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D4.3: Assessment of performance of AOGCMs coupled to Greenland and Antarctic models

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1. Introduction

The initial objective of WP4 in terms of including ice-sheets into the participating ESMs was very ambitious: including Greenland, and for some models, Antarctica, proved very difficult, for different reasons:
- For some models, there was no pre-existing coupling and modelling groups faced many unexpected technical issues in attempting to make an additional model interact with the atmosphere-ocean coupled models. Changing the topography and the ice-sheet extension during a simulation rather than to set them up once and for all for a given simulation was not an easy task and in some cases created numerical instabilities which significantly slowed the developing process;
- The state of the ice-sheets is extremely sensitive to biases both in temperatures and precipitation. Some groups spent quite a long time trying to correct for the impact of these biases;
- Some groups spent considerable time just trying to hire competent developers;
- Delays were due to late adjustment of the climate models for the CMIP5 exercise, which had an impact on the available manpower.

Given these elements, all groups which had initially planned to develop a coupling of both the Greenland and Antarctic ice-sheet into their ESMs finally decided to focus on Greenland. Modelling the Antarctic ice-sheet presents the further challenge of representing large ice-shelves and the transition between grounded ice-sheets and these floating ice-shelves. Considerable work has recently been performed on this topic, e.g. in the Ice2Sea project. In COMBINE, we preferred focusing on Greenland which represented a slightly simpler case and which in our opinion was the most vulnerable of the two ice-sheets in the coming centuries. The present deliverable therefore presents the developments in including the Greenland ice-sheets into the participating ESMs. It documents each new model and its performance in simulating the pre-industrial or present climate. The different models used by the participating groups and their characteristics are given in Table 1.

Table 1. ESM and the incorporated ice sheet models (ISM) for Greenland ice sheet

Partner		CNRS	DMI	MF-CNRM	MPG
ESM		IPSL-CM5	EC-EARTH	CNRM-CM5	MPI-ESM
ESM resolution	Atm.	96x95L39	T159L62	T127L31	T63L47
	ocean	2 to 0.5° L 31	1°x1°L42	1x1°L42	GR1.5L40
ISM		GRISLI	PISM	GRISLI	PISM
ISM resolution		15 x 15 km	20 x 20 km	5 x 5 km	10 x 10 km
Coupling method		PDD	Energy Balance	Downscaling (Geyer et al 2013)	Energy balance
Snow scheme over land ice		Single layer	Single explicit snow layer scheme with liquid water reservoir and conductivity at ice/snow interface, etc.	CROCUS multilayer scheme as used in SURFEX surface scheme, including refreezing, percolation, snow aging, etc.	Explicit snow-layer scheme
ISM-Ocean interaction		Fresh water flux linked to melting	Fresh water flux due to surface and basal melt; Fresh water flux and heat transfer due to calving and direct ocean-ice interaction.	Fresh water flux linked to melting	Fresh water flux linked to surface and basal melting; Fresh water flux and heat transfer due to calving and direct ocean-ice interaction.

2. Assessment performance of AOGCMs coupled to Greenland

CNRS: IPSL – GRISLI

The coupling between the IPSL_CM5A model and the GRISLI Greenland Ice Sheet model started late as a result of:

- the late adjustment of the IPSL model in view of the CMIP5 exercise,
- initial work on implementing a more complex snow scheme into the IPSL_CM5A model which was finally not useable because it required further adjustments of the atmospheric model (adding at least one level very close to the surface to improve the computation of latent and sensible heat fluxes over the ice and the resolution of the strong inversion above ice-sheets) which implied re-tuning the atmospheric model all over again, and this was not possible close to the CMIP5/IPCC AR5 related deadlines,

- difficulties to find competent scientist to work on the coupling.

In this context, we chose to develop the simplest possible coupling procedure, to ensure we would have a working prototype by the end of the project, which we could test under pre-industrial and increase CO_2 conditions. We have built up the procedure from the coupling procedure used in the IPSL model to couple the atmosphere and the ocean, based on the OASIS coupler (Figure 1). This choice actually proved to be more difficult technically than we initially thought and we spend a lot of time on the first implementation of the additional exchanges (compared to "just" atmosphere to ocean and back) between a new model, the Greenland ice-sheet model, and the OAGCM. Nevertheless, the exchanges between the ice-sheet and the atmosphere are performed via the OASIS coupler, using a simple bilinear interpolation. The ablation at the surface of the ice-sheet is passed to the overlying atmosphere which then passes it to the ocean. For this prototype, we chose the simple positive degree day approach which is based on few variables and was easiest to implement. We also chose to work with the low resolution version of the IPSL climate model so that we could obtain the runs in time for the end of the project.

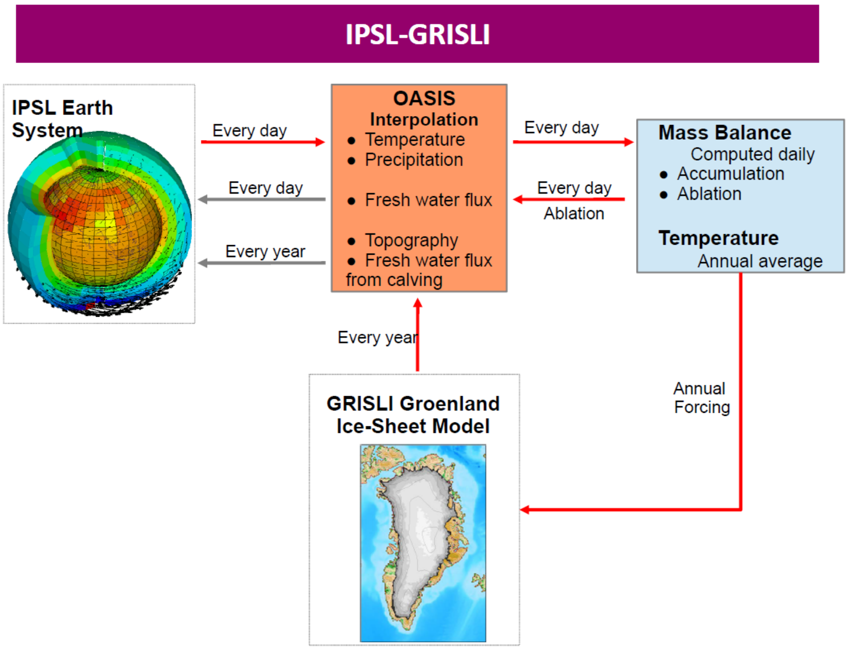


Figure 1: Schematics summarising the coupling procedure between the IPSL ocean-atmosphere model and the GRISLI Greenland Ice-sheet Model

The IPSL_CM5_LR model is characterised by quite strong biases in temperature and precipitation over and around Greenland, which are a regional aspect of the general biases of the model (Dufresne et al, 2013). These are summarised on the Figure 2: compared to present observations, the model yields temperatures which are mostly too cold in this region, especially over the ice-sheet plateau, and too warm over a narrow band around the Greenland southwest, north and northeast coasts in summer. The precipitation is too large over the northwest coast and too small over the southern part of the plateau and most notably over the southeastern coast, which is not surprising given the resolution of the atmospheric model. This results in a slightly positive bias in the surface mass balance over the southern part of the plateau, while this mass balance is correctly represented over the northern part of the plateau. As a result of the positive bias in accumulation, the mass balance over the southeastern mountains is also positively biased, while the warm summer temperature bias over the other coasts results in a negative bias in surface mass balance there.

Our first step to initialise the ice-sheet model was to perform a 50000-year-long run under such pre-industrial conditions, yielding the ice-sheet thickness shown on Figure 2, in anomaly compared to observations: the ice-sheet is too thin on the plateau and too thick on the margins. The latter bias can be related to mass-balance bias on all coasts (except the Southeastern one). The former bias cannot be related to biases in surface mass balance, since it is represented quite satisfactorily, especially over the northern part of the plateau. It therefore appears that the ice does not flow enough from the central part of the ice-sheet to the border and the ice-sheet model parameters would need to be adjusted to improve this feature. We have not attempted doing this with this version of the atmospheric model which we intend as a prototype, but this preliminary work is very useful to point towards forthcoming tasks.

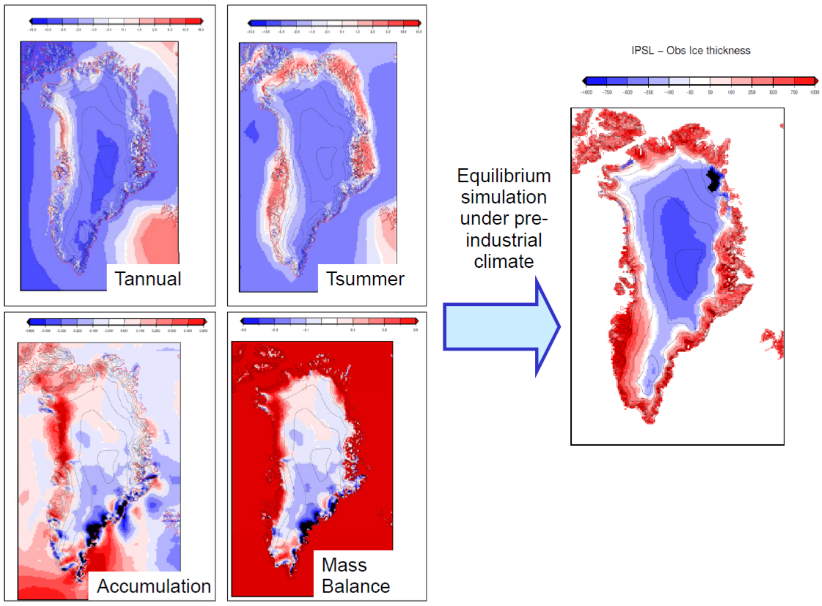


Figure 2: Summary of the IPSL model biases for Greenland climate (all fields shown are deviations of the IPSL_CM5A simulated pre-industrial climate to the observations), impact on simulated annual mean mass balance and on the thickness of the Greenland ice-sheet obtained after a long (50000 years) off-line equilibrium run.

We considered that these first results were rather satisfactory in the sense that we did not have major trends in ice-sheet size under pre-industrial climate, even though there are significant biases in this climate. We run additional off-line simulations as a preparation to the coupling, in particular to test whether including interannually variability in surface mass balance would not change the final state of the ice-sheet. This has not been found to be the case, at least for the pre-industrial cold climate. We then proceeded to the coupled model, starting from the long equilibrium pre-industrial ice-sheet and pre-industrial conditions for the IPSL_CM5A model. After 300 years of simulations, the trend is very small, as shown on Figure 3.

These encouraging results obtained for the preindustrial climate were hampered by those obtained in our subsequent abrupt4xCO2 run. Figure 4 illustrates the problem: we use the 2m air temperature for computing the surface ablation. Inversions at the surface of the Greenland ice sheet are strong in reality, but the lack of atmospheric levels close to the surface the LMDZ atmospheric model prevents the model to resolve these gradients. The diagnosed 2m air temperature does not appear to account

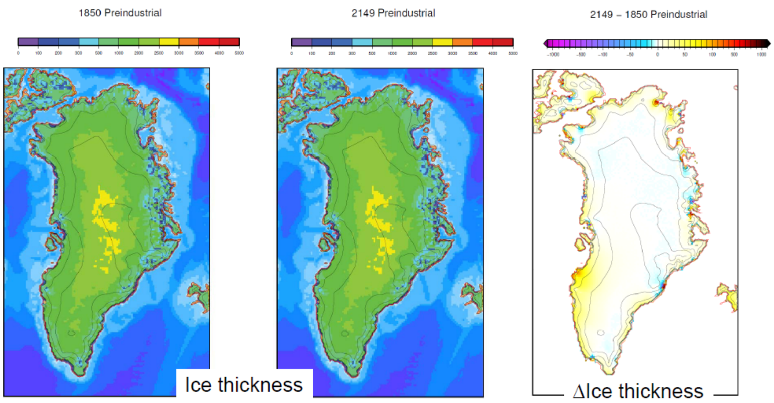


Figure 3: results from a 300 year long pre-industrial run using the IPSL_CM5A-GRISLI coupled climate ice-sheet model. The plotted variable is ice thickness, in m. From left to right: initial state of the ice-sheet (after long off-line equilibrium run using pre-industrial climate as a constant forcing), final state of the ice-sheet, difference between the two.

for these strong gradients close to the surface and this temperature is therefore closely linked to the surface temperature, which is constrained to be less than 0°C on the ice-sheet surface. This has an impact on the 2m air temperature anomalies (Figure 4), which do not warm as much over the coasts as over the surrounding ice-sheet or oceans. As the coasts are precisely the regions were the ice-sheet is supposed to melt first, this prevents the Greenland ice-sheet to melt significantly in our run. This problem could not be detected in our pre-industrial run, it only became apparent in our abrupt 4xCO_2 run. Using an energy balance method to compute the surface mass balance could help in resolving this problem, but we have to keep in mind that the surface energy balance is also strongly dependent on surface temperature, whose bias needs to be corrected anyway. So correcting this bias in the atmosphere-ice-sheet surface system will be an essential task to obtain a more reliable coupled climate-ice-sheet model. First steps have been taken with the attempt to use a more sophisticated snow model, but this too proved to be highly dependent on the existence of an atmospheric level close to the surface. The corresponding development will be carried out during the development of the next version of our atmospheric model.

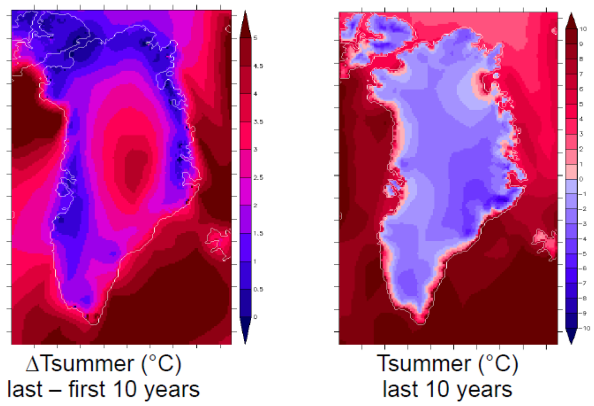


Figure 4: results from the 300 year long abrupt 4xCO2 run: summer temperatures over Greenland. Absolute values at the end of the run (on the r.h.s) and difference between the end and

the beginning of the run (on the l.h.s).

The results reported here are therefore very preliminary results. They constitute a basis for future developments, among which increasing the resolution of both the atmosphere and the ice-sheet models and improving on the mass balance calculations are the most urgent.

CNRM: CNRM – GRISLI

Our approach to include the Grisli Greenland ice-sheet model (LGGE, e.g. Quiquet et al., 2012) in the CNRM-CM5 AOGCM (Voldoire et al., 2013) was the following:

(1) Since Grisli is driven by the surface mass balance (SMB), we chose to work first on refining the representation of SMB (Greenland mean and spatial structure). However, CNRM-CM5's horizontal resolution (about 150km) is very different from Grisli's (5 or 15km), hence the need for a downscaling technique.
(2) Aiming at forcing Grisli with the downscaled mass-balance, we defined a realistic initial state of the Greenland ice-sheet under preindustrial climate.
(3) Finally, we coupled the correctly initialized Grisli model with CNRM-CM5. The AOGCM models the SMB at low resolution and transfers it to Grisli. Then the SMB is downscaled online within Grisli and used as an input of the ice-sheet model.

These points are developed hereafter in the following three sections.

1. Downscaling the SMB modelled by CNRM-CM5

SMB is used as a top boundary condition to simulate the ice flow in ice sheet models such as Grisli. As the characteristic spatial scale of some ice streams of the Greenland ice sheet is of the order of a few kilometres or less, it is essential to determine SMB at high spatial resolution, especially close to the ice margin. However, due to limitations in computing resources, contemporary GCMs such as CNRM-CM5, which are used for global climate projections, are run at relatively coarse resolution (typically 100 km for CMIP5 models). Hence the steep slopes and complex orography at the margins of the Greenland ice-sheet are not resolved. A simple horizontal grid interpolation is not sufficient to overcome this difficulty, which makes necessary the use of more complex SMB downscaling approaches. The simplest way, that we chose, since we need to run it online within CNRM-CM5, is the statistical downscaling approach.

This method consists in establishing statistical relationships between the different components of SMB (solid precipitation, sublimation and snowmelt) and predictors. These statistical relationships are based on historical (1850-2005) and future climate simulations (RCP4.5 and 8.5 for 2006-2300) performed with the detailed snowpack model CROCUS (Brun et al., 1992; Vionnet et al., 2012). Once the SMB horizontal interpolation is done, the downscaling is applied to compute SMB corrections as a function of altitude changes between the coarse (CNRM-CM5) and the fine grid

(Grisli). The corrections are computed on an annual basis. For the recent past (1989-2008) period, the Crocus simulation (included in the ensemble of simulations on the basis of which the statistical relationships were established) is in good agreement with the high-resolution simulation with MAR driven by ERA-Interim (see Figure 5, left). Moreover, Figure 5 (right) shows that the raw Greenland mean SMB change modelled by CNRM-CM5 (blue solid line), which is probably less realistic than the Crocus simulations after 2100 (red solid line), can be corrected after the downscaling approach is applied (dashed blue curve). Note that this method has been initially developed to downscale SMB to a 15-km resolution Grisli grid, but we also applied it successfully to a 5-km resolution grid. For full details about this method, see Geyer et al. (2013).

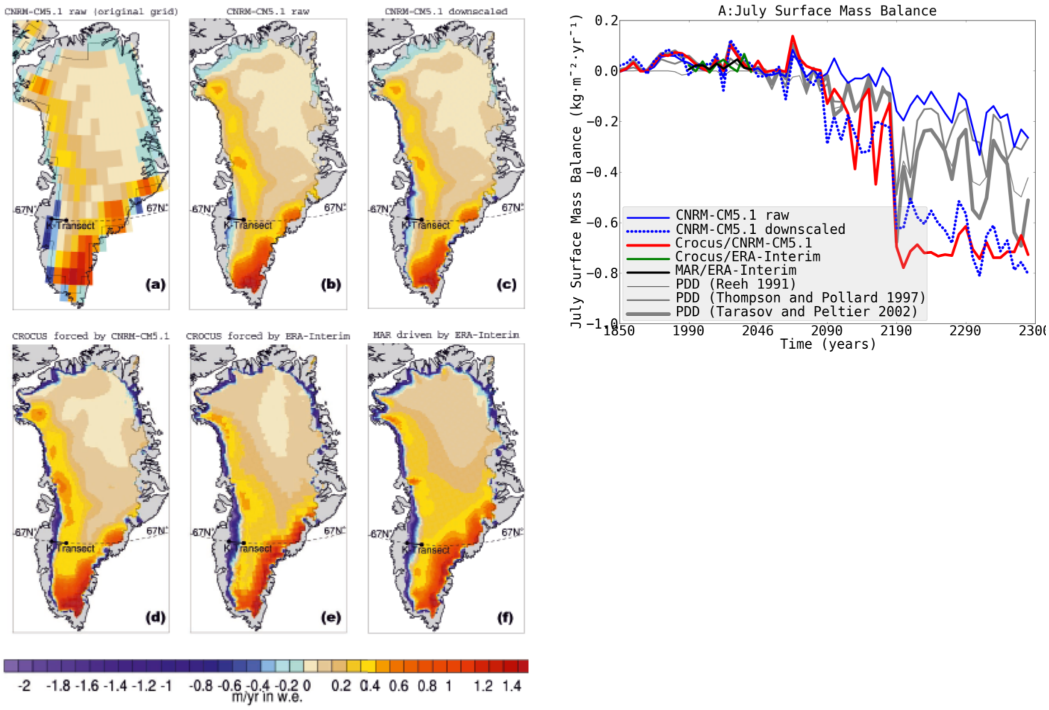


Figure 5. **Left panel:** (a) Annual mean 1989–2008 raw SMB (m yr^{-1} in water equivalent) modelled by CNRM-CM5.1 on the original 150 km grid. For 2006–2008 the RCP8.5 climate scenario is considered. The K-transect is represented as the solid, bold segment. (b) Same as (a), but for CNRM-CM5.1 SMB bilinearly interpolated from 150 km to 15 km-resolution. (c) Same as (a), but for downscaled CNRM-CM5.1 SMB. (d) Same as (a), but the SMB modelled by Crocus forced by CNRM-CM5.1 atmospheric outputs. (e) Same as (d), but for Crocus forced by ERA-Interim. (f) Same as (e), but for RCM MAR driven by ERA-Interim lateral boundary conditions. **Right panel:** Greenland-mean SMB obtained by different methods (in kg m^{-2} yr^{-1}).

2. <u>Defining a realistic initial state of the Greenland ice-sheet under preindustrial climate</u>

In a first attempt to define an initial state of the Greenland ice-sheet under preindustrial climate, we span up a 15-km horizontal resolution version of Grisli from the last interglacial (125,000 years BP), using several PDD techniques and different forcing data. We concluded that none of these methods produced a preindustrial Greenland ice-sheet that was close to the observed topography and whose contribution to global sea level rise was realistic. In agreement with LGGE, we decided to use a new version of Grisli (5-km horizontal resolution), and an entirely different spin-up technique. This complete change in strategy is the main reason why the coupling of Grisli in CNRM-CM5 was much delayed.

The new spin-up technique is based on short simulations (a few centuries) forced with downscaled SMB (as presented in Section 1). This technique originally consists in determining the basal friction map (one of the uncertain entries of ice sheet models) that allows the final state of the ice-sheet to be as close as possible to the current topography. MF-CNRM refined this technique further. After an 1850 state of the ice sheet has been obtained, an 1850-2015 simulation is performed. We impose the additional constraint that the modelled contribution of the Greenland ice-sheet to the recent sea level rise should be comparable to available estimates (we chose GRACE estimates for 2003-2011, see Figure 6).

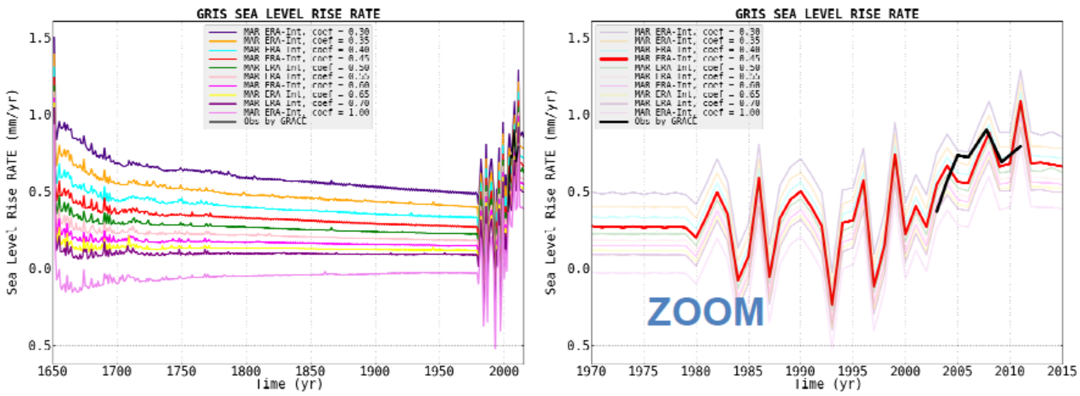
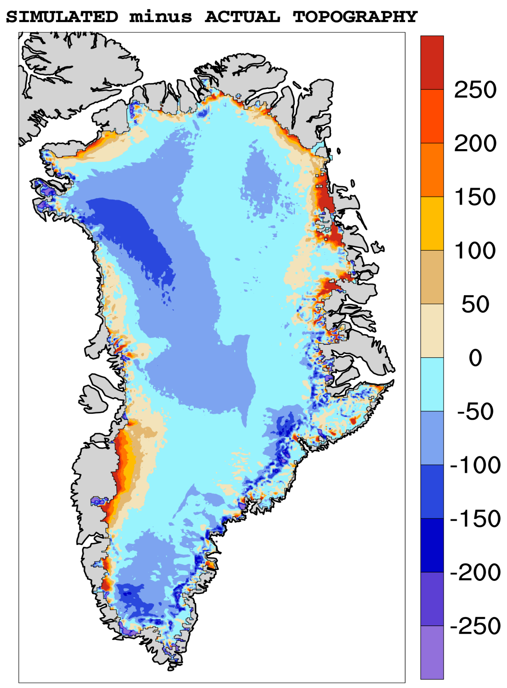


Figure 6. (top left) Yearly sea level rise rate (mm yr^{-1}) simulated by Grisli with different basal friction maps for 1650-2015. (top right) Same, but zoomed on 1970-2015. The red curve represents the Grisli simulation that was selected (hereby defining the friction map). The black curve represents GRACE estimates. (bottom right) Simulated Greenland topography for 2000 (after spin-up and a historical 1850-2000 simulation) minus present-day observed topography.



3. Coupling Grisli with CNRM-CM5

The Grisli model, tuned and initialized as presented in section 2, has been coupled with CNRM-CM5. A simulation is underway, but was not finished on 31st October 2013, due to the change in strategy we felt was necessary on a scientific point of view. Given that the feedbacks of the Greenland ice-sheet with the rest of the climate system are small, as shown by the other modelling groups involved in this deliverable, and on the basis of the results presented in Sections 1 and 2, we trust that this simulation will produce results that we will be able to be use beyond the end of the COMBINE project.

DMI: EC-EARTH – PISM

Model system description

At DMI the global climate model system including an interactive ice sheet module, EC-EARTH – PISM, has been developed to explore ice sheet-climate interactions and the impacts of evolving ice sheets on regional and global climate. The climate model in this system is the EC-EARTH v2.3 used for CMIP5 experiments (Hazeleger et al., 2012), which consists of the Integrated Forecast System (IFS) of the European Centre for Medium Range Weather Forecasts (ECMWF) as the atmospheric component, the Nucleus for European Modelling of the Ocean (NEMO) as the ocean component, and the Louvain-la-Neuve sea ice model (LIM). The ice sheet model is the 3-D Parallel Ice Sheet Model, PISM (version 0.5) (Bueler and Brown (2009), PISM, a Parallel Ice Sheet Model: User's Manual 2012, available at http:WWW.pism-docs.org), which has been used in several studies for modeling Greenland and Antarctic ice sheets.

In order to facilitate coupling to the ice sheet model, both the atmospheric and the ocean components have been modified to include the presence of explicit ice sheets. These model changes include in short:

- An explicit land ice mask is implemented in the IFS land surface scheme, so that glaciated regions are treated as exposed ice or ice with snow on top of it. Melting of land ice is introduced.
- A separate albedo parameterization is introduced for glaciated grid points so that the albedo decreases as melting occurs, allowing the model to simulate melt-albedo feedbacks.
- Explicit calving based on PISM dynamics is introduced as fresh water and heat released into ocean.

The coupling of EC-EARTH and PISM is performed at the script level as shown in Figure 7. For the forcing to PISM, the EC-ARTH soil temperature is interpolated bilinearly from the IFS grid to the PISM grid. A uniform lapse rate correction of -6.8 K/km is applied to account for height differences between the topography of the two models (Fausto et al., 2009). Surface mass balance (SMB), given by the sum of precipitation (P), evaporation (E) and run-off that includes surface melting (R), i.e., P + E – R, is calculated inside the EC_EARTH model on the IFS grid. The EC-EARTH outputted SMB is interpolated to the PISM grid using the SCRIPR conservative remapping method without any additional corrections. This approach is not able to capture the highly varying SMB within the narrow ablation zone or in the steep mountainous regions along the coastlines. The method, however, provides a very consistent treatment of the interface, which ensures the conservation of mass between the two models.

Topography and ice extent from PISM are re-gridded each model year to update the EC-Earth boundary conditions. The calving fluxes of heat and freshwater are provided to NEMO as an additional forcing, assumimg that the icebergs resulting from calving melt immediately by gaining energy from the ocean. The basal melt flux is distributed to the nearest IFS land points from where it is routed according to the standard EC-Earth scheme. The timestep for coupling the ice sheet is set to one year.

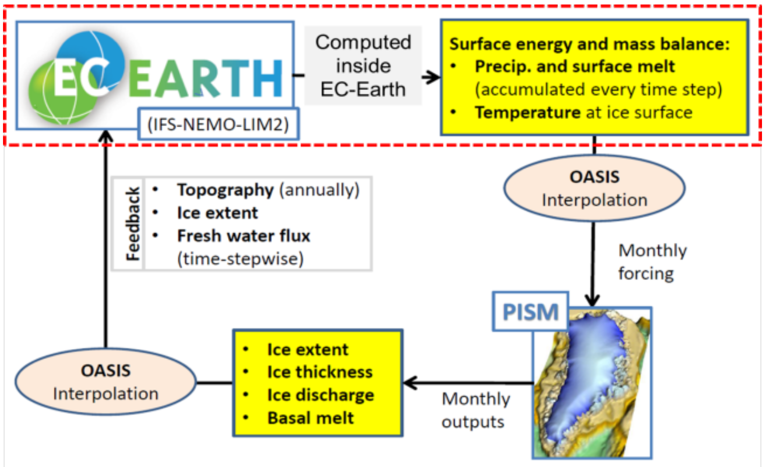


Figure 7: Schematic of the fully coupling climate – ice sheet model system, EC-EARTH – PISM. The EC-EARTH climate model computes the surface mass balance and the surface temperature (represented as soil temperature), that is given to the ice sheet model PISM as forcing. The PISM calculated ice geometry (extent and thickness), ice discharge and basal melt provide boundary conditions for EC-EARTH.

As in the CMIP5 experiments, the EC-EARTH model is configured at a spectral resolution of T159 and 62 vertical layers for the atmosphere, which is approximately 125 km horizontal resolution over Greenland, and a 1° horizontal resolution with refinement to 1/3° around the equator and 42 vertical layers for the ocean. The PISM is run at a 20x20 km grid resolution.

The EC-EARTH – PISM has been tested and evaluated for simulations including GrIS and the Antarctic ice sheet. A report for the assessment of the system for Antarctic ice sheet is under preparation at DMI and will be made public in a short time (Svendsen et al., 2013). Here we will assess the performance of this fully coupled model system with an interactive GrIS under the preindustrial conditions with the CO2 concentration of 285 ppm.

Assessment for modelling GrIS

To facilitate simulations of the climate system with the GrIS, the GrIS has been initialized use PISM by running a paleo-climatological pre-spinup based on the SeaRISE data set (Bindschadler et al., 2013) and then forcing the ice sheet with the EC-Earth pre-industrial climatology for several thousands of years until an equilibrium state was reached. The fully coupled EC-Earth-PISM system was then integrated under preindustrial conditions until it reached a quasi-stationary state for a considerably long period (preindustrial spin-up). After spin-up of the coupled system, the coupled model has been run for 350 years with constant preindustrial conditions.

Figure 8 shows the time series of the annual mean near-surface temperature (SAT) averaged over north of 60°N as simulated by the fully coupled EC-EARTH – PISM system (red lines) and the EC-EARTH CMIP5 model version (blue lines). To compare, the SAT simulated by the EC-EARTH – PISM system without the interactive ice sheet (i.e., the feedback by PISM to EC-EARTH is switched off) is also plotted as black. Further examination of the simulated circulations reveals that, un the relatively cold preindustrial conditions, there are little differences in characteristics between the simulated climatology with and without an interactive GrIS. The main differences lie mostly over Greenland and the surrounding ocean where the model is modified to adapt to the presence of the ice sheet, as shown in Figure 9.

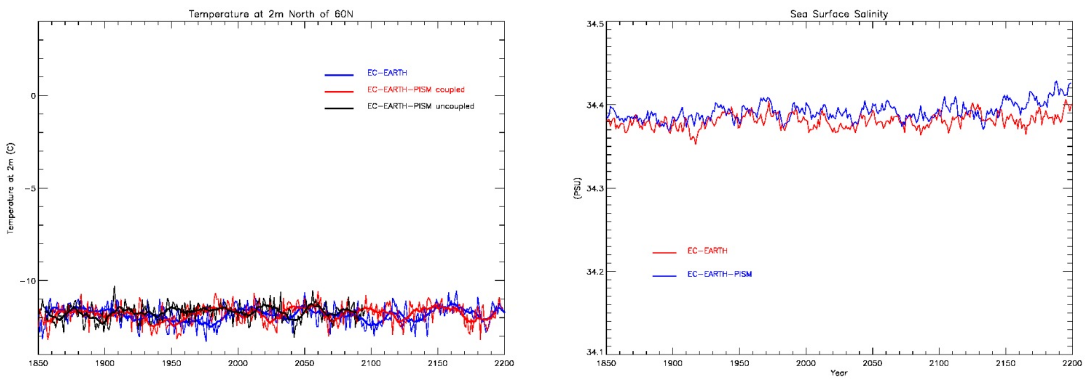


Figure 8: Annual mean near surface temperature averaged over north of 60°N (left, in C) and annual mean sea surface salinity averaged globally (right, in PSU) as simulated using the fully coupled EC-EARTH – PISM system (in blue) and the standard EC-EARTH model (in red), respectively. Also shown in right the Annual mean near surface temperature averaged over north of 60N as simulated by the EC-EARTH – PISM but without the GrIS feedbacks in black.

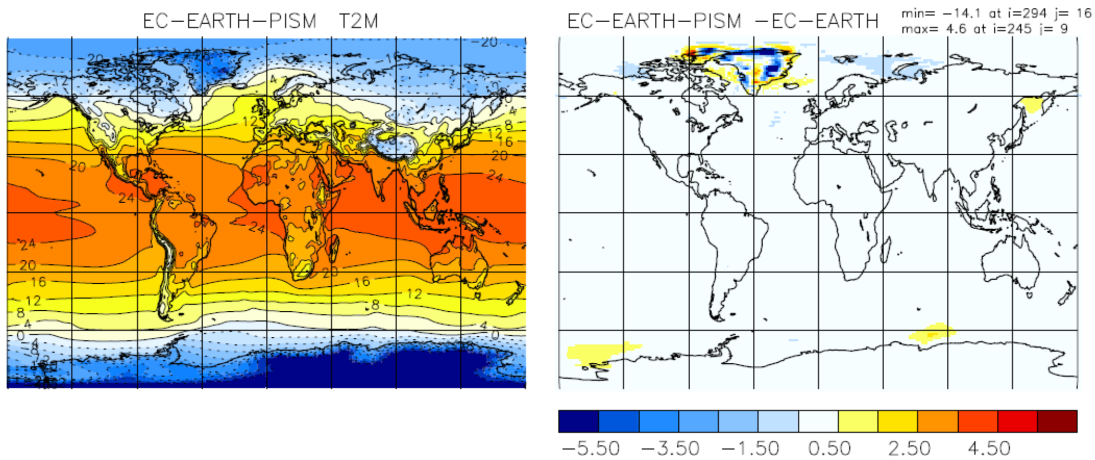


Figure 9: Annual mean SAT as simulated by the EC-EARTH – PISM system averaged over the last 50 years in the 350 year simulation (left) and its difference with respect to that simulated by the EC-EARTH CMIP5 version (right). Unit: °C.

The introduction of explicit ice sheets in EC-Earth modified strongly the modelled SMB. As seen in Figure 10, the simulated SMB has a reasonable seasonal behaviour with melting along the margins during summer and a high accumulation zone at the south-eastern coast resulting in a positive annual mean over ice sheet. The ice-sheet mass gain due to this positive SMB is mostly balanced by ice discharge (calving and basal melt), resulting in a nearly stable GrIS, as shown by Figure 11 that illustrates the time series of SMB, calving and basal melt, and total ice mass balance for the Greenland ice sheet throughout the 350 years of the coupled simulation. Theannual SMB is in the range of 286 to 713 Gt/years with an average of 510 Gt/years. This is higher than estimates in several previous studies. Vizcaino et al. (2012) used the CESM model and estimated the SMB of 390 ± 66 Gt/years under preindustrial conditions and 359 ± 120 Gt/years for the period 1960 to 2005, which is in good agreement with the observational data. Van Angelen et al. (2012) obtained the GrIS SMB of 376 ± 117 Gt/years for 1960 – 2005 in their simulation using the high-resolution regional model RACMO2. The annual calving in the EC-EARTH – PISM simulation is in the range of 389 to 1356 Gt/years with an average of 492 Gt/years. The contribution from basal melt is very small, with an average of about 17 Gt/year. The interannual variability is in general larger for the SMB than for the calving but sudden events of extraordinary high calving rates are seen in the .ong simulation. A close investigation reveal these sudden events occurred in only very limited areas (i.e., a few grid points) of the GrIS.

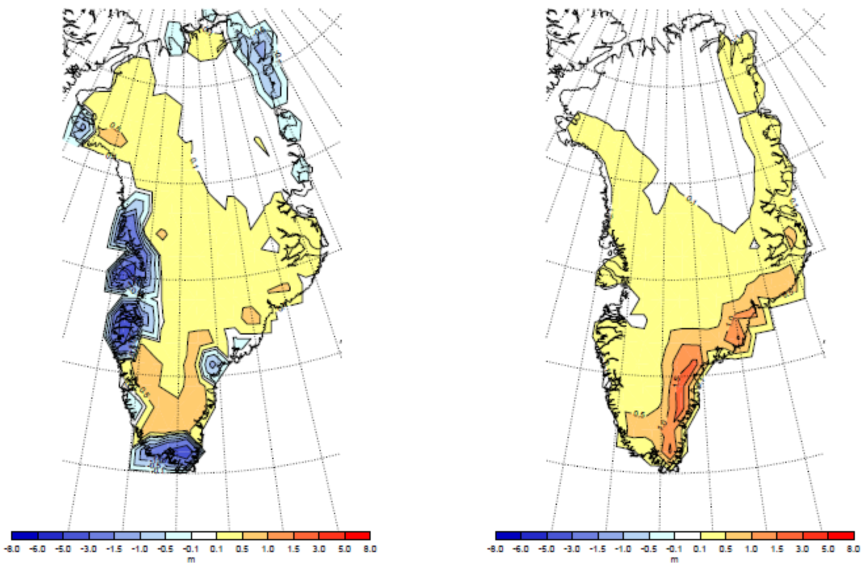


Figure 10: Summer (left) and winter (right) mean SMB averaged over the last 50 years in the 350 year simulation using EC-EARTH – PISM. Unit: m/year.

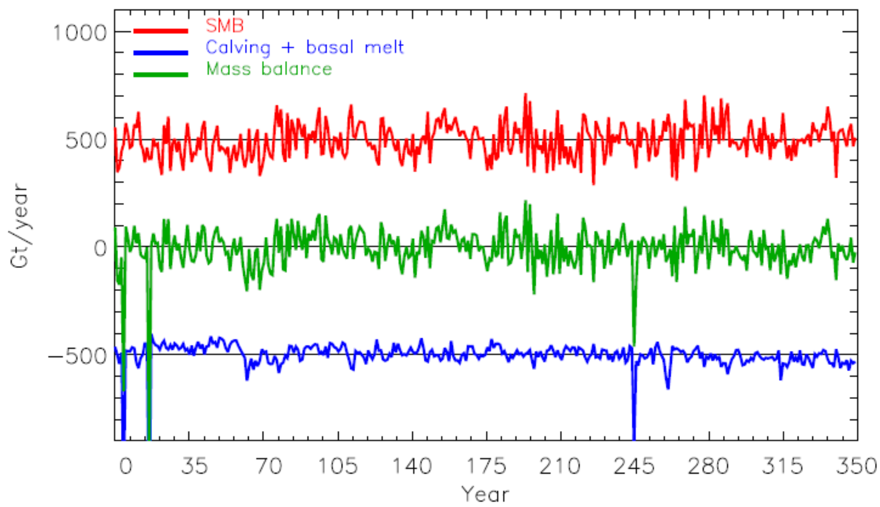


Figure 11: annual GrIS mass balance contributions from SMB, calving and basal melt as integrated over the GrIS. Unit: Gt/year.

In comparison with the ice topography from the SeaRISE dataset that is used as the initial state for the pre-spin up GrIS, the simulated GrIS is to a large degree similar in the overall pattern with the maximum ice thickness over the Greenland Summit, and a second maximum on the South Dome (Figure 12). However, simulated ice sheet covers a larger area than the observed one and extends to the coast lines in most regions, especially over the north and east of Greenland (Figure 12). Differences are also seen in the ice volumes that the modelled ice sheet is significantly larger along the edge of the ice sheet. These differences may be partly due to the presence of smaller glaciers and ice caps, which cannot be resolved in our ice sheet model and are merged with the main ice sheet in our simulation.

In summary, the dynamical ice sheet model PISM has been coupled to the EC-EARTH climate model. A multi-century simulation using the EC-EARTH – PISM coupled system under preindustrial conditions demonstrate a stable climatology similar to that of the EC-EARTH CMIP5 model version together with a stable GrIS state. The modelled ice sheet has a shape that agrees reasonably well with the observed state but its volume and area seems too large. One possible cause for the too large GrIS may be due to too high SMB in our model in comparison with other studies, although the SMB has a reasonable seasonal and geographical pattern. A further assessment of the EC-EARTH – PISM performance and its comparison with the MPI-ESM coupled to PISM is given below.

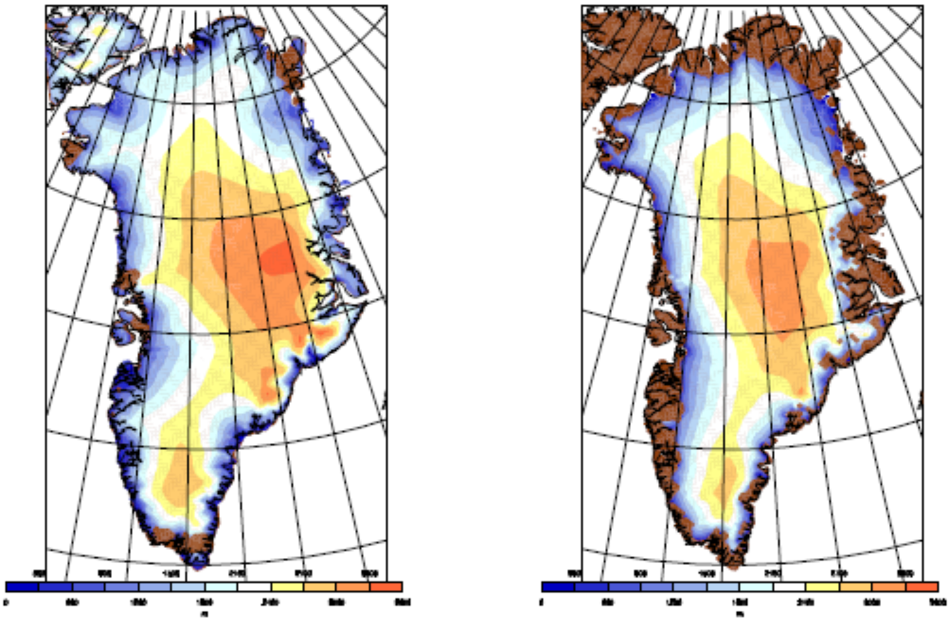


Figure 12: Ice thickness (m) averaged over the last 50 years in the 350 year EC-EARTH – PISM simulation (left) and based on the SeaRise dataset (right).

MPI: MPI-ESM – PISM (and joint comparison with DMI EC-EARTH – PISM)

In the framework of COMBINE both the EC-EARTH and MPI-ESM model systems have achieved a state, where a two-way coupling scheme between the Greenlandic ice sheet and the climate system model has been implemented that conserves mass. In addition, these systems exploit surface mass/energy balance models (EBM) of different sophistication levels that avoid the still usually used parameterization of melting commonly known as positive degree day (PDD) method (Hock, 2003; Reeh, 1991). Partners from MPI and DMI are taking a closer look at the common characteristics and differences between these two systems. One system is EC-Earth coupled to the ice sheet model PISM as described above, where the EBM is calculated within EC-Earth during the climate simulation, while in the other system the MPI-ESM is coupled to a slightly older version of PISM, where the EBM has been computed after the earth system model simulation has been performed. Here we report the common analysis on the assessment of these two model systems in modeling the GrIS. First we describe in few words how the Greenland ice sheet is represented in comparison to the observed state. Afterwards the reaction of the ice sheet under a strongly changing climate is evaluated briefly. The detected huge different in the ice sheets' reaction under a strongly changing climate between the model systems is strongly related to the utilized albedo parameterization.

Model descriptions

The coupling schemes of both models are depicted in Figure 13 and a summarization of the main characteristics follows below.

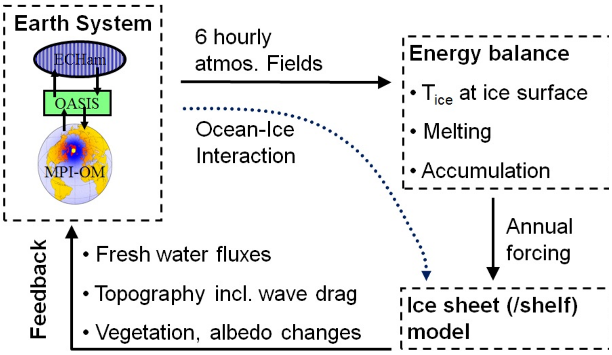


Figure 13: Sketch of coupling schemes of the considered fully two-way coupled ice sheet-climate/earth system models MPI-ESM in which the surface mass balance is calculated after the earth system simulations have been performed. Ocean-ice interaction (Holland and Jenkins, 1999) is also implemented in the MPI-ESM system.

As described in the previous section, the EC-Earth global climate model (Figure 7) has been coupled to the Parallel Ice Sheet Model (PISM, Version 0.5) at DMI. The atmospheric model has a spectral resolution of T159 and 62 vertical layers, which is approximately 125 km horizontal resolution over Greenland The ocean model has a 1.0 degree horizontal resolution and 42 vertical layers and the 3D Parallel Ice Sheet Model PISM was run at a 20x20 km grid resolution. An explicit ice sheet scheme was implemented in EC-Earth to improve the calculation of surface mass balance and thereby facilitate the direct coupling to the ice sheet model. The ice sheet model is forced with SMB and temperature fields from EC-Earth and the ice discharge, basal melt and ice cover (extent and thickness) calculated by PISM is used as boundary conditions for EC-Earth.

The MPI-ESM is based on the actual CMIP5 earth system model from the Max Plank Institute for Meteorology, a modified version of the Parallel Ice Sheet Model, based on version 0.3, as well as a mass and energy balance model. The mass and energy balance model has been enhanced compared to the former version (Vizcaino et al., 2010) by the implementation of a more sophisticated albedo scheme, consideration of rain induced melting, the temporal evolution of the density field, and the vertical movement of properties (see COMBINE report D7.7 for details).

During one coupling cycle (Figure 13) the MPI-ESM is run for one year and delivers 6-hourly atmospheric output, which drives the mass and energy balance model. Its results together with the oceanic hydrographic fields are the boundary conditions for the ice sheet model, where only the MPI-ESM system takes advantage of the ocean-ice interaction (Holland and Jenkins, 1999). A waxing or waning ice sheet epitomizes the feedback to the earth system model. These feedbacks are fresh water fluxes into the ocean, topographic changes of the ice geometry and the corresponding changes in the surface properties of the land surface.

Comparison of the simulated Greenland ice sheet against observations

In both fully coupled systems the Greenland ice sheet (GrIS) is almost in equilibrium under the pre-industrial climate state (Figure 14); this state is the control run and represents the base line. Quasi-equilibrium means here, that the ice volume is almost constant and the corresponding ice loss rates are nearly zero. In both models the total ice volume of the Greenland ice sheet exceeds the contemporary ice volume (EC-Earth: $3.84 \cdot 10^6$ km^3; MPI-ESM: $3.47 \cdot 10^6$ km^3; Reference: $Vol_{ice} = 2.93 \cdot 10^6$ km^3 which corresponds to $2.67 \cdot 10^6$ Gt of ice, see also Table 3). This additional volume in the simulations is far more than that from observations deduced accelerated ice loss rate between -267±36 Gt/year (Rignot et al., 2008), -238±29 Gt/year (Sasgen et al., 2012) and -142±49 Gt/year (Shepherd et al., 2012). These observed rates correspond to a mean sea level rise between 0.4 mm/year and 0.7 mm/year. Therefore these ice volume differences are significant and cannot be explained by internal variability, because we would need more than one and a half millennia of continuing currently observed accelerated ice loss for the models to reach the current observed state.

Table 3. Basic characteristic of the Greenland ice sheet in the two-way fully coupled model systems EC-Earth and MPI-ESM against observational estimates. The sea level equivalent has been computed by applying an ocean area of $A_{ocean} \approx 3{,}61 \cdot 10^{14}$ m^2 (Gill, 1982, p.597) together with the ice volume under the consideration of density difference between ice (910 kg/m^3) and ocean water (1027 kg/m^3).

Source (Model name/Reference)	Ice volume, Vol_{ice} (10^6 km^3)	Sea level equivalent (m)	Ice covered area, A_{ice} (10^6 km^2)
EC-Earth	3.84	9.40	2.3
MPI-ESM	3.47	8.52	2.2
Reference	2.93 (Bamber et al., 2001)	7.19	1.8 (Kargel et al., 2012)

In the simulations of both models the ice sheets cover a far too large area (EC-Earth: $2.3 \cdot 10^6$ km^2; MPI-ESM: $2.2 \cdot 10^6$ km^2; Reference: $A_{ice} = 1.8 \cdot 10^6$ km^2, see also Table 3) and they have expended in most regions until the coast line. This is not in agreement with observations for example in the northern part of Greenland, which is ice sheet-free (Figure 12, right). However in this region ice caps and glaciers are present, which cannot be resolved by our ice sheet model and are merged with the ice sheet in our simulations. However, even considering the widest extent obtained from observations, the model ice sheets are too large. This is a common problem bequeathed from the standalone (pre-) spin up of the ice sheet model over the course of at least several millennia. It is presumably related from even slight inconsistencies in the forcing fields and simplified representation of processes in the current generation of ice sheet models. Given that our ice sheet models have been driven solely by forcing fields obtain from simulations of the pre-industrial climate state, a divergence has to be expected. To conclude, there are significant differences but the Greenland ice sheet is reasonably represented.

The ice sheet's reaction under the pre-industrial and abrupt4xCO2 climate scenarios

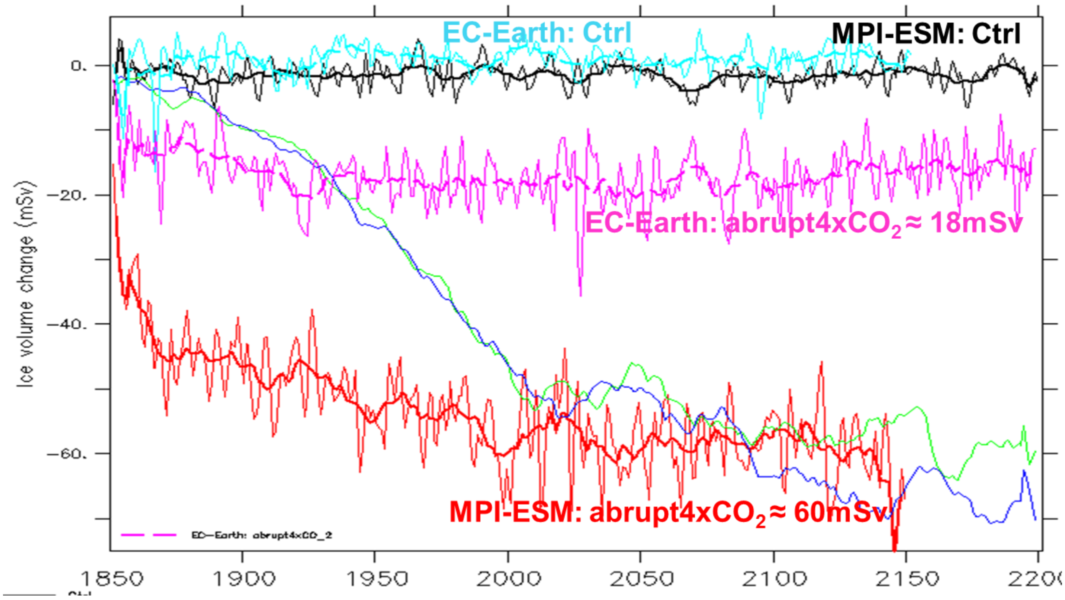


Figure 14: Computed net ice loss rate for both fully two-ways coupled ice sheet-climate model systems in the COMBINE. The ice loss rates are nearly zero for the control run (pre-industrial climate state) for the EC-Earth system (light blue/cyan) and the MPI-ESM (black line). Under the scenario abrupt4xCO2 the ice loss rates for the EC-Earth system is approximately 18 mSv (magenta line) and reaches almost 60 mSv for the MPI-ESM (red line). For these above described time series, the line lines represent yearly values while the thick lines are running means of 13 years. The tiny blue and green lines highlight the loss rate within the MPI-ESM under the scenario where the atmospheric carbon dioxide concentration raises by 1% per year until four-times the pre-industrial value has been reached; afterwards the concentration is kept constant. The green line considers the full two-way coupling, while the green line represents the response of the ice sheet without any feedback into climate model. Both latter lines are running means of 13 years. Please see the last reports for further details of the 1% scenarios.

These two systems have been exposed to the abrupt4xCO2 scenario, where the atmospheric carbon dioxide concentration skyrockets from the pre-industrial value to four-times the pre-industrial concentration at the start of the model year 1850. Afterwards the atmospheric concentration is held constant. As a result the atmospheric radiative forcing climbs sharply globally. As a consequence the mass balance of the Greenland ice sheet reacts almost immediately. The warmer climate is accompanied by an enhanced hydrological cycle (Held and Soden, 2006), which increases precipitation over Greenland and enhances the accumulation. In some limited regions at higher altitude this increased accumulation enlarges the ice thickness, but in general the ice sheet height decreases because the melting rises steeply within a course of years (not shown, please see former COMBINE reports). As a consequence the ice sheet's mass balance turns negative and the ice sheet starts to shrink (Figure 14). If we compare the ice loss rates of the Greenland ice sheet between the models, the mass loss rates for the EC-Earth system reaches an quasi-equilibrium-like loss rate of almost 20 mSv (1 mSv = 10^6 m(WE)^3/s), while the

MPI-ESM losses fresh water with a rate of approximately 60 mSv; an about three times higher ice loss than the EC-Earth system.

What causes the difference between EC-Earth and the MPI-ESM

The main candidates for this huge difference are
1. Different pre-spin up procedures of the ice sheet before they have coupled with the climate models.
2. Ice sheet-ocean interaction, which has only been implemented in the MPI-ESM system.
3. Diverging climate over Greenland between both systems.
4. Albedo parameterization in the applied mass and energy balance calculation models.

These coupled model systems have been spun up differently:
- EC-Earth
    1. Simulation of the last glacial-interglacial cycle
    2. Followed by an equilibrium climate forcing of EC-EARTH for approximately 100 thousand years
- MPI-ESM
    1. Latin Hyper Cube (McKay et al., 1979; Ye, 1998) simulations with 64 ensemble members obtaining under varying five parameters (lapse rate, enhancement factor, PPD factor for snow and ice, as well as temperature standard deviation in the PDD formulation (Calov and Greve, 2005) the best member of simulations covering the last glacial-interglacial period.
    2. The best performing members has been branched off at 10 kyr BP and driven by offline energy balance calculations. One member has been selected for the following coupling with the earth system model.
    3. Asynchronous coupling between ice sheet and earth system model until “1850” has been reached, whereby more than hundred years synchronous coupling between ice sheet and climate model has been applied.

The different pre-spin up procedures certainly determines the physical settings of the ice sheet, like the thermal distribution within the ice body. The temperature itself controls via an Arrhenius equation for viscosity of the ice, which determines the stiffness and ultimately the susceptibility to a changing climate. However the quite instant response of the mass balance questions the contribution of the initial state. In addition the surface mass balance in the MPI-ESM, for instance, changes by approximately 65 mSv (not shown, please inspect former COMBINE deliverables and reports), which indicates a strong control by the surface mass balance.
The contribution of the ocean-ice sheet interaction in the MPI-ESM system balances under the pre-industrial climate the surface mass balance excess in the interior of Greenland. Under the abrupt4xCO2 scenario the ocean-ice interaction ice loss rate drops from 7 mSv to 3 mSv, while at the same time the surface mass balances raises by some 65 mSv and drives therefore the ice loss. Therefore we can exclude the ice ocean interaction contribution, which is only implemented in the MPI-ESM system, as the decisive factor for the difference between EC-Earth and MPI-ESM.

To get a handle about the competing factors of the climate influence and the albedo parameterization, we have performed two offline runs with the mass and energy balance code of the MPI-ESM system, using climate forcings obtained from the MPI-ESM model. These runs start from an identical initial state. The only difference is the applied albedo parameterizations in the mass and energy balance model: the MPI-ESM system's standard parameterization or the EC-Earth albedo parameterization. In terms of melting, the main difference is how low the albedo value can drop: In the EC-Earth system the lowest value is 60%, while for the MPI-ESM the albedo can drop to 55% or 38% in areas where snow or ice surfaces, respectively, experiences melting.

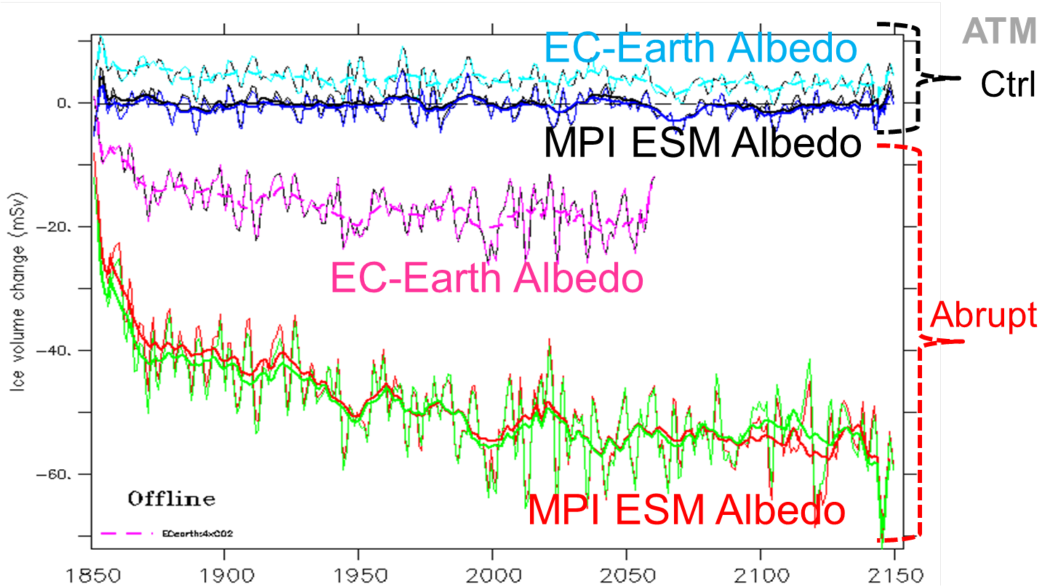


Figure 15: Offline simulations of the Greenland ice sheet loss rate utilizing atmospheric and oceanic forcings obtained from the MPI-ESM system only. All these simulations have been performed with the MPI-ESM mass and energy balance model coupled to the ice sheet model PISM. In the mass and energy balance model either the standard albedo description of the coupled MPI-ESM-ice sheet system has been applied (MPI ESM Albedo) or the albedo parameterization of the EC-Earth system has been used (EC-Earth Albedo). The black and light blue lines correspond to the simulations under the pre-industrial atmospheric and oceanic forcings (control run: Ctrl), while the red and magenta lines symbolize the corresponding simulations under the abrupt4xCO2 (Abrupt) scenario. To identify the influence of the oceanic forcing, which is only implemented in the MPI-ESM system, we permutated the ocean forcing for the MPI-ESM offline runs: The dark blue denotes the run where the atmospheric forcing comes from pre-industrial climate while the oceanic forcing originates from the abrupt4xCO2 scenario. The green line represents the run, where the abrupt4xCO2 scenario delivers the atmospheric forcing while the oceanic forcing characterizes the pre-industrial oceanic influence. Thin lines represents yearly values while tick lines illustrates running means of 13 years. All these simulations start from the same initial conditions. For further details the reader refers to the text please.

First let's inspect the conditions under the control run climate. The ice sheet is close to equilibrium using the MPI-ESM albedo (Figure 15, black line), while under the EC-Earth albedo scheme it growths due to a positive net mass balance rate of approximately 5 mSv (dashed light blue/cyan line). In both cases the ocean forcing determined under the control run has been applied. If we keep the atmosphere forcing unchanged (pre-industrial climate) under the MPI-ESM albedo and apply the ocean forcing obtained during the abrupt4xCO2 run, the ice sheet mass balance does hardly change (dark blue line). This confirms the above indicated minor importance of the ice-ocean interaction for the here considered model setups in the time frame of several centuries.

Under the abrupt4xCO2 forcing the surface mass balance turns clearly negative within a few years for both albedo schemes. Under the MPI-ESM albedo scheme we obtain a new quasi-equilibrium loss rate of approximately 60 mSv (red line). If we replace for the MPI-ESM setup the abrupt4xCO2 ocean forcing against pre-industrial control run forcing, the melting rate are initially slightly larger and finally slightly lower but still within the model variability (green line). This again confirms that the strength of the ocean forcing contributes only marginally to the detected strongly ice loss rates under the abrupt4xCO2 scenario.

Using the same abrupt4xCO2 forcings and applying the EC-Earth albedo scheme, gives an ice loss rate of almost 20 mSv (magenta line). This is a third of the run under the MPI-ESM albedo scheme. This results highlights that changing the albedo can explain to a large extent the difference between the fully coupled EC-Earth and MPI-ESM systems. Since the albedo determines how much of the incoming radiation – the principle driver of melting – is available for melting, this result is consistent with our physical understanding of the system. In addition it highlights undoubtedly that the albedo can be understood as the gatekeeper controlling the susceptibility of the land-based cryosphere under a changing climate.

Conclusion

Two two-way coupled ice sheet-climate system models have been compared. These use mass conserving coupling schemes, which determine the surface mass balance through mass and energy balance calculations at the ice surface and explore therefore the principle driver of melting: incoming radiation. The models reproduce reasonable well the contemporary Greenland ice sheet. The simulated Greenland ice sheets are in a quasi-equilibrium under the pre-industrial climate state, hence the ice sheets' reaction detected under the abrupt4xCO2 scenario are an expression of the applied climate change. The ice loss rates between the EC-Earth (approximately 20 mSv) and MPI-ESM (60 mSv) differ significantly by a factor of three. Four possible causes have been discussed to explain this huge difference: ice sheet model initialization, ice-ocean interaction that is only implemented in the MPI-ESM, climate state in the Greenland region and the albedo parameterization for ice and snow.
Offline coupled energy balance-ice sheet simulations, which differs only in the albedo parameterization, under identical forcing for both the pre-industrial and the abrupt4xCO2 climate states, have revealed that the albedo parameterization explains predominantly the huge difference in ice loss rate under the abrupt4xCO2 scenario. Albedo is a crucial element of the mass and energy balance calculations. In this study the mass and energy balance model does not only differ in the albedo parameterization but considers in contrast to the EC-Earth system a multi-layer snow scheme that takes percolation and refreezing into account and includes the temporal evolution of the density structure, for instance. Considering all these differences the reproduction of the EC-Earth melting rates seems to be suggestive for the following conclusions.

- The effects of percolation of liquid water into the snow pack, where it eventually refreezes and changes the thermal state, are deemed to be important. However in comparison to an adequate albedo representation these effects might be of minor importance when the albedo parameterization is not well chosen. Since the snow or ice states impacts the albedo, under an adequate albedo parameterization these processes are expected to be highly important.

- In glaciated terrain the correct representation of the snow and ice albedos is essential to determine the future behavior of the land-based cryosphere.

3. Design considerations for a coupled Antarctic ice sheet model

The Greenland ice sheet is coupled to climate models because changes in its albedo and topography directly influence the flow of the northern hemisphere mid-latitude westerlies. Tip jets around Cape Farewell and the North Atlantic storm tracks, both driving atmosphere-ocean heat exchange, are determined in part by the shape of Greenland. In addition freshwater input to the Labrador Sea, either directly or transported from East Greenland via the subpolar gyre, can reduce that branch of the overturning circulation. A reduction of the Labrador Sea branch will transfer more of the overturning to the Greenland Sea branch. Thus Greenland influences both the atmospheric and oceanic circulation in a manner which impacts on Northern European climate.

The role of Antarctica in the climate system is less certain. Increased melt of the ice will stratify the local ocean reducing atmosphere-ocean heat exchange and uptake of CO_2 and reducing the upwelling of nutrients to the marine ecosystem. In addition the freshwater input will reduce the formation of Antarctic bottom water and perhaps strengthen the North Atlantic overturning circulation. However, the main contribution is the possibility of a large contribution to future sea-level rise form the West Antarctic ice sheet (Mercier, 1978; Vaughan, 2008). An oceanographic understanding of the role of the Antarctic ice sheet in the climate system is not complete without coupling an ice sheet model in to GCMs. However, there are unique technical problems associated with Antarctica, associated with the floating ice shelves, which are not present (significantly) for Greenland.

The principle means of loss of Antarctic ice mass is from the basal melting of the floating ice shelves. Oceanic warming leads to increased melt and ice shelf thinning, which disturbs the force balance sustaining the ice shelf. Thinning can lead to grounding line retreat and hence increased mass flow from the ice sheet interior (speed-up of the ice streams). If the bedrock slopes downwards inland from the grounding line, a situation prevalent for the marine ice sheet of West Antarctica, the ice sheet is unstable and grounding line retreat and ice mass lost can run away. It is estimated that 3.3m of sea level rise may occur as a consequence of this effect, although the timescale over which this rise will occur is unknown. Representing these processes require several technical innovations before they can be adequately modeled.

3.1 Ice shelf cavity.

Representing the circulation (barotropic streamfunction) within the ocean cavity beneath an ice shelf is key to understanding and depicting the basal melt. The ideal solution would be to have the cavity intrinsic to the ocean model. This has been achieved with unique models (Meccia et al., 2013; Mimura et al., 2013), and for a standard Z-level model (Losch, 2008). It is an adaptation of the formulation of Losch (2008) that holds most promise to be adopted for generically for all ice shelves in an ocean model. To do so require a model horizontal resolution sufficient to resolve the ice shelf cavities, 1º x 1º is sufficient for the major ice shelves, and ¼º x ¼º for a complete simulation. In addition a sufficient vertical resolution is required to resolve the slope of the ice shelf base at ~600m depth. A maximum thickness of the model ocean layers of 60m is required, achievable by tuning the Z-level distribution or a model with at least 75 vertical levels (e.g. NEMO). If the ocean model does not satisfy these criteria then an alternative is a simplified model which represents just the basal ocean-ice interface (e.g. Holland & Jenkins, 1999), basal plume model, which can be built directly into the ice sheet model.

All the ice shelf cavity models, described above, assume constant ice shelf cavity geometries. The melt rate will be passed to the ice sheet model, which then adapts the ocean-ward flow rate to replace the ice shelf mass loss. To represent ice shelf thinning/thickening and grounding line migration adaptive cavity geometry is required. This would require a change to the ocean boundary conditions, which can be achieved through the use of partial ocean cells, however, this approach is numerically complex and is yet to be achieved.

A further problem with the implementation of ice shelf cavities in generic ocean models is that the model bathymetric boundaries halt at the ice shelf edge, which is treated as a land mask. An extension of the land mask under the ice shelves is feasible, but the longitude lines converge to the poles and the ocean CFL limit (necessary condition for convergence while solving certain partial differential equations) will be exceeded. A solution is to create an extension to the ocean grid which has equal area cells.

Neither the ocean model cavities nor the basal plume model have yet been adapted generically for any ice shelf, and this is work in progress. To complete this stage, a database of cavity bathymetry and ice shelf thickness is required (Timmerman et al., 2010).

3.2 Grounding line migration.

A model representation of grounding line slope instability is key to depicting the potential loss of marine ice sheets (e.g. West Antarctic). The grounding line dynamics has been solved analytically (Schoof, 2007), but requires a very fine model grid (~500 m) to do so numerically (Vieli & Payne, 2005). Solutions are to either represent the increased resolution through an irregular grid or a regular adaptive grid (Cornford et al., 2013).

The migration of the grounding line presents a problem to the ocean model as it changes the land mask, a process which cannot be achieved dynamically as doing so results in ocean stability issues. However, high resolution models have been using a shallow water approximation called wetting-drying to depict tidal processes (Oey, 2004). There is potential to adapt this approximation to allow gradual changes in the ocean land mask. However, it may require a merging of ocean bathymetry and land topography data sets to permit a smooth transition, applicable both to grounding line migration and model paleo simulations of sea level rise.

3.3 Summary

The simulation of the ocean interaction with the Antarctic ice sheet, through ice shelf basal melt, remains technically challenging. There are several elements of the system which remain unresolved for generic ice shelves in GCMs – an adaptive shelf cavity shape and an adaptive grounding line. However, these processes are not essential in depicting near future (<100 years), melt-water induced, changes to the Southern Ocean.

The element which is most uncertain in models is the performance of the Southern Ocean itself, with many models having warm SST biases (1-2 K) and lacking the resolution to resolve ocean eddies and hence poleward heat transport. The inability of the current generation of climate models to represent the processes on the continental shelf slope, may well compromise the required depiction of warm intermediate water emerging onto the continental shelf and available to melt (thin) the ice shelves. Thus, even if the perfect ice shelf cavity model were available, it is likely that the simulation of the observed ice shelf thinning would be compromised. Oceanographers need to attend to improving the Southern Ocean processes in parallel with the coupling of ice shelf and ice sheet models.

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