESM	AORI-UT-JAMSTEC-NIES/Japan
UKESM	MetOffice/UK

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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).

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	%	surface_snow_area_fraction	1
Land Ice area fraction	%	land_ice_area_fraction	1
Grounded Ice area fraction	%	grounded_ice_area_fraction	1
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. Tier indicate priority of variable: Mandatory (1), Desirable (2), Experimental (3).

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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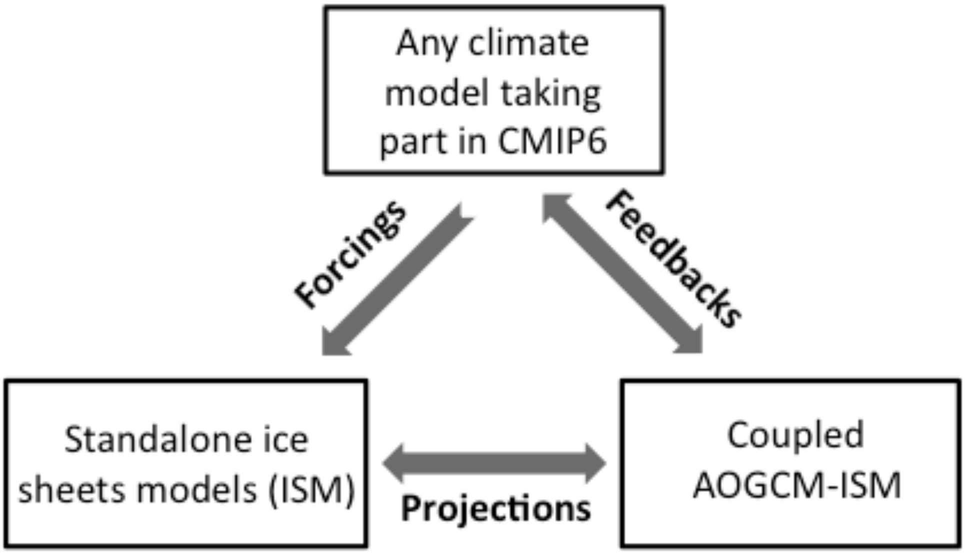
Table A3: Data on the Icesheetmon or Icesheetyear Tables needed to capture the dynamical ice sheet model realm. These fields are saved on the ice sheet grid and contain monthly or yearly output. Tier indicate priority of variable: Mandatory (1), Desirable (2), Experimental (3).

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
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	%	land_ice_area_fraction	1
Grounded ice area fraction	%	grounded_ice_sheet_area_fraction	1
Floating ice sheet area fraction	%	floating_ice_sheet_area_fraction	1
Surface Snow Area fraction	%	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



5 **Figure 1: Overview of the ISMIP6 effort designed to obtain forcing from climate models, projection of sea level change from ice sheet models, and explore ice sheet-climate feedbacks.**

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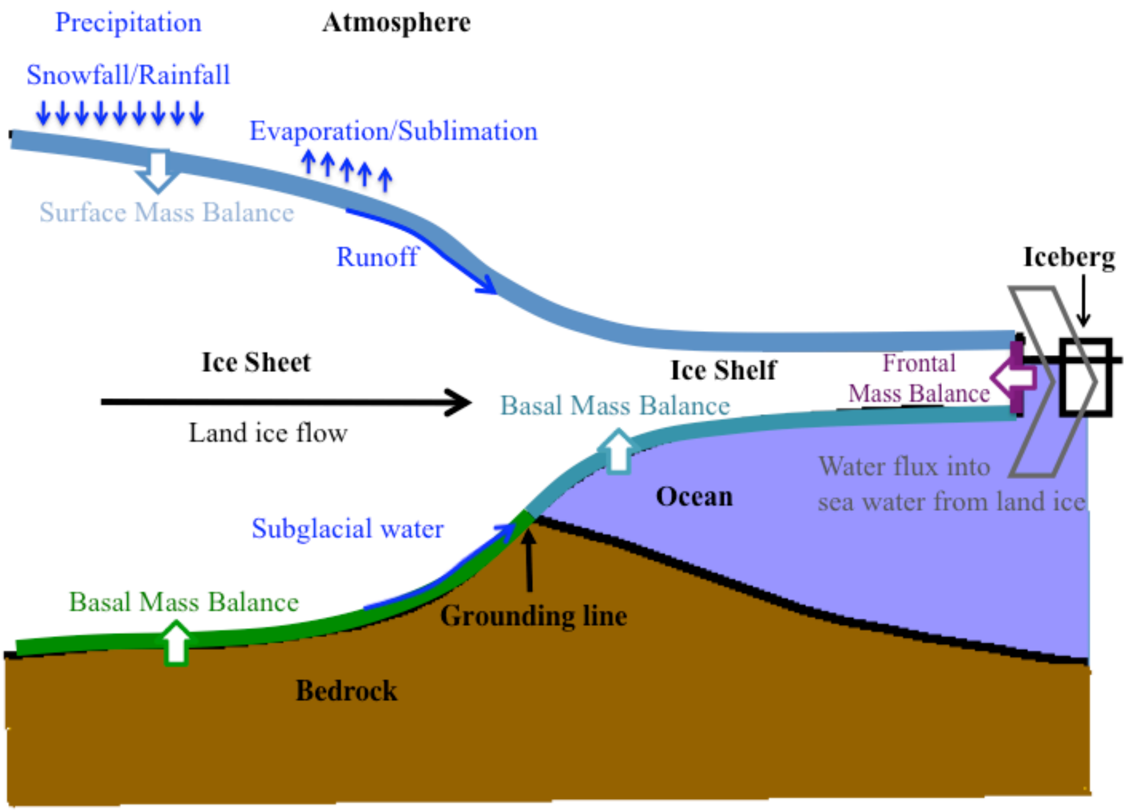

Figure A1: Illustration of mass change of ice sheet and key data request that are specific to ice sheets model evaluation or forcing. See text for details.

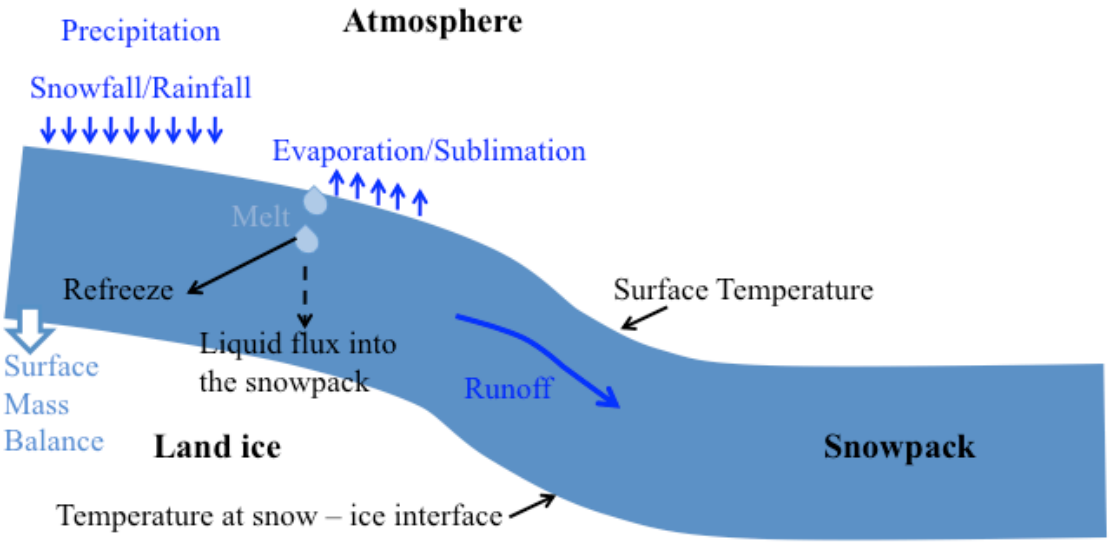

Figure A2: Illustration of key processes needed to compute atmosphere forcing for ice sheet models, and evaluation of surface mass balance of climate models.

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