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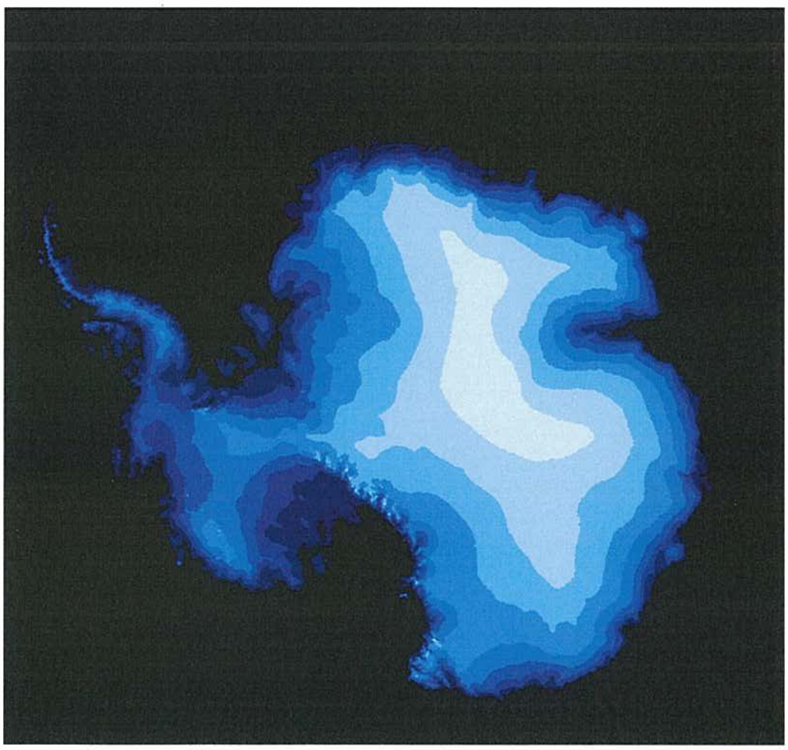
Modelling the Antarctic Ice Sheet: A preliminary study using the EC-Earth-PISM model system

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



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Contents

1. Introduction

The large ice sheets and ice shelves of Greenland and Antarctica exist in close interplay with the surrounding atmosphere and ocean and numerous feedback processes take place in the combined ocean-atmosphere-cryosphere system. In order to resolve these feedbacks and potentially quantify their effects on the ice sheets and the climate system as a whole, an implementation of the ice sheets over Greenland and Antarctica into the global circulation models is crucial.
One method of implementing ice sheets in a climate model is to couple two independent models, an ice sheet model and a climate model. The two models work as stand-alone models and are run in succession in individual cycles, each model receiving input data from one another prior to each run cycle. In the case of the Greenland Ice Sheet, such a coupled system has been developed at the Danish Climate Centre based on the ice sheet model PISM and the GCM EC-Earth. A number of changes to the surface scheme of EC-Earth were required to remedy the coupling, see [Madsen et al., 2014, Svendsen et al., 2014].
The present description of the setup of the ice sheet model PISM and how to drive PISM over Antarctica with data from the global climate model EC-Earth constitutes the outcome of preliminary studies to include the Antarctic ice sheet in a fully coupled ice sheet-climate model system following the structure already developed in the case of the Greenland Ice Sheet. These studies form part of the Danish Climate Centre's contribution to the research project COMBINE, funded by the European Commission's 7th Framework Programme under Grant Agreement 226520.
A general description of the ice sheet model PISM employed in the coupled setup along with descriptions of how to drive and spin up the ice sheet model in the coupled model system is given in [Svendsen et al., 2014]. In order to enable the climate model EC-Earth to work in a coupled setting, a number of changes have been made to EC-Earth as well and these, along with details of how to run the coupled system, are described in [Madsen et al., 2014]. It is important to note that the changes in EC-Earth have been developed and tested for Greenland, but not for Antarctica and that the coupling to the Antarctic Ice Sheet is a pilot study intended more as a feasability study rather than a rigourous development of a fully coupled system. The Greenland Ice Sheet and the Antarctic Ice Sheet have different characteristica, one obvious distinction being the sheer difference of scale between the two ice sheets. As opposed to the Greenland Ice Sheet, Antarctica is surrounded by massive ice shelves. The presence of ice shelves - or lack thereof - necessitates different treatments of calving for Greenland and Antarctica, respectively. In the case of Antarctica, the calving rate is determined by means of the eigen calving law developed by [Levermann et al., 2012] as ooposed to the mask-induced calving employed for Greenland.
Currently, the system only has very rudimentary ocean forcing schemes. However, ocean dynamics has a vast impact on the ice sheets and shelves [Årthun et al., 2013, Grosfeld et al., 1997] so an improvement of the current ocean forcing of the ice sheet model is a matter of priority for any future development. Likewise, the question of the resolution of the driving climate model and the method of downscaling the forcing fields based on climate model data are of great importance.
A brief introduction to the ice sheet model PISM is given in chap.(2). The basic dynamics is described with particular emphasis on PISMs treatment of ice shelves, an essential feature of the Antarctic ice sheet. Issues regarding the computational grid and the initialisation of PISM are addressed as well in this chapter.
Chap.(3) addresses the forcing of PISM with climate model data. The relevant PISM forcing fields are defined and their chosen climate model counterparts and their definitions are described and the PISM options relevant for forcing PISM in the coupled model setup are introduced. In addition, the chapter contains a description of methods for the extraction and grid interpolation of forcing fields for PISM from climate model data along with a discussion of the challenges concerning a proper

rendition of the conditions of the Antarctic peninsula.
In chap.(4) a short introduction to the initial set of observed data is given. The spinup procedure for the Antarctic ice sheet in the coupled model setup is described and some issues regarding stability and dependence on bedrock topography are addressed.
Chap.(5) of the report contains a description of short test runs with the fully coupled system and the outcome of the simulations before proceeding to chap.(6) where a number of issues regarding future development and improvements to the system are discussed.

2. The PISM ice sheet model

The ice sheet model used for ice sheet modelling, both coupled and stand-alone at the Danish Climate Centre is the Parallel Ice Sheet Model, PISM
[Winkelmann et al., 2011, Albrecht et al., 2012a]. PISM is an open-source, freely available iceh sheet model developed and maintained at the University of Alaska Fairbanks. The ice dynamics in PISM is centered around a superposition of the Shallow Ice Approximation and the Shallow Shelf Approximation (SSA), two different approximations of the Stokes equations for slowly-flowing fluids [Bueler and Brown, 2009]. This model setup has proven quite strong in describing ice sheet flow and within the model ice streams and outlets arise on their own account as a consequence of the underlying bed topography [Bueler and Brown, 2009, Winkelmann et al., 2011, Martin et al., 2011]. A cursory description of the structure of PISM and its dynamics is given below, but for any details regarding the dynamics and the numerical implementation the interested reader is referred to [Bueler et al., 2007, Bueler and Brown, 2009, Winkelmann et al., 2011, Martin et al., 2011] as well as the PISM documentation [Albrecht et al., 2012a]. For a more in-depth description of the setup of PISM at the Danish Climate Centre and its coupling to the climate model EC-Earth, please refer to [Svendsen et al., 2014, Madsen et al., 2014].
This chapter will introduce the basic dynamic priciples of PISM in sec.(2.1)-(2.2) along with methods for dealing with ice shelf mass loss in the form of ocean melt and iceberg calving (sec.(2.2.1)-(2.2.2)). In sec.(2.3) a schematic description of the model structure of PISM and the model settings relevant for model runs coupled to a climate model will be given.

2.1 PISM ice dynamics

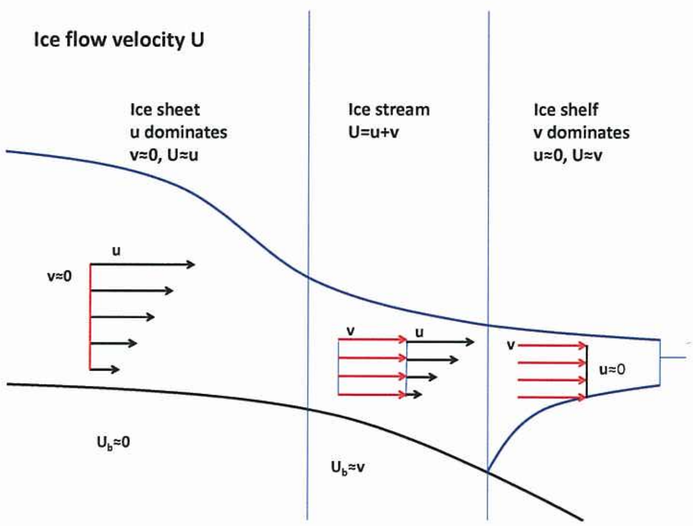

Figure 2.1: A schematic plot showing the PISM flow regimes for ice sheets, ice streams and ice shelves. U is the flow velocity.

The Stokes model for a slow flowing liquid is a comprehensive description of the flow of ice [Fowler, 1997], however, the computational cost of running such a model calls for approximations. 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 compuational cost. In models, ice is decribed as a slow, nonlinearly viscous isotropic fluid and two approximations 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 the 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 an 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 in flow rates that are comparable to observed 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 basae 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 a non-zero till strength and large ice sheets with zero till strength 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 defined 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 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 $\mathrm{v} = (v_1, v_2)$ the combined horizontal velocity $\mathrm{U} = (U_1, U_2)$ is given by [Bueler and Brown, 2009]:

$$\mathbf{U} = f(|\mathbf{v}|)\mathbf{u} + \{1 - f(|\mathbf{v}|)\}\,\mathbf{v}, \tag{2.1}$$

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

$$f(\mathbf{v}) = 1 - \frac{2}{\pi}\arctan\left(\frac{|\mathbf{v}|^2}{100^2}\right) \tag{2.2}$$

The weighting function f has values between zero and one and satisfies the general requirements of smoothness, monotone 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 negligibe 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 and the velocity profile will be given by $\mathrm{U}\approx\mathbf{u}$. In areas with basal sliding both SIA and SSA are relevant for the ice flow and the velocity will be given by eq.(2.1). In the case of an ice shelf, the SSA dominates, $\mathbf{u}\sim 0$, and $\mathrm{U}\approx\mathbf{v}$. In fig.(2.1) a schematic diagram of the various flow regimes is shown.

2.2 The description of ice shelves in PISM

Ice shelves are an essential feature of the Antarctic ice cover and span vast areas around Antarctica. Recent years have shown major breakups of some of the shelves and others seem close to the brink of stability [Doake et al., 1998, Jacobs et al., 1992]. The ice shelves exist in close interplay with the ocean and changes in ocean temperatures and currents will have a profound effect on the Antarctic ice sheet itself given the huge impact the ice shelves have on the ice sheet on accounts of their buttressing effect [Dupont and Alley, 2005, Gudmundsson, 2013]. Given the close interplay of the ice shelves with the ocean it is essential for modelling the Antarctic domain that an ice sheet model is capable of not only resolving the dynamics of the shelves, but is able to incorporate calving and melting from the shelves as well.

2.2.1 Melt from ice shelves

Mass loss from an ice shelf takes place either by melting or calving. The rate of melt is largely determined by the salinity, temperature and circulation of the ocean water in contact with the ice shelf. A complex interplay takes place at the ice shelf-ocean boundary, with the ice greatly affecting the ocean temperature, salinity and the resulting currents [Hellmer, 2004, Nøst and Foldvik, 1994]. PISM itself is uncoupled to any ocean dynamics but is, however, capable of exchanging water(ice) and heat across the ice-ocean boundary in order to mimic the effect of the ocean on the ice shelves. Melt from the ocean is described by a constant (in space and time) mass flux from the ice shelf into the ocean and a corresponding heat flux into the ice.

2.2.2 Calving in PISM

The calving of icebergs from the rim of the ice shelves is essential for the determination of the geometry, growth or demise of and ice shelf. Recently, PISM has been equipped with a novel calving scheme in order to allow for dynamic growth and retreat of ice shelves within PISM [Winkelmann et al., 2011, Martin et al., 2011, Levermann et al., 2012].
At the calving front of an ice shelf, the imbalance between vertically-integrated stresses in the ice and the hydrostatic pressure exerted by the ocean contributes to the ice flow upstream of the calving front. In order to be able to solve the SSA momentum balance equations a calving front stress boundary condition is needed. In addition, the calving front stress boundary condition is necessary for applying a dynamic calving law as a boundary condition to the mass continuity equation [Winkelmann et al., 2011]. For a detailed description of the calving front stress boundary conditions, see [Winkelmann et al., 2011]. Observations indicate that calving rates are linearly related to the production of the near-front thickness, half-width and strain rate [Doake et al., 1998, Alley et al., 2008]. Consequently, [Levermann et al., 2012] introduced a local, first-order law for large-scale ice shelf calving as a boundary condition ot the mass continuite equation the so-called Eigen Calving law. The calving rate is based on the eigenvalues $\dot{\epsilon}_{\pm}$ or the horizontal strain rate tensor. In most areas the the calving front the corresponding eigen-directions coincide with the directions parallel and transverse to the flow. in regions of divergent flow, where spreading occurs in both principle directions ($\dot{\epsilon}_{\pm} > 0$), the rate of large-scale calving, C, is defined as

$$C = K\det(\dot{\epsilon}) = K\dot{\epsilon}_{+}\dot{\epsilon}_{-} \qquad \text{for} \qquad \dot{\epsilon}_{\pm} > 0 \tag{2.3}$$

where $K > 0$ is a proportionality constant [Winkelmann et al., 2011]. Studies indicate that simulations of the Antarctic ice sheet using this calving law produce calving front locations that compare reasonably well with observations [Martin et al., 2011].
In PISM, any ice that is severed from the ice shelves by calving to form icebergs is removed from the PISM simulation by and algorithm that searches for isolated ice-covered grid cells entirely surrounded by ocean. This is because in the case of freely floating ice the SSA stress balance is no longer well defined [Winkelmann et al., 2011, Albrecht et al., 2012a].

2.3 The structure of PISM

An ice sheet is limited upwards by a surface layer of snow and firn, and, possibly, to the ocean and downwards by the bedrock at the base of the ice. A guiding principle in the structure of PISM is 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., 2012a]. In PISM, the ice sheet itself is

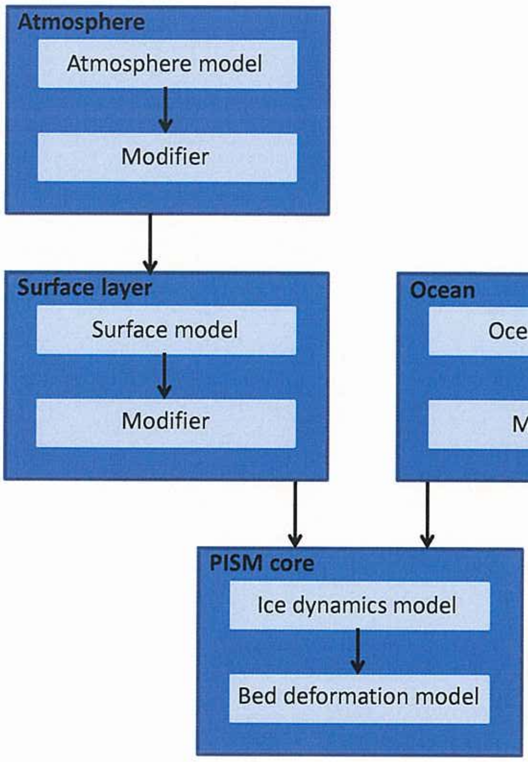

Figure 2.2: The structure of PISM and its boundary models. Adapted from [Albrecht et al., 2012a].

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

considered to have three boundaries: 1. The top ice surface below the firn layer, 2. The ice shelf basal surface and 3. The bottom surface of the thermal bed layer. Anything that happens outside these boundaries is not a part of the ice sheet dynamics model. Instead, necessary boundary conditions representing the conditions and possible fluxes across these boundaries are supplied by separate boundary models of PISM as illustrated in fig.(2.2). The various boundaries and the required boundary conditions are shown in tab.(2.1). This versatile struture provides ample opportunity for driving the PISM model using a variety of different types of data and makes it possible to couple PISM to a climate model without needing to modify the code of the ice dynamics itself.
EC-Earth as a coupled atmosphere-ocean model in combination with PISM provides the possibility 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.

2.4 PISM's boundary models

As mentioned in the previous section, sec.(2.3), the core part of PISM is reserved solely for the ice dynamics and everything outside the interfaces listed in tab.(2.1) and the communitcation across the interface boundaries is dealt with by the various boundary models of PISM, that is, the atmosphere, surface, bedrock uplift and ocean models. When running PISM, one must select the particular conditions of each of the boundary models. Note that none of the boundary models are actual models resolving the physics of the boundaring element (atmosphere, surface, bedrock or ocean), they merely serve to provide PISM with appropriately formulated driving data based on a number of input data sets, either observation-based or originating from a driving (climate) model such as e.g. EC-Earth.

Details of the different possibilities of the various boundary layer models may be found either in the PISM manual [Albrecht et al., 2012a, Albrecht et al., 2012a, Albrecht et al., 2012b, Albrecht et al., 2012c] or in [Svendsen et al., 2014]. Here, only the settings specific for the current setup are described. In the current setup the bedrock deformation model is used only with its default settings so no further description of its use is given. As for the atmosphere model, it is overruled by any settings of the surface model. Since forcing fields from EC-Earth are given to PISM as inputs through the surface model in the current setup, no mention of the atmosphere model of PISM is needed here and the interested reader is referred to the literature for details on boundary models for the bedrock deformation and the atmosphere.

2.4.1 The ocean boundary model

The version of PISM (PISM0.4) that has been used for simulations of the Antarctic domain has only a single available option in the ocean boundary model, and that is the **-ocean constant** option. This option provides a constant (in time and space) mass flux into the ocean and sea level elevation data to PISM [Albrecht et al., 2012a]. It is assumed that the mass flux is proportional to the heal flux into the ice and this heat flux may be altered by changing the **ocean_sub_shelf_heat_flux_into_ice** configuration parameter.

In terms of coupling PISM to a full atmosphere-ocean model system this setup is rather limited and does not allow the full potential of the ice-ocean interaction to be explored. However, in later versions of PISM not currently introduced in the coupled model system for Antarctica, a more diverse ocean boundary model i s available, allowing the mass flux between the ocean and the ice to vary with space and time [Albrecht et al., 2012b, Albrecht et al., 2012c]. The more diverse ocean boundary would definitely be an asset to the coupled model system and is strongly recommended in case of future updates of the system.

2.4.2 The surface boundary model

The PISM surface boundary model served the purpose of providing the ice dynamics core with a surface mass flux into the ice and ice temperature at the ice surface but below the snow and firn layers. A number of different possibilities exist for the nature of these forcing fields, but the current setup, where PISM is either driven by or coupled to the climate model EC-Earth, the chosen setting for the surface boundary model is the **-surface given** setting. With this option, fields of surface mass flux into the ice and temperature at the ice surface but below the firn are passed to PISM's dynamic core by the surface boundary model. These fields are read from a given file specified by the keyword **-suface_given_file** containing several records of surface mass fluxes and temperatures along with a time variable.

The surface model is set up to include a modifier (**-lapse_rate**) which allows for the correction of ice-surface temperature and mass balance by means of elevation lapse rates [Albrecht et al., 2012a]. This makes it possible to correct for any differences in altitude between the elevation of the forcings fields form the driving model and the elevation of the corresponding model points of PISM. In case the **lapse_rate** keyword is envoked, the size of the lapse rate correction should be supplied through the **temp_lapse_rate** keyword along with a file containing the surface elevation of the temperature field supplied in the **surface_given_file** in a file specified by the keyword **surface_given_lapse_rate_file**.

Option	Unit	Description	Value
-Lx	km	Half-width of the computational domain (x direction)	6000
-Ly	km	Half-width of the computational domain (y direction)	6000
-Lz	m	Height of the computational domain in the ice	5000
-Lbz	m	Depth of the computational domain in the thermal bedrock layer	2000
-Mx	-	Number of grid points in x direction	301
-My	-	Number of grid points in y direction	301
-Mz	-	Number of grid points in z direction within the ice	91
-Mbz	-	Number of grid points within the bedrock thermal layer	21

Table 2.2: The various parameters specifying the PISM computational grid with specific values for the Antarctica runs at $20km \times 20km$ used in the current study. Note that Mx, My, Mz, Mbz all specify the number of grid *points*. The number of grid *spaces* are one less, i.e. Mx-1, My-1, Mz-1, Mbz-1, respectively.

In the case of the spinup runs, for example, the input data of temperature and surface mass flux in the **surface_given_file** should be interpretated as periodic data by PISM. This may be achieved by envoking the option **surface_given_period** P which makes PISM interpret the input data as periodic with the period given by P.

2.5 The computational grid

PISM performs its calculations on a rectangular grid with x, y as horizontal coordinates and z as the vertical. The vertical coordinate z is defined to be positive upwards with $z = 0$ at the base of the ice and it is exactly opposite to the vector of gravity [Albrecht et al., 2012a]. The dimensions of the computational box are given by four numbers specifying the half-widths of the horizontal computational domain, the height of the computational domain in ice and the depth of the computational domain in the thermal bedrock layer with a corresponding set of numbers specifying the number of grid points to be distributed over those dimensions, see tab.(2.5).
When starting a new PISM run, PISM needs an initial file. This may be either an output from a finished PISM run or a file with a set of initial conditions/observables. In the case where a pre-existing PISM file is used as initial state, PISM automatically copies the grid and resolution from the initial file and uses this for the new run. In the case where another resolution is needed or the initial file is not a PISM output file with a full set of state variables, measures must be taken in order to obtain the desired resolution. In the case of runs based on an existing PISM output file, PISM offers regridding routines capable of regridding the various variables to the specified resolution. In this case PISM regrids all the fields included in a user-defined list (**-regrid_file** *infile* **regrid_vars** *variable list*). If the available file is not a file with a full set of state variables for the ice sheet, bootstrapping is needed. PISM has bootstrapping routines that only needs the bedrock topography and the ice sheet thickness and subsequently fills in all three-dimensional variables by means of the bootstrapping heuristics. If any three-dimensional variables are available in an input file used in a bootstrapping run they will be ignored and only the available two-dimensional fields will be used and any information found in three-dimensional variables will be lost, so when setting up runs it is important to distinguish between situations where bootstrapping is necessary or if a regridding run is more desirable, see sect.(2.6).

2.5.1 Grid selection and bedrock topography

PISM is quite flexible regarding model resolution and as mentioned in the previous section, sec.(2.5), PISM is capable of regridding to new resolutions. It is, however, worth to remember that

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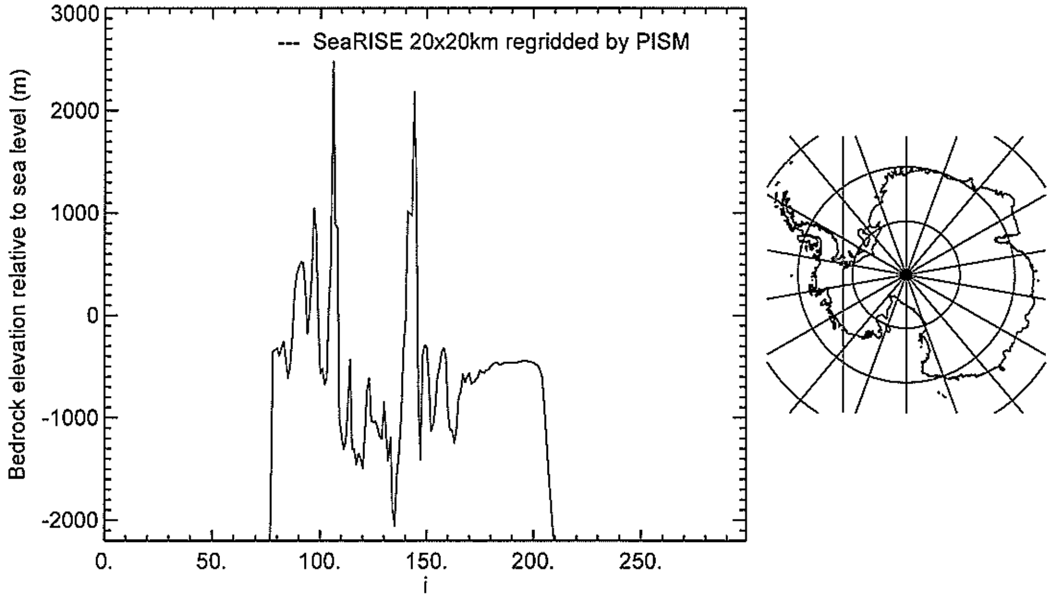

Figure 2.3: The bedrock topography resulting used by PISM in the simulations. The topography is based on the SeaRISE data set [Bindschadler et al., 2013, Le Brocq et al., 2010] but regridded to the PISM model resolution of $20km$ by PISM's own regridding routine. The location of the transect is shown on the right.

when bootstrapping or regridding from an initial (/observational) dataset that has a resolution higher than the target resolution, PISM subsamples the data and does not perform any interpolations in the data. Particularly regarding the bedrock topography this may be the cause of stability problems in the subsequent PISM runs.
In some extreme cases the bedrock topography may vary considerably from one grid point to the

next, see for example the transect of the bed topography in fig.(2.3), where the bedrock goes from less than -2000m to app. 2200m over the course of a few grid points (grid point index i 135-145). Such extreme gradients in the bedrock topography may in turn influence the overlying ice sheet dramatically, leading to very extreme cases of the ice sheet flow which hinders the convergence of the linear solvers, thereby causing PISM to crash.

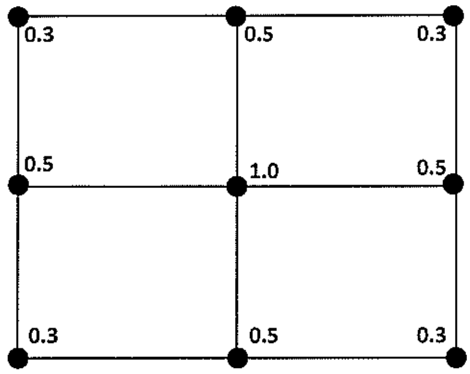

Figure 2.4: The weighting of points in the smoothing performed by the *smooth9* routine of **CDO** [Schulzweida et al., 2008].

In the cases where PISM produces computationally unstable states due to strong gradients in bedrock topography, the challenge of the fierce gradients may be ameliorated by introducing a smoothing of the bedrock resulting from PISM's regridding routine prior to performing the actual simulation. Such a smoothing can be achieved in a number of ways, in the current study the ver simple approach of applying the standard smoothing procedure *smooth9* from **CDO** [Schulzweida et al., 2008]. This smoothing procedure performs a 9 point smoothing on a rectangular grid. The smoothened result in each grid point is a weighted average of the grid point plus the 8 surrounding points. The center point is weighted by 1.0, the points besides, above and below the grid point are weighted by 0.5 and the corner points by 0.3, see fig.(2.4). All 9 points are multiplied by their weights, summed and subsequently divided by the total weight to obtaind the smoothened value. Any missing data points are not included in the sum and points beyond the grid boundaries are considered missing points. Using a smoothened topography reduces stability issues, but the ice dynamics, particularly regarding the development of ice streams and outlets, may suffer in the process. Too much smoothening may obliterate features of the bedrock topography essential for the proper development of ice streams. Therefore, in the current study the choice has been to use the regular bedrock topography as default and only resort to the smoothened bedrock topography in situations where PISM consistently fails due to computational instabilities.

2.5.2 Coordinate assignments in PISM

PISM operates on a rectangular grid with a constant grid spacing, this lattice is determined by PISM itself based on input information on the size of the PISM domain and the desired number of grid spacings within the domain, see tab.(2.2). The geographical corrdinates (lat-lon) are not used internally by PISM in its calculations, but lat-lon coordinates are assigned to each (x, y) gridpoint in the computational domain. As described in sect.(2.5) the coordinate assignment may happen in one of two ways; In a regular PISM run starting from an output file from a previous PISM run, PISM merely reads the lat-lon coordinates from the input file and passes the coordinates on to its output. In the case of a boot-strapping run where the chosen PISM grid is different from the one in the input file, PISM uses linear interpolation to put longitude and latitude fields on the new grid. Running PISM over the Antarctic poses a problem in this respect since the longitude field is not continuous.

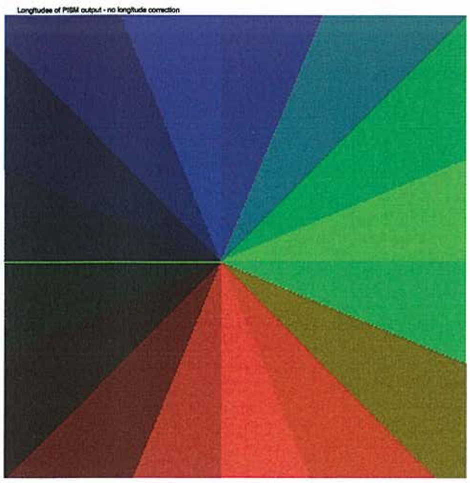

Figure 2.5: The longitudes from a PISM boot run where longitude assignment is based on linear interpolation of the input data. Note the artifact from the interpolation.

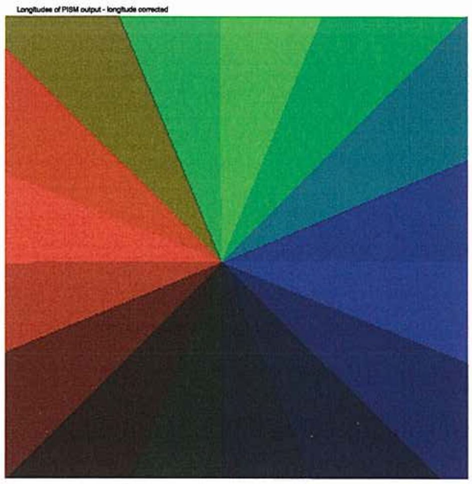

Figure 2.6: The longitudes from fig.(2.5) after longitude correction by the script *nc2cdo.py*.

The linear interpolation across the $-180°/180°$ longitude transition causes artifacts that need to be removed, see fig.(2.5). This may be achieved by first stripping the PISM output file of its longitude and latitude data using the **nco** command

ncks -x -v lon,lat infile.nc outfile.nc

Subsequently, applying the python script *nc2cdo.py* which adds longitude and latitude coordinates to any gridded variable found in the output file based on mapping and projection information equips the file with a new, corrected set of longitudes and latitudes, see fig.(2.6). PISM output files have the relevant gridding and map projection information available in the 'grid_mapping' attribute. The script *nc2cdo.py* is available from the PISM repository

https:github.com/pism/pism/blob/dev/util/nc2cdo.py

In the current setup for the spinup runs performed in order to obtain an initial state of the ice sheet to use in the coupled model runs, an initial bootstrapping run with no physics is performed on the initial data set. This initial bootstrapping run regrids the initial data to PISM computational grid. The output from this bootstrapping run will contain the artifact from the linear interpolation across the $-180°/180°$ transition. After correcting the longitude using the *nc2cdo.py*-script the longitude field looses the artifact, see figs.(2.5)-(2.6). After the bootstrapping and the longitude correction, the spinup process proceeds to the actual PISM production run.

2.6 Initialising PISM

Running PISM in order to simulate the evolution of an ice sheet requires an initial state for the model to base its simulations on. Available ice sheet data sets are most often of the 2D variety such as, e.g. fields of ice sheet thickness, surface elevation and surface temperatures. 3D variables such as temperature and visocity are only available from a few, selected locations, not over the entire ice

sheet. In addition, information about the conditions at the bottom of the ice sheet are not readily observable. Consequently, no data set of observables exists that may provide a full, integrable state of the ice sheet that may serve as the initial state for a simulation.
PISM deals with this issue through its boot-strapping mode (using run option **-boot_file** *infile* instead of run option **-i** *infile*), where PISM based on a set of observables uses heuristics to fill out the remaining grid points of, say, the temperature at depth. PISM can manage a boot-strapping procedure with as few initial data sets as fields of bedrock topography and ice thickness. If any other of PISM's two-dimensional variables are present in the initial file these are used in the initialisation, otherwise they are filled in by the bootstrapping procedure. It is worth noticing, however, that this is not the case for the 3-dimensional variables. In a boot-strapping run, all 3-dimensional variables present in the initial data set will be ignored [Albrecht et al., 2012a]. Due to this elimination of any 3-dimensional variables when performing a boot-strapping run, other options should be used when e.g. shifting from one grid resolution to another. In this case, PISM's regridding options rather than boot-strapping should be considered (run option **-regrid_file** *infile*). In the current set of Antarctic simulations PISM is using the SeaRISE dataset [Bindschadler et al., 2013, Le Brocq et al., 2010] as its initial state. A description of the SeaRISE dataset may be found in sect.(4.1).

3. Forcing PISM with climate model data

Running PISM requires an input of data to drive the model and, depending on the chosen PISM model configuration, different input data is needed. In the current coupled EC-Earth PISM model (PISM0.4), only a simple ocean configuration is possible (**-ocean** *constant*) which provides a constant in both the temporal and spatial sense of the word flux into the ocean and sea level elevation ot PISM's ice flow core [Albrecht et al., 2012a] and, hence, no input data need to be prepared for the ocean part of PISM. In later version of PISM (from version 0.5 and onwards) the ocean module has been improved and now makes ocean-based forcing for PISM's ice dynamics core possible [Albrecht et al., 2012b, Albrecht et al., 2012c]. This is, however, not included in the current model setup and is therefore beyond the scope of the current report.
In the coupled model setup, EC-Earth based forcing fields are passed to PISM's surface model. If the **-surface** model is called in PISM any atmosphere model selections made using the **-atmosphere** option are ignored by PISM [Albrecht et al., 2012a] and, hence, only the production of forcing data for PISM's surface model is described here. When forcing PISM's surface model with climate model data, one may choose to read **top-surface boundary conditions** from a file in which case records of **temperature** and **surface mass balance** are needed, or, one may choose to use a **positive degree day (PDD) scheme** where records of **temperature** and **precipitation** are required.

3.1 Temperature fields

From the perspective of PISM, any input temperature field is interpretated as being the temperature at the interface between the firn layer and the ice sheet itself [Albrecht et al., 2012a]. However, in the standard version of EC-Earth, there is no representation of ice sheets and hence, no well-defined temperature at the ice-firn interface.
Motivated by these shortcomings of EC-Earth an improved surface scheme has been developed [Madsen et al., 2014] which introduces ice as a separate variable in EC-Earth and includes a representation of the soil temperature in ice-covered areas. The temperature in a given grid point is considered to be the soil temperature of the lowermost soil layer in the model, regardless of whether the temperature is in the soil or, in the case of ice-covered grid points, in the ice. However, this surface scheme has so far only been tested over Greenland, not Antarctica. For the spinup runs, the EC-Earth $2m$-temperature field (EC-Earth variable 167, see tab.(3.1)) is used as a proxy for the ice surface temperature to force PISM over Antarctica.
Multi-year monthly means of temperature and surface mass balance spanning 30 years of preindustrial conditions are used to drive PISM in the spinup runs whereas time series of monthly

Variable	Variable code	Use
$2m$ temperature	167	Temperature forcing
Snow precipitation	144	PDD scheme
Stratiform precipitation	142	Surface mass balance forcing
Convective precipitation	143	Surface mass balance forcing
Evaporation	182	Surface mass balance forcing
Runoff	205	Surface mass balance calculation
Topography	129	Lapse rate correction
Land-sea mask	172	Grid interpolation

Table 3.1: Table of variables extracted from EC-Earth data and their use in the production of forcing files for PISM.

mean values may be used in 1-way or 2-way coupled runs.

3.2 Surface Mass Balance - SMB

In PISM, the surface mass balance is defined as the local difference between accumulation and ablation. These variables, however, are not present in the EC-Earth output data set and an alternative definition of the surface mass balance based on EC-Earth output data is necessary. Instead, the local surface mass balance is defined as the total precipitation,P, minus the evaporation, E (EC-Earth variable 182), and runoff, R (EC-Earth variable 205):

$$\mathrm{SMB} = P - E - R \tag{3.1}$$

The total precipitation P is defined as the sum of the stratiform and the convective precipitation (EC-Earth variables 142 and 143, respectively). It is important to keep i mind that in EC-Earth, these variables are 6-hourly accumulated fields and not daily fields. In addition, 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 SMB. Also, whereas PISM requires its input SMB as meters of ice, the relevant variables in EC-Earth are given in units of meters of water and, hence, a conversion from meters of water to meters of ice is necessary.
There are other ways of defining the local surface mass balance field passed on to PISM, for example basing the surface mass balance calculation on the energy fluxes at the surface, see. e.g. [Vizcaíno et al., 2010]. In such a setup melt rates are calculated from the balance of radiation, latent and sensible heat fluxes, taking into account heat conduction between the snow layers and the surface.

3.3 Positive Degree Day - PDD

Positive degree day schemes have been used in a number of ice sheet modelling studies, e.g. [Braithwaite, 1995] and is a method for determining the mass loss or gain from an ice sheet based on the temperature and precipitation fields. PISM allows for a choice of a number of different PDD methods [Albrecht et al., 2012a, Calov and Greve, 2005, Fausto et al., 2009], but all of these require the same input, that is, fields of snow precipitation and temperature.
Traditionally, PDD schemes have been used extensively in ice sheet modelling and are an excellent tool to resolve temporal development in the surface mass balance in a model simulation of an ice sheet. The PDD schemes rely on the use of degree-day factors to accomodate temperature fluctuations that can cause melt within months with negative mean temperatures [Fausto et al., 2009]. However, degree-day factors vary from location to location and vary with summer mean temperature and albedo as well [Braithwaite, 1995]. As a consequence, PDD schemes may not be particularly suited for climate scenario runs since choices of degree-day factors that were suitable at the conditions prevalent in the early stages of the simulation may not be appropriate at later stages. Given that the ultimate aim of the coupled system will be performing scenario runs rather than historical runs it has been decided to refrain from using PDD schemes to determine the surface mass balance but instead to rely on a direct calculation of the surface mass balance based on climate model data as described in sec.(3.2).
In the current setup for the production of PISM forcing files, relevant fields have been included in order to be able to make PISM runs with PDD forcing even though it is not the forcing method of choice for the coupled system. But PDD runs have been used for comparisons and for some of the spinup-routines for the ice sheet that have been tested over the course of the project. As mentioned above, the necessary fields for a PDD-driven run are fields of temperature and snow precipitation. Here, the temperature is taken to be the $2m$ temperature field from EC-Earth (field 167) and the snow precipitation is taken as the snowfall (convective+stratiform) field from EC-Earth (field 144).

3.4 Lapse rate correcting the forcing files

Due to differences in the PISM and EC-Earth resolution and topography, lapse rate corrections need to be applied to the forcing fields. This is accomplished through the built-in lapse rate correction scheme in PISM. In the run call, the **lapse_rate** option and associated keywords will invoke the lapse rate correction scheme, adjusting the temperature and surface mass balance prior to forcing PISM with these fields.
The temperature lapse rate γ_T is defined as

$$\gamma_T = -dT/dz \tag{3.2}$$

where T is the temperature and z is the altitude. In the present setup a value of $\gamma_T = 6.8K/km$ is used. As mentioned above the lapse rate correction scheme of PISM is envoked by adding the **lapse_rate** keyword to the run call:

-surface given,lapse_rate -temp_lapse_rate γ_T -smb_lapse_rate γ_SMB -surface_lapse_rate_file $FORCING_FILE

where $FORCING_FILE is the name of a file that contains the reference surface elevation field. Currently, the surface elevation field of EC-Earth interpolated onto the PISM grid is included in the overall file with forcing fields for PISM based on EC-Earth data. However, one may keep the surface elevation data in a separate file should that be the more practical solution, e.g. for studies examining the effect of a possible altitude bias.
In the present setup of the coupled system only the temperature lapse rate is corrected even though a similarly defined surface mass balance lapse rate correction is available in PISM as well. However, at present no well-defined value of γ_{SMB} is available. Lapse rate correcting the surface mass balance implies knowing how to lapse rate correct the precipitation and the evaporation. Further studies are needed in order to obtain reasonable γ_{SMB} values based on the altitude dependence of the relevant variables.
Given the large difference in the spatial resolution of EC-Earth and PISM, lapse rate corrections may in some areas be substantial and including surface mass balance lapse rate corrections may improve the performance of the coupled system.

3.5 Making forcing files for PISM

A major challenge when producing forcing data for any model is to obtain the forcing data in the proper format and on the correct grid. The climate model of the coupled model system, EC-Earth, runs on a reduced Gaussian Grid in T159 resolution [Hazeleger et al., 2011], whereas PISM in its current configuration runs over Antarctica on a $20km \times 20km$ rectangular grid. As previously mentioned, the necessary forcing fields for PISM in the coupled model setup are fields of temperature and surface mass balance. After obtaining the necessary forcing fields, interpolation of the EC-Earth output data is necessary in order to get data on the PISM grid. A description of the surface mass balance calculation was given in sec.(3.2) and in the following the procedures for interpolating the data from the EC-Earth grid to the PISM grid will be described.

3.5.1 Extracting PISM grid information

In order to produce forcing files for PISM based on EC-Earth output, information on PISM's and EC-Earth's grid points is needed for the interpolation routines. In PISM's output files, the longitudes and latitudes refer to the centers of the various grid cells. However, for the transformations between the PISM and EC-Earth grids the coordinates of the grid cell corner points and the surface area of each grid cell are necessary.

The grid cell corner points may be determined by running the script *nc2cdo.py* developed by Andy Aschwanden, University of Fairbanks, Alaska, which is part of the PISM package and may be downloaded from the PISM website. After retrieving the corner point information, NetCDF files with the corner points, grid cell areas and mask values must be generated. These files are necessary for the interpolation between the PISM and EC-Earth grids.

3.5.2 Making forcing files from EC-Earth output

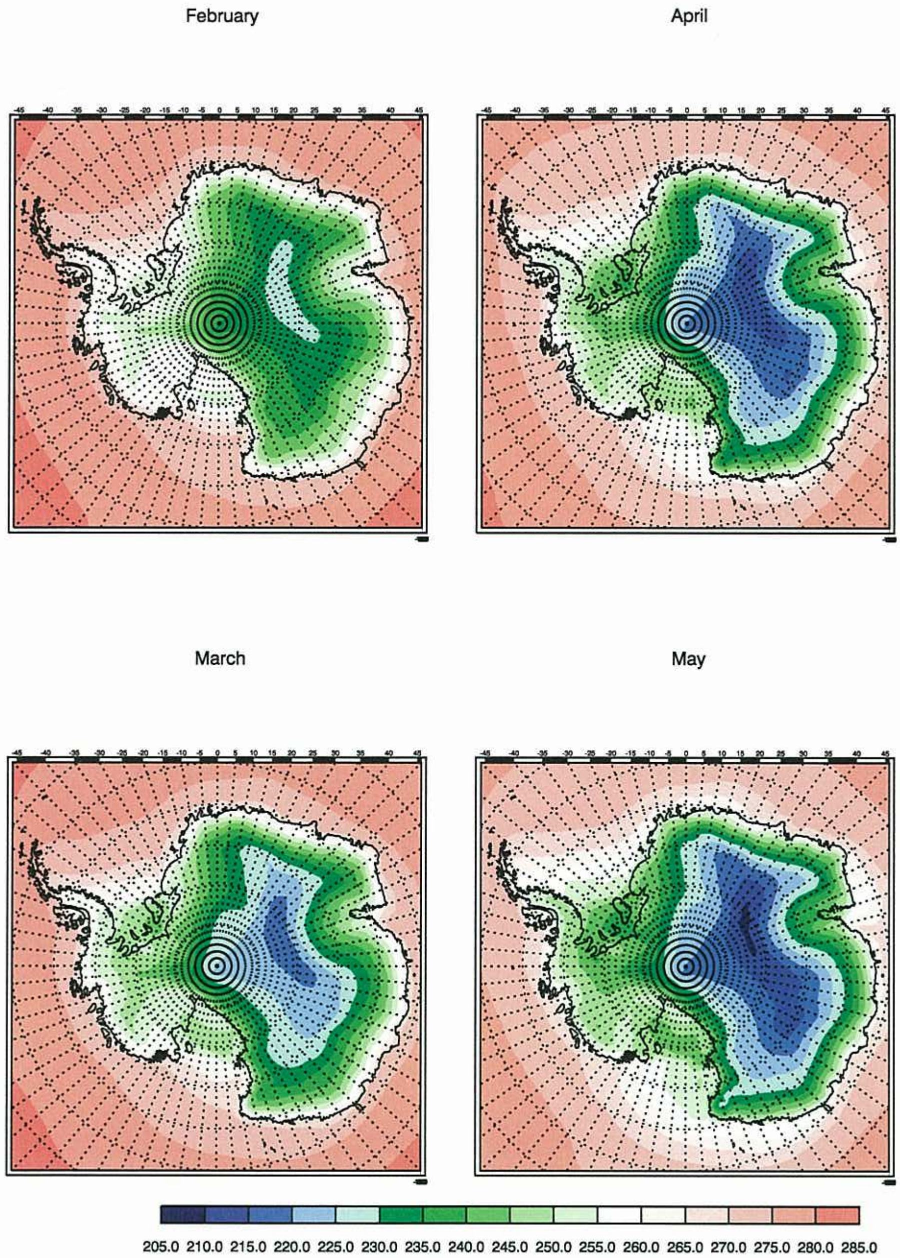

Figure 3.1: Temperature forcing fields for PISM derived from EC-Earth data for February, March, April and May. Based on multi-year monthly means of a 30-year period of a preindustrial control run.

The production of forcing files for PISM consists of three main tasks; first, to obtain fields of snow precipitation, temperature and surface mass balance from climate model inputs, second, to

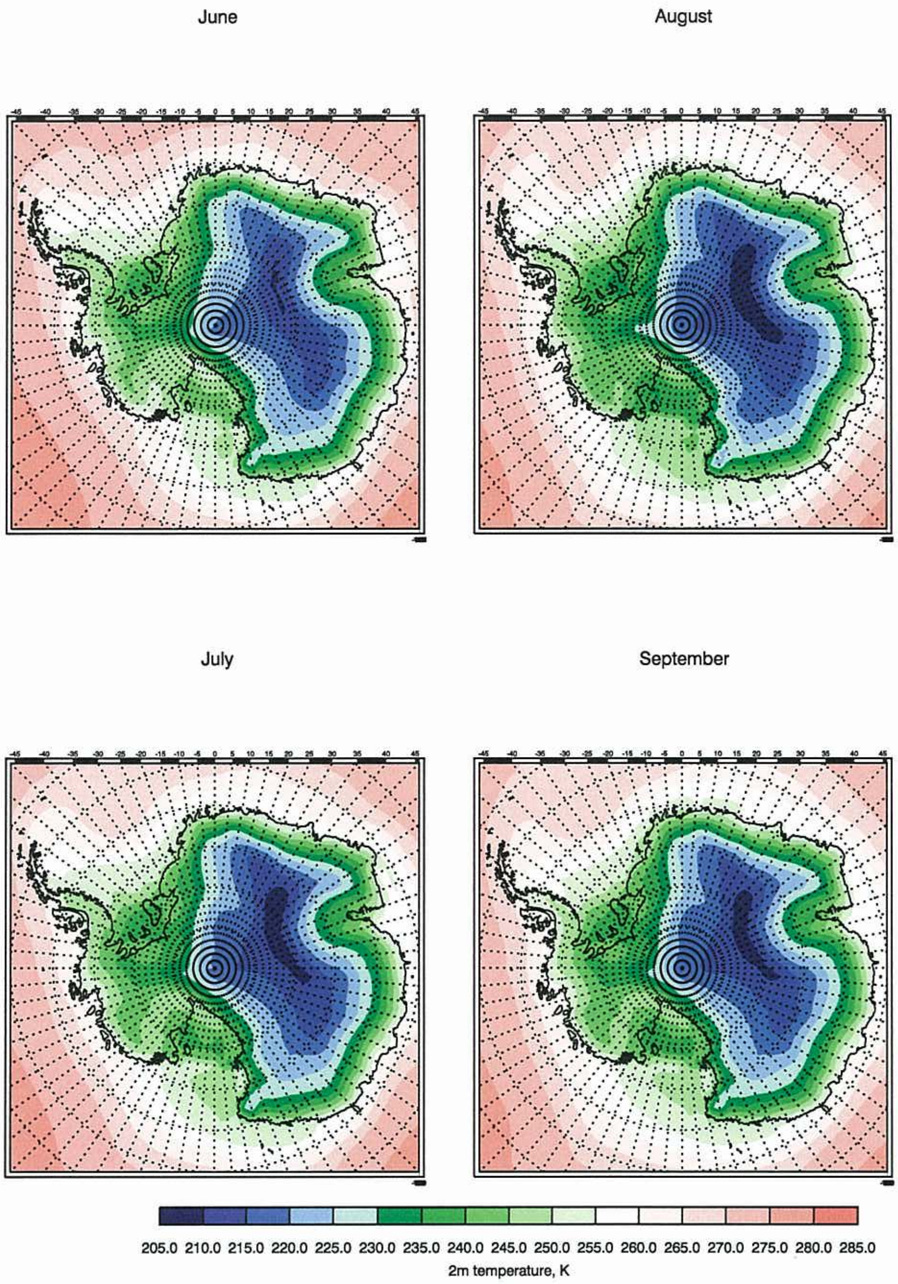

Figure 3.2: Temperature forcing fields for PISM derived from EC-Earth data for June, July, August and September. Based on multi-year monthly means of a 30-year period of a preindustrial control run.

interpolate this data from the climate model grid to the PISM model grid, and, third, to ensure that data format, units and naming conventions comply with PISM's standards. Two shell scripts addresses these points.

The scripts extract the relevant fields (see tab.(3.1) for a list of the variables in question) from the EC-Earth data sets and concatenates the files to produce one continuous time series. Multi-year monthly means are then produced for each of the variables and the surface mass balance as defined in eq.(3.1) is calculated in the case of forcing files for spinup runs whereas monthly mean values for each individual year in the time series is needed for production runs driven by a time series of climate model data. Note that some of the EC-Earth variables are accumulated variables and must be

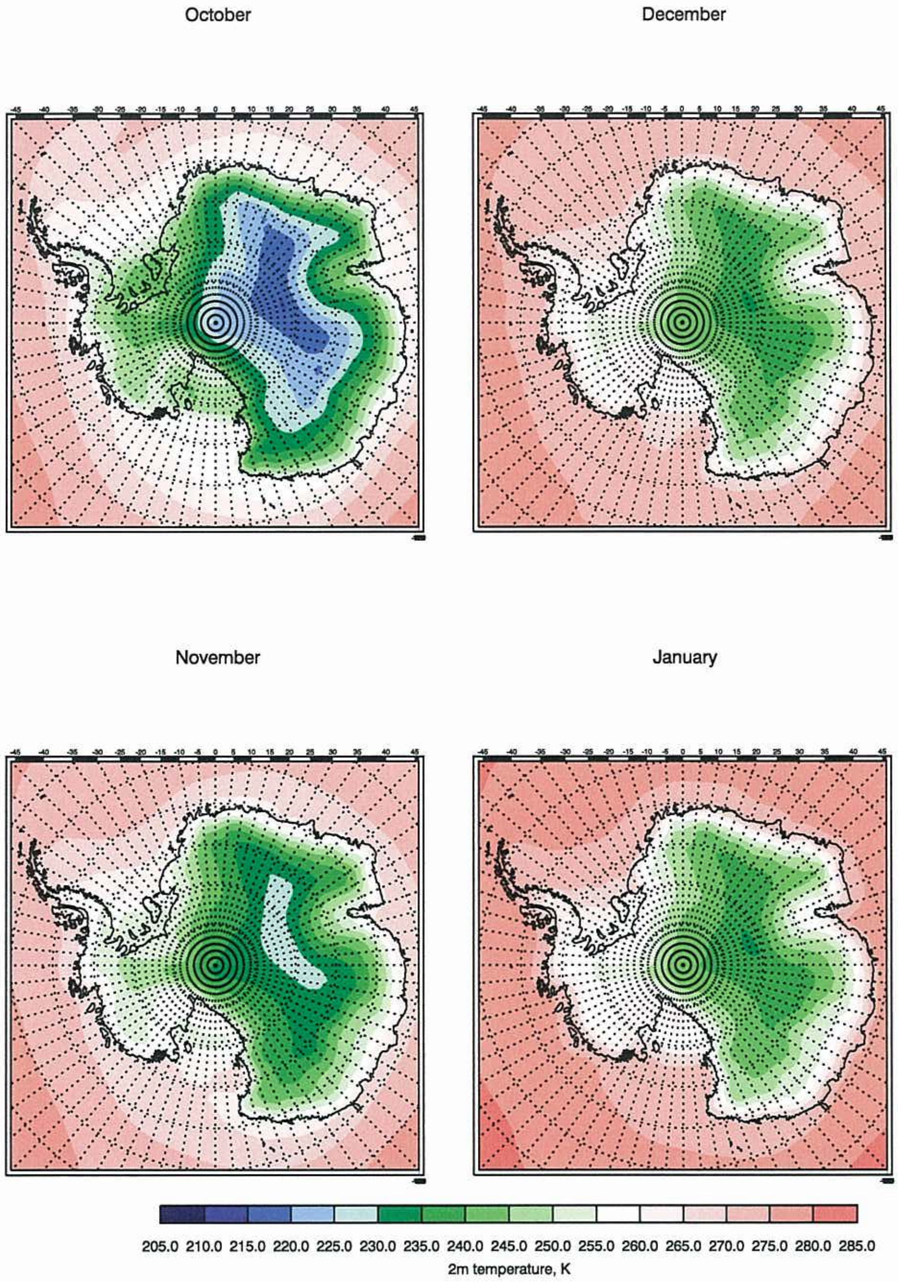

Figure 3.3: Temperature forcing fields for PISM derived from EC-Earth data for October, November, December and January. Based on multi-year monthly means of a 30-year period of a preindustrial control run.

treated accordingly in order to obtain the correct means. Sine the EC-Earth precipitation, evaporation and runoff is given in meters of water and PISM needs the surface mass balance imput in meters of ice, a conversion from meters of water to meters of ice is carried out by dividing the surface mass balance by the density of ice, ρ_i. Once the multi-year monthly means of the relevant variables have been calculated, these variables are interpolated from the EC-Earth grid to the PISM grid by means of a number of calls to OASIS routines. For details on the field interpolations, the reader is referred to sec.(3.5.3) below.
Next, variables are renamed in order to comply with PISM convention. In addition, the EC-Earth topography interpolated onto the PISM grid is included. The topography information is needed for

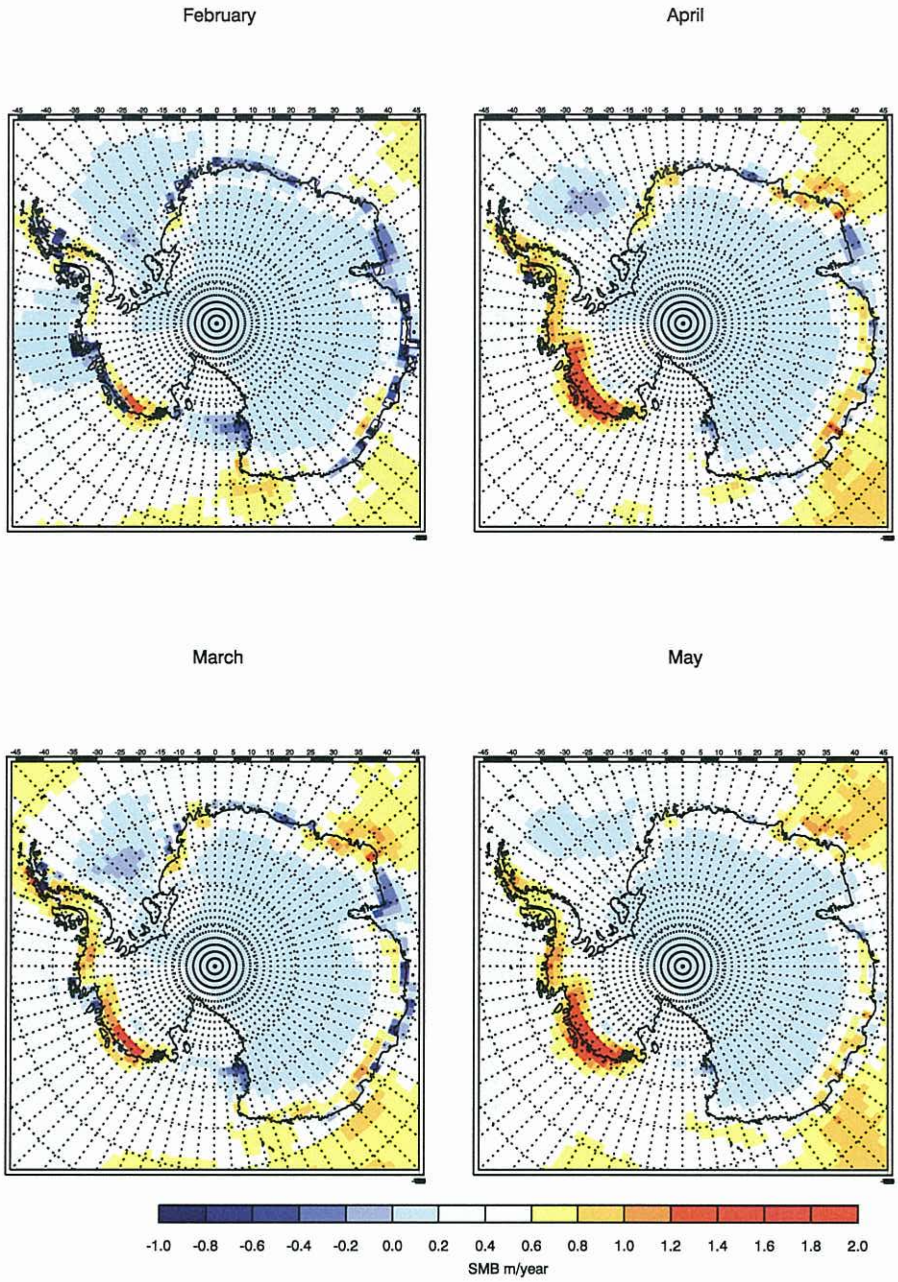

Figure 3.4: Surface mass balance forcing fields for PISM derived from EC-Earth data for February, March, April and May. Based on multi-year monthly means of a 30-year period of a preindustrial control run.

lapse rate corrections of the temperature fields, see sec.(3.4). In addition, information on the (x, y)-coordinates of the PISM grid is added to the forcing files.
Examples of forcing files for PISM produced according to this setup can be seen in figs.(3.1)-(3.3) for the temperature fields and figs.(3.5)-(3.6) for the surface mass balance fields. These figures show the monthly forcing field based on multi-year annual means of EC-Earth output of a 30-year period of a pre-industrial control run.
In the case of the temperature fields, an annual cycle is evident, with the lowermost temperatures occurring during June, July, August and September, corresponding to austral winter. The lowest temperatures are reached in the interior of the continent, east of the tranantarctic mountain range.

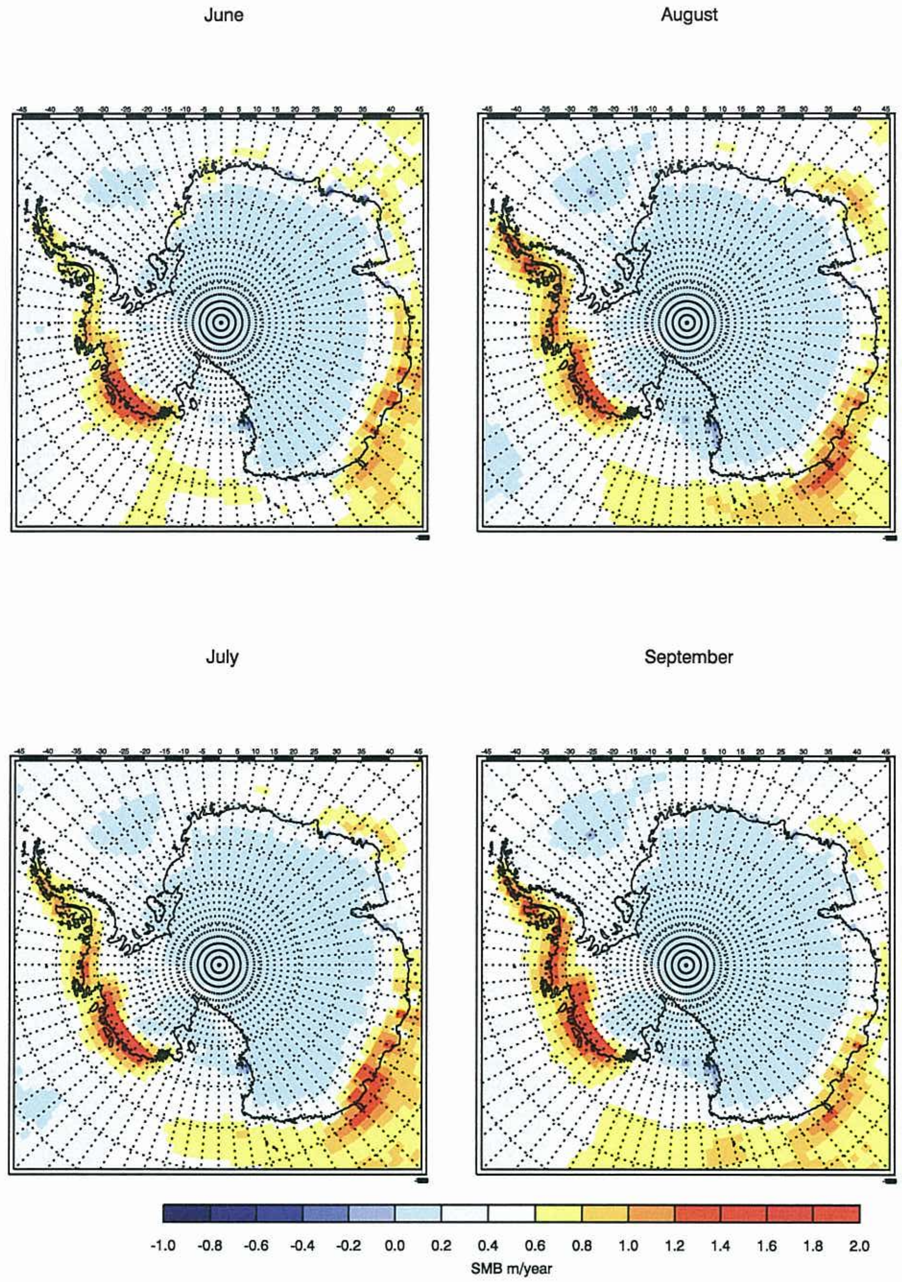

Figure 3.5: Surface mass balance forcing fields for PISM derived from EC-Earth data for June, July, August and September. Based on multi-year monthly means of a 30-year period of a preindustrial control run.

As for the surface mass balance, the interior of both the East and the West Antarctic ice sheet display a more or less constant small positive surface mass balance regardless of the season, whereas the coastal regions and the Antarctic peninsula shows a lot more variability. Along the coast of the East Antarctic, the surface mass balance is negative during the months of austral summer and positive throughout the winter season, as would be expected. By far the largest variability is seen in the coastal regions of Marie Byrd Land and on the Antarctic peninsula. The overall amounts of precipitation falling in these areas is large compared to the interior, leading to significantly higher values of the surface mass balance. Note the tendency of the surface mass balance of the Antarctic peninsula to be higher on the western coast compared to eastern, reflecting the general direction of

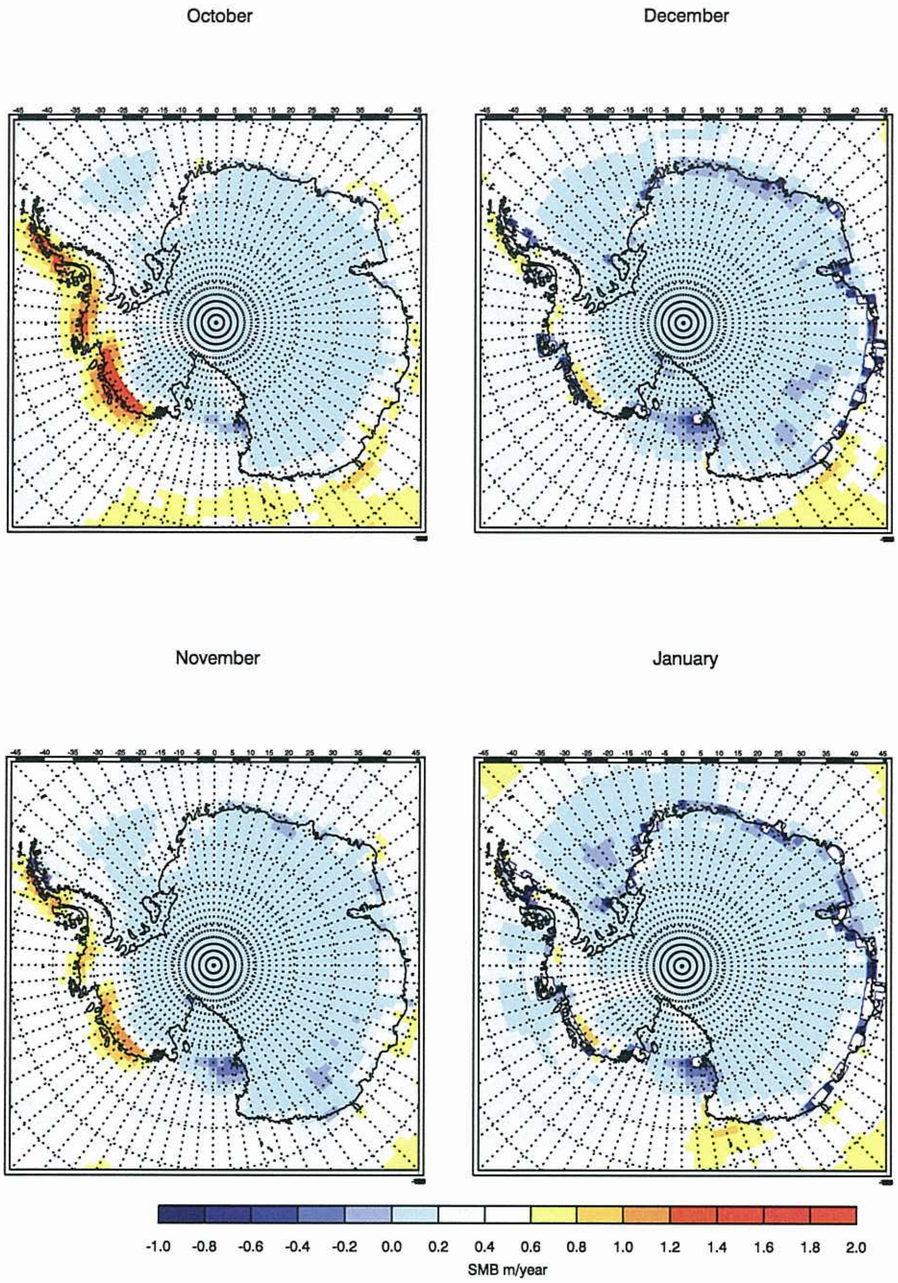

Figure 3.6: Surface mass balance forcing fields for PISM derived from EC-Earth data for October, November, December and January. Based on multi-year monthly means of a 30-year period of a preindustrial control run.

the flow of the weather patterns.

3.5.3 Interpolation of forcing fields

As mentioned in sec.(3.5.2) the interpolation of the EC-Earth data onto the PISM grid is carried out using the OASIS software [Valcke et al., 2013]. In order to do so, OASIS needs information about the structure of the modelling grid 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 OASIS should include this grid box in the interpolation or not. As mentioned in sec.(3.5.1) on how to extract the PISM grid information, the longitudes and latitudes of the PISM output indicates the longitude and latitude of the center of each grid box. Running the script *nc2cdo.py* supplied by the PISM developers on a PISM output file stripped of 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 of the file and the projected x and y coordinates. The grid and corner point information, the grid cell area and the mask values are written to a set of three NetCDF files in the format requested by OASIS. 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 then used by OASIS when called upon to perform the interpolations in the forcing file production script. Apart from these grid information files, a namelist file for the OASIS coupler is needed as well.
It is worth noticing that OASIS is extremely selective in terms of naming conventions of the various in- and output fields of the interpolation and their order in the grid information files and namelists and great care must be taken when producing the grids and masks files needed by OASIS in order to ensure its functionality. In addition, a number of different options specific to OASIS determines the exact nature of the interpolation criteria to be used.

3.6 Running PISM with external forcing files

As mentioned in sec.(2.4), the PISM model complex is structured around the ice dynamics model with separate models for the various interfaces between the ice and its surroundings such as bedrock, ocean, atmosphere and surface. It is through these models that the ice communicates with its surroundings and, consequently, any external forcing should be applied through them. In the case of coupling EC-Earth to PISM, the relevant boundary models are the **ocean** and **surface** models. Since no forcing fields are communicated through the **atmosphere** model in the coupled setup, the options connected to this model will not be considered here.

3.6.1 The ocean model

In the case of the ocean boundary, the version of PISM currently in use for the Antarctic ice sheet (PISM0.4) only has a very simple ocean boundary model called **constant**. This model provides a constant mass flux into the ocean and sea level elevation to PISM's ice flow core [Albrecht et al., 2012a]. In this respect, it is currently not possible to introduce any sort of temporal variation in the ocean forcing. For a coupled atmosphere-ocean-ice-sheet model this is not optimal given the vast influence of the ocean on both ice sheets and shelves, see e.g. [Payne et al., 2004, Paillard and Parrenin, 2004]. A setup with no temporal variation in the ocean-based forcing is far from ideal, particularly when considering the extensive ice shelves in Antarctica. Later versions of PISM, however, has introduced possibilities for varying ocean forcings but theses later versions (PISM0.5 and onwards) has not yet been implemented and tested for Antarctica in the coupled model system. In the event of any further development of the coupled model system, an inclusion of ocean-based forcing fields would be of the highest priority.

3.6.2 The surface model

In the case of the surface boundary model, a number of different possibilities exist [Albrecht et al., 2012a, Albrecht et al., 2012c]. However, the one with the most relevance for the coupled EC-Earth-PSIM is the surface model allowing for input of top-surface boundary conditions from a file (**-surface given**).
The surface model takes input fields of temperature and surface mass balance and provides them directly to the ice dynamics model [Albrecht et al., 2012a]. The temperature (*artm*) and surface mass

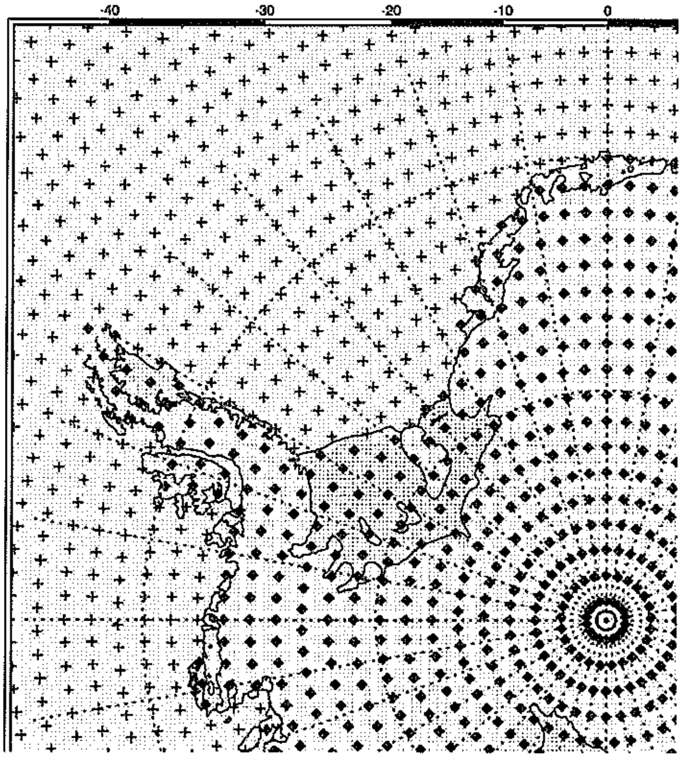

Figure 3.7: Plot of the locations of the EC-Earth grid points over the Antarctic peninsula. **Crosses** mark the EC-Earth grid points whereas points considered to be land points are indicated by overlaid **diamonds**. Small dots indicate the grid points of PISM. **Green dots**: ice-free ocean. **Red dots**: floating ice. **Light blue dots**: grounded ice. **Dark blue dots**: ice-free bedrock. Note the very limited number of EC-Earth land points over the peninsula.

balance (*acab*) are read from a file using the syntax

-surface given -surface_given_file *filename*

The input file *filename* should, apart from the records of temperature (*artm*) and surface mass balance (*acab*) hold a time variable, *t*, describing what model times the records in the file correspond to. In the coupled model setup, this input file holds output from EC-Earth, modified to match the PISM requirements as described in sections (3.1),(3.2),(3.5). The forcing file may hold any number of records for a run forced by a time series or, in the case of lengthy spinup runs with constant forcing, it may be interpreted as containing periodic data by invoking the **surface_given_period** option:

-surface given -surface_given_file *filename* **surface_given_period** *period*

3.7 The challenges of the Antarctic peninsula

The Antarctic peninsula and its surrounding archipelago houses some of the most intricate topography of Antarctica resulting in a number of challenges for the coupled model system. Numerous islands surround the relatively narrow Antarctic peninsula and the terrain of both the archipelago and the peninsula itself is mountaineous, leading to a complex land-sea pattern with very steep gradients in the topography. It is most challenging to provide a proper description of the complex terrain for both the circulation models and the ice sheet model in the coupled model system. The Antarctic peninsula is extremely important to the overall circulation and weather patterns of Antarctica as well as the conditions for the ice shelves along the coast of the peninsulat and in the

Weddell Sea [Russell and McGregor, 2010, Genthon et al., 2003]. At the same time, in recent years the Antarctic Peninsula has experienced some of the largest and fastest surface temperature increases observed [Vaughan et al., 2001, Vaughan et al., 2003, Hansen et al., 1999, Turner et al., 2002]. The combination of crucial importance to the overall circulation patterns of the continent and vast observed local changes only serves to emphasize the importance of a proper representation of this complex terrain in the model system.

In case of EC-Earth, the major difficulty regarding the Antarctic peninsula is one of resolution. At its current resolution of T159, resolving the complex structure of the peninsula and its surrounding archipelago is extremely difficult. In fig.(3.7) the grid points of EC-Earth over the Antarctic peninsula are shown. A resolution of T159 roughly corresponds ot $125km$ resolution leading to a somewhat simplified surface topography both regarding gradients in the surface topography and the distribution of land masses as evident in the land-sea mask.

The spatial resolution of a climate model naturally affects the outcome of the climate model itself and the distribution of temperature and precipitation in near-coastal areas may change significantly depending on the choice of resolution, see e.g. [Lucas-Picher et al., 2012]. Since the forcing of the ice sheet model is based on fields of temperature and surface mass balance, any shortcomings of the climate model will be reflected in the forcing fields for the ice sheet model and its performance. Changing the spatial resolution of PISM will be of great importance for resolving ice streams and outlet glaciers, but concerning the Antarctic peninsula, the fact that the current forcing is based on such a scarce number of EC-Earth grid points may be the more limiting factor to PISM's performance in this area.

4. Spinning up PISM

When performing simulations of the Antarctic ice sheet, spinup runs are necessary in order to ensure the stability of the ice sheet prior to the actual model runs. Over the course of simulations with constant forcing, the ice sheet should display a reasonably constant behaviour and should, after any initial transients have subsided, exhibit constant volume and geometry indicative of an ice sheet in equilibrium. In order to make sure the outcome of any subsequent variations in the forcing fields are not completely obscured in undesired transient behaviour the constant forcing fields used for the spinup runs must be based on the long-term mean of the forcing. This way, the spinup-state of the ice sheet will be in thermal equilibrium with the mean climate of the driving model.

4.1 Initial state of the Antarctic ice sheet

Any numerical simulation of an ice sheet must start with a set of initial conditions, preferably a set of observations in order to be able to work with as realistic an ice sheet as possible. However, as mentioned in sect.(2.6), such data sets are never complete, integrable states of the ice sheet, but rather a set of observables which subsequently by means of a bootstrapping process renders an initial ice sheet state with full 3D fields of the relevant variables.
In the current set of simulations, the SeaRISE dataset [Bindschadler et al., 2013, Le Brocq et al., 2010] is used as the initial state of the Antarctic ice sheet. This dataset is a $5\times5km$ reference dataset of the Antarctic ice sheet, comprised from a number of different data sources to serve as the common reference dataset for various simulations within the SeaRISE project. Before using it as an initial state in PISM, the relevant variables must be renamed in order to comply with PISM standards just as a few unit conversions are needed. This may be done by the script *preprocess.sh* which is available from the PISM repository.
In fig.(4.1), the ice sheet elevation according to the SeaRISE dataset is shown. The figure shows the dataset in its original $5\times5km$ resolution. However, prior to using the data for PISM simulations, the data must be regridded to match the PISM grid. This regridding is achieved by letting PISM do a one-year bootstrapping run (using the option -boot_file *infile* instead of -i *infile*) with no physics and with specification of the grid dimensions (see tab.(2.2) for a list of settings and values for the $20km\times20km$ grid), thereby obtaining the SeaRISE data set on the $20\times20km$ grid used for the Antarctic simulations. After the short bootstrapping run, the longitude coordinates need to be corrected as described in sect.(2.5.2) in order to account for the flaw in PISM's assignment of longitudes. Fig.(4.2) shows the topography of the SeaRISE data set after regridding to the $20km$ grid. At this scale, differences between the two data sets are not easily seen, but in fig.(4.3) a transect of the bedrock topography is shown at the two different resolutions and here differences are evident. Note how some of the fine scale features are obliterated.

4.2 Spinup of Antarctica including paleo data

The flow properties of a layer of ice are determined by the prevailing climate at the time of formation and, optimally, a spinup process of an ice sheet should include information on its past climate [Rogozhina et al., 2011, Calov and Hutter, 1996]. In the following sections, experiences concerning spinup runs by PISM of the Antarctic ice sheet including paleo data are described.

4.2.1 Using paleo data to force PISM over Antarctica

Setting up a paleo spinup run may be done in a vast number of different ways, see e.g. [Vizcaíno et al., 2010, Aschwanden et al., 2013], but for the current study the structure of the paleo spinup run closely mimics that provided in the examples given by the PISM developers

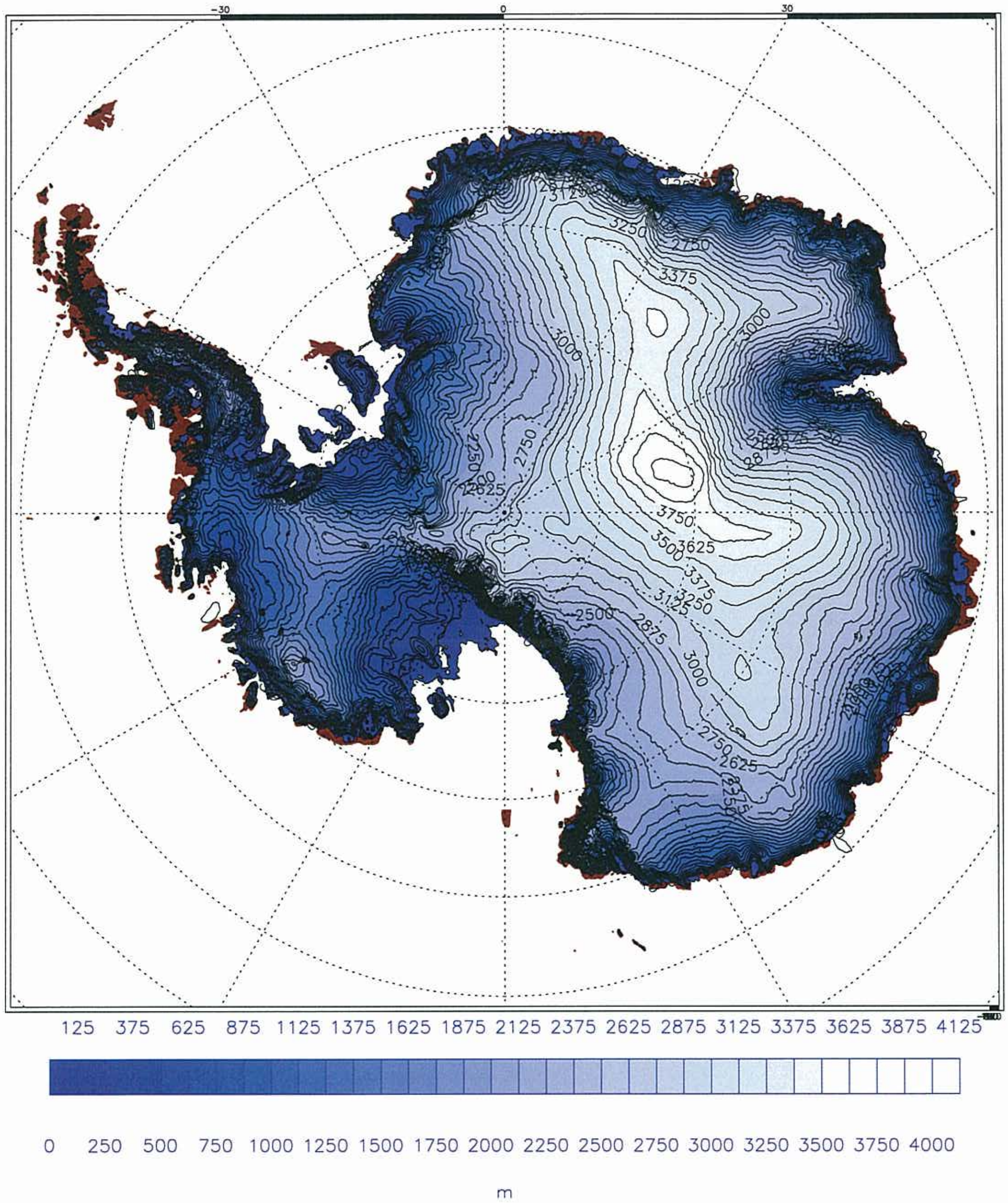

Figure 4.1: The surface topography of the Antarctic ice sheet as given by the SeaRISE data set at $5km$ resolution.

[Albrecht et al., 2012a] which is based on the SeaRISE data set [Bindschadler et al., 2013]. The paleo spinup is initiated with a short 100-year bootstrapping run with no physics followed by a 100.000 year run with the *no_mass* option in order to obtain energy balance. In *no_mass* runs the ice upper and lower surface are held fixed. Such a run serves to generate a sensible enthalpy field in which the modeled ice internal energy, temperature, softness, basal water and basal melt rate are in balance with the ice sheet geometry [Albrecht et al., 2012a]. Following suit, a 5000 year run with full physics and paleo forcing based on the SeaRISE paleo temperature and sea level record is

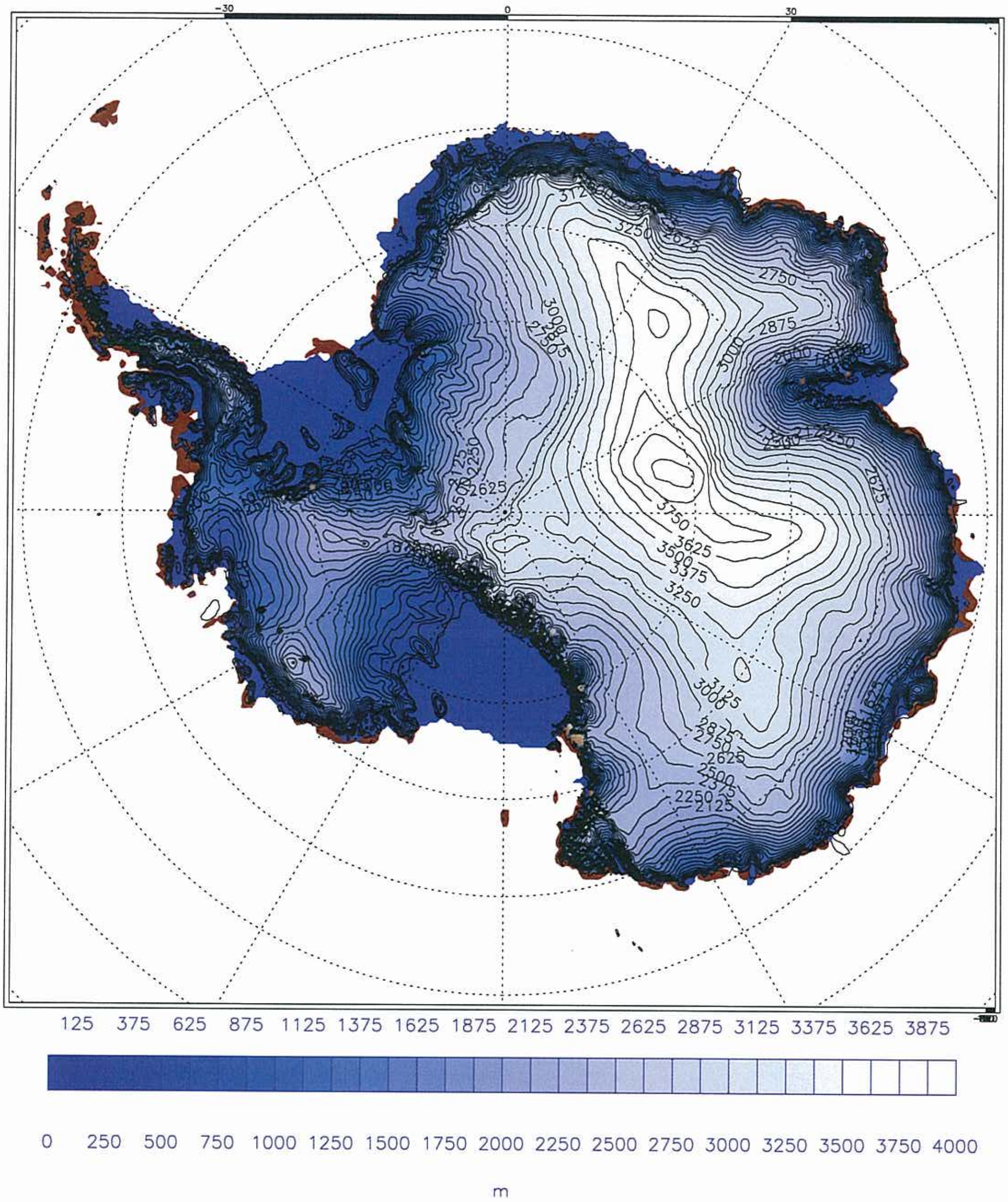

Figure 4.2: The surface topography of the Antarctic ice sheet as given by the SeaRISE data set at $20km$ resolution, the regridding of the data from fig(4.1) done by PISM's own regridding routine.

performed. The setting of various model parameters is given in tab.(4.1).
Time series of the total ice volume, area and enthalpy, respectively are plotted in figs.(4.4)-(4.5). Fig.(4.4) shows the full time series of the entire paleo spinup run suite whereas fig.(4.5) focuses on the last part of the spinup run where full physics and paleo forcing is applied. In the figures, the black curves refer to the **-no_mass** run whereas the red curves refer to the part of the spinup using full physics and paleo forcing. Also shown is the observed total volume and area of the Antarctic ice sheet. The observed values are taken from the BEDMAP2 dataset, with a total volume of

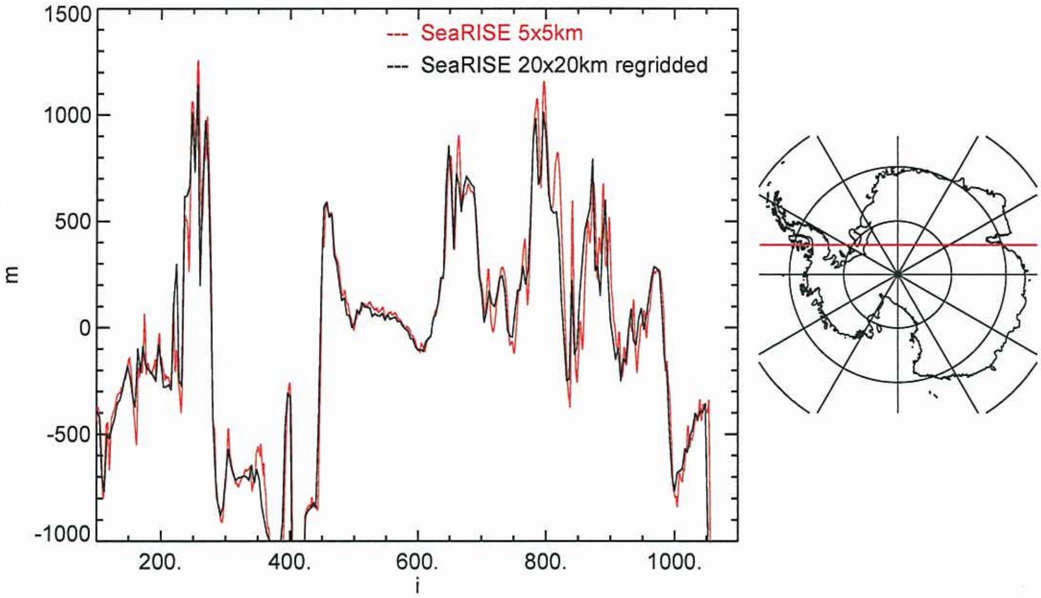

Figure 4.3: Left: The bedrock topography of a transect of the SeaRISE data set at the original $5km$ resolution shown in red and the same transect taken from the data set regridded by PISM to $20km$ resolution shown in black. Right: The location of the transect shown in the plot to the left

$26.9{\cdot}10^6 km^3$ and a total area of $13.9{\cdot}10^6 km^2$ [Fretwell et al., 2013]. The modelled volume and area are slightly lower than the observed values, but these observed values are from the BEDMAP2 dataset, not the SeaRISE data the runs are based upon. As expected, throughout the *no_mass* run both volume and area stay constant given that both the upper and lower surface of the ice sheet are kept constant. However, if one considers the total enthalpy in the bottom part of fig.(4.4) one can see the relaxation of the ice sheet towards an equilibrium enthalpy field for the initial ice sheet.

Parameter	Value	Description
e_ssa	1.0	Shallow Shelf Approximation enhancement factor
pseudo_plastic_q	0.25	Exponent in power-law description of stress
plastic_pwfrac	0.98	The fraction of overburden pressure which is assumed as the till pore water pressure
topg_to_phi	5.0,20.0,-300.0,700.0,10.0	Constants used to compute the till friction angle ϕ as a piecewise linear function of bed elevation
eigen_calving	$2.0 \cdot 10^{18}$	Proportionality factor in physically-based calving parameterisation.
calving_at_thickness	150.0	Critical thickness for grid-cell wise calving depending on terminal ice thickness

Table 4.1: Table of parameter settings for the paleo spinup run

Once the full physics and the paleo forcing is activated, some initial transient behaviour is seen (the red part of the curves in figs.(4.4),(4.5)), although both volume and area seem to become reasonably stable rather quickly. In the enthalpy field an increasing trend is seen.
The ice sheet of the paleo spinup has a shape that shows reasonable agreement with observations, see figs.(4.2,4.6,4.7). The difference between the initial (observed) state and the ice sheet after the paleo spinup run is shown in fig.(4.7). Over the interior parts of both the East Antarctic and Marie Byrd Land the the ice sheet thickness is smaller in the paleo spinup than the initial state. Along the entire range of the transantarctic mountains, in Victoria Land, in the interior part of the Antarctic peninsula and the north western part of the the west Antarctic the ice sheet is too thick compared with observations. This is also the case of the area inland of the Amery ice shelf and at a number of locations along the coast. All things considered, the ice sheet produced by the paleo spinup run has a reasonable likeness to the observed ice sheet, reproducing the general shape and prominent features of the ice sheet.

4.2.2 Continuing the spinup using EC-Earth forcing

For any PISM model run forced by external forcing data from a climate model it is necessary to have a PISM state which is in equilibrium with the mean climate of the driving model lest any signal or trend be blocked out by transients. In order to obtain a such a state a spinup run of the ice sheet need to be performed where the external forcing is based on the mean climate of the driving climate model, EC-Earth. In order to maintain the influence of the climate history on the thermomechanical properties of the ice sheet the initial state used for the spinup run of constant climate model forcing should be the ice sheet state resulting from a paleo-forced spinup run such as the one described in the previous section, sec.(4.2.1). The forcing files are based on monthly multi-year means from a 30-year timeseries of EC-Earth data from an uncoupled control run with preindustrial conditions. The details of the production of the forcing files may be found in chap.(3). Apart from the use of an external forcing, all other parameter settings remain unaltered compared to the paleo spinup described in the previous section, sec.(4.2.1) and, hence, the values listed in tab.(4.1) still apply for the runs driven by EC-Earth forcing.
Unfortunately, this continuation of the paleo spinup run using forcing based on the mean climate of EC-Earth has proven rather unstable; after approximately 10.000 years of the intended 100.000 year run PISM consistently crashes. The shallow ice approximation (SIA) used in PISM is in some aspects ill-posed since it allows for undampened growth of transverse short-wave length nodes [Hindmarsh, 2004a, Hindmarsh, 2004b, Hindmarsh, 2006, Saito et al., 2006] and fingering and ringing behaviour is not uncommon even in completely symmetric control experiments. However, considering the plot of the total volume and enthalpy of the continuation of the spinup run using

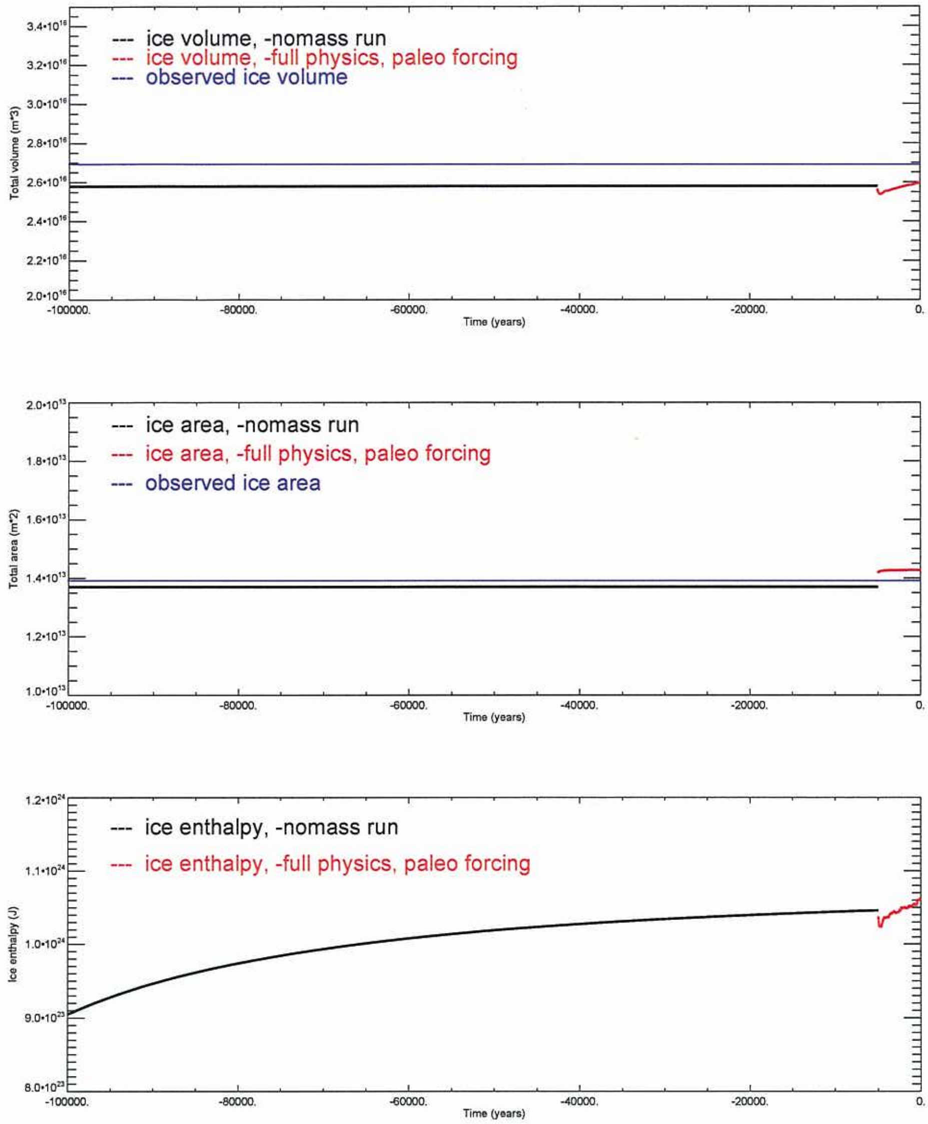

Figure 4.4: Time series showing the total ice volume (top), area (middle) and enthalpy (bottom) of the Antarctic ice sheet during the paleo spinup run based on the SeaRISE dataset. Black curves refer to the **no_mass** run whereas the red curves refer to the full physics run using paleo forcing. Also shown (in blue) are the observed volume ($26.9{\cdot}10^6 km^3$) and area ($13.9{\cdot}10^6 km^2$) of the Antarctic ice sheet including the ice shelves. The observed values are taken from the BEDMAP2 dataset [Fretwell et al., 2013]. In fig.(4.5) the last 5000 years of the spinup run with full physics and paleo forcing is shown in greater detail.

EC-Earth forcing, no such ringing behaviour is evident in the total volume, see fig.(4.8), so the problem with the consistent model crashes is evidently not linked to stability issues with the SIA

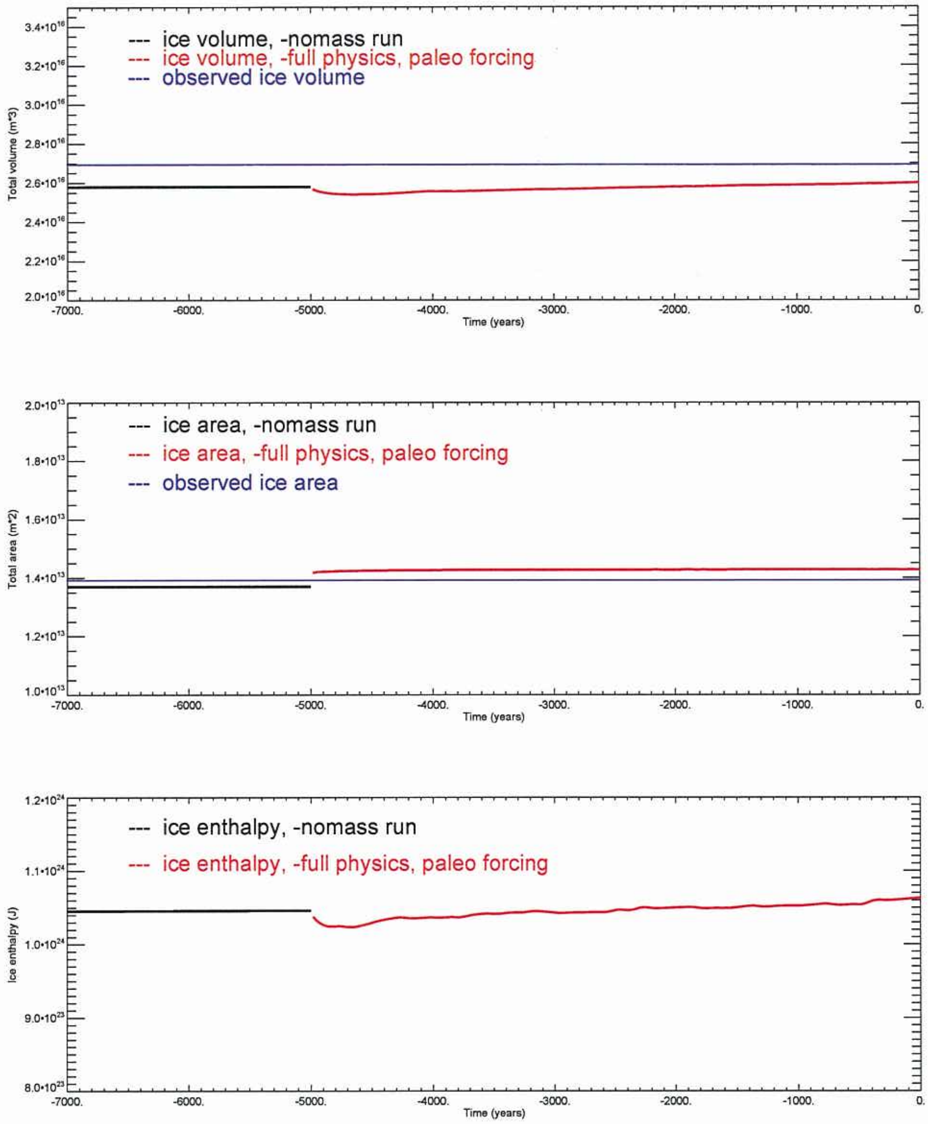

Figure 4.5: As in fig.(4.4), only this plot only shows the last 5000 years of the spinup run where full physics and paleo forcing is applied. The plots show the total ice volume (top), area (middle) and enthalpy (bottom) of the Antarctic ice sheet during the paleo spinup run based on the SeaRISE dataset. Black curves refer to the **no_mass** run whereas the red curves refer to the full physics run using paleo forcing. Also shown (in blue) are the observed volume ($26.9{\cdot}10^6 km^3$) and area ($13.9{\cdot}10^6 km2$) of the Antarctic ice sheet including the ice shelves. The observed values are taken from the BEDMAP2 dataset [Fretwell et al., 2013]. In fig.(4.4) the full time series of the spinup run is shown.

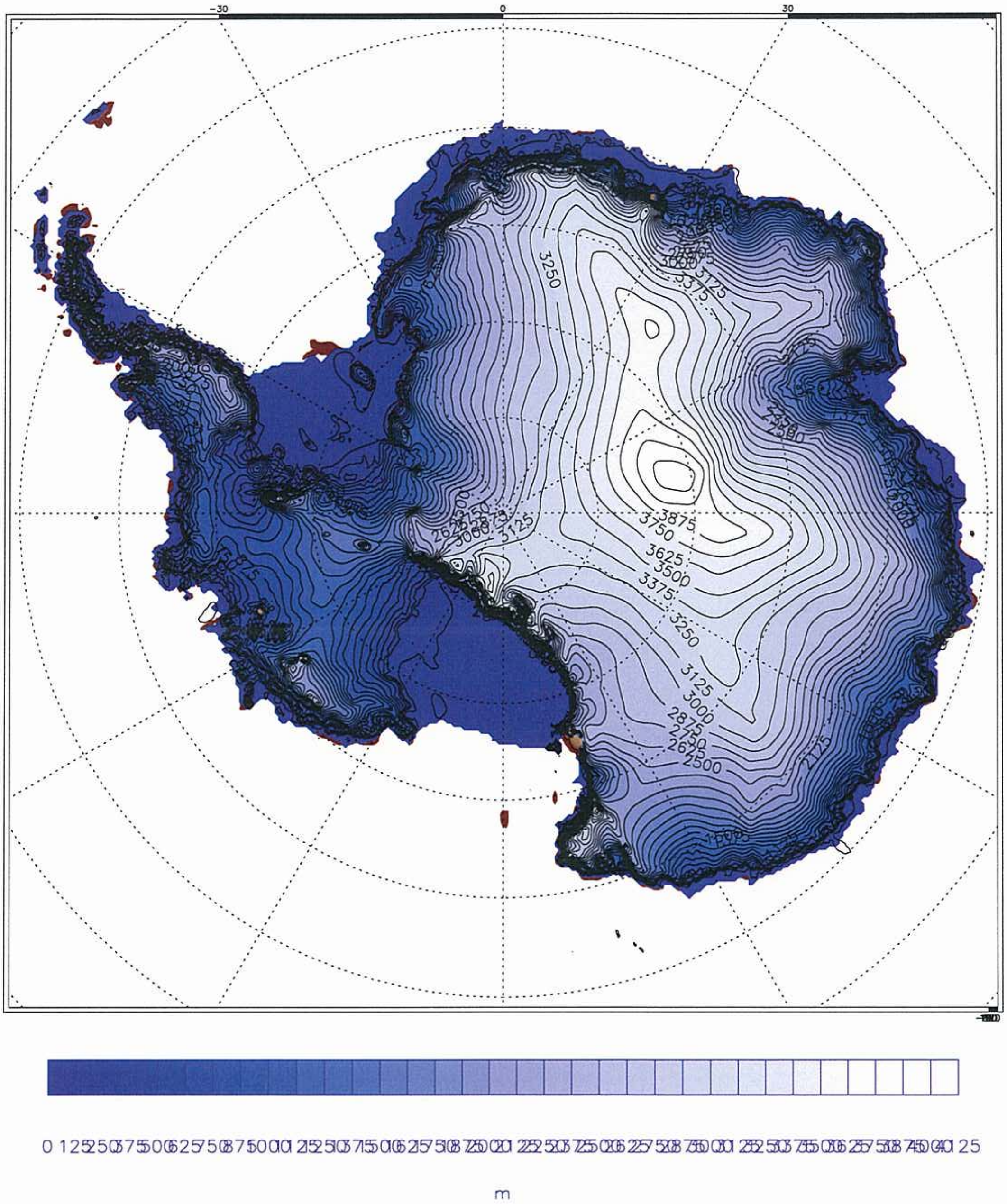

Figure 4.6: The surface topography of the Antarctic ice sheet after the paleo spinup run based on the SeaRISE dataset.

approximation. A closer inspection of the log files of the PISM run reveals problems with the SSA solve when PISM is determining the sliding velocity using the stress balance. The attempt to solve the nonlinear equations for velocity given the ice sheet geometry, the ice softness and the basal resistance fails. The probable cause is linked to a subglacial mountain/trench complex in the Western Antarctic Ice Sheet where the bedrock elevation goes from -1800m to +2400m over the span of a few grid points. This causes very thin ice over the subglacial mountain right next to very thick ice in the trench, leading to rather peculiar qualities of the ice in this area and, particularly, to very extreme

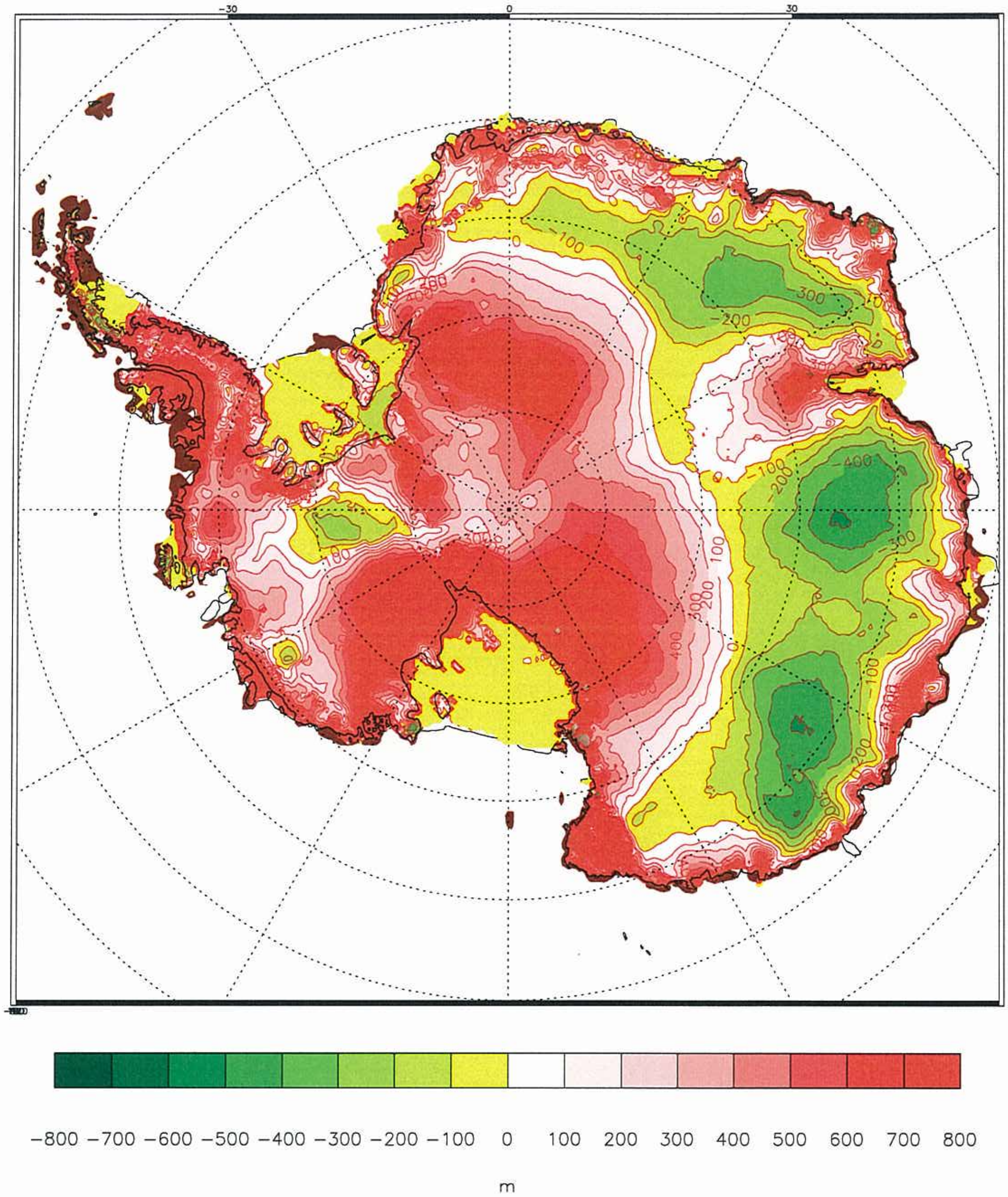

Figure 4.7: The difference in the surface topography of the Antarctic ice sheet after the paleo spinup run and the surface topography of the SeaRISE dataset at the $20 \times 20 km$ resolution.

gradients of the field variables, see fig.(4.9), thereby causing the failure of the linear solvers of the model [Bueler, 2012].

Given that very extreme gradients in the bedrock topography (see fig.(4.9), top panel) is the likely culprit considering the instability of the run, a few different avenues have been taken in an attempt to alleviate the problem. Shifting the lattice somewhat has at least in the case of the paleo spinup run proven sufficient to bypass the stability issues of the linear solver, but in the current case, this proved to be insufficient. A simple smoothing procedure using the closest neighbouring grid points has been

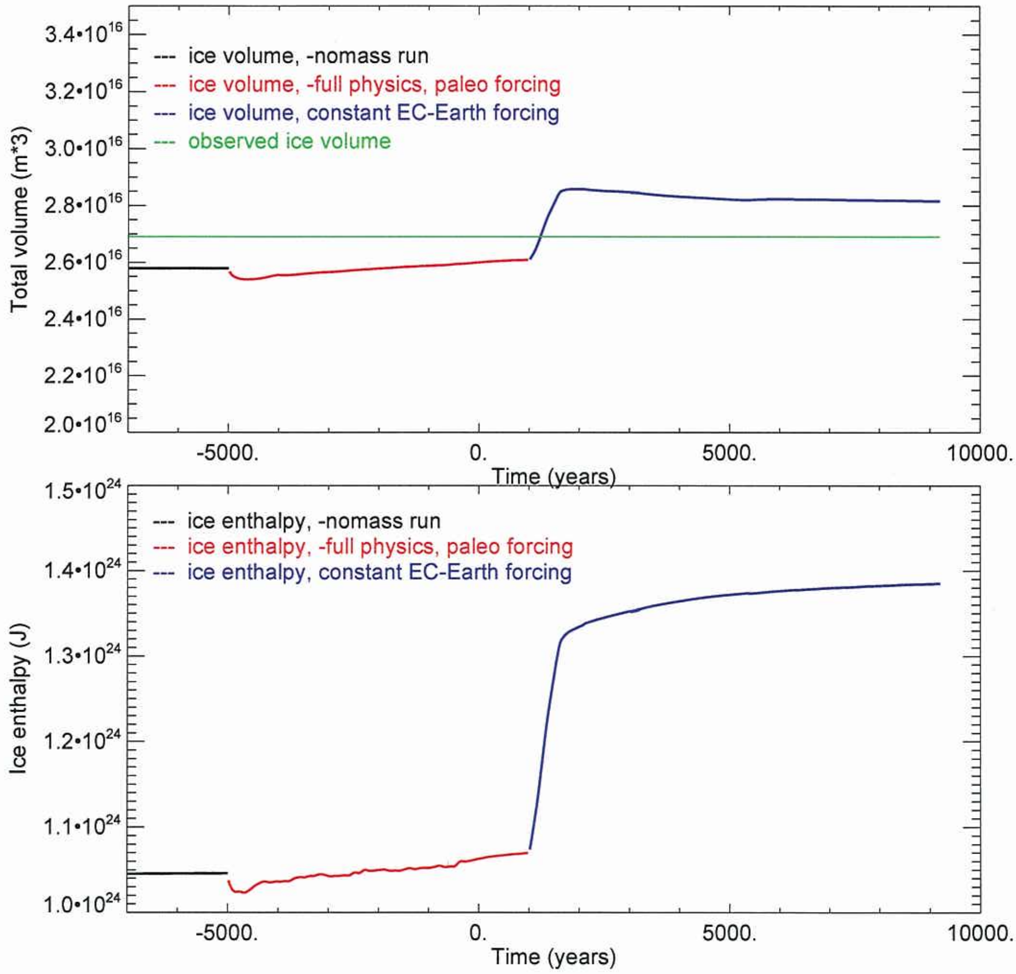

Figure 4.8: The total volume and enthalpy of the spinup run including the EC-Earth driven part of the spinup run (shown in blue). The time series shows the EC-Earth driven part of the run in its entirety up until the model crash shortly after 9.000 years. The black and red parts of the spinup run are the last part of the **no_mass** run and the full physics run using paleo forcing as in figs.(4.4-4.5).

introduced as well. Redoing the spinup after smoothening the bedrock topography using the *smooth9* routine of **CDO**, [Schulzweida et al., 2008] described in sec.(2.5.1) and fig.(2.4), has, however, also proven to be insufficient to overcome the stability issues of this particular mountain/trench complex in the Western Antarctic Ice Sheet, preventing the EC-Earth-forced spinup on top of the paleo spinup to run to completion.

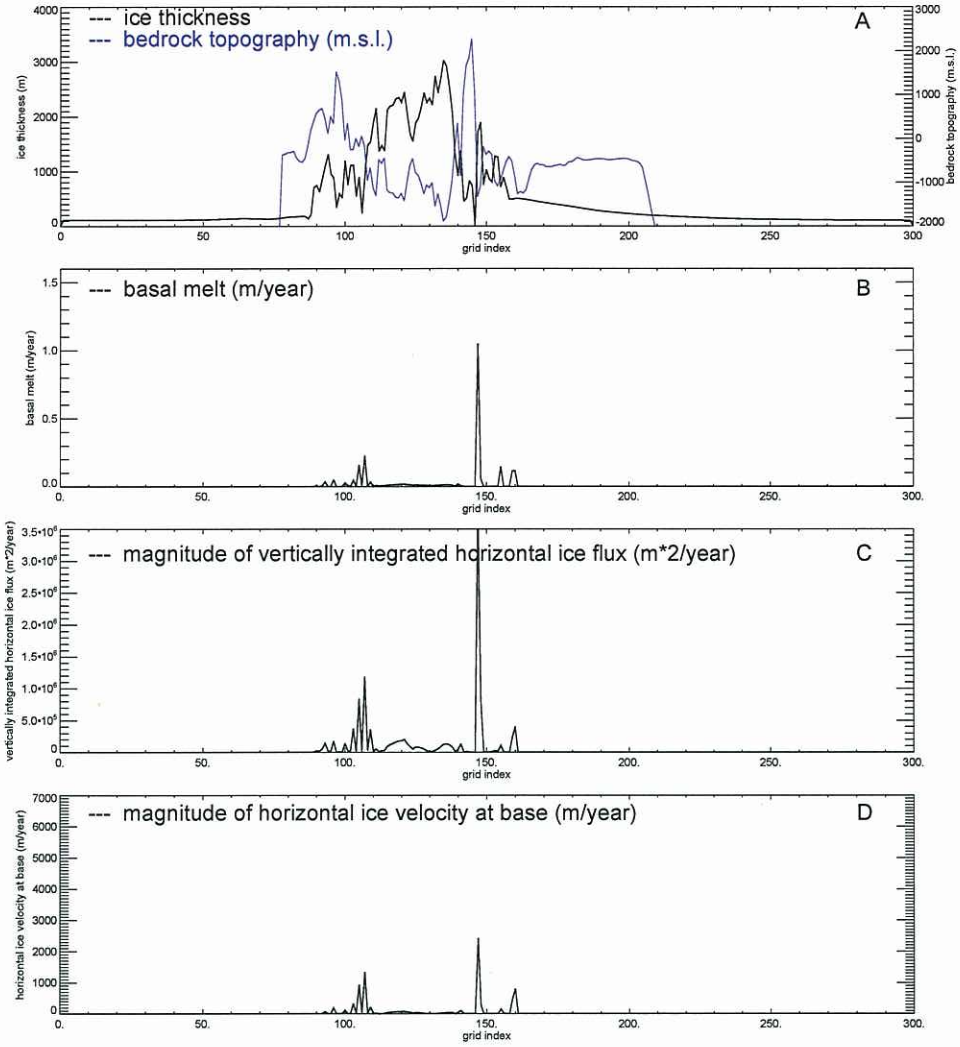

Figure 4.9: The ice sheet thickness (black) and bedrock topography (blue) (panel A), the basal melt (panel B), the magnitude of the vertically integrated horizontal ice flux (panel C) and the magnintude of the horizontal ice velocity at the base of the ice (panel D) along a transect of the ice sheet passing through the critical area of the mountain/trench complex of the Western Antarctic Ice Sheet. Note the large dip/spikes in the various variables just prior to the grid index 150, indicating the extreme qualities of the ice sheet flow in this area. The location of the transect is shown in fig.(4.10).

Due to time-limitations and priorities concerning the main scope of the current project, that is, the construction of a coupled ice-sheet-GCM model, further attempts to obtain stable EC-Earth driven PISM runs based on the outcome of a paleo-spinup run have been abandoned for the time being. In

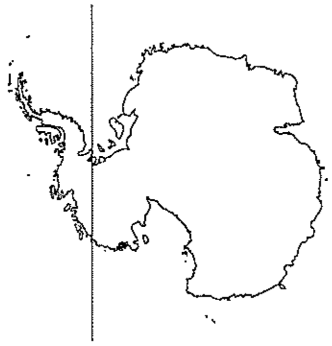

Figure 4.10: The location of the transect shown in fig.(4.9).

order to run and test the fully coupled system any reasonable spinup-state of the ice sheet is sufficient and one may use a less optimal spinup state as long as it is in equilibrium with the driving model (EC-Earth). At some later stage, as part of the fine-tuning and optimization of the coupled system, one may consider revisiting the EC-Earth driven spinup runs based on the outcome of a paleo forcing run, this time using a more carefully computed bedrock topography. Presently, the bedrock is based on PISM's inherent regridding routine, causing the computational grid to be a mere subsampling of the $5km \times 5km$ SeaRISE data to PISM's $20km \times 20km$ resolution. It would be more advisable to perform an initial, off-line interpolation of the bedrock topography onto the computational grid, if proven necessary with some degree of additional smoothing prior to the PISM runs themselves. The issues of grid resolution and the choice of bedrock topography are further addressed in [Svendsen et al., 2014].

4.3 Spinup of Antarctica based on EC-Earth forcing

In the previous sections, secs.(4.2, 4.2.1, 4.2.2), a spinup procedure making use of paleo data was described. Given the difficulties in achieving a stable state of the ice sheet in the case where the constant EC-Earth forcing followed the paleo spinup, a different approach has been taken in order to obtain an initial spinup state of the ice sheet. One may opt to bypass the paleo forcing and instead perform the external forcing spinup directly on top of the initial data set. This may be a viable solution in situations where adequate paleo forcing data is unavailable or in the event of a lack of numerical stability of the combined spinup procedure of sec.(4.2). In this case, one loses the advantage of the retained memory of the past climate within the ice sheet in terms of its thermomechanical properties.

In the present case, the same external forcing that was used for the continuation of the paleo-forced spinup run of sect.(4.2.2) is used to force PISM, only this time the forcing is applied directly to the SeaRISE data set rather than to the outcome of a paleo-forced PISM run. The various parameter settings of the PISM run are kept unchanged compared to the runs described above, and, hence, the parameter values of tab.(4.1) still apply. The spinup run is performed as a 50.000 year run using constant monthly forcing fields based on multi-year monthly means originating from an uncoupled control run of the driving climate model under preindustrial conditions, see chap.(3) for details concerning extraction of the forcing fields used to drive PISM from climate model data.

The time series of the total volume, area and enthalpy of the ice sheet throughout the spinup run is shown in fig.(4.11) along with the observed values of total volume and area according to the BEDMAP2 data set [Fretwell et al., 2013]. The run appears stable although the ice volume is

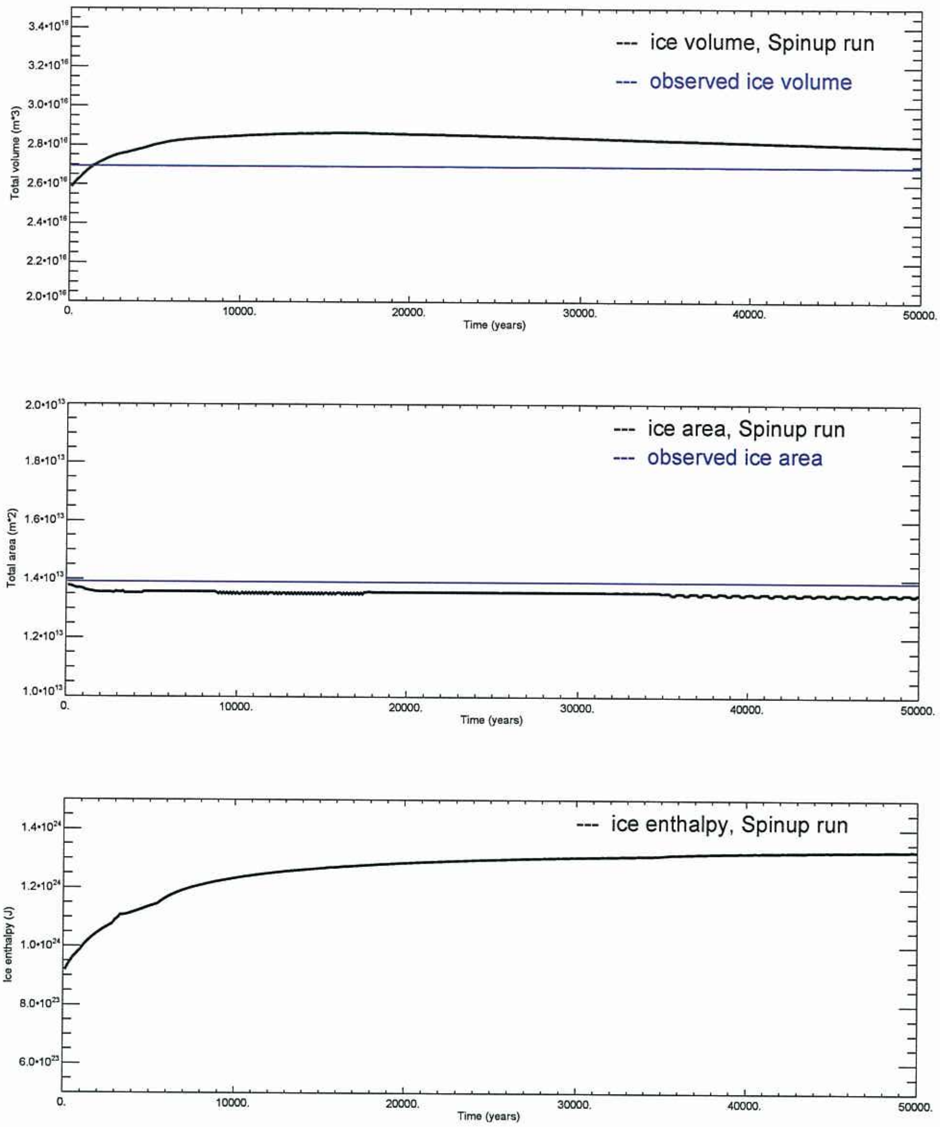

Figure 4.11: Time series showing the total ice area and volume of the Antarctic ice sheet during the spinup run using EC-Earth based forcing directly on the SeaRISE dataset. Also shown (in blue) is the observed total ice volume and area according to the BEDMAP2 data set [Fretwell et al., 2013].

somewhat larger than the observed volume whereas the area is a bit smaller, hinting at an ice sheet that is too thick. Fig.(4.12) shows the ice sheet topography at the end of the spinup run whereas fig.(4.13) shows the difference in topography between the SeaRISE dataset and the EC-Earth driven spinup. It is evident that the thickness of the ice sheet is too large along the coast line, along the transantarctic mountain range, in the western part of Marie Byrd Land and inland just east of the Filchner-Ronne ice shelf as well as the innermost part of the Antarctic Peninsula and the area

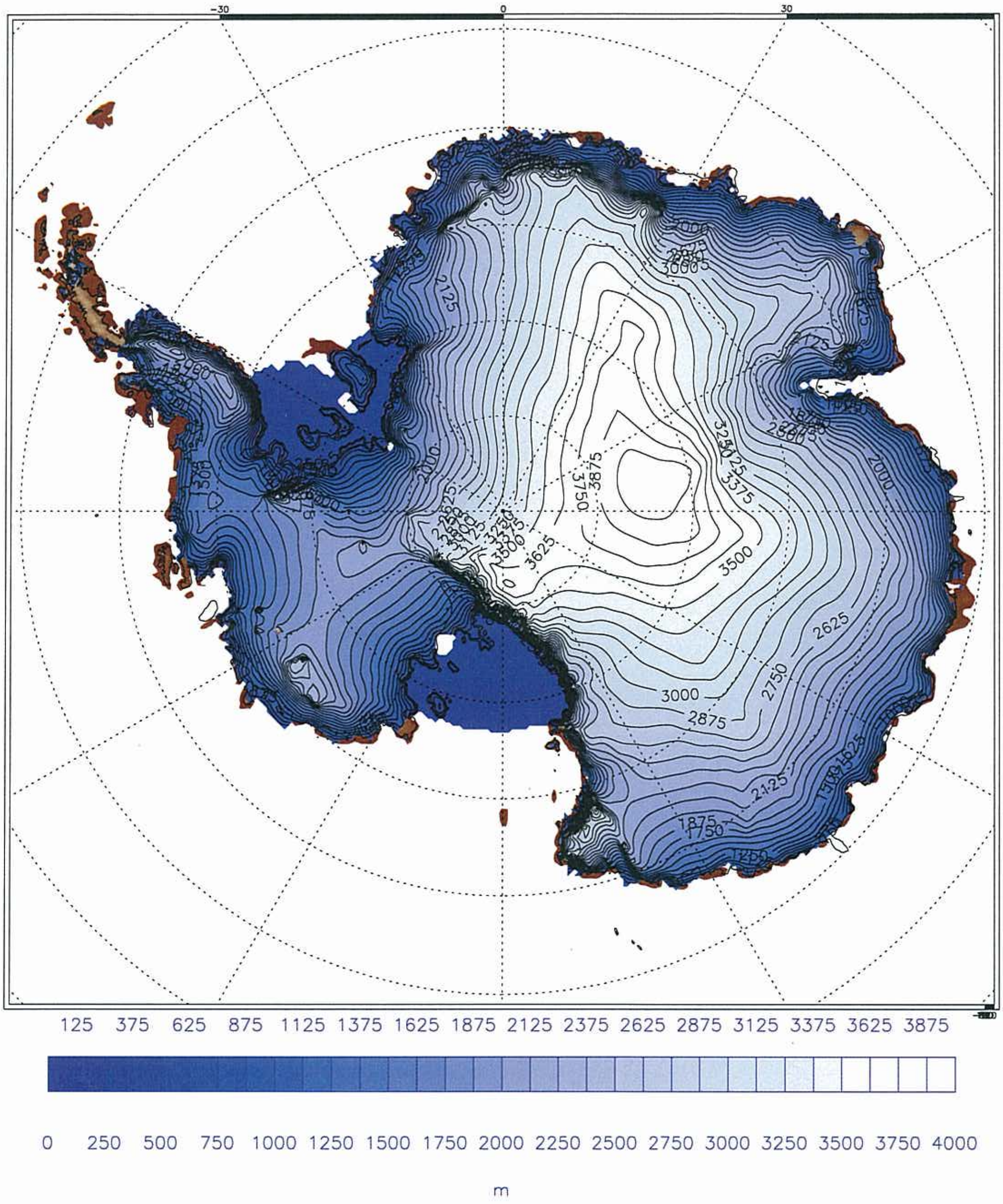

Figure 4.12: The surface topography of the Antarctic ice sheet after the spinup run using EC-Earth based forcing directly on the SeaRISE data set.

upstream of the Amery ice shelf. Large areas of the East Antarctic Ice Shelf as well as the shelves appear to be too thin compared to observations and, contrary to observations, there is no ice present on large parts of the outer half of the Antarctic Peninsula.

Misrepresentations of the ice sheet geometry in a model run may have a number of different causes; there may be problems with the representation of the dynamics or the bedrock topography and there may be issues with the forcing fields, with biases in temperature and/or precipitation. If one considers the corresponding plot of the difference between the SeaRISE data set and the paleo spinup

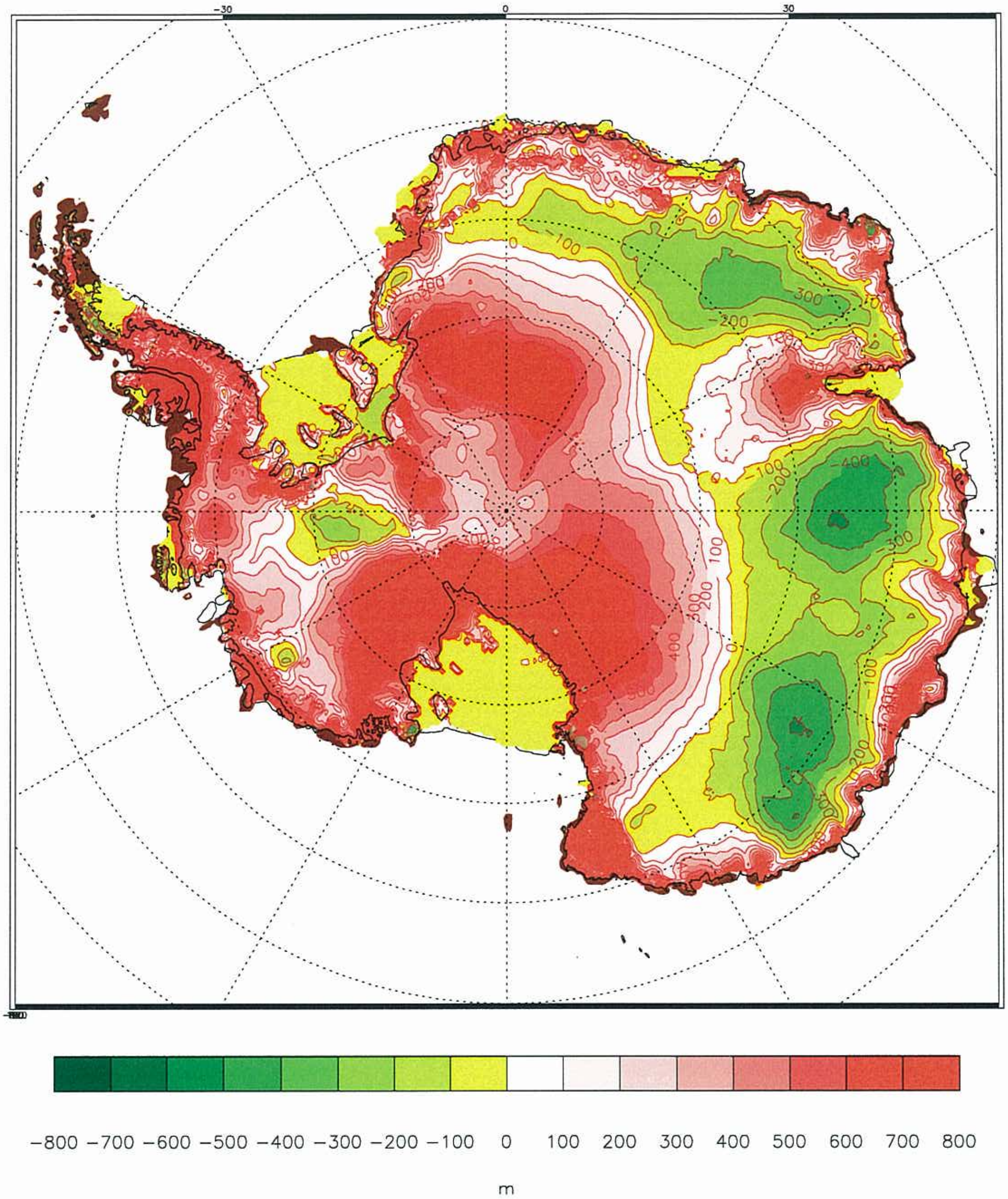

Figure 4.13: The difference in surface topography of the Antarctic ice sheet after the spinup run using EC-Earth based forcing directly on the SeaRISE data set and the SeaRISE data.

run, fig.(4.7), a similar pattern of topography differences, although much weaker, is evident. The same overrepresentations of ice are seen at the coastal rim, along the transantarctic mountains, just east of the Filchner-Ronne ice shelf, in the area upstream of the Amery Ice Shelf and at the innermost part of the Antarctic Peninsula. At the same time underrepresentations of ice are seen in the interior parts of West Antarctica, throughout most of East Antarctica and in the outer regions of the Antarctic Peninsula. These features are similiar, although much stronger in the strictly EC-Earth driven spinup than in the paleo-driven spinup, hinting at other factors to these features than merely the forcing. In

these cases representations of the ice dynamics and the bedrock may be the cause of a major part of the observed differences. Resolution is important for the proper representation of outlet glacier flow and even though the Antarctic ice streams and outlet glaciers are much larger than in the narrow fjord systems of Greenland, resolution may be an issue for the correct representation of the ice flow. The importance of higher resolution and better representation of the bedrock are certainly aspects of the model system to place under closer scrutiny in future developments of the coupled model system. Concerning the forcing fields used for the spinup run some issues springs to mind as well; one naturally being that running a simulation with constant forcing fields for 50.000 years is bound to be very sensible towards any biases in the forcing fields. And, considering the Antarctic peninsula, it is evident that the coarse resolution of the climate model has trouble providing proper forcing fields for this particular area. Depending on the choice of masks used in the interpolation of the forcing fields between the two model grids, ocean points of EC-Earth may or may not be included in the interpolations [Madsen et al., 2014, Svendsen et al., 2014] of the forcing fields from the EC-Earth grid to the PISM grid. The current forcing fields are made with masks that only includes the EC-Earth land points in the interpolations. Considering the scarcity of land points over the peninsula, see fig.(3.7), the resulting forcing field for PISM will be even more sensitive, see also the discussion in sec.(3.7). In this case, improving the PISM resolution may not alleviate the problems of the peninsula which seem to be more closely linked to the resolution of EC-Earth.
The ice sheet based on this constant spinup run will be used as the initial state of the ice sheet in the coupled model runs even though the geometry of the paleo spinup run is a better match compared to observations. In order to get stable and reliable results from the coupled model runs it is imperative that the ice sheet is in thermal equilibrium with the mean climate of the driving model and this equilibrium has been given priority over the details of the ice sheet geometry. As mentioned in sec.(4.2.2), improvements in the bedrock representation may be the key to overcome the difficulties in obtaining a stable PISM run combining both paleo and EC-Earth forcing and at some later stage, the effort of obtaining a more accurate initial state will definately be worthwhile, but as for the current exercise of merely demonstrating the functionality of the system, the initial state driven solely by EC-Earth data is sufficient.

5. Two-way coupled runs

Fully coupled ice-sheet-climate models are in great demand due to the need to examine and quantify the numerous feedback effects related to ice sheets in the climate system. Such a coupled system may be designed in numerous different ways, but the current is based on script-level coupling of two separate models that exchange relevant forcing fields from one another at given time intervals.

5.1 The structure of the coupled system

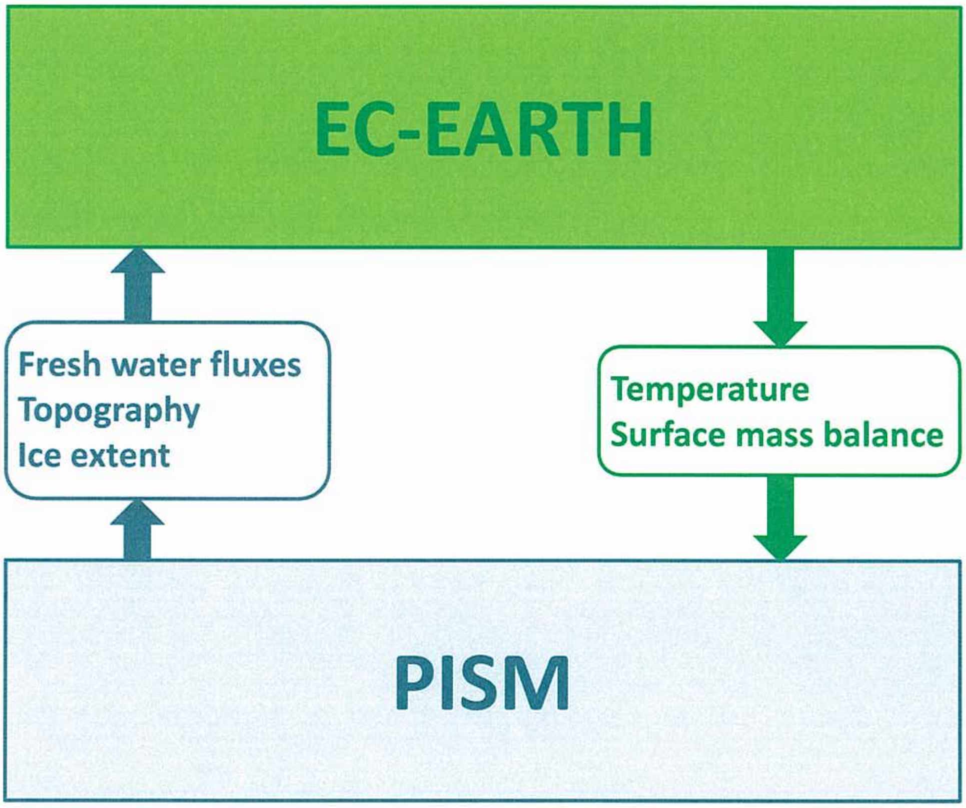

Figure 5.1: The overall structure of the 2-way coupled system.

A two-way coupled system has been set up consisting of the GCM EC-Earth and the ice-sheet model PISM, as described in [Madsen et al., 2014, Svendsen et al., 2014]. The coupling between the various parts of the system works at the script level, each model in turn runs for one year at a time after receiving updated information on forcing fields in the case of the ice sheet model and updated masks and topographies as well as freshwater inputs in the case of the GCM, see fig.(5.1). The generation of the forcing files for PISM and EC-Earth are done in separate scripts, the interpolation between the two different model grids handled by OASIS [Valcke et al., 2013], see chap.(3). This setup causes the ice and climate components of the coupled system to function independently of one another, rendering the system quite flexible in the event of updates or improvements made to the individual components of the system.
The coupling procedure between EC-Earth and PISM was originally developed for the Greenland Ice Sheet and more extensive information on the changes in EC-Earth as well as the details of the coupling scheme itself may be found in [Madsen et al., 2014, Svendsen et al., 2014] and the interested reader is referred to these publications for details. In fig.(5.1) the overall structure of the coupled system is shown. The climate model EC-Earth runs for a year after which fields of monthly

mean temperature and surface mass balance are calculated for both the Greenlandic and Antarctic domains. These fields are then used as forcings to drive PISM over Greenland and Antarctica for one year. Upon completion of the one-year run, information on fresh water fluxes and changes in the ice sheet topography are given back to EC-Earth. As mentioned in sec.(2.2.2), the SSA stress balance of a freely floating body of ice is not well defined and PISM therefore has an in-built algorithm that removes any calved-off icebergs by searching for isolated grid cells entirely surrounded by ocean. The corresponding amount of fresh water and energy needed for melt is given to/taken from the ocean in EC-Earth.

When running the coupled system including both Greenland and Antarctica, two different run calls to PISM are set up in the overall run script; one for the Greenland domain and one for the Antarctic domain. At the moment both domains run at the same resolution, but in principle, the domains are independent and may run on different resolutions.

5.2 Test runs of the fully coupled system

In the case of Antarctica, PISM is run on the same $20 \times 20km$ grid as for the spinup runs and the outcome of the spinup run using constant EC-Earth based forcing directly on the SeaRISE data set with no prior paleo forcing (see sect.(4.3) for details) has been used as the initial state of the Antarctic ice sheet in the simulation. A short test run of 35 years has been performed with EC-Earth running under preindustrial control conditions. The coupled run including coupling to both the Greenland Ice Sheet and the Antarctic Ice Sheet spans 35 years. A 35-year time interval is too short to perform actual statistics, but sufficient to demonstrate the functionality of the system.

In figs.(5.2-5.3) time series of a number of total values such as total ice volume, area, enthalpy and calving fluxes for the Antarctic ice sheet are shown. From the figures it is evident that the overall behaviour of the system is reasonable; the various variables display a relatively constant behaviour even though the total ice volume seems to be slightly increasing, and, consequently, the total enthalpy of the system increases as well due to the larger ice volume. An annual cycle is evident in the total ice enthalpy as well as in the total area of the ice sheet where the basal ice is cold. The floating ice volume shows a good correspondence to the calving; when the floating ice volume is decreasing, increases are seen in the amount of calving as well. As for the shape of the ice sheet and changes in topography, no significant changes are seen over the course of the short test run. Longer runs and runs with a systematic variation in the forcing fields is expected to influence the overall geometry of the ice sheet.

The short available test run demonstrates the functionability of the system and gives reasonable results considering basic properties of the Antarctic ice sheet. A number of characteristic features of the Antarctic ice sheet are not taken into account in the system's current configuration, but the essential parts of a two-way coupled system are in place and provides a platform for further development and studies of the Antarctic ice sheet in the perspective of climate change.

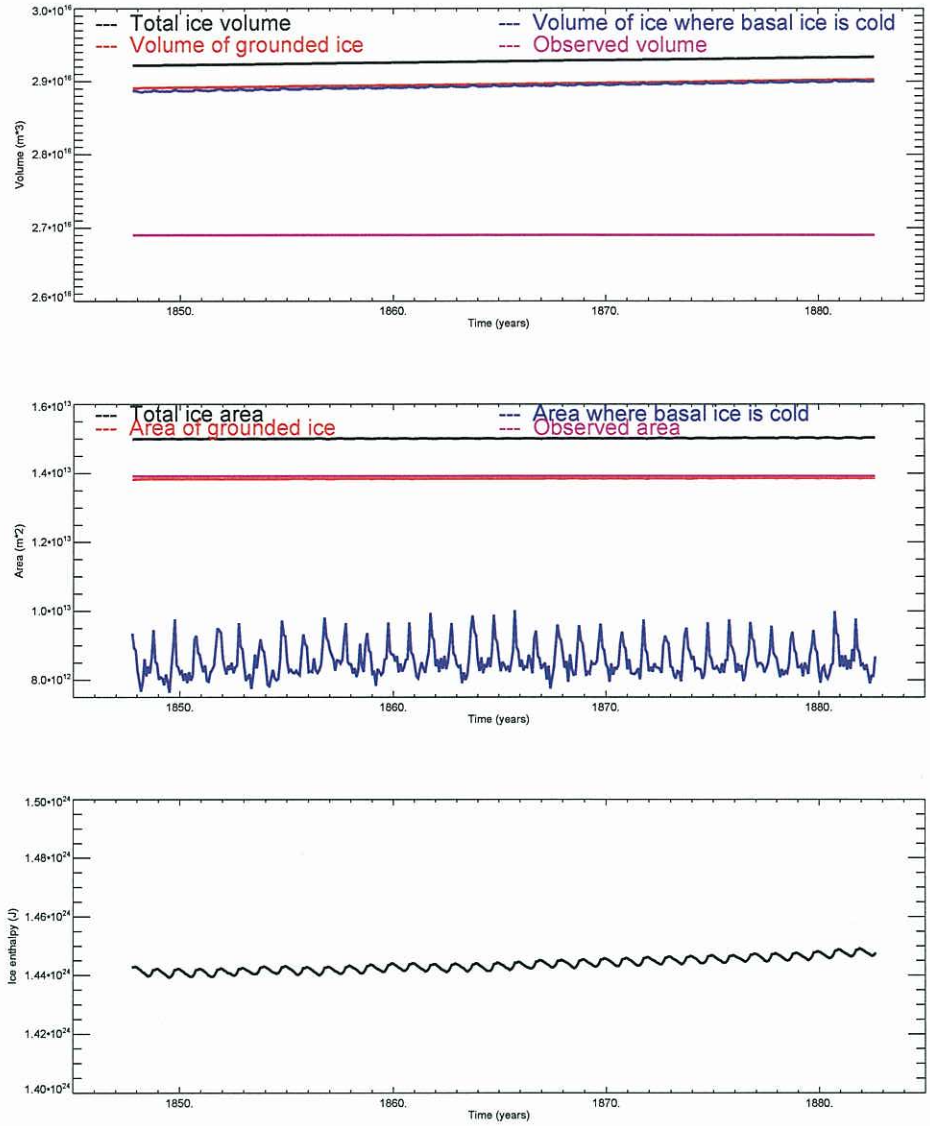

Figure 5.2: Time series of total values for the Antarctic ice sheet. The top plot shows the total volume of the ice sheet in black, the volume of grounded ice in red, the volume of ice where the basal ice is cold in blue and, for comparison, the observed volume as given by [Fretwell et al., 2013] in pink. The middle plot shows the corresponding ice areas with the same colour coding. The bottom plot shows the total enthalpy of the ice. Note the annual cycle visible in the volume and area of the ice sheet with cold basal ice and the total enthalpy.

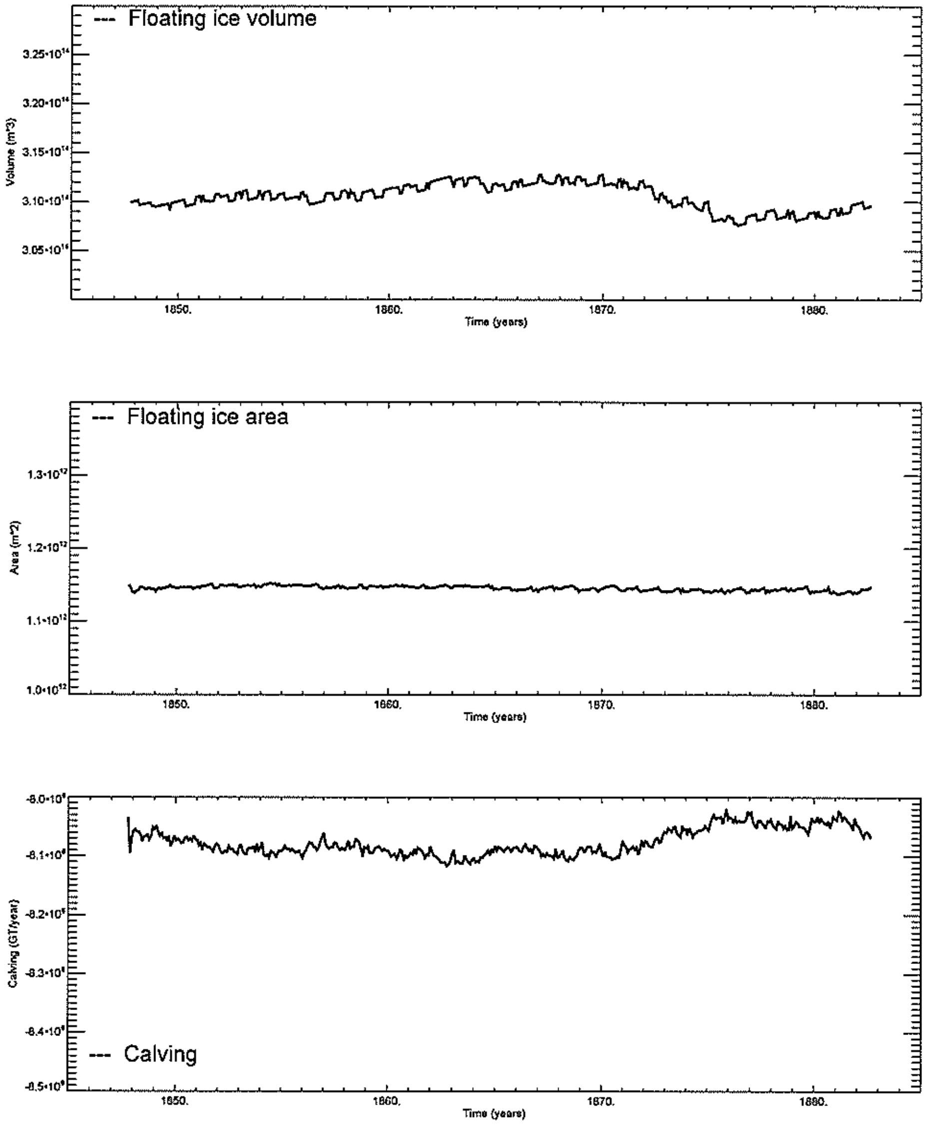

Figure 5.3: Time series of total values for the Antarctic ice sheet. The top plot shows the floating ice volume, the middle plot show the floating ice area and the bottom plot shows the calving.

6. Challenges and possible improvements

In the preceding chapters the coupled model system currently implemented has been described. It has been demonstrated how to set up the coupled system and some short test runs with the full system have been presented. The coupled system is, however, still in its early stages of development and many possibilities for improvements exist. This chapter is intended to bring forward some ideas and possibilities for improving the coupled model system.

6.1 Ocean-Ice-sheet interaction

One thing that really sets Antarctica apart from the Greenland ice sheet is the presence of the vast ice shelves around the Antarctic coast. These shelves have their own dynamics and complex interplay with both ocean [Shepherd et al., 2004] and atmosphere and also have a vast impact on the flow dynamics of the ice sheet itself through buttressing effects [Dupont and Alley, 2005, Gagliardini et al., 2010, Gudmundsson, 2013]. Acceleration of the velocity of inland glaciers indeed followed the demise of the Larsen B ice shelf, as observed by [Rignot et al., 2004].

Given the intricate interactions between the atmosphere, the ocean and the ice shelves a coupled model system is essential in order to assess the feedbacks of the system. However, in the present configuration of the coupled model system only a rather rudimentary ocean forcing of the ice shelves is available. As mentioned in secs.(2.4.1,3.6.1), in the current setup PISM's ocean boundary model provides a contant sea level elevation to PISM's ice flow core and a constant (in space as well as time) mass flux from the ice into the ocean. This mass flux may be controlled by the configuration parameter **ocean_sub_shelf_heat_flux_into_ice** under the assumption that the mass flux is proportional to the heat flux from the ocean into the ice [Albrecht et al., 2012a].

This constant ocean forcing does not utilize the full potential of the coupled model system, where ocean temperatures and salinity are actually available from NEMO. Allowing for variations in the ocean forcing of PISM would be a great advance towards resolving feedback processes between the ocean and the ice shelves. In later versions of PISM (from pism0.5 and onwards), time dependent and spatially varying inputs of sub-shelf ice temperature and sub-shelf mass flux are possible [Albrecht et al., 2012c], providing an excellent opportunity to utilize the available oceanic output from NEMO towards a better understanding of the coupled ocean-ice-sheet system. Due to these upgrades in the ocean forcing component of PISM that are available, an obvious improvement to the coupled model system would be to implement temporal variation of the ocean forcing component forcing of PISM based on EC-Earth output.

As mentioned above, the possibility of forcing PISM with time-varying ocean-forcing fields exists. However, a good representation of the ocean in the ice-shelf cavity has yet to be developed. In NEMO, the model grid is restrained to the open ocean outside the shelves and hence, NEMO does not include any dynamics of the sub-shelf cavities. Ice-shelf cavity models do exist, see e.g. [Holland and Jenkins, 1999, Padman et al., 2003, Hellmer et al., 2012], as well as work on ice shelf cavities in ocean models, see e.g. [Grosfeld et al., 1997, Losch, 2008, Årthun et al., 2013], but all of these are, however, based on the assumption of constant ice shelf cavity geometries. A change in the ice shelf geometry or grounding line migration in response to atmospheric or oceanic forcing would require an adaptive cavity geometry, something which in turn would require dynamic changes in the ocean boundary conditions over the course of the simulation. Such changes has vast implications for ocean stability and sound techniques for dealing with this issue remains to be developed.

These various issues require some rather fundamental changes in the ways the driving ocean model deals with the land mask and boundary conditions. The current work has focused on the ice sheet model itself and not the ocean model of the driving climate model. However, as mentioned above, the current oceanic forcing of PISM may be improved greatly if time-varying forcing fields were to be provided. This possibility exists in newer releases of PISM and it is strongly recommended to upgrade PISM in the coupled model system to a version that allows for time-varying ocean forcing fields. As mentioned earlier, the ocean model in the system does not apply to the waters in the subshelf cavities, but it should be a feasible task to set up a rudimentary ocean forcing files for PISM based on approximations of the conditions of the sub-shelf waters to those of the nearest open ocean grid points where NEMO data is available. These forcing fields will naturally not be sufficient to resolve the complex sub-shelf dynamics and intricate ice-shelf-ocean feedback processes but the large scale changes in the ocea will be able to influence the ice shelves, thereby improving the performance of the system.

6.2 Resolution

Resolution is a critical factor in the modelling of physical systems, the Antarctic ice sheet being no exception. There are a number of challenges in this respect, the resolution for the ice sheet model itself being one, the resolution of the climate model providing the forcings being another.

6.2.1 Ice dynamics

Ice streams are believed to be one of the primary sources of mass loss from the Antarctic interior and variations in the flow velocities of the ice streams may affect the overall mass balance of the Antarctic ice sheet [Rignot et al., 2008]. The inclusion of ice streams is therefore essential in order to obtain a proper rendition of the development of the Antarctic ice sheet.
The PISM dynamics are based on a combination of the Shallow Shelf Approximation (SSA) and the Shallow Ice Approximation (SIA), see sec.(2.1). This setup allows for the spontaneous emergence of ice streams and outlets as a consequence of the bedrock topography [Albrecht et al., 2012a, Bueler and Brown, 2009]. Consequently, detailed information on the bedrock topography is essential for performance of the ice dynamics. The Antarctic ice streams vary greatly in size, from a few kilometers to streams $50 - 80km$ wide [Bentley, 1987] and, necessarily, this requires a great deal of detail of the bedrock topography and the model resolution.
Studies of Greenland using EC-Earth to force PISM has shown the dependence on the model resolution in order to obtain proper dynamics. The bedrock topography needs a certain resolution in order to properly resolve outlets from the interior of the ice sheet. In the case of Greenland, experiments have shown that a bedrock resolution of $20km$ is too coarse [Svendsen et al., 2014] and optimally, the PISM runs should be performed at a higher resolution than this. In Antarctica, the scale of essential dynamical features is typically larger than in Greenland, nevertheless investigating the effect of resolution on the Antarctic dynamics is advisable.
The SeaRISE dataset including the bedrock topography used in the current study is given at a resolution of $5 \times 5km$, providing an ample amount of detail [Bindschadler et al., 2013] and recently the BEDMAP2 dataset with improved bedrock topography has recently been made available [Fretwell et al., 2013], presenting the opportunity to perform studies in even greater detail. However, currently, PISM is running over Antarctica at a resolution of $20 \times 20km$, thereby not utilizing the full potential of the bedrock topography to facilitate proper dynamics. Running PISM for a single year at a time, as is done in the coupled model setup, is not very computationally expensive compared to the costs of the ocean-atmosphere part of the system and on that account the spatial resolution of PISM could be increased. There is, however, significant cost at producing the spinup states of the ice sheet that are needed as initial states for the coupled model runs. These spinup runs which are described in detail in chap.(4) easily run for 100.000 years, significantly tapping into the available computational ressources.

In order to improve the performance of the system, an increase in PISM's resolution would most likely be worthwhile. This could either be done by running a rather costly full spinup cycle at the increased resolution or by regridding the available spinup state at $20 \times 20km$ resolution to the desired -possibly $10km$- resolution. As part of this process, it is essential to pay attention to the corresponding regridding of the bedrock topography. As described earlier, when PISM performs a regridding from a fine resolution data set to a coarser grid, PISM merely subsamples, and the $20 \times 20km$ spinup states currently used are based on a subsampling of the $5 \times 5km$ SeaRISE dataset, something which should definately be kept in mind for either solution, be it a regridding of the existing data set or a whole new suite of spinup runs. For future work, it is recommended to do the regridding of the bedrock topography to the desired PISM resolution outside PISM making use of some remapping scheme rather than merely subsampling.

6.2.2 Forcings

In the preceeding section, the importance of the resolution of the ice sheet model was discussed and it was suggested to increase the resolution of the ice sheet model in future studies. However, one must also keep in mind the resolution of the driving model. At present, the resolution of the atmosphere model in the coupled system is T159, corresponding approximately to a horizontal resolution of $125km$. As mentioned in sec.(3.7), properly resolving complex structures like those of the Antarctic peninsula and its surrounding archipelago is not possible. Given the vast importance of the Antarctic peninsula to the dynamics of the entire Antarctic continent, increases in model resolution could probably bring added value to the system, but unfortunately, the additional computational cost would be extensive. EC-Earth as a stand-alone model is capable of running on a number of different resolutions [Hazeleger et al., 2011, Basu, 2010], versions have been running with resolutions of the atmospheric part as higs as T799, corresponding to $0.25°$, and and ocean resolution of ORCA0.25, corresponding to $0.25°$, although the computational cost of such runs is massive.

If at some point an increase in the standard resolution of EC-Earth is made, characteristic features like the Antarctic peninsula, mountain ranges and coastal features would be much better resolved, thereby possibly improving the forcing fields for PISM significantly leading to an altogether more accurate model system.

7. Conclusions

In the preceding chapters, the overall structure of a fully coupled atmosphere-ocean-ice-sheet model system setup for Antarctica has been introduced. The spinup process of the Antarctic ice sheet has been described and the resulting initial states of the ice sheet have been compared to obervations. It is possible to produce initial stable states of the ice sheet that are in equilibrium with the mean model climate of the coupled atmosphere-ocean model. These initial states have a geometry that is generally thicker than the observed state, but given the long spinup times using constant forcing, any biases in either temperature or precipitation will be given much weight. Keeping in mind the objective of these initial states, that is, to serve as the basis in coupled model runs, thermodynamic equilibrium with the mean climate of the driving model rather than reproducing the observed geometry has been given priority.

The fully coupled system has been demonstrated to work in short control runs where the near-constant pre-industrial conditions produce a stable and reasonable behaviour of the Antarctic ice sheet. However, the system has not been tested in full-length scenario runs so far.

The model runs, particularly the spinup runs of the ice sheet model has shown a strong dependence on the bedrock topography, both regarding the resolution of essential dynamic features such as the ice streams but also regarding the stability of the model runs. For future experiments, it is adviced to redo at least part of the spinup runs using bedrock topographies that have been subject to somewhat more refined methods of regridding to the chosen model resolution.

A number of possibilities exist for improvements and further development of the system. One issue being that of the resolution, both regarding the ice sheet model itself, but also the resolution of the climate model, particularly regarding resolving the intricate topography and dynamics around the Antarctic peninsula. Another crucial issue has to do with the ocean forcing, which would greatly benefit from an expansion from the current setup with constant forcing fields to a system where the oceanic forcing components vary in time. The ice sheet model itself may quite readily be updated to such a setup. However, a number of issues regarding the modelling of the ocean itself in the sub-shelf waters remains to be addressed.

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10. Appendix A

This appendix contains a list af various scripts used for generating forcing files for PISM. The appendix is for internal use at DMI.

Python script developed by Andy Aschwanden, University of Alaska, Fairbanks, to extract grid cell center coordinates and corner point coordinates based on mapping info:

/home/shs/PISM/GridManip/nc2cdo.py

on *Kystpilen.*

IDL routine to produce NetCDF files with corner point information, surface area and mask values of the PISM grid cells:

/home/shs/PISM/GridManip/create_corner_point_301x301.pro

on *Kystpilen.*

Shell script covering the first stage of the forcing file production. This script extracts the relevant EC-Earth fields, produces the multi-year monthly means and interpolates the fields from the EC-Earth grid to the PISM grid:

/home/shs/PISM/PISMscripts/Antarctica/Forcings/Ant_DPIC4PISM/EC_Forcing_Ant.ksh

on *hpcdev.*

Shell script that converts to proper units and renames variables to comply with PISM's naming conventions:

/home/shs/PISM/PISMscripts/Antarctica/Forcings/Ant_DPIC4PISM/PISM_Forcing_Ant.sh

on *hpcdev.*

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