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DMI Report 21-17
Including a dynamic Greenland Ice Sheet in the EC-Earth global climate model

Final scientific report of the 2020 National Centre for Climate Research Work Package 1.1.1, Indlandsisen

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Indhold

Abstract

Recent observations have indicated rapidly increasing mass loss from the Greenland Ice Sheet. To explore the interactions and feedbacks of the ice sheets in the climate system, it is important to develop coupled climate-ice sheet models. The integration of an ice sheet model in a global model is challenging, and, currently, relatively few climate models include a two-way coupling to a dynamical ice sheet model.

In this work package, we have continued developing the coupled ice sheet-climate model system comprising the global climate model EC-Earth and the Parallel Ice Sheet Model (PISM) for Greenland. The new model system, EC-Earth3-GrIS, is upgraded to include the recent model versions, EC-Earth3 and PISM version 1.2. In addition, a new module has been developed to handle the exchange of information between the ice sheet model and EC-Earth using the OASIS3-MCT software interface. The new module reads output from the ice sheet model and exchanges the fields with the relevant EC-Earth components. The ice sheet mask and topography are provided to the atmosphere and land surface components. The heat and freshwater fluxes from basal melt and ice discharge are provided to the ocean module via the runoff-mapper that routes surface runoff into the ocean. The new module also prepares the forcing fields for the ice sheet model, i.e., subsurface temperature and surface mass balance. These fields are calculated in EC-Earth3 using a land ice surface parameterization, developed explicitly for the Greenland ice sheet. The parameterization contains a responsive snow and ice albedo scheme and includes land ice characteristics in the calculation of heat and energy transfer at the surface.

Experiments with and without the land ice surface parameterization have been carried out for preindustrial and present-day conditions to assess the influence of the surface parameterization on the calculated surface mass balance. The results show that the ice sheet responds stronger and more realistically to forcing changes when the new surface parameterization is used.

Besides the model development, the results from experiments with the first model version, EC-Earth-PISM, have been analyzed. These results stress that a decent surface scheme with a responsive snow albedo scheme is necessary for investigating mass balance changes of the Greenland Ice Sheet. Overall, our results indicate that the feedbacks induced by the interactive ice sheet have a significant influence on Arctic climate change under warming conditions. In warm scenarios where the CO_2 level is raised to four times the preindustrial level, the coupled model has a colder Arctic surface, a fresher ocean, and more sea-ice in winter.

Resumé

Observationer viser, at Indlandsisen på Grønland taber masse i et stadigt højere tempo. For at kunne undersøge samspillet mellem klimaet og Indlandsisen og de tilhørende feedback-mekanismer, er det nødvendigt at udvikle klimamodeller, der indeholder en dynamisk iskappe.

Det er en udfordring at integrere en iskappe-model i en global klimamodel, og der findes fortsat kun få klimamodeller, der er fuldt koblede til en dynamisk iskappemodel.

I denne arbejdspakke, WP1.1.1, har vi fortsat udviklingen af det koblede modelsystem, der består af den globale klimamodel, EC-Earth, og iskappemodellen, PISM. Det nye model-system, EC-Earth3-GrIS, er blevet opgraderet så det nu indeholder de nyeste modelversioner, EC-Earth3 og PISM v.1.2. Desuden, er der udviklet et nyt modul, der udveksler information mellem EC-Earth3 og

iskappemodellen ved hjælp af den nyudviklede software OASIS3-MCT, der i forvejen anvendes i EC-Earth3.

Det nye modul læser output fra iskappemodellen og udveksler information med de relevante komponenter i EC-Earth: udbredelsen af iskappen og dens topografi sendes til atmosfære/jordoverflade-modulet, og ferskvandsfluxen fra kælvning og afsmeltning fra undersiden af iskappen ledes ud i havet. Det nye modul forbereder også den forcering, der skal bruges til at køre iskappemodellen. Forceringen består af temperaturen i isens overflade og overflademassebalancen. Disse felter beregnes i EC-Earth3 ved hjælp af et overfladeskema, der er udviklet specifikt for Grønland. Det indeholder et fleksibelt albedo-skema for sne og is og medtager desuden isens karakteristika i beregningen af energibalancen ved overfladen. Resultater fra eksperimenter med og uden det nye overfladeskema viser, at iskappen reagerer mere realistisk på ændringer i forceringen, når det nye overfladeskema anvendes.

Ud over modeludviklingen, har vi i arbejdspakken analyseret resultater fra eksperimenter med den første modelversion, EC-Earth-PISM. Disse resultater viser, at det fleksible sne-albedo skema er nødvendigt for at kunne modellere ændringer i Grønlands massebalance. Samlet set viser resultaterne, at feedbackmekanismer har en betydelig indflydelse på klimaændringerne i Arktis under varmere betingelser. I scenarier, hvor CO_2-niveuet øges til fire gange det før-industrielle niveau, er temperaturen i Arktis lavere i den koblede model, havet er ferskere og der er mere havis om vinteren.

Introduction

The Danish National Centre for Climate Research (Nationalt Center for Klimaforskning, NCKF) has completed its first year in 2020. It has been a source of funding for the Danish Meteorological Institute and collaborators for climate change related research during this year. The 18 work packages fall under 4 general themes:

1. Arctic and Antarctic Research
2. Climate change in the near future
3. Use of climate data
4. Support for the IPCC

WP1.1.1 (Indlandsisen) focuses on the role of the Greenland ice sheet in the climate system and thereby contributes to themes 1 and 4. The main task for WP1.1.1 is the coupling of the EC-Earth global climate model (Hazeleger et al., 2012; Döscher et al., 2021; submitted) to the Parallel Ice Sheet Model (PISM; Bueler and Brown 2009; Aschwanden et al., 2019; http://www.pism-docs.org) for Greenland. The coupled model system provides an internally consistent tool for studying the interactions between different components in the climate system, including the connections between Greenland surface mass balance, iceberg discharge, Arctic sea-ice, and ocean circulation.

WP1.1.1 has common goals with WP1.1.3 (IskappeANT), which couples EC-Earth to the PISM ice sheet model for Antarctica, and both WPs will contribute to the Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6). The long-term plan is to have a coupled model system including both the Greenland and the Antarctic ice sheets.

Ice sheets are dynamical components of the climate system. Snow falling on the ice sheet's surface is compressed to ice and starts to flow towards the ice margins. At the margin, ice is removed by discharge of icebergs to the ocean or melting in the ablation zone.
Observations indicate that the mass loss from the Greenland Ice Sheet has been rapidly increasing since 2000 (The IMBIE Team 2020; Khan et al., 2020). The surface area experiencing melt has become wider, and the melting season is prolonged (Tedesco and Fettweis 2020). The state-of-the-art models participating in the Climate Model Intercomparison Project Phase 6 (CMIP6) assume fixed ice sheets (Eyring et al., 2016) and do not include enhanced runoff and calving. The accelerating changes of the Greenland Ice sheet call for process-based models to explore ice sheet climate interactions under changing climate conditions. Because of the different spatial and temporal scales, it is not straightforward to include an ice sheet model in a global climate model and relatively few coupled ice-sheet climate models exist (Ridley et al., 2005; Mikolajewicz et al., 2007; Fyke et al., 2018; Vizcaino et al., 2013, Muntjewerf et al., 2020).

At DMI, we have developed a climate-ice sheet-model system: EC-Earth-PISM. It comprises the global climate model EC-Earth (version 2.3) and the Parallel Ice Sheet Model PISM (version 0.5). In WP1.1.1, this model system has been upgraded to include the new model versions EC-Earth3 and PISM v1.2, and a new coupling interface. The new model system, EC-Earth3-GrIS, will be part of EC-Earth3 and available to the EC-Earth model Consortium (www.ec-earth.org). EC-Earth3 is described in a common EC-Earth3 paper led by SMHI (Döscher et al., 2021; submitted).

This report describes the development of a new module included in EC-Earth3 for exchange of information between PISM and EC-Earth, and it considers the influence of the EC-Earth surface parameterization on the calculated surface mass balance. As part of WP1.1.1, the results from experiments with the former version of the coupled model system have been analyzed and documented in a submitted manuscript (Madsen et al., 2021; submitted). This manuscript contains a detailed description of the coupled model system, EC-Earth-PISM, including the modifications of the EC-Earth surface parameterization, an analysis of the mass balance of the modeled Greenland ice sheet under preindustrial conditions as well as an assessment of the influence of the interactive Greenland ice sheet on the climate system in scenarios with increased levels of CO_2. A summary of these results is given at the end of this report.

The models

EC-Earth3

EC-Earth is a modular Earth System Model that is collaboratively developed by the EC-Earth Consortium. EC-Earth3 (Döscher et al., 2021; submitted) is the newest model version used by the EC-Earth consortium to contribute to CMIP6. EC-Earth3 includes model components describing the physical processes in the atmosphere, land surface, ocean, and sea-ice. The atmosphere component is IFS cycle 36r4, coupled to the HTESSEL land surface scheme. The ocean model is NEMO3 coupled to the LIM3 sea-ice model. The EC-Earth3 model is run at a T255 spectral resolution for the atmosphere, which is approximately 80 km global resolution, and 1 degree for the ocean. The OASIS3-MCT software interface (Valcke et al., 2015; Craig et al., 2017) is used to interpolate and exchange the coupling fields between the different climate model components, thereby forming the coupled system. EC-Earth3-GrIS is a new model configuration in which EC-Earth is coupled to the PISM ice sheet model for the Greenland Ice Sheet.

PISM

The Parallel Ice Sheet Model version 1.2 (PISM; Bueler and Brown 2009; Aschwanden et al., 2019; http://www.pism-docs.org) will be used to model the evolution of the Greenland Ice Sheet in the coupled model system. The dynamical and thermodynamical processes handled by PISM include ice flow, subglacial hydrology, and bed deformation. A combination of two shallow ice approximations is used, dependent on the ice regime. The non-sliding Shallow Ice Approximation (SIA) is used for grounded ice, whereas the Shallow Shelf Approximation (SSA) is applied for ice shelves and as a sliding law in regions with low basal resistance. This formulation effectively models whole ice sheets where fast-flowing ice streams and outlet glaciers need to be resolved without solving the full set of stress balance equations. The ice sheet model utilizes a regular polar-stereographic grid at a 5 km resolution and is run for the entire Greenland ice sheet.

For the coupled set-up, the main parameterizations of calving of marine-terminating glaciers implemented in PISM have been tested for various parameter settings (Gevik 2019). When the surface mass balance from EC-Earth is used as a boundary condition, the ocean-kill condition, i.e., the calving of ice expanding beyond a predefined boundary, is necessary to avoid a too large expansion of the ice sheet. This simple calving approach is combined with the more physically based von Mises calving, derived from ice fracturing and developed for modelling calving in Greenlandic fjords (Morlighem 2016).
The initial state used for testing the coupled set-up was initialized by a paleoclimate pre-spin up following by a constant climate initialization using forcing fields from a preindustrial EC-Earth experiment (Gevik 2019). The resulting initial ice sheet is 8-15% larger by volume than the observed ice sheet, depending on the exact initialization method and the implementation of the forcing. Preliminary results indicate that the way the SMB field is transformed onto the actual ice sheet region impacts the simulated ice sheet size strongly (Gevik 2019). The initial ice sheet state used for the test experiments is based on a pre-spin-up using PISM version 1.0. Thos initialization procedure will be repeated using PISM version 1.2.

EC-Earth3-GrIS

Surface processes are modelled in EC-Earth and the resulting surface mass balance (SMB) is used to force the ice sheet model. The representation of surface mass balance, i.e., precipitation, evaporation, and snow and ice melt from the ice sheet, is crucial.
In the EC-Earth standard configuration, the physics of land ice is not accounted for. Instead, the Greenland and Antarctic ice sheets are represented by a deep layer of perennial snow in thermal

contact with the underlying snow and with a fixed albedo of 0.8. Snow accumulation above 9 m.w.e. leads to a redistribution of the excessive snowfall into the ambient ocean (Hazeleger et al., 2012; Döscher et al., 2021; submitted). Since this simple scheme is based on an assumption of a stable ice sheet, it is not well suited for the coupling to the Greenland Ice Sheet, where enhanced ablation at the margin contributes to observed accelerated mass loss.

Hence, in EC-Earth3-GrIS, the land surface parameterization is enhanced to account for the presence of the ice sheet. An explicit ice sheet mask is introduced in the HTESSEL land surface code. For glacierized grid points, values representative of ice are adopted in the surface energy balance computation and for calculating the subsurface heat and energy fluxes. An important part of the ice sheet surface scheme is a time-varying snow albedo parameterization for snow on ice sheets. Instead of the constant value of 0.8, the albedo depends on the snow state and can vary between 0.6 and 0.85. For fresh snowfall, the maximum value of 0.85 is used. Aging may reduce the albedo to 0.75, while the albedo decreases to the lower limit of 0.6 during melting. For refrozen meltwater, a value of 0.65 is used (Helsen et al., 2017). The land surface parameterization described above has been implemented in EC-Earth3. It plays a vital role in the EC-Earth3-GriS configuration but can also be activated without including the dynamic ice sheet model and is, e.g., used for paleoclimate experiments.

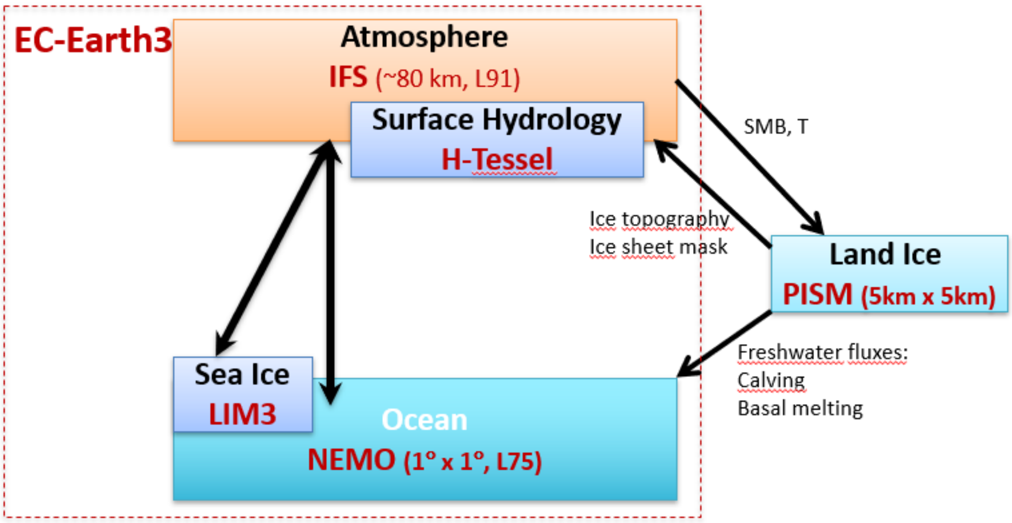

Figure 1 The structure of the EC-Earth3-GrIS model system, indicating the exchange of information between the land ice module and the EC-Earth model components.

The second part of the EC-Earth3-GrIS development is the actual 2-way coupling to the PISM ice sheet model. Technically, the coupling is performed at the script level, and the PISM ice sheet model is run one year at a time. The exchange of fields between the ice sheet and EC-Earth is handled by an EC-Earth module, developed in this work package. This module reads PISM output and exchanges information via the OASIS3-MCT interface, which handles the spatial interpolation between the grids as well as any required time interpolation. The implementation of the new module in EC-Earth is illustrated in Figure 1 and described in more detail in the following section.

The coupling interface

As part of WP1.1.1, a new EC-Earth module has been developed to handle the transfer of fields between EC-Earth and PISM. The new module reads PISM output from a file and feeds the information into EC-Earth via the OASIS-MCT software interface (Valcke et al., 2015; Craig et al., 2017). For this to work, information about the coupling fields is given in the model components sending or receiving information, and all details of the coupling method is compiled in the namcouple file, which describes how the fields are interpolated in time and space. In the current set up for the ice sheet coupling, a total of eight coupling fields are added to the standard set-up (Table 1). For now, the SMB components are written out separately, but in longer experiments only SMB and subsurface temperature will be written out.

Coupling field	Source grid	Target grid	Interpolation method	Implementation
Ice sheet mask	PISM	IFS Greenland land surface	Conservative	Fractional ice sheet mask defining ice sheet area in EC-Earth
Ice sheet topography	PISM	IFS Greenland land surface	Conservative	Greenland Ice Sheet topography merged with global topography field
Ice sheet basal melt flux	PISM	Runoff mapper/NEMO	GAUSWGT + GLBPOS	Mass flux distributed to the surrounding ocean
Ice sheet calving flux	PISM	Runoff-mapper/NEMO	GAUSWGT + GLBPOS	Mass and heat flux distributed to the surrounding ocean
EC-Earth precipitation	IFS	PISM	Conservative	Contribute to SMB forcing
EC-Earth runoff	IFS	PISM	Conservative	Contribute to SMB forcing
EC-Earth evaporation	IFS	PISM	Conservative	Contribute to SMB forcing
EC-Earth sub-surface temperature	IFS	PISM	Bilinear	Ice surface temperature forcing

Table 1 Coupling fields transferred from/to the ice sheet module. All spatial and temporal transformations are handled vias the OASIS3-MCT interface. Gauswgt denotes a nearest neighbour interpolation weighted by distance and a Gaussian function. GLBPOS is applied as a second step to secure mass conservation; mass on the source and target grids is compared after the first interpolation, and the deficit is distributed according to the original weighting.

Freshwater fluxes from the ice sheet to the ocean

In the coupled model system, freshwater fluxes from calving and basal melt are given back to the ocean model via the EC-Earth runoff mapper module. In EC-Earth3, the runoff-mapper handles the distribution of runoff from snowmelt, land surface liquid precipitation, and river runoff into the ocean. The runoff mapper receives runoff from the atmosphere and land surface and distributes it into predefined drainage basins. The runoff is then distributed to the ocean points connected to each drainage basin. The runoff mapper uses a separate grid, on which the distribution is performed. The transformations between IFS, the runoff mapper, and the ocean grids are all performed using the OASIS3-MCT coupling interface. Each interpolation is done in two steps. First, the nearest neighbor interpolation is performed, weighted by distance and a Gaussian function. Next, the *GLBPOS* option is applied to distribute the residual (mass flux on target grid minus mass flux on source grid) equally over the target grid, proportional to the original field values. In this way, mass conservation is ensured.

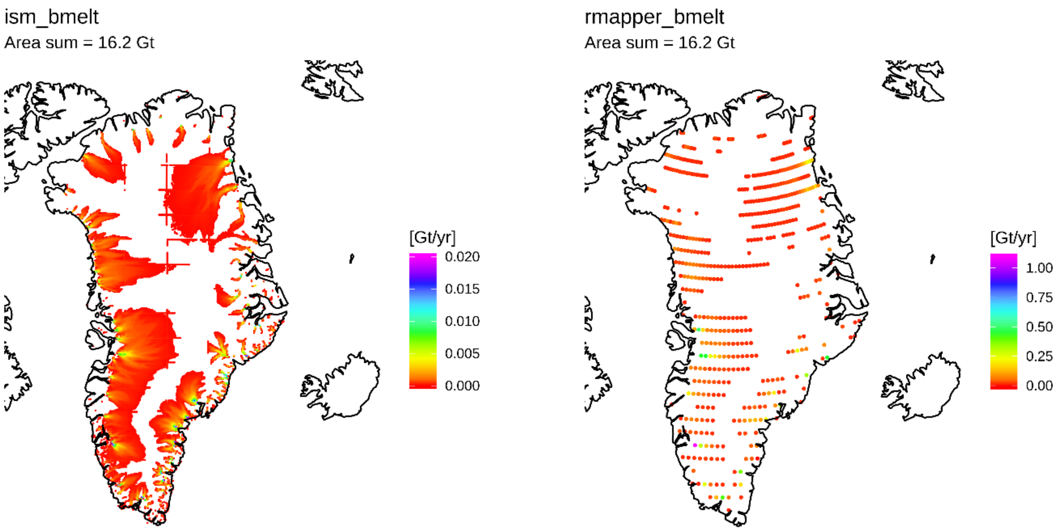

Figure 2 Basal melt on the ice sheet model (left) and the runoff mapper (right) grids for an example year with a total mass contribution of 16.2 Gt due to basal melting.

In EC-Earth3, excess snow (i.e., snow depth > 9 m.w.e.) is removed as 'calving' and distributed into the ocean. As the excess snow is added to the ocean before melting, energy is subtracted from the ocean. Calving and surface runoff are therefore handled separately in the runoff mapper module. When the interactive Greenland ice sheet is included, the calving from PISM is given directly to the runoff mapper and from there added to the global calving field and distributed to the ocean. In this case, the removal of excess snow is inactivated for the Greenland Ice Sheet (defined by the ice sheet mask).
Figure 2 shows the remapping of basal melt from PISM (kg/m2/s) to the runoff mapper grid. Here it is added to the surface runoff, before the remapping to the ocean grid. As basal melt of grounded ice only makes up 10-20 Gt/year under preindustrial conditions, it is only a small contribution to the liquid runoff. The ice discharge typically makes up 400-600 Gt/years for the preindustrial ice sheet. The distribution of calving in PISM and the corresponding mass flux from the Greenland Ice Sheet to the surrounding ocean is illustrated in Figure 3.

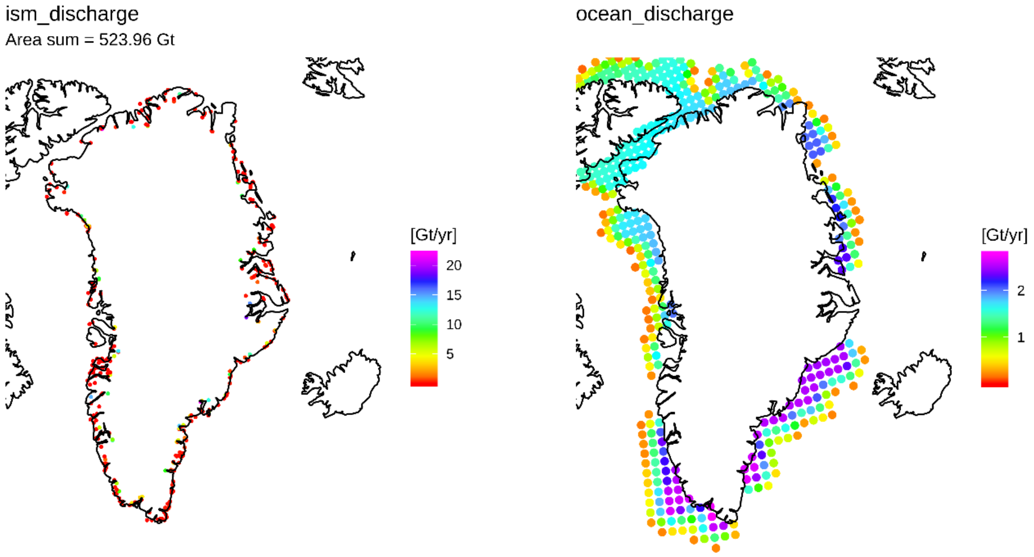

Figure 3 Ice discharge on the ice sheet model grid (left) and after the distribution to the ocean (right) for an example year with a total mass contribution of 524 Gt/year due to ice discharge.

Ice sheet mask and topography to the atmosphere/land surface

The ice sheet mask in EC-Earth is based on the ice thickness calculated in PISM. A lower limit of 10-meter water equivalent (m.w.e.) is used in order to avoid treating grid cells with only a thin ice coverage as glacierized. For each PISM grid point, a value of either 0 or 1 is set depending on the thickness being below or above 10 m.w.e. The PISM mask values are interpolated to the IFS grid using a conservative method. The IFS ice sheet mask determines the fraction of the grid box covered by land ice. The subsurface is considered ice if the fraction is above 0.5 and soil if it is below. In the surface scheme, the fractional mask values are applied. In the test experiments, the ice sheet mask is updated once per year, but monthly time steps will be used for the CMIP6 experiments. The new topography from PISM replaces the default IFS topography for the ice sheet area. The IFS topography will be updated once per year based on the field transformed from the PISM grid via the coupling interface. As the topography acts on the model dynamics, the grid point field is transformed to spectral coordinates in the IFS model.

Ice sheet forcing fields: SMB and temperature

The EC-Earth ice sheet module prepares monthly mean fields of SMB and sub-surface temperature, which are output on the PISM grid (netCDF format) and makes up the forcing for the next PISM simulation.

The EC-Earth3 SMB

In this section, the influence of the land ice surface parameterization on the calculated surface mass balance is considered. The EC-Earth surface mass balance used to force the ice sheet model is calculated from precipitation, evaporation, and runoff. Experiments under preindustrial (historical forcing; 1850-1879) and present-day (ssp5-8.5 forcing; 2015-2044) conditions are performed with and without the land ice surface parameterization. In these experiments, there is no coupling to the ice sheet model, and the ice sheet mask is based on the initial snow depth. Table 2 summarizes 30-year annual means of accumulation, runoff and SMB integrated over the

Greenland ice sheet for the four experiments. Maps of annual mean accumulation and surface runoff are given in Figures 4 and 5.

	Accumulation	Run-off	SMB
Preindustrial (1850-1879) - std	610	63	547
Preindustrial (1850-1879) - land ice	632	98	534
Present-day (2015-2044) - std	797	169	627
Present-day (2015-2044) - land ice	809	400	409

Table 2 Annual mean surface mass balance components in Gt/year for experiments with and without the land ice parameterization for preindustrial (1850-1879) and present-day (2015-2044) conditions. Accumulation is calculated from (precipitation minus evaporation), and the surface mass balance is (accumulation minus runoff).

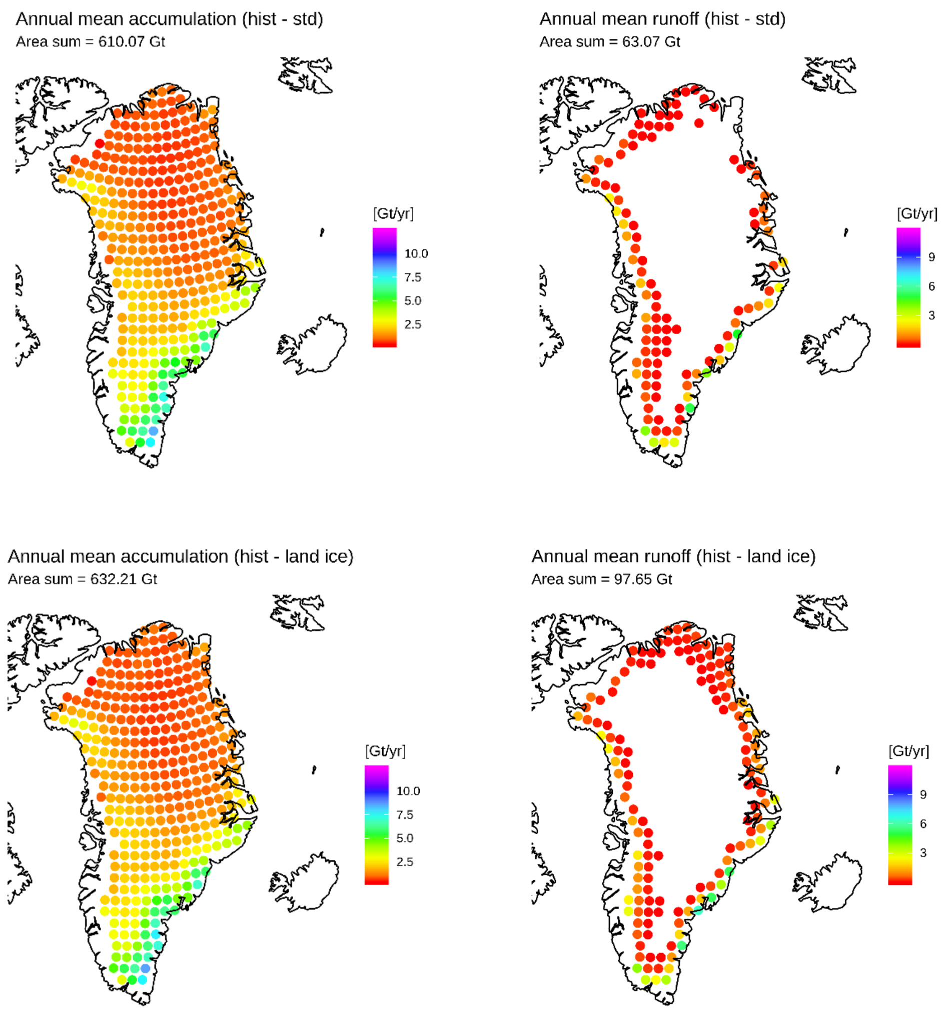

Figure 4 Annual mean accumulation (left) and surface runoff (right) under preindustrial conditions with (bottom) and without (top) the land ice surface parameterization.

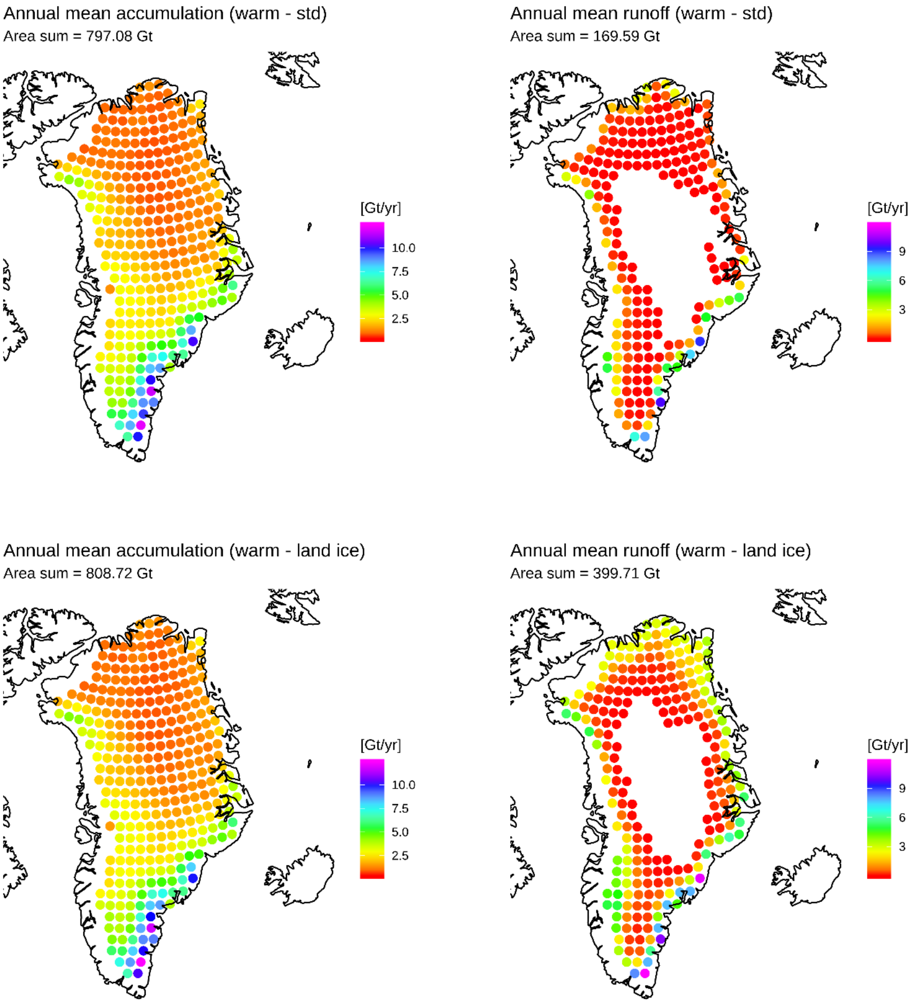

Figure 5 Annual mean accumulation (left) and surface runoff (right) under present-day conditions with (bottom) and without (top) the land ice surface parameterization.

The comparison shows that the accumulation is very similar in experiments with and without the land ice parameterization. Under preindustrial conditions, runoff is about 30% larger in the experiment with land ice. This experiment has slightly more melting in a few grid points at the ice margin and a small amount of runoff in the north-eastern part of Greenland. However, the total amount of runoff is small, and the SMB is very similar in the two experiments. Under warmer conditions, the intensified hydrological cycle increases the accumulation by more than 30% in both experiments. The largest increases occur in the high-accumulation zone in south-eastern Greenland. As expected, the response to warmer conditions is much stronger in the experiment with the land ice parameterization; here, the runoff increases by a factor of four. As seen from Figure 5, both the area experiencing surface melting and the melt rate at the margin are larger when the land ice parameterization is applied. These results fit well with the lowering of the snow albedo for melting conditions, which is part of the land ice parameterization. The responsive albedo scheme enables the activation of the melt-albedo feedback, which is highly important in the coupled system.

The differences in the amount of surface melt affect the calculated SMB. For preindustrial conditions, the SMB is similar in the experiments with and without land ice (534 and 547 Gt/year). Under the warmer conditions, the SMB decreases to 409 Gt/year in the land ice experiment as the increase in surface melting is larger than the increase in accumulation. Without the land ice parameterization, the increase in surface melting is not big enough to compensate for the increase in accumulation, and the SMB increases to 627 Gt/year under the warmer conditions.

For comparison, a recent model intercomparison paper (Fettweis et al., 2020) used an ensemble of different models and estimated an ensemble mean SMB of 338 ± 111 Gt/year for 1980-2012. Vizcaino et al., (2013) used the CESM model to estimate an SMB of 390 ±66 Gt/years for preindustrial conditions and 359±120 Gt/years for 1960-2005. The Greenland SMB modelled in EC-Earth compares better with these studies when the land ice parameterization is applied as melting increases more realistically under warming conditions.

To further explore the SMB dependencies, an off-line energy balance model (EBM; CISSEMBLES, developed at DMI) has been set up to calculate the SMB from the 6-hourly atmospheric forcing. The EBM computes the surface mass balance grid cell by grid cell. The EBM can be used to explore further the energy transfer at the ice surface, e.g., the dependence on albedo, ice sheet mask, and resolution. The first results from the EBM show a good agreement between SMB calculated directly in EC-Earth and estimated using the energy balance model under preindustrial conditions. Further work is on-going to address the influence of the land ice surface parameterization on the surface fluxes.

EC-Earth-PISM: the impact of the Greenland Ice Sheet on climate

This section summarizes the analysis of the results from the experiments with the first model version comprising EC-Earth v2.3 (Hazeleger et al., 2012) and PISM version 0.5. A more detailed description and analysis is presented in Madsen et al., (2021, *submitted*) and Svendsen et al., (2015). This EC-Earth-PISM model version was run at a lower resolution, i.e., a spectral resolution of T159 and 62 vertical layers for the atmosphere, which corresponds to approximately 125 km horizontal resolution globally. The ocean has a 1° horizontal resolution with refinements to 1/3 degree around the equator and 42 vertical layers. The ice sheet model was run at 20 km horizontal resolution.

Experiments under preindustrial conditions (piControl) and an abrupt increase of the greenhouse gas forcing to four times preindustrial levels (Abrupt4xCO2) have been performed and compared with the uncoupled counterparts to explore the impact of the interactive ice sheet component. The analysis in WP1.1.1. has focused on the freshwater fluxes from the Greenland Ice sheet and their influence on the ocean response.

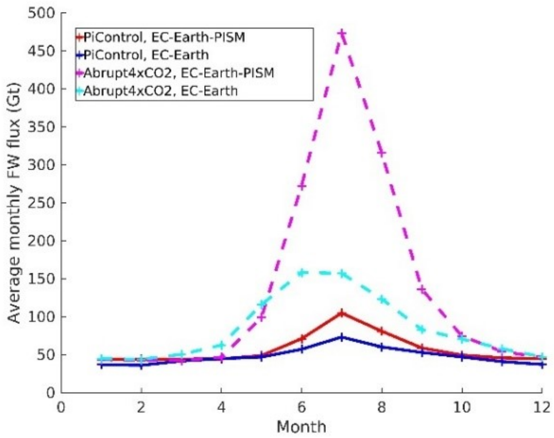

Figure 6 Monthly mean freshwater flux from the Greenland Ice Sheet during the last 50 years of each experiment.

The freshwater flux from the Greenland Ice sheet to the ocean is calculated as the sum of calving, basal melt, and runoff from the ice sheet surface. Figure 6 compares the monthly mean freshwater flux for the four experiments as an average over simulation years 301-350. The freshwater is distributed in the surrounding ocean and contributes to increased freshwater content in the Arctic and North Atlantic Oceans (Figure 7). The freshwater flux from the Greenland ice sheet is larger in the summer months, where runoff from surface melting increases. The seasonal cycle is stronger pronounced in the coupled experiments. Under preindustrial conditions, the annual mean freshwater flux is about 10% larger in the coupled experiment. A much larger difference is found for the warm scenario, where the melt-albedo feedback is triggered in the coupled system. It results in a 65% larger freshwater flux. The melting season is longer, and the July melt rate is about three times the uncoupled melt rate (Madsen et al., 2021; submitted).

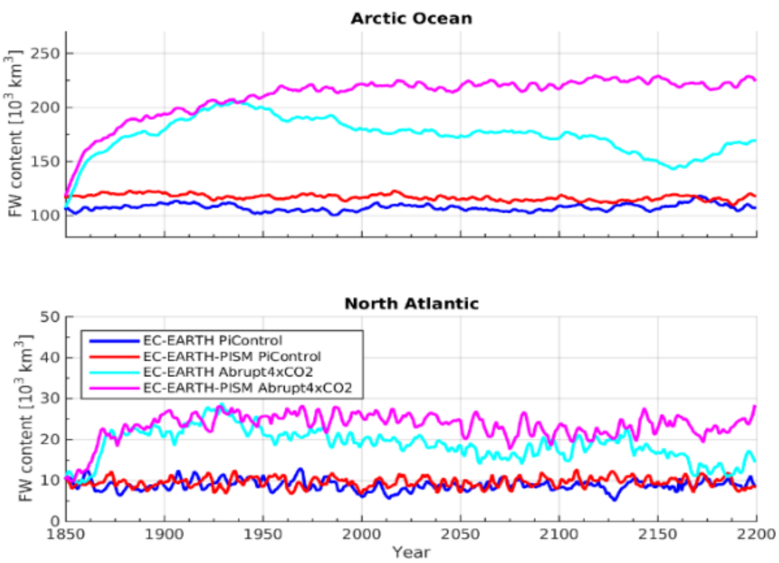

Figure 7 Freshwater content in the Arctic and North Atlantic throughout the 350 years of experiment.

In the uncoupled EC-Earth model, the surface runoff in Abrupt4xCO2 is too low to compensate for the increase in precipitation caused by the intensification of the hydrological cycle under warmer conditions. Therefore, the results show a positive surface mass balance and a mass gain of the Greenland ice sheet even under the very warm conditions of Abrupt4xCO2. Conversely, the coupled model projects a negative surface mass balance and a total mass loss of several hundred gigatons per year. These results stress the shortcomings of the uncoupled model when it comes to simulating mass balance changes and, eventually, sea-level rise. For long-term projections, the assumption of a stable ice sheet is invalid, and the interactive ice sheet model is essential for realistic projections of ice sheet climate interactions.

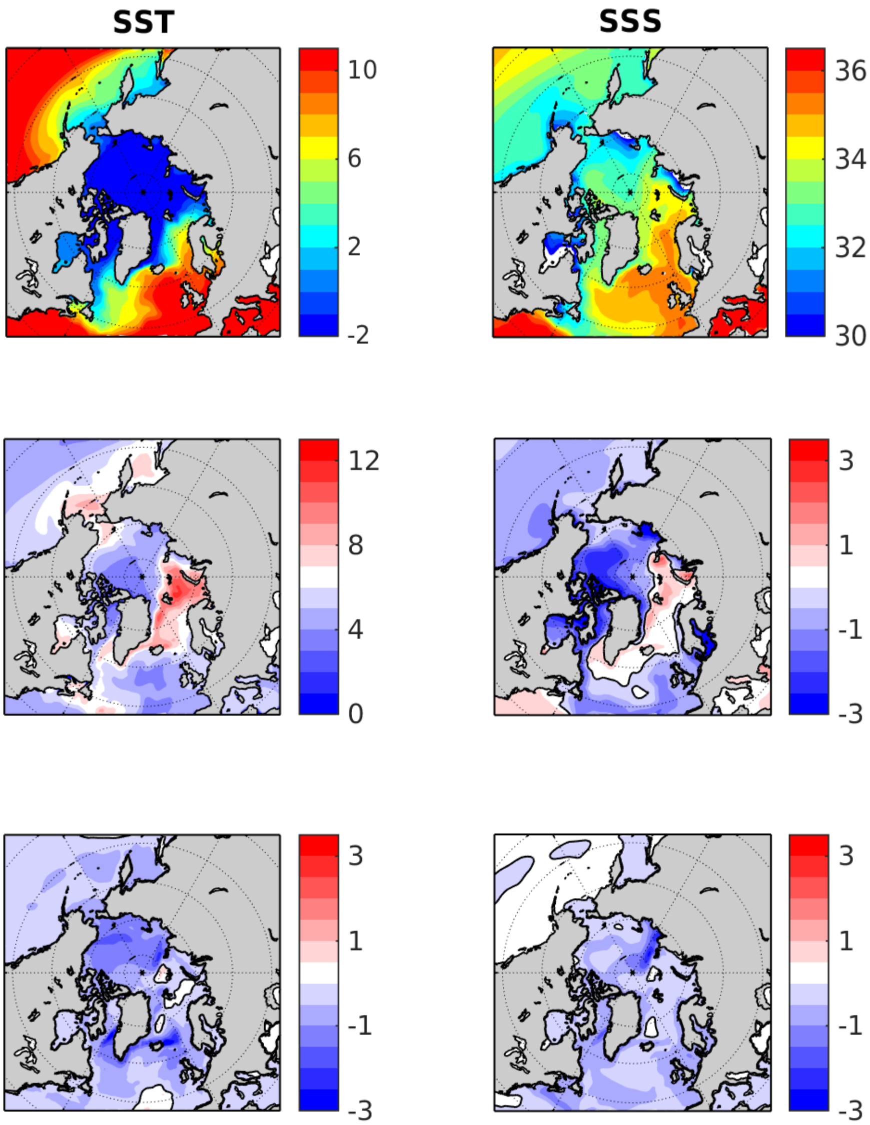

Figure 8: Top: EC-Earth sea surface temperature (SST) and sea surface salinity (SSS) under preindustrial conditions. Middle panel: Difference between Abrupt4xCO2 and preindustrial experiments for SST (left) and SSS (right). Bottom: Differences between changes in EC-Earth-PISM and EC-Earth.

Figure 8 shows the influence of the interactive ice sheet on the sea surface temperature and sea surface salinity in the Abrupt4xCO2 experiments. Under preindustrial conditions, sea surface temperature and salinity compare well in the coupled and uncoupled experiments with no significant differences. Due to the large increase in the forcing in Abrupt4xCO2, the temperature increases in the whole northern hemisphere, up to 12 K close to the sea-ice edge in the Barents and Kara Seas (figure 8, middle panel). In the warm scenario, the model response is influenced by the interactive ice sheet; the ocean warms less in the whole Arctic region, and the ocean surface is fresher (Figure 8, bottom).

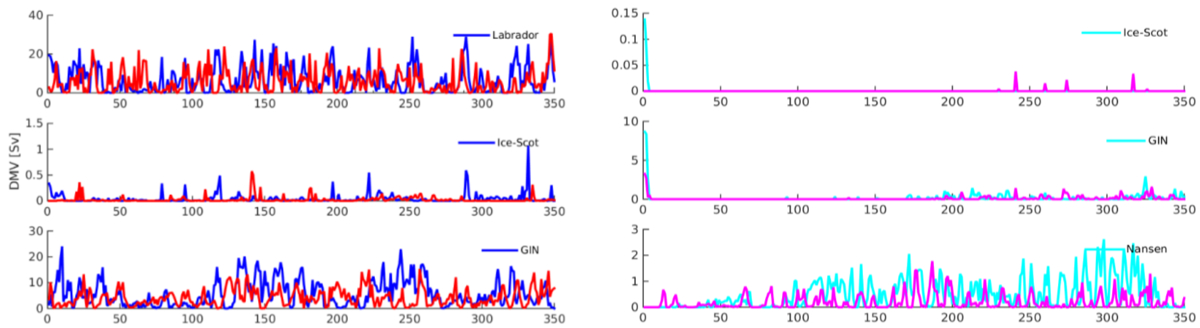

Figure 9 Location of deep water formation under preindustrial (left) and Abrupt4xCO2 (right) conditions based on the Deep Mixed Volume (Brodeau and Koenigk; 2016). Blue/red is EC-Earth/EC-Earth-PISM piControl, cyan/magenta is EC-Earth/EC-Earth-PISM Abrupt4xCO2. Figure courtesy I. M. Ringgaard.

In the preindustrial experiments, deep water predominantly forms in the Labrador and Greenland-Iceland-Norway Seas. The formation strength is comparable between coupled and uncoupled experiments. In Abrupt4xCO2, the formation of deep water immediately disappears from the Labrador Sea. Instead, it moves northward into the Nansen region north of the Barents and Kara Seas by following the sea-ice edge. The North Atlantic Meridional overturning circulation (AMOC) also slows down immediately after the strong forcing is applied. Deep water formation is weaker in coupled experiments. As the AMOC starts to recover in the coupled experiment, the recovery pace is slower, and the AMOC is weaker (12.1 ± 1 Sv compared to 13.8 ± 0.8 Sv). At last, at the end of Abrupt4xCO2, the interactive ice sheet reduces the warming in the North Atlantic region. It is pronounced in the Arctic (north of 60° N), where the atmospheric near-surface temperature is about 1 K lower in the coupled experiment (Madsen et al., 2021; submitted).

Conclusions

A coupled climate-ice sheet model system, including the EC-Earth3 climate model and the PISM ice sheet model for Greenland, has been developed. The model system will be used to explore the interactions and feedbacks between the Greenland ice sheet and the climate system. In EC-Earth3-GrIS, the EC-Earth and PISM components have been updated to newer versions. A separate land ice surface physics parameterization has been implemented in EC-Earth3 to improve the estimation of SMB. The land surface parameterization includes a responsive albedo scheme, which allows the melt-albedo feedback to be activated and is essential for modelling surface melt and surface mass balance in the coupled system under climate change conditions. A new module has been developed to exchange information between EC-Earth and the PISM ice sheet model via the OASIS3-MCT software interface. The mass and freshwater fluxes due to calving and basal melting from the ice sheet are remapped and distributed to the ocean. Ice sheet thickness and topography are given to the atmosphere/land surface model for updating the ice sheet mask and topography. The new module further writes out forcing fields of SMB and subsurface temperature at the PISM grid and thereby prepares the forcing fields for the subsequent year of PISM simulation. The fully coupled EC-Earth3-GrIS system will be established from the model components. The script-level part is simplified compared to the previous model version as the new EC-Earth module handles the spatial and temporal interpolations between the model components. After some final testing and spin-up, the EC-Earth3-GrIS model system will be used to perform the ISMIP6 experiments, including extended scenarios reaching beyond 2100. The analysis of results from experiments with the first version of the coupled model system emphasizes the importance of including an interactive ice sheet in climate change projections. In a warming climate, the increased freshwater flux from the Greenland Ice Sheet affects the North Atlantic deep water formation and delays the recovery of the reduced AMOC, which results in colder atmospheric conditions in the northern hemisphere (Madsen et al., 2021; submitted). As most global climate models include fixed ice sheets (Eyring et al., 2016), they may underestimate the freshwater fluxes to the surrounding ocean under warm climate conditions and hence overestimate the warming in the northern hemisphere.

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