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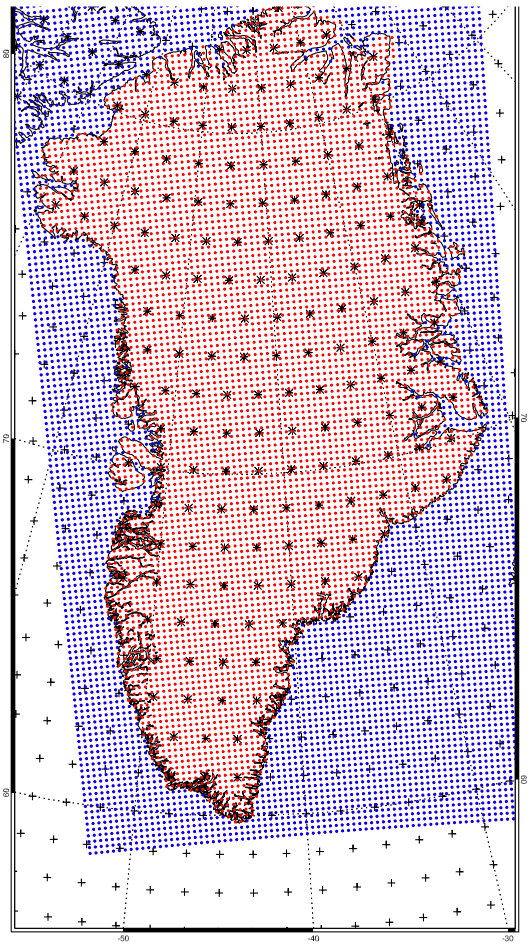
An Introduction to the Coupled EC-Earth-PISM Model System

Synne Høyer Svendsen, Marianne Sloth Madsen, Shuting Yang, Christian Rodehacke, Guðfinna Aðalgeirsdóttir



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Contents

1. Introduction

In order to be able to assess future sea-level rise in a changing climate, reliable estimates of ice sheet melt are in great demand. In the polar regions, numerous feedbacks processes are active, rendering the areas very sensitive to climate change. Given the large amounts of feedback mechanisms between the major ice sheets and the remaining climate system, model setups that include the ice sheets are essential in order to capture the effect of these feedback mechanisms.
As part of an effort to understand the future of the Greenland Ice Sheet and the interplay between the ice sheet and the rest of the climate system, a coupled model system encompassing the Greenland Ice Sheet, the global atmosphere and global oceans has been developed. Two existing models, an ice sheet model, PISM, and a global climate model, EC-Earth, has been coupled. The present report describes the coupled model setup, the necessary configurations of and modifications to the individual models as well as the coupling itself by means of exchange of relevant fields.
The model system shows stable behaviour in control runs, with melt water fluxes etc displaying reasonable values, providing a useful tool for examing the response of the combined ice-sheet-climate system to various climate change scenarios. The coupled model is used to perform scenario runs driven by the RCP8.5 scenario, thereby providing estimates of future melt and potential sea level rise from the Greenland Ice Sheet.

2. The Structure of the Coupled System

Currently, the Arctic is undergoing noticeable changes as a consequence of anthropogenic climate change [IPCC, 2013]. Due to the numerous feedback processes involving the ice sheets in the Arctic climate system, climate models that are capable of including these feedback processes are needed in order to predict the effect of climate change on the Arctic.
In order to meet this demand a coupled model system has been developed which combines an ice sheet model (PISM, [Albrecht et al., 2012]) for Greenland with a global circulation model (EC-Earth, [Hazeleger et al., 2011]). The two models are coupled at script level, with each model running a single year before a script-based interface procedure extracts relevant fields from one model and passes them on to the other.
The ice sheet model is driven by fields of surface mass balance and temperature, the surface mass balance currently being determined by a straightforward budget calculation of precipitation, evaporation and runoff. In the case of the ice sheet model, suitable model configurations for a coupled model scenario are available by means of utilising existing model options. In order for the climate model to make use of the fresh water fluxes from the ice sheet model, its spatio-temporal distribution is needed. Two-dimensional fields of the fresh water fluxes were not available as an output field in the standard version of PISM, only total values for the entire ice sheet were given. As part of setting up the coupled system, PISM has been modified to produce two-dimensional output fields of the fresh water fluxes. These changes have been made available to the PISM development team and has been made available in later releases of PISM. A short description of the ice sheet model and the model options relevant for the coupled setup is given in chap.(3).

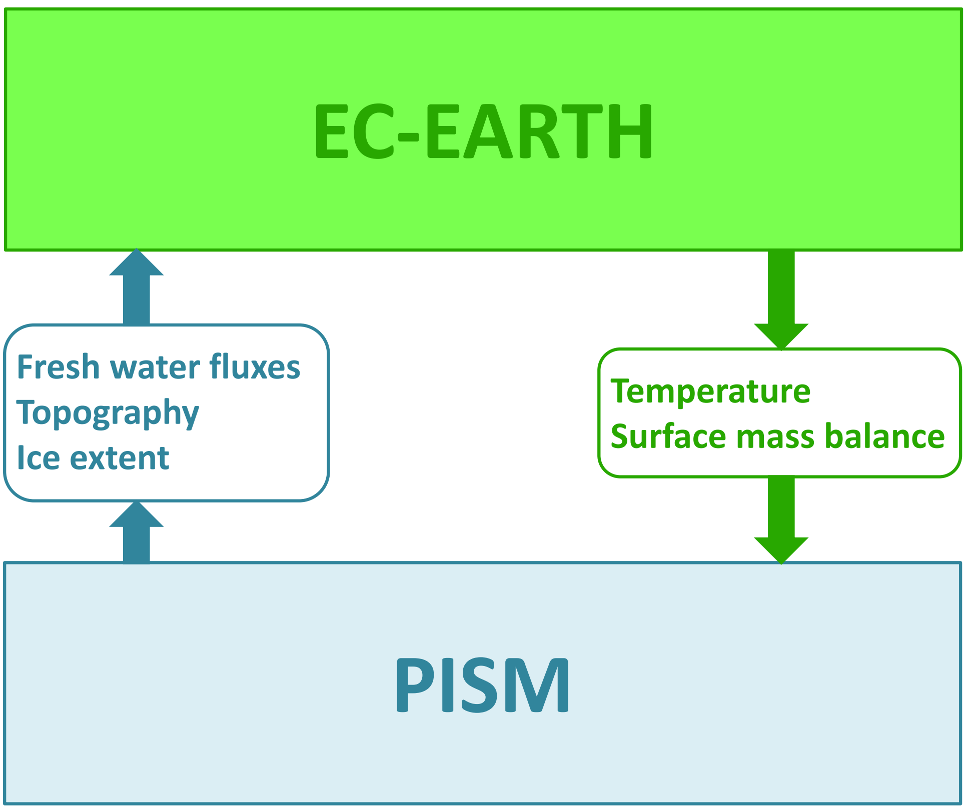

Figure 2.1: Schematic view of the structure of the coupled system. Output fields from one model used as a driver for the other are indicated.

The climate model receives information on the fresh water fluxes from the ice sheet as well as the ice extent and topography. Whereas the ice sheet model merely required proper selection of various configuration parameters, a number of changes were necessary in the climate model EC-Earth in order to make it suitable for coupling with an ice sheet model. The original version of EC-Earth did not include land ice as a separate variable, but relied on perennial snow fields and a forced melting scheme in order to prevent unlimited build-up of snow in polar regions instead. Here, land ice has been introduced as a separate variable in the model, necessitating the substantial changes to the surface scheme of the model. These changes are described in chap.(4).

Coupling between the two models (PISM and EC-Earth) is done at the script level; relevant fields from one model is extracted and interpolated onto the grid of the other model by means of OASIS3 [Valcke et al., 2013] where they are, in turn, used as forcing fields in the next run cycle. A description of the production of forcing fields and interpolation between model grids is given in chap.(5).

3. The Coupled System Part 1: The Ice Sheet Model PISM

In the coupled atmosphere-ocean-ice sheet system, ice dynamics is described by the Parallel Ice Sheet Model (PISM) [Winkelmann et al., 2011, Albrecht et al., 2012]. PISM is an open-source, freely available ice sheet model, developed and maintained at the University of Alaska, Fairbanks. The PISM model is a comparatively new addition to DMI's model suite and, hence, an overview of PISM's structure and dynamics is included.

3.1 The Structure of PISM

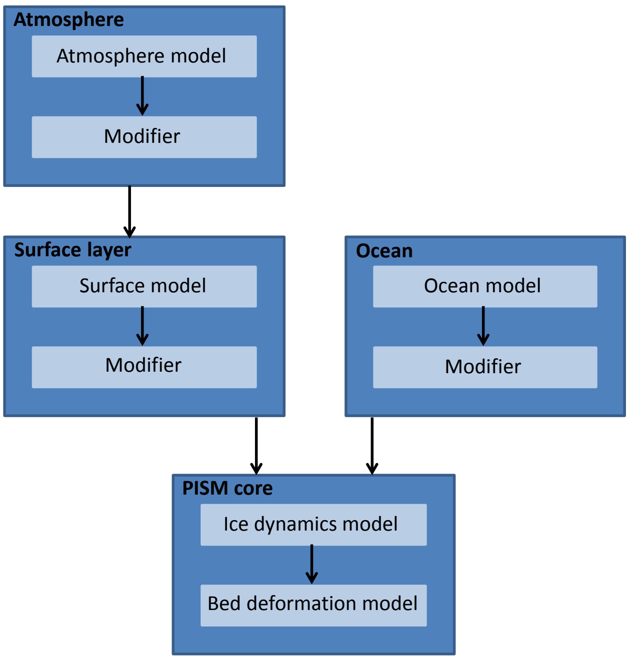

Figure 3.1: The structure of PISM and its boundary models. Adapted from [Albrecht et al., 2012].

An ice sheet has a number of interfaces, separating it from its surroundings. Upwards, the ice sheet is limited by a surface layer of snow and firn and downwards by the bedrock at the base of the ice. In some cases, there is also an ocean-ice sheet interface. A pivotal point in the structure of PISM it that it is centered solely around the ice sheet and the ice dynamics, excluding any climate effects in the model itself. It is a fundamental principle in the PISM design that *'climate inputs should affect ice dynamics by a well-defined interface* [Albrecht et al., 2012]. In PISM, the top ice surface below the firn layer, the ice shelf basal surface and the bottom surface of the thermal bed layer constitutes the ice sheet boundaries. Only processes taking place within these boundaries are considered by PISM and hence, it deals solely with the ice dynamics. The necessary boundary conditions representing the conditions and possible fluxes across these boundaries are supplied by PISM's separate boundary models as illustrated in fig.(3.1). The boundaries and their respective boundary conditions are shown in tab.(3.1). This setup allows PISM to be driven using a wide range of different data types and it is possible to couple PISM to a climate model without having to modify the code of the ice dynamics itself. In combination with PISM, EC-Earth as a coupled atmosphere-ocean model provides the

Boundary	Necessary conditions
Top ice surface (below firn)	Ice temperature (or enthalpy) and mass flux into the ice
Bottom surface of the thermal bed layer	Geothermal flux
Ice shelf basal surface	Mass flux into the ocean and ice boundary temperature

Table 3.1: Boundary conditions required by PISM's dynamics core, from [Albrecht et al., 2012].

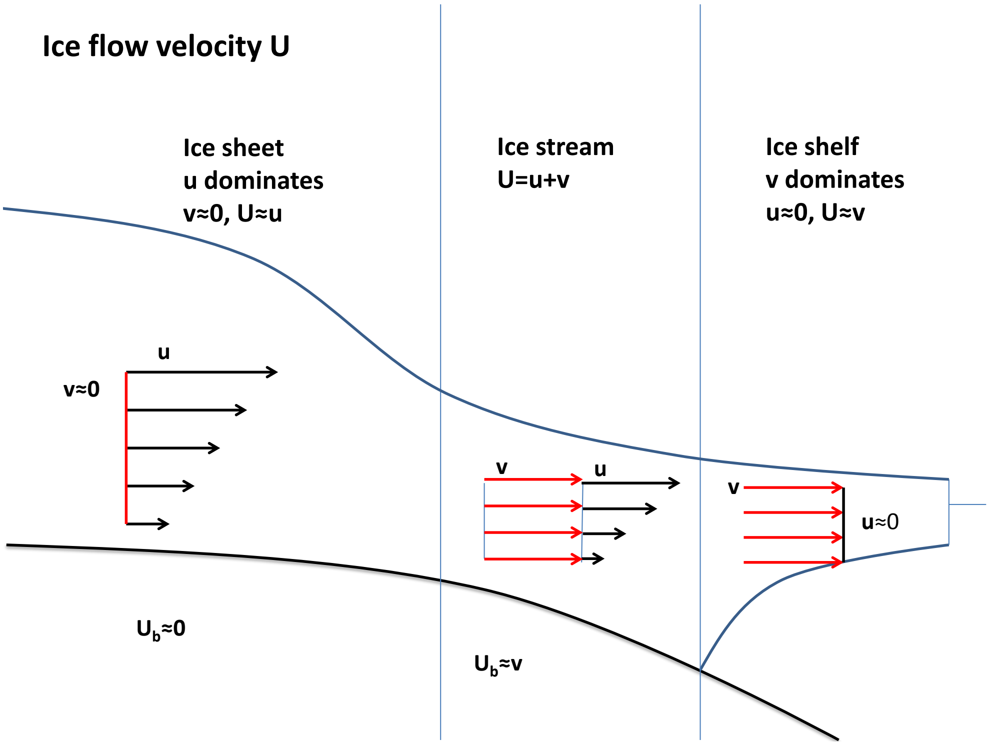

Figure 3.2: The flow regimes of PISM.

possiblity of obtaining a two-way coupled system of the combined atmosphere-ocean-ice sheet system including both atmospheric and oceanic forcings of the ice sheet.

3.2 PISM Ice Dynamics

In PISM, the geometry, temperature and basal strength of the ice sheet are included into momentum/stress balance equations in order to determine the velocity of the flowing ice for each time step. Below short descriptions of the various elements of the PISM dynamics are given. For details the reader is referred to the PISM documentation and scientific literature.

3.2.1 Ice Velocity

An inertia-free approximation of the equations for conservation of momentum are the Stokes model for slowly-flowing liquids [Fowler, 1997]. However, the computational cost of running such a model calls for approximations. PISM considers to such approximations, the Shallow Ice Approximation (SIA) and the Shallow Shelf Approximation (SSA) of the stress balance equations in order to determine the ice flow velocity. In the case of ice sheets, the shallowness (i.e. the small depth to width ratio) may be utilized to simplify the flow equations and reduce computational cost. In models, ice is described as a slow, nonlinearly viscous isotropic fluid and two applroximations of the full Stokes model are the Shallow Ice Approximation (SIA) [Hutter, 1983] and the Shallow Shelf Approximation [Morland, 1987, Weis et al., 1999]. How to arrive at the SIA and SSA from the

Stokes flow is described in [Schoof and Hindmarsh, 2010].
The SIA gives a reasonable description of shallow, grounded and nonsliding ice, conditions which are applicable for large portions of many ice sheets. The non-sliding SIA gives and ice flow where the driving force of gravity is balanced solely by shearing within the ice [Bueler and Brown, 2009]. For areas of the ice sheet with rather modest bed topographies and bases that experience minimal sliding the SIA results inflow rates that are comparable to obeserved values [Greve, 1997].
The SIA is unsuitable for the description of the ice flow in ice streams and glaciers, where the fast ice flow is caused by a combination of sliding over the base and shear deformation of a thin till and ice layer at the base [Clarke, 2005]. Sliding applies a boundary force (stress) to the base of the ice mass, the effect of which is distributed by the stress [Bueler and Brown, 2009]. The SIA has no method for setting up stress balances and dealing with sliding and, hence, an alternative approximation of the flow law is needed in areas where non-negligible sliding is present. The shallow shelf approximation (SSA) is applicable in these situations; the sliding-induced flow of ice streams and outlets may be described by the SSA with with a non-zero till strength and large ice sheets with zero till strengths are well described by the SSA [Weis et al., 1999].
In the pursuit of a unified description of the entire ice sheet and shelf system PISM combines the SSA and the SIA, with the SSA used as a sliding law in a thermomechanically coupled SIA model where the boundaries of the sliding regions are defines as the locations where the sliding velocity goes to zero. In this case, the majority of the ice flow is determined by the SIA but areas naturally arise where the flow is partly by the SIA but mostly by additional basal sliding constrained by the SSA membrane stress balance.
In simple terms, using the SSA model as a sliding law in a SIA model amounts to combining the velocities computed by the SIA and the SSA, respectively. The resulting velocity is subsequently used in the mass continuity and energy conservation equations. Denoting the SIA velocity $\mathbf{u} = (u_1, u_2)$ and the SSA velocity $\mathbf{v} = (v_1, v_2)$, the combined horizontal velocity $\mathbf{U} = (U_1, U_2)$ is given by [Bueler and Brown, 2009]:

$$\mathbf{U} = f(|\mathbf{v}|)\mathbf{u} + 1 - f(|\mathbf{v}|)\mathbf{v}, \tag{3.1}$$

where $|\mathbf{v}|^2 = {v_1}^2 + {v_2}^2$ and

$$f(|\mathbf{v}|) = 1 - \frac{2}{\pi}\mathrm{arctan}\left(\frac{|\mathbf{v}^2|}{100^2}\right) \tag{3.2}$$

The weighting function f has values between zero and one and satisfies the general requirements of smoothness, moneotone decrease; $f(|\mathbf{v}|)\sim 1$ for small $|\mathbf{v}|$ and $f(|\mathbf{v}|)\sim 0$ for large $|\mathbf{v}|$. As described above, different locations in an ice sheet will have different flow regimes; in areas with negligible basal sliding such as the interior of the ice sheet, the flow will be almost entirely dominated by the SIA and friction at the bed leads to shearing in the ice column and the velocity profile will be given by $\mathbf{U}\approx\mathbf{u}$. In areas with basal sliding both SIA and SSA are relevant for the ice flow and velocity will be given by eq.(3.1). In the case of an ice shelf, the SSA dominates, $\mathbf{u}\sim 0$, and $\mathbf{U}\sim\mathbf{v}$. In fig.(3.2) a schematic diagram of the various flow regimes of PISM is shown.

3.2.2 Rheology and Driving Stress

The flow law is the function $F(\sigma, T, \omega, P, d)$ in the relation

$$\dot{\epsilon}_{ij} = F(\sigma, T, \omega, P, d)\sigma'_{ij} \tag{3.3}$$

where $\dot{\epsilon}_{ij}$ is the strain rate tensor, σ'_{ij} is the stress deviator tensor, T is the ice temperature, ω is the liquid water fraction in the ice, P is the pressure, d is the grain size and σ is the second invariant of the stress deviator tensor; $\sigma^2 = \frac{1}{2}\|\sigma'_{ij}\|_F$ [Albrecht et al., 2012]. Per default, PISM assumes the ice to be polythermal and applies the Glen-Paterson-Budd-Lliboutry-Duval flow law [Aschwanden and Blatter, 2009, Lliboutry and Duval, 1985, Paterson and Budd, 1982]:

$$F = A(T)\sigma^{n-1} \tag{3.4}$$

where the Glen exponent $n = 3$ and

$$A(T) = A\exp\left(\frac{-Q}{RT^*}\right) \tag{3.5}$$

with T^* being the pressure-adjusted temperature and

$$A = \begin{cases} 3.615{\cdot}10^{-13}\mathrm{s}^{-1}\mathrm{Pa}^{-3} & : \quad T^* < 263\mathrm{K} \\ 1.733{\cdot}10^{3}\mathrm{s}^{-1}\mathrm{Pa}^{-3} & : \quad T^* > 263\mathrm{K} \end{cases}$$

$$Q = \begin{cases} 6.0{\cdot}10^{4}\mathrm{J{\cdot}mol}^{-1} & : \quad T^* < 263\mathrm{K} \\ 13.9{\cdot}10^{4}\mathrm{J{\cdot}mol}^{-1} & : \quad T^* > 263\mathrm{K} \end{cases}$$

PISM uses surface gradients to getermine the driving stress that enters into both the SIA and the SSA stress balances:

$$(\tau_{d,x}, \tau_{d,y}) = -\rho g H \nabla h \tag{3.6}$$

where H is the ice thickness and $h = H + b$ is the ice surface elevation.

3.2.3 Basal Strength and Sliding

In PISM, sliding over the bed is described by a nearly-plastic power law which related the bed-parallel shear stress $\boldsymbol{\tau}_b$ to the sliding velocity $\mathbf{u}_b$ [Schoof and Hindmarsh, 2010]:

$$\boldsymbol{\tau}_b = -\tau_c \frac{\mathbf{u}_b}{|\mathbf{u}_b|^{(1-q)} u_0^q}, \tag{3.7}$$

where τ_c is the till yield stress, q is the pseudo-plasticity exponent, and $u_0 = 100\mathrm{ma}^{-1}$ is a threshold speed. The till yield stress τ_c represents the strength of the material at the base of the ice sheet, consisting of a mix of liquid water, ice, granular till and rock and the formulation above assumes the basal till to be partially saturated with water. The till yield stress is given by

$$\tau_c = \tan(\phi)\,(\rho g H - p_w) \tag{3.8}$$

where ϕ is the till friction angle, ρ is the ice density, g is the acceleration of gravity, H is the ice thickness and the pore water pressure p_w is given as a fraction of the ice overburden pressure:

$$p_w = \alpha w \rho g H \tag{3.9}$$

The relative amount of water stored in the till, w, is determined at each time step by time-integrating the basal melt. Excess water drains when the thickness of the stored water exceeds 2m. The alllowed pore-water pressure fraction is given by the coefficient α. In PISM, the till friction angle ϕ is a given as a piece-wise linear function of the bed elevation [Albrecht et al., 2012] characterized by the parameters ϕ_{min}, ϕ_{max}, b_{min}, b_{max}, where b is the bed elevation

$$\phi(x,y) = \begin{cases} \phi_{\mathrm{min}} & : \quad b(x,y) \le b_{\mathrm{min}} \\ \phi_{\mathrm{min}} + [b(x,y) - b_{\mathrm{min}}]\,M & : \quad b_{\mathrm{min}} < b(x,y) < b_{\mathrm{max}} \\ \phi_{\mathrm{max}} & : \quad b_{\mathrm{max}} \le b(x,y) \end{cases} \tag{3.10}$$

3.2.4 Thermodynamics in PISM

In glaciers, polythermal conditions are ubiquitous, and formulating the energy balance in terms of the temperature variable proves problematic due to the inability to account for the portion of the internal energy stored as latent heat of liquid water within temperate ice. PISM instead makes use of a formulation of the energy balance based on enthalpy [Aschwanden et al., 2012] that enables solutions for polythermal ice masses.

3.3 PISM Outflow

In the coupled system, PISM feeds relevant fields back into EC-Earth. These fields are freshwater input to the ocean from melt and runoff, basal melt and calving along with the ice topography and extent.

3.3.1 Basal Melt

PISM considers conservation of energy within the ice, the thin subglacial layer and a layer of thermal bedrock. As mentioned above in sect.(3.2.4), PISM uses an enthalpy-based scheme which allows for conservation of energy even at the pressure melting-point. The energy conservation calculation determines the amount of basal melt, **bmelt**, and that melt water is stored locally in the till under the ice sheet [Aschwanden et al., 2012]. Of the water added by the basal melt rate, a fraction may refreeze onto the bed of the ice and the rest decays away according to the configuration parameter **bwat_decay_rate**. This decay is bounded by the effective thickness of the configuration constant **bwat_max** which sets the limit for the output variable **bwat** holding the effective thickness of the subglacial layer of liquid water in the till. The lost melt water is added to the output field of **land_flux**, the fresh water contribution to the ocean originating from in-land processes.

3.3.2 Surface Melt and Runoff

In the chosen setup, PISM takes as input the net surface mass balance and interprets the input temperature field as the temperature at the ice surface beneath the firn layer. The net surface mass balance may be positive or negative and, hence, PISM does not include any calculations of surface melt and, consequently, no runoff fields are given by PISM either. In other configurations, including, e.g. positive degree day models, PISM does calculate surface melt, but, as mentioned, these other possible configurations are not utilised in the coupled model setup so the way PISM handles surface melt and runoff is not currently relevant and therefore not included here.

3.3.3 Calving

A physically-based calving scheme where calving rates are based on the eigenvalues of the horizontal strain rate tensor is available in PISM. However, this calving scheme is only well-defined for floating ice shelves and, consequently, it does not apply in the case of Greenland. Instead, calving is handled by a mask approach, where a single mask determines the cut-off point of floating ice in the model. The mask determines a boundary beyond which no floating ice can grow. This calving approach is envoked by the keyword **-ocean_kill** [*mask_file*] [Albrecht et al., 2012]. The calving mask set by the *mask_file* remains constant throughout the entire simulation; in that sense, ice shelves are allowed to retreat freely, but can not advance beyond the limit set by the initial mask. If a separate calving mask is not provided by adding the name of the *mask_file* to the **ocean_kill** setting, the calving mask is defined as the values of PISM's *mask* variable at the onset of the simulation. The water removed from the ice sheet by calving is added to the output field of **ocean_kill_flux**.

3.4 Drivers and Boundaries of PISM

As described in sect.(3.1), the basic PISM design separates the ice dynamics itself from its surrounding climate drivers. Numerous different possibilities for driving PISM exist, but presently, only the model options that are active in the coupled model setup are mentioned here.

3.4.1 Bedrock

PISM includes a bed deformation component that approximates the movement of the Earth's crust and upper mantle. At the bottom of the bedrock thermal layer, PISM recieves an influx of geothermal heat that is included in the energy balance equations. This geothermal heat flux is given by the reference data set provided by [Shapiro and Ritzwoller, 2004]. The option **-bed_def** [*model*] invokes the bed deformation models of PISM. Currently, the chosen bed deformation model is **lc**, which is an improved version of the flat earth Elastic Lithosphere Relaxing Astenosphere (ELRA) model [Le Meur and Huybrechts, 1996], based on work by [Lingle and Clark, 1985, Bueler et al., 2007].

3.4.2 Ocean

The version of PISM (pism0.5) that is currently running as part of DMI's model suite has a simple forcing component. The basic assumption is that the mass flux into the ocean is proportional to the heat flux into the ice which in turn is controlled by the configuration parameter **ocean_subshelf_heat_flux_into_ice**, thereby providing a constant (in time as well as space) mass flux into the ocean. The ocean forcing is activated by adding **-ocean constant** to the PISM run call.

3.4.3 Atmosphere

A number of different methods for driving PISM exist, but in the coupled setup, PISM is currently driven by fields of monthly mean temperatures and fields of the monthly mean surface mass balance in ice equivalents. This is done by using the option **-surface given -surface_given_file** [*Forcing_file*] in the PISM run call.
In the case of the temperature, PISM interprets any temperature input as being the temperature at the interface between the firn layer and the ice sheet itself [Albrecht et al., 2012]. The surface mass balance is defined as the local difference between accumulation and ablation.

3.5 Modifications to PISM

During the development of the coupled system a few issues with PISM that needed to be addressed became evident. These are centered around PISM's book-keeping of its fresh water outflows and will be descried below.

3.5.1 Adding Two-dimensional Fresh Water Outputs

In standard-issue PISM, time series of fresh water flows due to basal melt and calving are stated as total values for the entire domain. From the perspective of the ice sheet itself, this is sufficient to be able to partition mass loss from the ice sheet between the different loss mechanisms. However, in a coupled model setup, the fresh water outflow from the ice sheet is needed as input to the ocean part of the climate model. Adding a whole year's worth of melt water from the Greenland ice sheet in a single time step and a single location is an unphysical solution. Instead, the fresh water input to the oceans needs to be added at a distribution of locations at suitable time intervals.
In order to address this issue, the two-dimensional variables *land_flux* and *ocean_flux* have been added to the output fields of PISM. Basal melt and surface melt (if any is available by the chosen PISM setup) are included in the *land_flux* field and calved-off ice (be it by a calving mask or some

Value	Classification
0	Ice-free bedrock
2	Grounded ice
3	Floating ice
4	Ice-free ocean

Table 3.2: Table of the different mask values in PISM and their interpretation.

calving parameterisation) is included in the *ocean_flux* field.
The addition of two-dimensional fresh water fields to PISM has been reported back to the PISM developers and this modification will be included in later versions of PISM.

3.5.2 Mask-Related Fresh Water Flows

PISM has a variable, *mask*, which keeps track of the nature of each point in the model grid. Grid cells can either be ice-free bedrock, grounded ice, floating ice or ice-free ocean, the corresponding mask values are listed in tab.(3.2). In PISM, any grid cell not covered in grounded ice with a bedrock elevation lower than sea level will be interpreted as an ocean grid cell by PISM. In model runs where the **ocean_kill** option is set, any ice progressing into an ocean grid cell will be cut-off immediately. As described in sect.(3.3.3), the calving mask is constant, and a grid cell that initially is classified as ocean will remain ocean for the duration of the simulation. This, in combination with PISM's interpretation of a grid cell being ocean if it is ice-free and the bedrock topography is below sea level, may lead to discrepancies in some instances.
During the development phase, isolated inland grid cells within the ice sheet boundary were found, that were interpreted as ocean points regardless of the fact that they were located inland with no contact to the ocean and surrounded by ice. Additionally, these points persistently shed any ice advancing into the grid cell from the surrounding ice sheet because of their initial classification as ocean, thereby contributing to the *ocean_flux* field. These land-locked grid cells were initially ice-free, but with a bedrock topography below sea level and, hence, were interpreted as ocean by PISM. Due to the mask-defined calving, these grid points constantly shed any inflowing ice, thereby artificially keeping the grid-cell ice-free and contributing to the calving.
Modifications were made to the PISM code to locate any such artificial land-locked ocean points, convert their mask value and allowing ice to fill the grid cell in question and stop the unphysical calving contribution. This issue and the necessary code modifications have been conveyed to the PISM developers and will not feature in later versions of the model.

4. The Coupled System Part 2: The Climate Model EC-Earth

The atmosphere and ocean part of the coupled system is simulated using the climate model EC-Earth [Hazeleger et al., 2011]. EC-Earth is comprised of the Integrated Forecast System (IFS) (see [Temperton et al., 2001, Hortal, 2002, Untch and Hortal, 2004] and the official IFS documentation at *https://software.ecmwf.int/wiki/display(IFS/Official+IFS+Documentation*) of the European Centre for Medium Range Weather Forecasts (ECMWF) as the atmospheric component, the Nucleus for European Modelling of the Ocean (NEMO v2.0) as the ocean component and the Louvain le Neuve sea-ice model LIM2 [Fichefet and Morales Maqueda, 1997, Bouillon et al., 2009]. As mentioned, the atmospheric component is based on IFS (cycle 31r1) but the model has been extended with the H-Tessel land surface scheme
[Viterbo and Beljaars, 1995, van den Hurk et al., 2000, Balsamo et al., 2009], an improved snow scheme [Dutra et al., 2010] and the convection scheme by [Bechtold et al., 2008].
In order to facilitate coupling to the ice sheet model, both the atmospheric and the ocean component of EC-Earth have been modified to include the presence of explicit ice sheets. The model changes include and explicit land ice mask, a separate albedo parameterization for snow on land ice and the calculation of surface mass balance (SMB). The ocean model has been modified to include the read-in of freshwater and heat fluxes related to ice discharge (as calculated by PISM).

4.1 Modifications to EC-Earth

In the standard EC-Earth model, land ice is not treated explicitly. Instead, the mass balance of the Greenland and Antarctic ice sheets are obtained by special constraints on albedo, snow density and melting conditions of perennial snow. In the coupled model, a glacier mask is introduces and the surface parameterization has been adjusted to account for the presence of the ice surface. Surface melting of ice is included as part of the surface energy balance equation and the surface mass balance is calculated based on precipitation, evaporation and runoff from surface melt. The modifications to EC-Earth can be summarized by these points:

- PISM's ice extent is interpolated onto the EC-Earth grid and defines the regions where special ice-related surface treatment applies.
- The surface scheme uses new values of conductivity, volumetric heat capacity and roughness lengths for land ice but keeps the four layer structure of the soil.
- Exposed land ice is allowed to melt if the snow on top of the ice has melted. The resulting melt water is added to the snow melt and runs off following the same scheme.
- The radiative properties of the surface are changed in the case of exposed ice.
- The enforced melting of excess snow from the original version of EC-Earth is removed. However, the maximum amount of snow is set to $10\mathrm{kg/m^2}$. Information on excess snow is provided to the ice sheet model in the form of positive values of the surface mass balance (SMB) field.
- The snow density remains fixed (for more than 1 m of snow) to account for the use of a single layer snow model.

4.1.1 The Glacier Mask

In the H-Tessel surface scheme
[Viterbo and Beljaars, 1995, van den Hurk et al., 2000, Balsamo et al., 2009], six land surface tiles are defined including high vegation, low vegetation, interception reservoirs, bare ground, snow on glound/low vegetation and snow under high vegetation. The surface type may vary within a gridbox reflecting the subgrid variability in e.g. vegetation and snow cover and the surface enrgy balance equation is formulated separately for each of the tiles which have their own skin temperature. In the coupled model, the six land surface tiles are kept and the ice extent is introduced as a fractional mask where grid boxes with at least 50% ice coverage are treated as glaciated. The ice mask is read from a file each model year with a time resolution of one month. For each tile, the surface properties of albedo, emissivity and roughness lengths are specified. For the snow-free tiles of glaciated grid boxes values representative of an ice sheet surface are used: and albedo of 0.6, a long-wave emissivity of 0.98 and roughness lengths of 0.001.
In EC-Earth, the soil is discretized into four layers extending to a total depth of 2.89m (0.07m, 0.21m, 0.72m, 2.89.), representing the vertical profiles of temperature and moisture. In order to construct a proper boundary between the ice sheet and the climate model, all vertical layers are treated as ice if the grid-box is glaciated. In this case we introduce a constant heat conductivity of 2.2W/mK and a volumetric heat capacity of $2.05 \cdot 10^6 \mathrm{J/m^3} K$ and thereby adjust the distribution of heat within the layers and the exchange of energy with the overlying snow or atmosphere to the presence of the ice sheet.

4.1.2 The Snow Scheme

The snow pack is represented by a single snow layer on top of the four soil/ice layers. The energy absorbed in the snow pack is used to change the temperature or melt the snow if the snow temperature T_{sn} exceeds the melting point temperature. The energy equation for the snow temperature reads

$$\left[(\rho C)_{sn} D_{sn} + L_f S_l^c \frac{\partial f(T_{sn})}{\partial T_{sn}}\right] \frac{\partial (T_{sn})}{\partial t} = R_{sn}^N + L_s E_{sn} + H_{sn} - G_{sn}^B - L_f M_{sn} \tag{4.1}$$

where $(\rho C)_{sn}$ is the volumetric heat capacity of snow, D_{sn} is the snow depth, L_f is the heat of fusion, S_l^c is the snow liquid water capacity, R_{sn}^N is the net radiative fluxes, L_s is the heat of sublimation, E_{sn} is the snow evaporation, G_{sn}^B is the heat flux at the bottom of the snow pack and M_{sn} is the snow melt. Liquid water can co-exist in the snow pack and the second term in the dquare bracket represents an additional snow heat capacity assicated with internal phase changes of the snowpack liquid water. Since a single layer snow scheme is used, a maximum snow depth of 7cm is used in the snow energy budget to allow heating and melting of the upper layer of a deeper snow pack. The basal heat flux at the bottom of the snow pack is given by

$$G_{sn}^B = \frac{T_{sn} - T_{soil/ice}}{r_{sn}} \tag{4.2}$$

where r_{sn} is the resistance betweenthe middle of the snow pack and the middle of the upper soil/ice layer. This resistance is calculated from the conductivity of the soil/ice and the presence of the underlying ice sheet is thus accounted for in the snow energy balance equation. As there is no ice dynamics in standard EC-Earth, snow would pile up the interior of the ice sheet where practically no melting occurs and compaction, followed by ice flow and eventually calving at the margins would be the actual redistribution mechanism. Therefore, snow accumulation in excess of 10 m.w.eq. is melted whenever the net radiative flux at the surface is positive and the heat flux into the snow layer is reduced accordingly. Since the melting of excess snow is included as part of the run-off in standard

EC-Earth, the surface mass balance as calculated from the output of precipitation, evaporation and run-off would be close to zero for a stable ice sheet and thus not suitable for forcing an ice sheet model. In the coupled setup, the melting of excess snow is deactivated. Instead, the accumulated snow is used to force the PISM ice sheet model as part of the surface mass balance and the changes of ice extent and topography as well as the ice discharge calculated by PISM are passed back to EC-Earth. In this setup, the climate model takes care of the surface melting and accumulation whereas the ice sheet model controls the ice dynamics which is more physically consistent.

4.1.3 Albedo

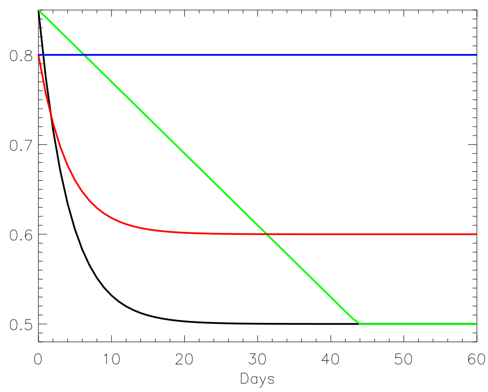

Figure 4.1: Snow albedo for seasonal snow under melting (black) and ageing (green) conditions. For snow on ice sheets, a constant value of 0.8 is used (blue) for non-melting conditions and an exponential decay is applied for melting conditions (red) in the coupled model.

The EC-Earth snow albedo scheme distinguishes between seasonal snow (less than 1 m.w.eq.) and permanent snow. For seasonal snow, the albedo ranges from 0.5 for old snow and 0.85 for fresh snow. The snow albedo decreases linearly with snow age and exponentially in case of melting conditions as illustrated by the green and black lines in fig.(4.1). After a snowfall, the albedo is continuously reset to its maximum value of 0.85 which is reached with 1 cm of fresh snow. In the case of permanent snow, the snow albedo has a fixed value of 0.8 for both melting and non-melting conditions. In the coupled setup, we keep the value of 0.8 for non-melting conditions (the blue line in fig.(4.1)) but in order to activate the albedo-melt feedback the snow albedo decays exponentially under melting conditions, although with a lower limit of 0.6 (red line in fig.(4.1)). In order to account for subgrid variability, the melting formulation is also active for $T_{sn} \geq T_f - 2$, where T_f is the triple point temperature of snow [Dutra et al., 2010]. In the coupled setup, the snow albedo is continuously reset on snowfall too, but for snow on ice sheets a maximum value of 0.80 is used.

4.1.4 Ice Surface Melt

In a snow-free part of a grid box, any ice surface is exposed and allowed to melt whenever at least 10% of the grid box is glaciated and the skin temperature, i.e. the temperature of the surface in radiative equilibrium, would exceed 273.16K. The tiled surface is thermally coupled to the snow layer or the upper soil/ice layer. The surface energy balance equation assumes a zero heat capacity of the skin layer and is solved for each tile separately

$$(1 - \alpha_i)R_s + \epsilon(R_T - \sigma T^4_{sk,i}) + H_i + L_{v,s}E_i = \Lambda_{sk,i}(T_{sk,i} - T_s) \qquad (4.3)$$

where i denotes the tile index. R_s and R_T are downward shortwave and longwave radiation, σ is the Stefan-Boltzmann constant, T_s the temperature of the upper snow, soil or ice layer, H_i the sensible heat flux, $L_{v,s}$ the latent heat of vapourization/sublimation, E_i the evaporation from the skin layer and $\Lambda_{sk,i}$ the skin conductivity for tile i. The term on the right represents the conductive heat flux G_i. If the calculated skin temperature exceeds the melting point temperature, T_{sk} is reset to 273.16K and the conductive and longwave radiative fluxes are recalculated using the new skin temperature and the energy available for melting is calculated as

$$Q_{Melt,i} = (1-\alpha_i)R_s + \epsilon(R_T - \sigma T_{sk,i}^4) + H_i + L_{v,s}E_i - G_i \tag{4.4}$$

The energy available for ice melt is summed over the tiles and multiplied by the fractional ice coverage of the grid box. Melt water from snow and ice is assumed to run off immediately. It is collected in pre-defined river basins and instantaneously distributed into ocean points nearby the outlets of major rivers according to the EC-Earth routing scheme [Hazeleger et al., 2011]. Refreezing is not implemented in the present version of the model.

4.2 PISM Drivers of EC-Earth

In the coupled system, a number of fields based on PISM output are given to EC-Earth. These are the land ice mask, the ice discharge, the basal melt and the ice sheet topography.

4.2.1 Land Ice Mask

As described above, the modified surface scheme for EC-Earth is applied in areas covered by land ice. The extent, growth or decay of the areas covered by land ice is determined by the ice sheet model, more specifically, by PISM's mask variable, that takes on separate values in the case of a grid point being either ice-free ocean, floating ice, grounded ice or ice-free bedrock, see tab.(3.2). The PISM mask values are interpolated onto the EC-Earth grid, making it possible to determine the partial ice cover, C_{ice}, for any given grid box in EC-Earth.

4.2.2 Ice Discharge

The ice discharge from the ice sheet is given to EC-Earth as variable 83 (PICEDIS) in units of $\mathrm{kg}/6\mathrm{s}$. In order to convert this figure to $\mathrm{Gt}/\mathrm{year}$, multiply by the EC-Earth grid cell areas (saved in file areas_IFS.nc), multiply by 86400/6 in order to get the daily value, by 365.25 to obtain the annual value, and, finally, divide by $1.0{\cdot}10^{12}$ to convert from kg to gigatons.

4.2.3 Basal Melt

The basal melt from the ice sheet is given to EC-Earth as variable 84 (PICEBAS) in units of $\mathrm{kg}/6\mathrm{s}$. As before, in order to convert this figure to $\mathrm{Gt}/\mathrm{year}$, multiply by the EC-Earth grid cell areas (saved in file areas_IFS.nc), multiply by 86400/6 in order to get the daily value, by 365.25 to obtain the annual value, and, finally, divide by $1.0{\cdot}10^{12}$ to convert from kg to gigatons.

4.2.4 Topography

The ice sheet topography is given to EC-Earth (variable 129) and affects the surface pressure p according to

$$\frac{dp}{dH} = \rho g \tag{4.5}$$

where the acceleration of gravity $g = 9.80665\mathrm{m}/\mathrm{s}^2$ and the density ρ at sea level and $15°\mathrm{C}$ is $1.225\mathrm{kg}/\mathrm{m}^3$. In the current set-up, the field mean of the topography is increased by approximately

1.93m by the contribution from the PISM ice sheet, resulting in a pressure difference of 23.15 Pa according to eq.(4.5).

5. Forcing Fields and Interpolations

The coupling between EC-Earth and PISM is done by exchanging relevant forcing fields at regular intervals. However, necessary forcings for one part of the systemay not be available as a direct output from the other part and, consequently, such fields need to be calculated or approximated based on available output. Also, the two models run on different grids and at different spatial and temporal resolutions, so the various forcing fields must be interpolated before being passed from one part of the system to the other. This must be done in a manner that preserves mass and energy.
In the case of fields being passed from PISM to EC-Earth, the needed variables are directly available as output fields from PISM, and only unit conversions and grid interpolations are necessary. In the case of forcing fields from EC-Earth begin passed to PISM, however, not all the needed forcing fields are directly available.

5.1 Input Fields to PISM Based on EC-Earth Fields

In the coupled model setup, PISM is driven by fields of the temperature of the ice surface below the snow and firn layer and the total surface mass balance. None of these fields are in the EC-Earth output, but are calculated or approximated based on available EC-Earth fields instead.

5.1.1 Surface Mass Balance

The surface mass balance is defined as the local difference between accumulation and ablation. In terms of available EC-Earth output the surface mass balance is defined as the total precipitation (The sum of EC-Earth variables 142 and 143), P, minus the evaporation, E (EC-Earth variable 182), and runoff, R (EC-Earth variable 205):

$$\mathrm{SMB} = P - E - R \tag{5.1}$$

The total precipitation P is defined as the sum of the stratiform and convective precipitation (EC-Earth variables 142 and 143, respectively). These fields are 6-hourly accumulated fields rather than daily fields. Also, due to the sign convention in EC-Earth, the evaporation field must be added to the precipitation and runoff terms rather than subtracted when calculating the surface mass balance. The relevant EC-Earth fields are given in meters of water. However, PISM requires its surface mass balance input fields to be given in meters of ice, so a conversion from meters of water to meters of ice is necessary when determining the surface mass balance. An overview of the various EC-Earth model fields used to drive PISM is given in tab.(5.1).

Variable	**Variable code**	**Use**
Lowermost soil temperature	236	Temperature forcing
Stratiform precipitation	142	Surface mass balance calculation
Convective precipitation	143	Surface mass balance calculation
Evaporation	182	Surface mass balance calculation
Runoff	205	Surface mass balance calculation
Topography	129	Lapse rate correction
Land-sea mask	172	Grid interpolation

Table 5.1: Table of variables extracted from EC-Earth data and their use in the production of forcing files for PISM.

5.1.2 Temperature

As mentioned in sec.(3.4.3), PISM interprets any temperature input as being the temperature at the interface between the firn layer and the ice sheet itself [Albrecht et al., 2012]. In the coupled model setup, EC-Earth's temperature of the lowermost soil (ice in the case of ice-covered grid points) layer (var 236) is used as a proxy for this temperature.

5.1.3 Lapse Rate Corrections

Due to differences in the PISM and EC-Earth resolution and topographies, lapse rate correction of the temperature field is necessary. This is accomplished by means of the built-in lapse rate correction scheme in PISM. The temperature lapse rate, γ_T, is defined as

$$\gamma_T = -dT/dz \tag{5.2}$$

where T is the temperature and z is the altitude. In the present setup of the model system, a value of $\gamma_T = 6.8\mathrm{K/m}$ is used [Fausto et al., 2009]. Given the large diffence in the spatial resolution of EC-Earth and PISM, lapse rate corrections may be substantial in some areas.
Activation of PISM's lapse rate correction scheme is done by adding the modifiers *lapse_rate -temp_lapse_rate* γ_τ to the part of the run call dealing with the choice of forcing:
-surface *given,lapse_rate -temp_lapse_rate* γ_τ

5.2 Interpolation of Fields

Both the two separate parts of the coupled system need input from the other part. Due to differences in model grids and resolution, prior to an annual run of one of the system components, the drivers based on output from the other component must be interpolated onto the relevant grid. The interpolations are performed by means of OASIS3 [Valcke et al., 2013].
The EC-Earth soil temperature is interpolated bilinearly from the IFS to the PISM grid and lapse rate corrected, see eq.(5.2) whereas the surface mass balance is interpolated using a conservative remapping. This approach provides a very consistent treatment of the interface which ensures the conservation of mass between the two models. However, since the resolution of IFS is relatively coarse, this method does not resolve the highly varying surface mass balance within the narrow ablation zone or the in the steep mountaineous regions along the coast lines.
The calving fluxes of heat and freshwater are provided to NEMO as an additional forcing, assuming that the resultings icebergs melt immediately by gaining energy from the ocean. The basal melting occurs over land and the resulting fresh water is regridded to the nearest EC-Earth land point from where it is distributed according to the EC-Earth routing scheme also used for redistributing the surface melt water. The fields of fresh water and energy fluxes are evenly distributed throughout the year.

5.2.1 Interpolations Using OASIS3

When performing the interpolations, OASIS3 relies on the *namcouple* file. This file assigns target and source grids and contains descriptors for the various interpolations needing to be performed. For each field to be interpolated, the *namcouple* file has a section like this:

```
field_in field_ou 1 1 3 12_in.nc pr_12.nc EXPORTED
atmo pism
P 0 P 0
CHECKIN SCRIPR CHECKOUT
INT=1
CONSERV D SCALAR LATLON 10 FRACNNEI FIRST
```

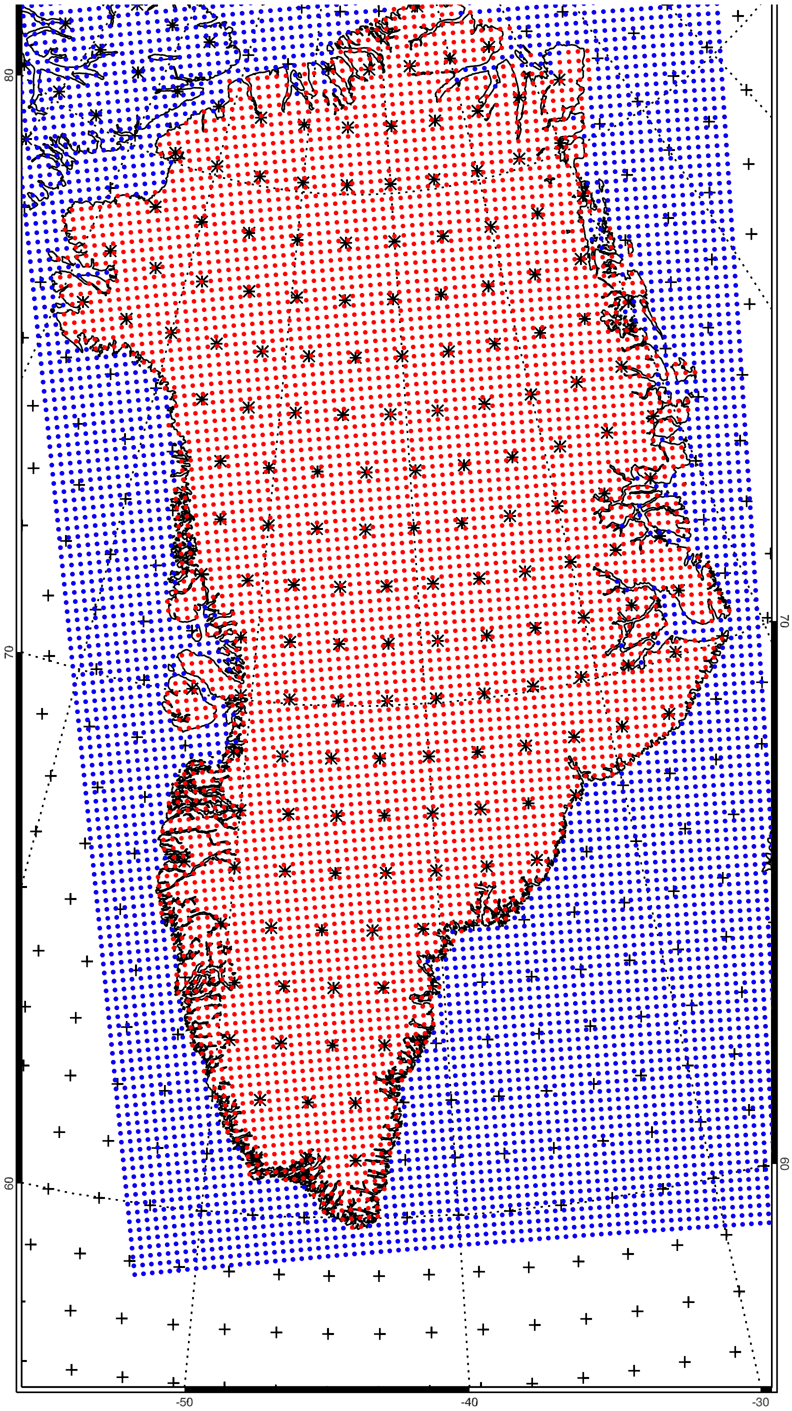

Figure 5.1: The EC-Earth and PISM grids. EC-Earth grid points are indicated by crosses and asterisks; crosses indicating grid points classified as ocean points, the asterisks indicating grid points classified as land points. The EC-Earth land-sea mask stays constant throughout the simulations. Dots indicate the location of the PISM grid points, blue points signifying ocean point, red points signifying land points. The mask of PISM may vary through time.

INT=1

The example above will do a conservative remapping from the EC-Earth (atmo) source grid to the PISM (pism) target grid. The field to be interpolated is found in the file 12_in.nc and is given as field_in. The interpolated field field_ou is written to the file pr_12.nc. The additional keywords are

Field	Source grid	Target grid	Interpolation	Normalization option	Namcouple file
SMB	EC-Earth	PISM	Conservative	FRACNNEI	nam_SMB
Temperature	EC-Earth	PISM	Bilinear	-	nam_temp
Elevation	EC-Earth	PISM	Bilinear	-	nam_ele
Topography	PISM	EC-Earth	Conservative	FRACNNEI	nam_topo
Basal melt	PISM	EC-Earth	Conservative	FRACNNEI	nam_basal
Discharge	PISM	EC-Earth	?	?	?

Table 5.2: Options and settings used by OASIS3 for interpolation in the coupled EC-Earth-PISM system.

details on the exact rempping method, such as normalization option and search region. Further information on the various keywords and settings may be found in the OASIS manual, [Valcke et al., 2013].

When performing the interpolations, OASIS3 requires information about the structure of the modelling grids in EC-Earth and PISM, respectively. This information is given by three files, one with longitudes and latitudes of the grid boxes and their corner points for each of the two grids, one with surface areas of every grid box for each of the respective grids, and a file with a mask value for each grid box, indicating whether or not OASIS3 should include this particular grid box in the interpolation or not.

The longitudes and latitudes provided in the PISM output files indicate the latitude and longitude of the center of each grid box. However, when running the python script *nc2cdo.py* supplied by the PISM developers on a PISM output file strippe dof its inherent longitude and latitude fields calculates the grid box longitudes and latitudes and the coordinates of the grid box corner points based on the mapping information in the file and the projected x and y coordinates. The grid and corner point information, the grid cell areas and the mask values are written to a set of three NetCDF files in the format requested by OASIS3. These files with the PISM grid information are concatenated with a set of corresponding grid information files for the EC-Earth grid and the resulting file is the used by OASIS3 when called upon to perform the interpolations. It is worth noticing the OASIS3 is rather selective in term of naming conventions of the various in- and output fields of the interpolation and their order in the grid information fields and namelists and great care must be taken when producing the grids and masks files needed by OASIS3 in order to ensure its functionality.

5.2.2 Forcing Files for PISM

When producing the forcing files for PISM based on EC-Earth output, the monthly mean surface mass balance is calculated from precipitation, runoff and evaporation fields as described in sect.(5.1.1) and converted to ice equivalents and the monthly mean temperature is calculated from the temperature fields. Then the monthly surface mass balance and temperature fields are interpolated along with the topography field are interpolated onto the PISM grid by OASIS using the options listed in tab.(5.2). The interpolated fields are then renamed to comply with PISM standards for input fields and concatenated with a dummy NetCDF file containing information on the PISM grid to produce the final forcing file.

5.2.3 Updating the Climate File of EC-Earth

In the case of EC-Earth, the new state of the ice sheet as simulated by PISM is passed to EC-Earth via the climate file. Prior to a new one-year run with EC-Earth, the relevant PISM fields (mask, topography, basal melt and ice discharge) are interpolated onto the EC-Earth grid by OASIS3 and are then used to update the climate file of EC-Earth. The PISM output is in NetCDF format and

EC-Earth requires grib files, so a modified version of the *Interpo* programme which is part of the EC-Earth package is used to convert from one format to another.

6. Spinning up the System

Prior to any scenario runs, spin-up runs are needed in order to ensure stability of the system and avoiding transients. The ice sheet is taken through a separate spin-up process to obtain a stable ice sheet initial state in equilibrium with the driving climate model and the coupled system is taken through a spinup process as well.

6.1 Ice Sheet Initial States and Spin-up

Considering the spinup process for the ice sheet, this is a process in multiple stages. Firstly, a basic initial state must be chosen and then this basic state must be brought through a spinup process in order to ensure its stability and memory of its climatic history.

6.1.1 Basic Initial State Prior to Spin-up

Running PISM requires an initial state of the ice sheet for the model to base its simulations on. Ideally, such an initial state would be based on observations. However, available ice sheet data sets are most often various 2D fields such as fields of ice sheet thickness, surface elevation and surface temperatures. The 3D variables needed for the numerical simulations such as e.g. temperature and viscocity fields are only available from a few, selected locations, not from the entire ice sheet. Also, the necessary information about conditions at the ice base are not readily observable. No data set of observables exist that may provide a full, integrable state of the ice sheet that could serve as the initial state for a simulation.
In order to address this, PISM may be run in boot-strapping mode (using run option **-boot_file** *infile*) where PISM uses heuristics to fill out the remining grid points of, e.g., the temperature at depth based on an incomplete set of observables. In order to perform a boot-strapping run, PISM needs at least fields of bedrock topography and ice thickness. In case any other 2D fields are available they are used for the initialisation as well, otherwise they are filled in by the boot-strapping process. Note that any 3D variables present in the initial data set will be ignored by the boot-strapping process [Albrecht et al., 2012]. As part of the boot-strapping PISM is given information on the needed spatial resolution and produces the initial state at this resolution. However, since PISM eliminates any given 3D variables prior to the boot-strapping, it is not recommended to use the boot-strapping mode for regridding PISM output from one resolution to another since all 3D information will be lost in the process. Instead, PISM has a regridding option (**-regrid_file** *infile*) for such tasks. In the current setup, the set of observables used to obtain the initial state by boot-strapping is the dataset of bed elevation and ice sheet thickness for Greenland published in [Bamber et al., 2013a]. In the current model configuration, the chosen grid resolution is $20\text{km}\times 20\text{km}$. In the PISM run call, the parameters determining the grid are set as follows:

-Mx 76 -My 141 -Lz 7750 -Lbz 2000 -Mz 156 -Mbz 41

where Mx, My, Mz, Mbz define the number of grid points in the x, y, z, zb directions, z being the vertical coordinate above bedrock, zb being the vertical coordinate below bedrock. Lz defines the height (in meters) of the computational domain in the ice and Lbz defines the depth (in meters) of the computational domain in the bedrock. In the current setup, the spatial extent in the x and y are defined by the extent of the input data set. It is, however, possible to specify the half-widths of the computational domain in the x and y direction (in kilometers) by means of the parameters Lx and Ly, respectively.

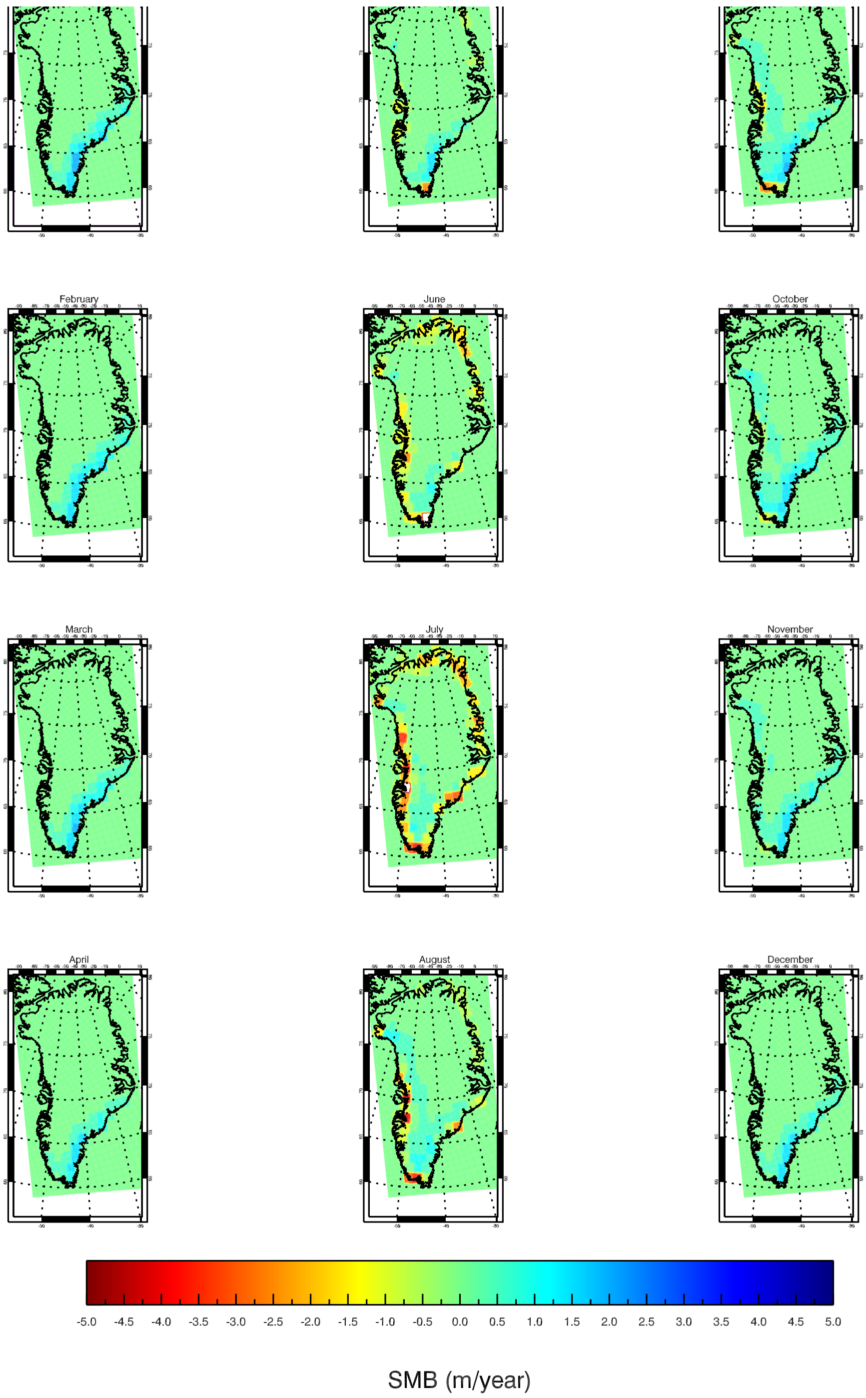

Figure 6.1: Monthly surface mass balance fields used to drive the spinup run.

6.1.2 Spinning Up the Ice Sheet

The basic initial ice sheet states obtained by PISM's boot-strapping procedure described in sect.(6.1.1) above are not sufficient as initial states in projection runs. The ice sheet initial state should preferably carry the load of the climate history of its past. In addition, the ice sheet initial state needs to be in equilibrium with the mean climate of its driving model, EC-Earth, in order to avoid any climate signals being obscured by transients in a projection run. In order to address these issues, the ice sheet is taken through a two-step spinup procedure where PISM is run as a stand-alone model. First, the ice sheet is taken through the past glacial cycle using SeaRISE sea level and