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How do icebergs affect the Greenland ice sheet under pre-industrial conditions? – A model study with a fully coupled ice sheet–climate model

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Abstract

Icebergs have a potential impact on climate since they release freshwater over a wide spread area and cool the ocean due to the take up of latent heat. Yet, so far, icebergs have never been modelled using an ice sheet model coupled to a global climate model. Thus, in climate models their impact on climate was restricted to the ocean. In this study, we investigate the effect of icebergs on the Northern Hemisphere climate and the Greenland ice sheet itself within a fully coupled ice sheet (GRISLI)–Earth system (*i*LOVECLIM) model set-up under pre-industrial climate conditions. This set-up enables us to dynamically compute the calving sites as well as the ice discharge and to close the water cycle between the climate and the cryosphere model components. Further, we analyse the different impact of moving icebergs compared to releasing the ice discharge at the calving sites directly. We performed a suite of sensitivity experiments to investigate the individual role of the different factors presiding at the impact of ice release to the ocean: release of ice discharge as icebergs vs. as freshwater fluxes; freshening and latent heat effects. We find that icebergs enhance the sea ice thickness south and east of Greenland, thereby cooling the atmosphere and decreasing the Greenland ice sheet's height. In contrast, melting the ice discharge locally at the calving sites, causes an increased ice sheet thickness due to enhanced precipitation. Yet, releasing the ice discharge into the ocean at the calving sites while taking up the latent heat homogeneously, results in a similar ice sheet configuration and climate as the icebergs. Therefore, we conclude that in our fully coupled atmosphere–ocean–cryosphere model set-up, the spatial distribution of the take-up of latent heat related to icebergs melting has a bigger impact on the climate than the input of their melt water. Moreover, we find that icebergs affect the ice sheet's geometry even under pre-industrial equilibrium conditions.

1 Introduction

During the last decade satellite observations have shown a reduction of the Greenland ice sheet's height by up to 8 $cm\,yr^{-1}$ (Chen et al., 2006). This reflects an accelerated mass loss of the Greenland ice sheet (GIS), which has been associated with a continuous rise in the annual surface temperature observed over Greenland since 1994. Compared to the average over 1951–1980, temperatures increased by about 1.5 °C (Hanna et al., 2011; Box et al., 2013). Even though this mass loss was partly counteracted by higher accumulation rates, the net GIS mass balance (accumulation minus ablation) decreased during the past two decades by about 20 $Gt\,yr^{-1}$ caused by increased ice discharge (Rignot et al., 2011). Although we have clear evidence for major changes of the GIS in the past and present, our understanding of the potential impact of the GIS mass loss due to interactions with the ocean and the atmosphere is still limited and has never been investigated in a fully coupled global climate–cryosphere modelling framework. In this paper, we therefore analyse these interactions using an earth system model including fully dynamic components for land ice, ice shelves and icebergs. We focus on the question of how icebergs affect the GIS and the regional climate under preindustrial conditions.

There are numerous feedback mechanisms related to the growing and shrinking of ice sheets (Clark et al., 1999). Most importantly, changes in topography can lead to altered atmospheric circulation patterns (Ridley et al., 2005). Further, when an ice sheet is shrinking, there are less ice-covered areas and the resulting decrease in surface albedo enhances the uptake of heat by newly exposed land surfaces. Vizcaíno et al. (2008) showed that under future warming the decrease in both topography and albedo of the GIS strongly enhances its decay. A further effect of the ice sheet's shrinking is enhanced runoff into the ocean and, as a consequence, a reduced sea surface salinity that increases the stability of the water column. This process, depending on the position and strength of the freshwater flux, might lead to a reduction or even collapse of the Atlantic Meridional Overturning Circulation (AMOC, e.g. Roche et al., 2009;

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Swingedouw et al., 2009). Besides runoff, iceberg calving is one of the main mechanisms of mass loss of ice sheets and in a warming climate it is expected to increase. Recently, an increase in ice speed of the Greenland glaciers of up to 200 % and Arctic ice shelf breakups lead to enhanced ice discharge (e.g. Mueller et al., 2003; Rignot and Kanagaratnam, 2006; Nick et al., 2009). Since icebergs act as a mobile freshwater source and a sink of latent heat, they freshen and cool the ocean thereby facilitating the stratification of the ocean as well as the formation of sea ice (Jongma et al., 2009).

Numerical ice sheet models are valuable tools to study the evolution of the ice sheet during different climate states and its impact on climate. Therefore, they are used to better understand and investigate the aforementioned interactions between the GIS and the other climate components. Most ice sheet models currently used for performing longer-time simulations are three-dimensional thermomechanical models, thus they account for the relationship between temperature and ice velocity. Moreover, they are based on the shallow ice approximation (SIA), which assumes that the horizontal gradient of the bedrock and surface topographies are much smaller than the vertical ones (Hutter, 1983; Morland, 1984). Further, the ice-sheet's thickness and extension are calculated at every time step as is the rebound of the bedrock below the ice. Some models also differentiate between fast flowing ice, grounded ice and ice-shelves to allow for a dynamic computation of the grounding line (e.g. Huybrechts, 1990; Huybrechts and de Wolde, 1999; Greve et al., 1995, 1997; Ritz et al., 2001; Pollard and DeConto, 2007). On the one hand, these models are used to predict the future development of the ice sheets and on the other hand, to model their evolution during the past millennia and even millions of years.

The simplest approach to investigate the ice sheet's development over the past, is by evaluating the impact of the forcing fields on it. This can be done by either using reconstructed air temperature and precipitation fields as input data (e.g. Ritz et al., 2001) or by using climate model output of specific time periods to drive the evolution of the ice sheet (e.g. Huybrechts et al., 2004; Charbit et al., 2007) or a combination of both (e.g. Gates, 1976a; Pollard and Thompson, 1997b; Broccoli, 2000). Using this set-up, the interactions are only one-sided as the climate is applied to the ice sheet but not altered by it.

A further and more complex approach is to couple ice sheet models to Earth System Models of Intermediate Complexity (EMICs, Claussen et al., 2002). In this case, the exchange of input (temperature and precipitation) and output (albedo, topography, melting and calving of the ice sheet) fields can either be synchronous or asynchronous (e.g. Wang and Mysak, 2002; Kageyama et al., 2004). In the synchronous method the climate and ice sheet model are performed for the same model years between the coupling steps. In the asynchronous set-up however, the EMIC is run for a certain amount of years and then coupled to the ice sheet model which is then run for a longer time period before returning its output to the EMIC. This approach is valid due to the longer time scale of the involved ice sheet processes compared to the atmospheric and oceanic ones (Pollard, 2010) and has the advantage of a short computation time for longer time periods (thousands of years). In both methods the interactions are two-sided as the ice sheet's geometry and its freshwater fluxes are used as input for the EMIC, where the runoff (surface and basal melt) as well as the ice discharge are considered as freshwater fluxes that are released into the ocean directly at the coastline (e.g. Bonelli et al., 2009; Goelzer et al., 2010). Therefore, the melt water released due to iceberg calving and the related take up of latent-heat by them is considered in the same way as the runoff and consequently spatially restricted to the coastline.

The most complex approach so far is to couple ice sheet models to general circulation models (GCMs), which is mostly done to perform relatively short (i.e. a few centuries) future scenarios as the computation is time consuming (e.g. Ridley et al., 2005; Vizcaíno et al., 2008). This set-up also allows two-sided interactions, yet, icebergs have not been modelled explicitly so far either. A more complete description of coupled ice sheet–climate modelling can be found in Pollard (2010).

The importance of icebergs has been shown in different studies where an iceberg module was coupled to climate models and forced with climatological data (e.g. Bigg et al., 1996, 1997; Gladstone et al., 2001; Death et al., 2005; Green et al., 2011;

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Jongma et al., 2009, 2013). Jongma et al. (2009, 2013) highlighted the effect of icebergs under pre-industrial conditions using an EMIC that included an interactively coupled iceberg module based on Bigg et al. (1996). Focusing on the Southern Ocean, Jongma et al. (2009) revealed that icebergs significantly facilitate the formation of sea ice. Moreover, Green et al. (2011) and Jongma et al. (2013) highlighted the importance of including icebergs in model simulations of past ice shelf breakups since the ocean, and consequently the Atlantic Meridional Overturning Circulation (AMOC), respond differently to them than to directly applied freshwater fluxes. A shortcoming of the studies done so far was that the locations and the amount of water used to generate icebergs were prescribed according to observations and reconstructions. Recently, Martin and Adcroft (2010) coupled an iceberg module to a GCM. Thus, the excess snow calculated by the climate model was used to generate icebergs at the coastal sites defined by the river routing system thereby assuming that the ice sheet was in long-term equilibrium. This approach allows the background climate to define the amount of calving. Yet, none of these studies focusing on icebergs incorporated an ice sheet model. Consequently, the interactions between the ice sheet and the icebergs were not taken into account.

Our aim is to include all the previously mentioned feedbacks (albedo, topography, runoff and icebergs) in a fully coupled climate system. Therefore, we use the *i*LOVECLIM climate model of intermediate complexity (Roche et al., 2013) and in addition include a dynamic-thermodynamic iceberg module (Jongma et al., 2009, 2013; Wiersma and Jongma, 2010) and an ice sheet/ice-shelves module (Ritz et al., 1997, 2001). The cryosphere part is coupled to the climate part on a yearly basis and the changes in ice sheet geometry depend on the climate background that is defined by the atmosphere–ocean–vegetation component that itself is modified by alterations of the ice sheet topography, albedo and freshwater fluxes.

To achieve a fully coupled climate system, we further developed the model compared to previous studies (Jongma et al., 2009, 2013; Roche et al., 2013) by including the following two extensions. First, instead of prescribing the locations and the amount of icebergs being calved, they are now generated according to the ice lost by the dynam-

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ical ice sheet model at the corresponding positions. Second, the water cycle is now closed between all the climate components. Therefore, the precipitation coming from the atmospheric model is used to build the ice sheet, its runoff is given to the river routing system and finally put into the ocean and the calved mass is used to create icebergs that then release melt water to the ocean. This fully coupled model set-up allows us to analyse the following questions. (1) How well are we able to reproduce the dynamics and main features of northern hemispheric iceberg calving and ice sheet development in a coupled climate model under pre-industrial conditions? (2) What is the influence of icebergs on the northern hemispheric climate and the modelled Greenland ice sheet itself? (3) How well can the effect of icebergs on climate be reproduced by freshwater fluxes that are applied at the same calving sites and with the same daily amount but miss the dynamic characteristics of icebergs? The difference between direct freshwater fluxes and icebergs has already been investigated by Jongma et al. (2009, 2013), but in their work the freshwater fluxes used to parameterise icebergs were distributed homogeneously around the Antarctic ice sheet (Jongma et al., 2009) or at a certain latitude belt in the North Atlantic (Jongma et al., 2013). In the present study however, we introduce the freshwater fluxes into the ocean at the actual calving sites, a set-up that is closer to what has been done in other coupled climate models (e.g. Vizcaíno et al., 2008; Bonelli et al., 2009; Goelzer et al., 2010).

The questions stated here are addressed by performing and comparing four different model experiments that were all done under pre-industrial conditions and were performed until the ice sheet was equilibrated. The experiments differ in the way how the freshwater fluxes (runoff and calving) of the ice sheet and the related take-up of latent heat are included in the climate part.

The manuscript is structured as follows: first the global climate model *i*LOVECLIM, as well as the included iceberg and ice sheet module (GRISLI) are described. Second, the different set-ups of the runs are explained. Third, we present the results of our simulations and finally proceed to discussions and conclusions.

2 Methods

The earth system model of intermediate complexity used in this study is the so-called *i*LOVECLIM model (version 1.0) which is a code fork of the LOVECLIM climate model version 1.2 (Goosse et al., 2010). The physical climate components (atmosphere, ocean and vegetation) are the same, yet, *i*LOVECLIM differs in the iceberg and the ice sheet module included (Roche et al., 2013).

2.1 Atmosphere–ocean–vegetation model

The atmospheric model ECBilt (Opsteegh et al., 1998) is a quasi-geostrophic, spectral model calculated on a horizontal T21 truncation (5.6° in latitude/longitude) and three vertical pressure levels (800, 500, 200 hPa) with a time step of 4 h. The precipitation is computed in the lowermost layer according to the available humidity. The excess snow, which is the amount of snow that would cause the equilibrated ice sheet to grow, is put into the river routing system and enters the ocean accordingly. ECBilt interacts with GRISLI through precipitation and surface temperature.

The sea-ice and ocean component CLIO consists of a dynamic–thermodynamic sea-ice model (Fichefet and Morales Maqueda, 1997, 1999) coupled to a 3-D ocean general circulation model (Deleersnijder and Campin, 1995; Deleersnijder et al., 1997; Campin and Goosse, 1999). The ocean model has a free surface allowing the use of real fresh-water fluxes and a realistic bathymetry. It has a horizontal resolution of approximately 3° × 3° in longitude and latitude and 20 unevenly spaced vertical levels. In the default model set-up, the iceberg module is not coupled. Therefore, the presence of icebergs is parameterised as homogeneous take up of latent heat around Greenland (Fig. 1) according to the amount of excess snow calculated in ECBilt. CLIO has a daily time step.

The vegetation model used is VECODE (Brovkin et al., 1997) that accounts for two plant functional types (trees and grass) and bare soil. It has the same resolution as the atmospheric model but allows fractional use of one grid cell to consider small spatial changes in vegetation. It depends on the temperature and precipitation provided by ECBilt and accounts for long-term (decadal to centennial) changes of the climate.

2.2 GRISLI – ice sheet model

The GRenoble model for Ice Shelves and Land Ice (GRISLI) is a three-dimensional thermomechanical model which was first developed for the Antarctic (Ritz et al., 1997, 2001) and then further expanded for the Northern Hemisphere (Peyaud et al., 2007). In the present study only the Northern Hemisphere grid is used with a horizontal resolution of 40 km × 40 km on a Lambert azimuthal grid. It predicts the evolution of the geometry (thickness and extension) of the ice sheet according to the surface mass balance, ice flow and basal melting. GRISLI takes into account three different types of ice flow namely inland ice, ice streams and ice shelves. The ice flow of the grounded parts of the ice sheet is based on the 0-order shallow ice approximation (Hutter, 1983; Morland, 1984). The fast flowing ice, corresponding to ice streams, is calculated using the shallow shelf approximation (MacAyeal, 1989) as are the ice shelves. The impact of the ice load on the bedrock is determined by the flow of the astenosphere with a characteristic time constant of 3000 yr as by the rigidity of the lithosphere. Calving occurs whenever the ice thickness at the border of the ice sheet is below 150 m and the upstream points are not providing enough ice to maintain the height above this threshold. In the iceberg module this mass is used to generate icebergs at the calving site. Runoff is computed at the end of the coupling time step, in our case one year, by calculating the difference in ice sheet thickness between the beginning and the end of the year and taking into account the mass that is lost due to calving. A more detailed explanation of the ice sheet model GRISLI can be found in Roche et al. (2013).

2.3 The iceberg module

We use the optional dynamic–thermodynamic iceberg module (Jongma et al., 2009, 2013; Wiersma and Jongma, 2010) with the same parameter set as in Jongma et al. (2009). It is based on the iceberg-drift model published by Smith and coworkers (Smith and Banke, 1983; Smith, 1993; Loset, 1993) and was further developed by Bigg et al. (1996, 1997) and Gladstone et al. (2001). It was implemented in CLIO by Jongma et al. (2009) and Wiersma and Jongma (2010). The icebergs are calculated on the CLIO grid and moved according to the Coriolis force, the air drag, sea-ice drag, the horizontal pressure gradient force and the wave radiation force. These forces depend on the wind and the ocean currents calculated in ECBilt and CLIO which are then interpolated linearly from the surrounding grid corners to fit the icebergs location. Melting of the bergs occurs due to basal melt, lateral melt and wave erosion. As the icebergs melt their length to height ratio changes and they are allowed to roll over. Yet, break-up of icebergs is not considered. The melt water fluxes are added to the ocean's surface layer of the current grid cell and the latent heat fluxes associated with the icebergs' melting are taken from the ocean layer according to the depth of the iceberg.

In contrast to Jongma et al. (2009, 2013) who prescribed the release position and amount of icebergs, we have coupled the iceberg module to GRISLI. Thus, we generate icebergs according to the mass loss that is calculated by GRISLI over one year and then given to the iceberg module. Therefore, we divide the yearly amount of mass at the calving sites into monthly values considering the seasonality of calving. We follow the results of Martin and Adcroft (2010) with the maximum occurring in spring and the minimum in late summer (Fig. 2a). The monthly mass is then transformed into a daily available mass as follows in Eqs. (1) and (2):

$$\mathrm{MAM}(i,j) = \mathrm{TYM}(i,j) \cdot \mathrm{percentage\_month} \quad (1)$$

$$\mathrm{DAM}(i,j) = \mathrm{MAM}(i,j)/30 \quad (2)$$

with MAM defining the Monthly Available Mass at the grid point i, j; TYM the Total Yearly Mass at the grid point i, j; percentage_month the percentage that is used of the TYM per month and DAM being the Daily Available Mass at the grid point i, j. The gridpoints i, j are always referring to the CLIO grid.

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Furthermore, 10 size classes of bergs have been determined as described by Bigg et al. (1997), which are based on present-day observations in the Arctic done by Dowdeswell et al. (1992). Each class corresponds to a defined percentage of the daily available amount. Thus, every day we produce icebergs of the 10 different size classes as:

$$\mathrm{NBS}(i,j,k) = \mathrm{DAM}(i,j) \cdot \mathrm{percentage\_sizeclass}(k)/\mathrm{mass\_sizeclass}(k) \quad (3)$$

with NBS being the Number of Bergs of Size class k at the grid cell i, j; DAM the daily available mass at the grid cell i, j; the percentage_sizeclass(k) corresponds to the percentage of DAM used for bergs of size class k and mass_sizeclass(k) corresponds to its mass. Following this Eq. (3), we get a number of bergs per different size class at each calving site. Yet, as icebergs of the different classes can only be generated if there is enough ice available, the bigger size classes are not represented at all times at all sites. The part of the daily available mass that has not been used is saved and added to the available amount of the following day.

2.4 The coupling method and experimental set-up

We have performed four different experiments (Table 1) that vary in the implementation of the freshwater fluxes (runoff and calving) calculated in GRISLI and the take up of latent heat related to calving. All experiments have in common that GRISLI is coupled to *i*LOVECLIM applying a yearly time step. A schematic representation of the water cycle between the atmosphere (ECBilt) – ocean (CLIO) – ice sheet (GRISLI) and iceberg model is displayed in Fig. 3. Volume changes of the ice sheet are considered as calving and runoff. The latter is given to the land routing system of ECBilt and thereby transported into the ocean. Runoff is included in all the experiments besides the CTRL run.

The first experiment is the control set-up (CTRL) – that has already been used and explained in detail by Roche et al. (2013): it takes no water feedback into account. As a consequence ECBilt is only influenced by the albedo and topography of GRISLI. The ice-sheet's calving flux is parameterised as homogeneous take up of latent heat around Greenland (Fig. 1).

In the second experiment, the calving run (CALV), the ice discharge of GRISLI is used in the iceberg module to generate icebergs as described above. The melt water of the icebergs is released at their current position and the latent heat needed to melt them is absorbed there. Hence, the cooling effect of the icebergs depends on their movement and is not spread homogeneously around Greenland as is done in the parameterisation (Fig. 1). In the third experiment, the "fresh" freshwater run (FWFf), the calving mass of the ice sheet is divided into a daily mass, as described above, which is converted into a water flux and put directly into the surface layer of the ocean cell at the GRISLI calving site. The water flux freshens the ocean, yet, in this experiment, it does not take up the latent heat needed to melt. Instead, the take up of latent heat is parameterised in the same way as in the CTRL experiment. In the fourth experiment, the "cool" freshwater set-up (FWFc), the calving is included as in the FWFf. Yet, in this set-up, the calving flux put into the ocean not only freshens it but also absorbs the heat needed to melt at its position.

When we compare these four experiments (Table 2), we can analyse the impact of the icebergs on the Northern Hemisphere climate caused by the distribution of their melt water and the related cooling and freshening of the ocean (CALV – CTRL). Moreover, we can separately analyse the impact of freshening (FWFf – CTRL) and of cooling the ocean (FWFc – FWFf) as the freshwater experiments only differ in the treatment of latent heat. Further, the differences between simulated icebergs and directly applied freshwater fluxes (CALV – FWFc), that ignore the spatial distribution of the melt water, are investigated.

All runs were done under pre-industrial conditions and the ice sheet was initialized from present day observations (Bamber et al., 2001). The experiments were continued until the ice sheet was equilibrated which took about 11 000 model years. In total the experiments were performed for 12 000 model years and the results of the last 1000

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model years are presented in the following section. The climate is equilibrated, with no detectable drift in the deep ocean temperature.

3 Results

3.1 Representation of icebergs compared to observations

The results of the CALV experiment reveal that the modelled calving sites and iceberg tracks fit the observations reasonably well. As is shown in the Arctic Monitoring and Assessment Programme (AMAP) plot (Fig. 2b), calving occurs along almost the entire coast of Greenland with major calving sites in Baffin Bay and along the south-east coast of Greenland. Despite the coarse resolution of GRISLI and the simplified calving scheme used, these calving sites are generally well captured (Fig. 4a). Only at the sites south-east of Greenland too little ice is calved. This might be due to the underestimation of the ice sheet's height compared to observations (Roche et al., 2013). The resulting number of icebergs is almost twice as large as indicated by present day observations (Church et al., 2001), which is partly due to the calving method, that assumes calving as soon as the ice sheet's thickness is below 150 m, and partly due to the applied pre-industrial forcings, producing a colder climate than observed present day.

The mean yearly distribution of icebergs (Fig. 4b) illustrates that the majority of bergs travels along the east and west coast of Greenland reaching as far south as about 50° N with a few bergs moving further south and even travelling up to Europe. The transportation of the icebergs depends on both the winds and ocean currents. But it can be seen that most bergs calved east of Greenland are transported southward with the East Greenland Current and the ones calved west of the GIS are first moved northward by the West Greenland Current and then southward again by the Baffin Island and Labrador Currents (Fig. 4b and c). Further, the icebergs calved along the north coast of the GIS are distributed in the Arctic ocean by the Beaufort Gyre. These

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modelled patterns fit well with observations (Fig. 2b) and are also found in the model study of Bigg et al. (1996).

3.2 Impact of icebergs on the pre-industrial climate and the Greenland ice sheet

Including icebergs in the model set-up (CALV experiment) causes a cooler and fresher ocean state east and south of Greenland and consequently an increased sea ice thickness (SIT) thereby increasing the surface albedo which leads to a cooler atmospheric state compared to CTRL. The reduced air temperature in the CALV set-up causes a decrease in precipitation and therefore a reduced ice sheet thickness over central and east Greenland. Due to the movement of the icebergs, their melt water is distributed away from their calving sites all around the GIS and reaching up to Svalbard and Iceland (Fig. 5a) with the maximum being released along the coast. In accordance with the icebergs' melt flux, there are decreased sea surface temperatures (SSTs) found east and south of the GIS as a result of the take up of latent heat needed to melt the icebergs. But in the Barents Sea and along the coast of North America, the CTRL displays lower SST despite the big iceberg melting rates (Fig. 7a). These differences arise due to the parameterisation of the take up of latent heat used in the CTRL run, which distributes the excess snow homogeneously all around Greenland. Hence, the SST is altered homogeneously whereas in the CALV experiment the impact on the SST depends on the amount of melt water released by the icebergs. This indicates that the parameterisation used in CTRL overestimates the latent heat take up west of the GIS as well as further away from shore, but underestimates it along the east coast and south of Greenland (Fig. 7a). Additionally, the higher sea surface salinities (SSS) in the CALV set-up in the Baffin and Hudson Bay region (Fig. 7b) indicate that less freshwater is released by the icebergs than by the excess snow used in CTRL. A different pattern is seen in the Greenland Sea where the icebergs freshen the ocean's surface due to the major calving sites along the east coast of Greenland and in the Labrador Sea where they cause a decline in SSS as well as a decrease in convection depth (Fig. 7d) whereas in the GIN (Greenland – Iceland – Norwegian) Seas the centre of the deep convection site is shifted northward in the CALV experiment, without a change in convective activity. The strongest impact on sea ice is found along the east coast of Greenland where it becomes thicker due to the lower SST (Fig. 7c).

As a consequence of the enhanced sea ice cover and thickness, the surface albedo (ALB) increases in the CALV set-up (Fig. 10a), while the sensible heat flux (SHF) from the ocean into the atmosphere declines (Fig. 10d). As less heat is exchanged between the ocean and the atmosphere, the air temperatures over the GIN Seas and central Greenland decrease. Less snow fall is found in the CALV set-up (Fig. 10b and c) owing to the lower air temperatures. The decrease in accumulation results in a diminution of the ice sheet's height of about 150 m in the CALV experiment compared to CTRL (Fig. 6d). In the Arctic on the contrary, the air temperatures are increased as is the amount of snow (Fig. 10b and c), which leads to an increased ice sheet thickness (Fig. 6d).

From the comparison of the CALV with the CTRL run we conclude that the effect of icebergs on the Northern Hemisphere climate is strongest around the GIS, reaching into the North Atlantic but decreasing towards Norway. This pattern is not captured by the homogeneous take-up of latent heat in the CTRL run. The effect of icebergs on the ice sheet's development under pre-industrial equilibrium conditions are small ($\sim$ 150 m) and caused by the local effect of the icebergs on the sea ice thickness.

3.3 Parameterizing icebergs using freshwater fluxes – how well does it work?

3.3.1 The freshening effect (FWFf – CTRL)

Releasing the calving fluxes instantaneously into the ocean, without forming icebergs, does not alter the climate strongly compared to CTRL. The FWFf and CTRL set-up share the same parameterisation of homogeneous take-up of latent heat and result in a very similar ocean and atmospheric state, as well as ice-sheet configuration at the end of the experiments (not shown). Therefore, the impact of the freshwater fluxes

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(freshening effect), related to calving under pre-industrial equilibrium conditions, is relatively small.

3.3.2 The freshening and cooling effect (FWFc – CTRL)

Applying the calving fluxes in the form of instantaneous freshwater fluxes that do take up the latent heat needed to melt them at the calving sites both freshens and cools the ocean close to the GIS margin. Thereby, they cause warmer and saltier GIN Seas as well as a cooling and freshening in the Davis Strait and Labrador Sea.

The local impact of the freshwater fluxes (Fig. 5b) on the one hand provokes an increase in sea ice thickness west of Greenland and on the other hand a decrease in sea ice thickness in the GIN Seas (Fig. 8c). In the latter, the inflow of the ice discharge lowers the SST (Fig. 8a) and thereby enhances the sea ice thickness along the north-east coast of Greenland (Fig. 8c). The SST and SSS are further increased by more extensive convective activity in the GIN Seas (Fig. 8a, b and d), resulting in an enhanced inflow of relatively warm and saline Atlantic waters and a stronger ocean-to-atmosphere heat flux. South of Greenland the input of the freshwater fluxes lead to a shift of the convection site eastward.

In Baffin Bay the release of the calving flux and the take up of heat needed to melt it causes lower SST and SSS (Fig. 8a and b) thereby facilitating the formation of sea ice, thus enhancing the albedo in this region (Fig. 11a). The former is linked to a decrease in the exchange of sensible heat between the ocean and the atmosphere (Fig. 11d). This effect is in contrast with the intensified sensible heat flux over east and central Greenland. Hence, higher air temperatures (Fig. 11b) and increased snow fall (Fig. 11c) are found there, caused by the stronger ocean convection in the GIN Seas. This different accumulation pattern, with more snow over the eastern and less over the western GIS, is reflected by the resulting ice sheet thickness, which over eastern (western) Greenland is up to 300 m increased (decreased) compared to CTRL (Fig. 6f) as well as in the mass balance (Fig. 13a), though not as pronounced.

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The comparison of the FWFc with the CTRL experiment shows that the absorption of latent heat from the ocean and the location of the take-up of latent heat have a stronger impact on the climate and consequently on the evolution of the ice sheet than the input of freshwater.

3.3.3 The distribution effect (CALV – FWFc)

Using the calving mass calculated by GRISLI to generate icebergs (as in CALV) instead of applying this mass in the form of direct freshwater fluxes (as in FWFc), has an almost opposite effect on climate and the GIS. Due to the movement of the bergs and their slow release of melt water, their impact on climate is over a wider area with less water being directly released at the calving sites than in FWFc (Fig. 5c). Therefore, the CALV experiment results in a much fresher and cooler Denmark Strait (Fig. 9a and b) with a reduced convection depth than seen in FWFc. This is due to the release of melt water in this area by the icebergs, which is not the case for the directly applied freshwater fluxes. In the GIN Seas the decrease in SST and SSS in the CALV run are linked to a spatially smaller deep convection area compared to the FWFc set-up (Fig. 9d). It is interesting to notice that in Baffin Bay the instantaneous release of the calved mass provokes a stronger cooling and freshening than the slow release of melt water by icebergs, even though they release more freshwater (Fig. 5c) since they are not only calved but also transported there.

The thinning of the sea ice thickness west and north of the GIS and its thickening south east of Greenland in CALV cause a two-sided response in albedo and sensible heat flux (Fig. 12a and d). Thus, the air temperature is reduced over the GIS and increased over the Arctic (Fig. 12b). The different effectiveness of direct freshwater fluxes and icebergs leads to different ice sheet geometries at the end of the simulations with a up to 300 m higher western and lower eastern GIS in the CALV set-up (Fig. 6e). This is a consequence of the mass balance (Fig. 13c) and the surface melt.

From our studies we conclude that the main effect of calving on the climate is due to the take-up of latent heat absorbed to melt the calved mass and its spatial distribution.

Therefore, the use of local freshwater and latent heat fluxes does not represent the effect of icebergs well as it strongly underestimates the distribution effect of the icebergs. In our model and under pre-industrial conditions, the FWFf experiment reveals the most similar results to the CALV run (not shown) as it includes the wider spread, parameterised take-up of latent heat and the local freshening.

4 Discussion

In the presented study the earth system model of intermediate complexity *i*LOVECLIM and the coupled ice sheet model GRISLI were further coupled to the dynamical iceberg module. This set-up was used to investigate the impact of icebergs on climate and the ice sheet itself in a fully coupled low resolution model. To model iceberg calving is a complex task as small scale processes are involved, which we cannot expect to represent with the 40 km × 40 km resolution of GRISLI. Still, the calculated calving sites fit reasonably well with observations as do the modelled iceberg trajectories. Moreover, we are interested in the impact of the icebergs on the climate and the ice sheet especially in the mechanisms behind, which are independent of the model resolution. The icebergs are moved according to the winds calculated by ECBilt and by the ocean currents as modelled by CLIO. However, due to the relatively coarse resolution of *i*LOVECLIM, our set-up is not suitable for tracking individual bergs or to forecast their movement. Moreover, we have to keep in mind that refreezing of the melt water, as well as splitting up of bergs is not accounted for. Excluding this latter process probably leads to an underestimation of the spread of the fresh anomaly, but an overestimation of the near-shore freshwater input, as has been reported by Martin and Adcroft (2010). Despite the mentioned shortcomings, this model set-up is a valuable tool to investigate the effect of icebergs on the Northern Hemisphere climate and the GIS. Especially as the EMIC is coupled to a dynamically computed ice sheet model and therefore accounts for changes in calving rates and positions. This is of particular interest for the study

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of past climate changes at relatively long time-scales (centennial to multi-millennia), when also large changes in ice sheet geometries can be expected.

In the prevailing study the resulting climate conditions and ice sheet geometries do not differ strongly between the experiments since they were done under pre-industrial conditions where the calving rates are relatively constant and small. Therefore, the impact of icebergs on the ice sheet's development is thought to be stronger during colder climate conditions with higher calving rates. Moreover, icebergs influence the timing of the climatic response during changing climates. On the one hand, this effect has been seen by Jongma et al. (2013) who investigated the impact of the so-called Heinrich events using the same iceberg module coupled to LOVECLIM (Goosse et al., 2010). Heinrich events are large surges of icebergs released from the Laurentide ice sheet during the last glacial (Hemming et al., 2004), for which widespread evidence has been found in marine sediment cores. Jongma et al. (2013) mimicked the impact of these Heinrich event by introducing large surges of dynamical icebergs in the model under glacial boundary conditions. They compared the results with a run in which an equivalent volume of water was released as liquid freshwater fluxes. Jongma et al. (2013) revealed that icebergs that freshen and cool the ocean cause a faster climatic response as well as a faster recovery of the system. On the other hand, Green et al. (2011) used the global climate model FRUGAL coupled to the iceberg module based on Bigg et al. (1997) to analyse the impact of deep-draft icebergs released due to the break-up of the Barents ice sheet collapse during MIS 6 (140 kyr B.P.). They found that the effect of icebergs on the ocean circulation is weaker in the beginning, but lasts over a longer time period. Both studies display that not only the input of the calving fluxes, but also their form – either icebergs or freshwater fluxes – is important.

So far, icebergs have mostly been parameterised using freshwater fluxes to save computation time. To study the impact of such parameterisations, we compared dynamical included icebergs to freshwater fluxes released at the same locations and according to the same seasonal cycle as the icebergs and found noticeable differences. Icebergs facilitate the formation of sea ice especially in the GIN seas compared to the freshwater fluxes being applied at the calving locations together with homogeneous take-up of latent heat around Greenland. This is consistent with the findings of Jongma et al. (2009) who performed sensitivity studies under pre-industrial conditions, where they investigated the different impact of icebergs compared to homogeneously distributed freshwater fluxes. They found that the effect of icebergs is restricted closer to shore than the freshwater fluxes and that the sea ice formation is facilitated by icebergs. Yet, when we apply local freshwater fluxes together with their related local take-up of latent heat, these fluxes are more efficient in producing thicker sea ice than icebergs. This is in agreement with Martin and Adcroft (2010) who investigated the impact of interactively coupled icebergs in a GCM and also compared it to directly applied freshwater fluxes. They find a decrease in sea ice thickness in the Southern Ocean when generating icebergs using the excess snow instead of applying it directly to the ocean. Also Hunke and Comeau (2011) investigated the interactions between sea ice and both giant and small icebergs in the Southern Ocean using a stand-alone ocean model with explicitly included icebergs that are moved according to the ocean currents and the atmospheric forcing applied. They revealed that the bergs locally affect the sea ice thickness and area, but conclude that on a global scale these dynamically induced differences are negligible. In our study the effects on sea ice are locally confined, yet, the feedback on the atmosphere and consequently the development of the ice sheet indicates more extensive impact. The CALV experiment is the only one which enhances the sea ice thickness east and south of Greenland, all the other runs increase the sea ice thickness only west of it. This different impact on the sea ice and consequently on the atmospheric state results in different ice sheet geometries.

The presented coupled model set-up offers a great approach to conduct long term experiments to better understand the role of icebergs and the interactions between the different climate components during abrupt climate changes. This is feasible with the presented model since the computation time for 1000 model years is about two days in the fully coupled set-up. A useful next step could be to use this model set-up to study

Heinrich events in detail, as the crucial question how the icebergs' feedback was on climate under colder and more instable times has not yet been fully addressed.

5 Conclusions

We have coupled the ice sheet model GRISLI to the earth system model *i*LOVECLIM to study the impact of dynamical-thermodynamical icebergs on climate and the Greenland ice sheet under pre-industrial conditions. We find that the modelled calving sites correspond well with present day observations with a slight underestimation of the calving along the southern east margin of Greenland. The amount of ice being calved is almost two times the value observed for the present-day climate, which can be explained by the colder pre-industrial than present day climate conditions and the simple calving method used. Further, the main iceberg routes are reproduced using the modelled winds and ocean currents.

According to our study, the impact of icebergs on the Northern Hemisphere climate is strongest east and south of Greenland where they increase the sea ice thickness and consequently change the heat exchange between the ocean and the atmosphere due to a higher surface albedo and a weakened sensible heat flux. Therefore, icebergs provoke cooler air temperatures above Greenland, which then cause a decrease in snow fall. This leads to a reduction of the ice sheet height by up to 150 m over central Greenland.

From the presented analysis we conclude, that the strongest impact of calving on the climate is due to the take up of latent heat needed to melt the ice mass and that the freshening due to the released melt water has a smaller impact. Applying direct freshwater fluxes together with homogeneously distributed take up of latent heat results in a similar climate and ice sheet geometry as in the CALV experiment. However, directly applied freshwater fluxes that absorb the latent heat needed to melt at the calving site, lead to an enhanced deep ocean convection and a decrease in sea ice thickness in the GIN Seas. Moreover, they cause lower SSTs and SSSs north and west of the GIS, con-

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sequently increasing the sea ice thickness. This different impact on the sea ice causes increased air temperatures east and decreased ones west of Greenland. These temperature changes are linked to an elevated ice sheet thickness over east and a reduced thickness over west Greenland of up to 300 m compared to the CTRL and especially to the CALV experiment.

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Table 1. Summary of treatment of freshwater fluxes coming from the ice sheet and of latent heat fluxes related to iceberg melting; runoff = basal and surface melting of the ice sheet; iceberg FWF = melt flux related to iceberg calving; direct FWF = input of calving mass as freshwater flux into the first ocean cell next to the ice sheet margin instead of forming icebergs; local LHF = take up of latent heat at the position where the freshwater related to iceberg melting is put into the ocean; homogeneous LHF = parameterisation of freshwater fluxes related to iceberg calving as take up of latent heat homogenously around Greenland.

	Runoff	Iceberg FWF	Direct FWF	Local LHF	Homogeneous LHF
CTRL (1)	–	–	–	–	X
CALV (2)	X	X	–	X	–
FWFf (3)	X	–	X	–	X
FWFc (4)	X	–	X	X	–

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Table 2. Summary of anomalies analysed.

Anomaly	Interpretation
CALV-CTRL	Effect of non-parameterized take up of latent heat as well as slow and spatially spread melting due to moving icebergs (= cooling + freshening + distribution effect)
FWFf-CTRL	Effect of Freshwater (= freshening)
FWFc-CTRL	Effect of freshwater and non-parameterized take up of latent heat (= freshening and cooling effect)
FWFc-FWFf	Effect of non-parameterized take up of latent heat (= cooling effect)
CALV-FWFc	Effect of slower and spatially spread melting due to moving icebergs (= distribution effect)
CALV-FWFf	Effect of non-parameterized take up of latent heat as well as slower and spatially spread melting due to moving icebergs (= cooling + distribution effect)

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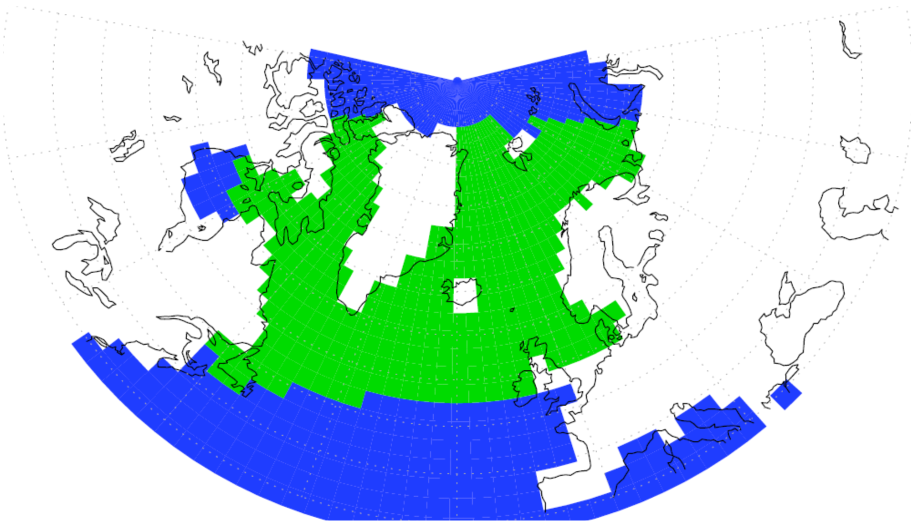

Fig. 1. The green cells correspond to the locations in CLIO where the latent heat needed to melt the excess snow is homogeneously taken up to parameterize icebergs.

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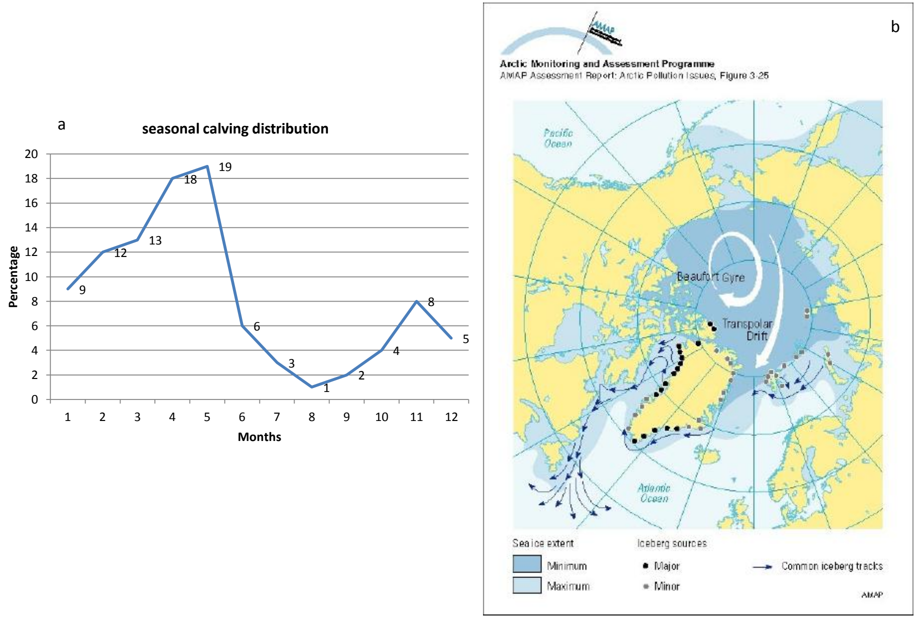

Fig. 2. (a) Seasonal calving distribution in % of yearly mass per month as calculated by Martin and Adcroft (2010); **(b)** sites and tracks as stated in the AMAP Assessment Report (2007), reproduced with permission.

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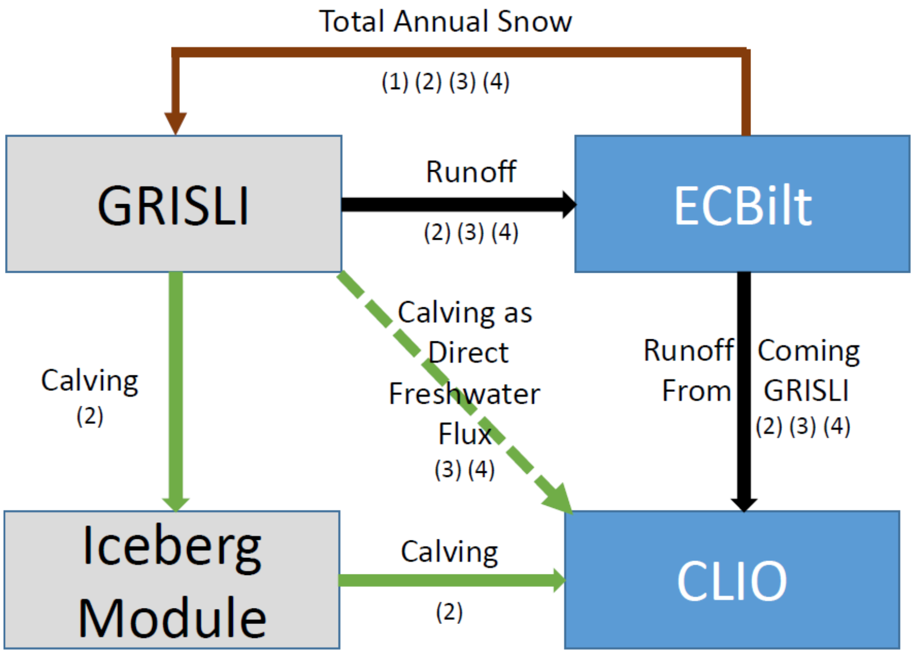

Fig. 3. Schematic representation of the water cycle between the atmospheric component ECBilt, the ice sheet module GRISLI, the iceberg module and the oceanic component CLIO; numbers correspond to experiments (1 = CTRL, 2 = CALV, 3 = FWFf, 4 = FWFc).

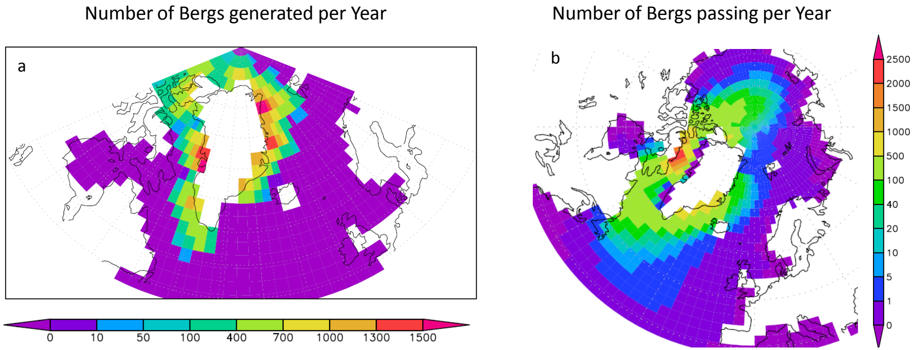

Fig. 4. iLOVECLIM: **(a)** number of icebergs being generated per year; **(b)** number of icebergs passing a grid cell per year.

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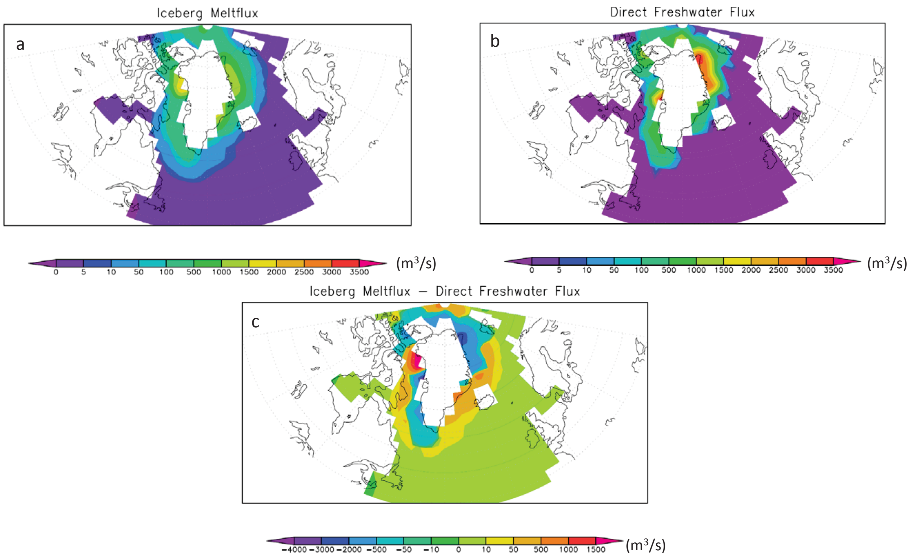

Fig. 5. (a) 1000 yr averaged iceberg melt water fluxes ($m^3 s^{-1}$) of the CALV experiment; **(b)** 1000 yr averaged melt water flux due to calving put into the ocean directly at the ice sheet margin (FWFc); **(c)** difference between iceberg melt flux and direct freshwater flux.

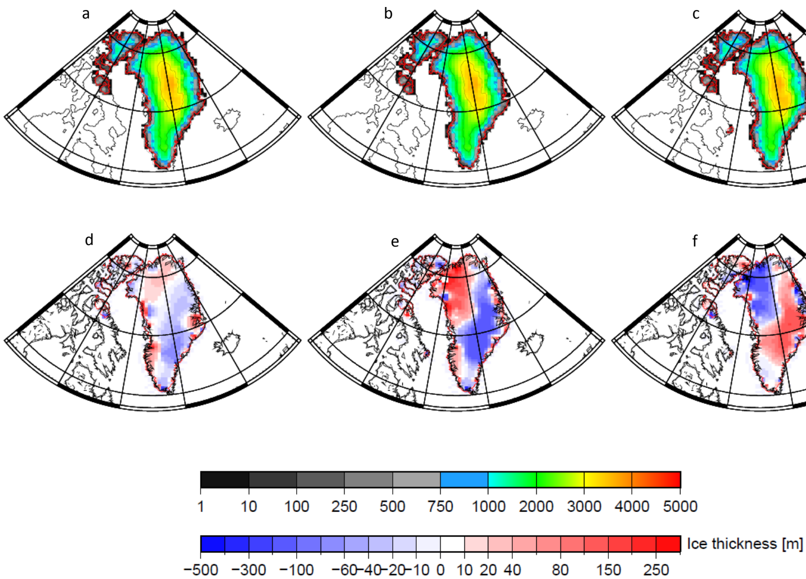

Fig. 6. 1st row: ice sheet thickness (m); **(a)** CTRL run; **(b)** CALV run; **(c)** FWFc run; 2nd row displays the differences: **(d)** CALV-CTRL; **(e)** CALV-FWFc; **(f)** FWFc-CTRL.

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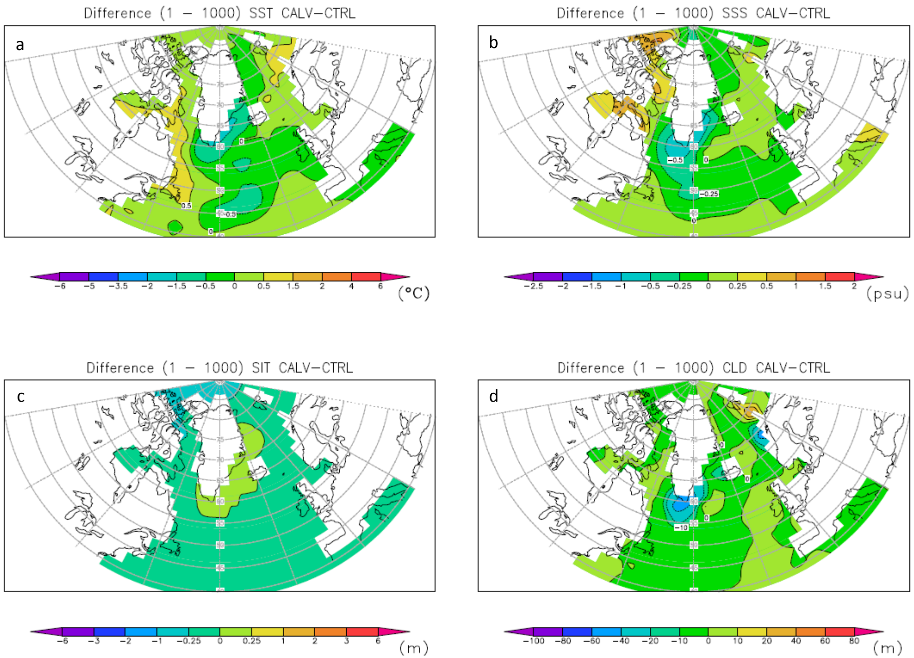

Fig. 7. CALV – CTRL differences of 1000 yr averages; **(a)** Sea Surface Temperature SST (°C); **(b)** Sea Surface Salinity SSS (psu); **(c)** Sea-Ice Thickness SIT (m); **(d)** Convection Layer Depth CLD (m).

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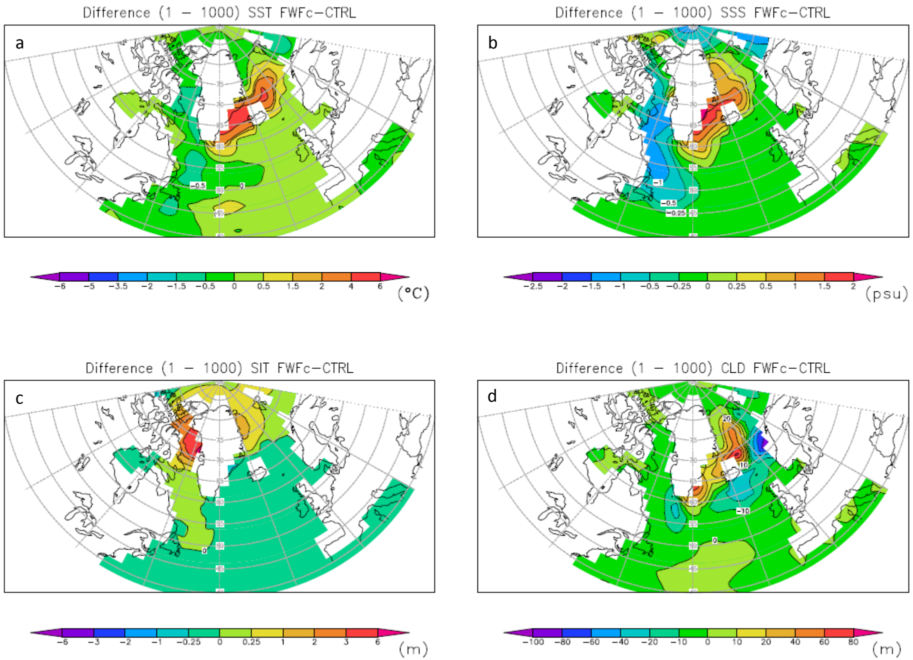

Fig. 8. FWFc – CTRL differences of 1000 yr averages; **(a)** Sea Surface Temperature SST (˚C); **(b)** Sea Surface Salinity SSS (psu); **(c)** Sea-Ice Thickness SIT (m); **(d)** Convection Layer Depth CLD (m).

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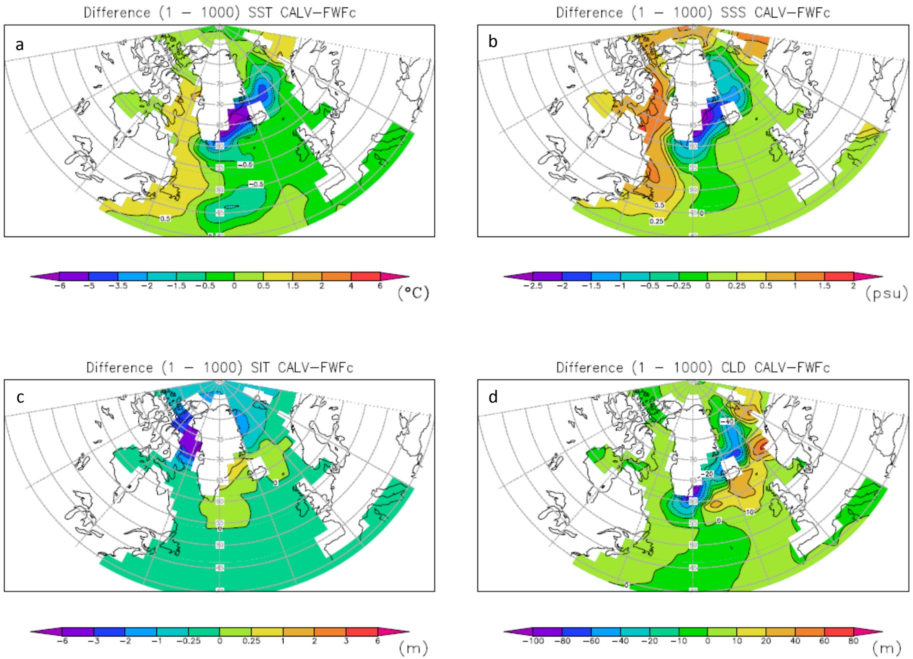

Fig. 9. CALV – FWFc differences of 1000 yr averages; **(a)** Sea Surface Temperature SST (˚C); **(b)** Sea Surface Salinity SSS (psu); **(c)** Sea-Ice Thickness SIT (m); **(d)** Convection Layer Depth CLD (m).

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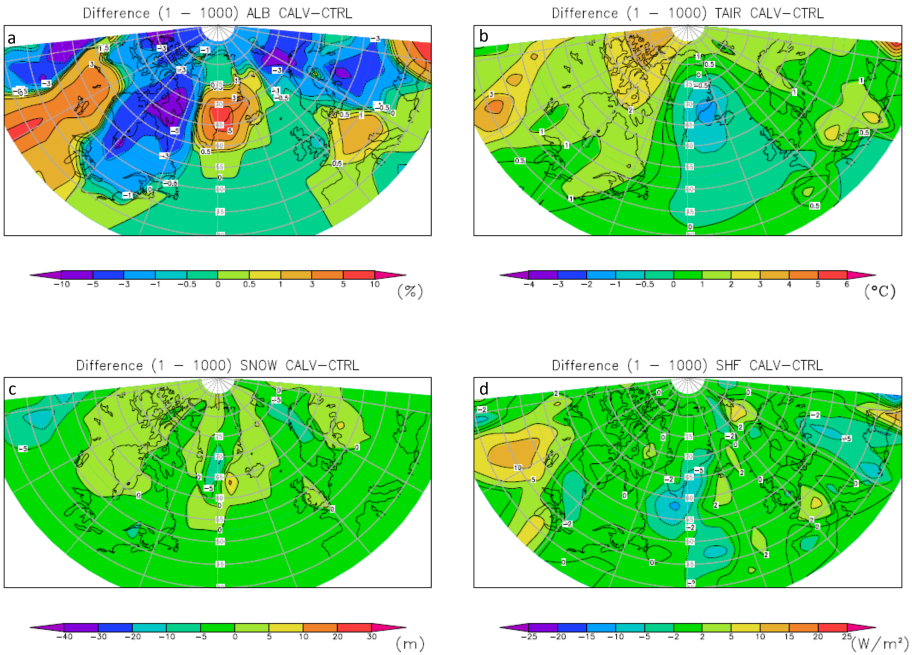

Fig. 10. CALV – CTRL differences of 1000 yr averages; **(a)** Albedo ALB (%); **(b)** Air Temperature TAIR (°C); **(c)** Total Snow Fall SNOW (m); **(d)** Sensible Heat Flux SHF (W m^{-2}).

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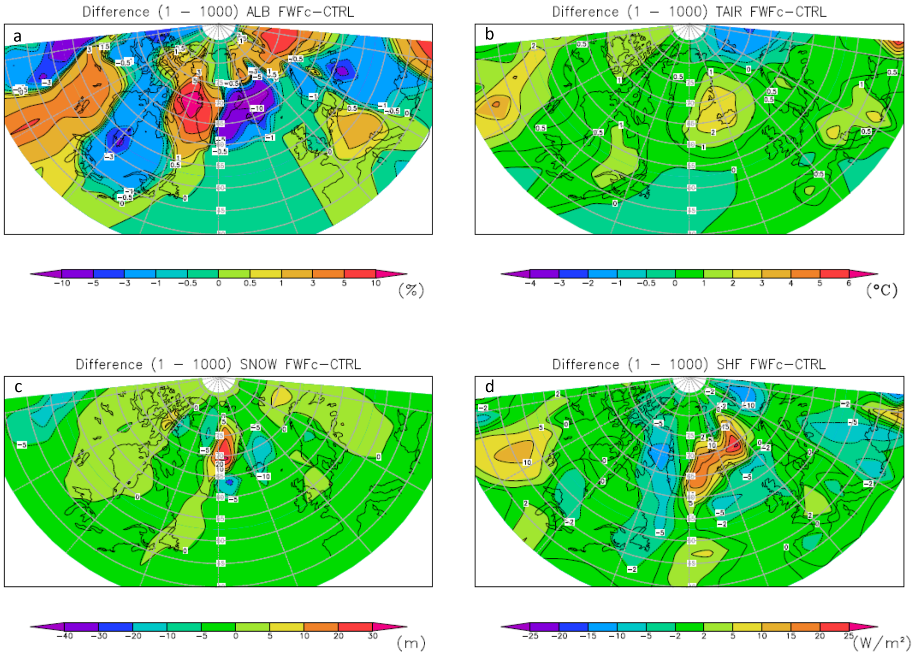

Fig. 11. FWFc – CTRL differences of 1000 yr averages; **(a)** Albedo ALB (%); **(b)** Air Temperature TAIR (°C); **(c)** Total Snow Fall SNOW (m); **(d)** Sensible Heat Flux SHF (W m^{-2}).

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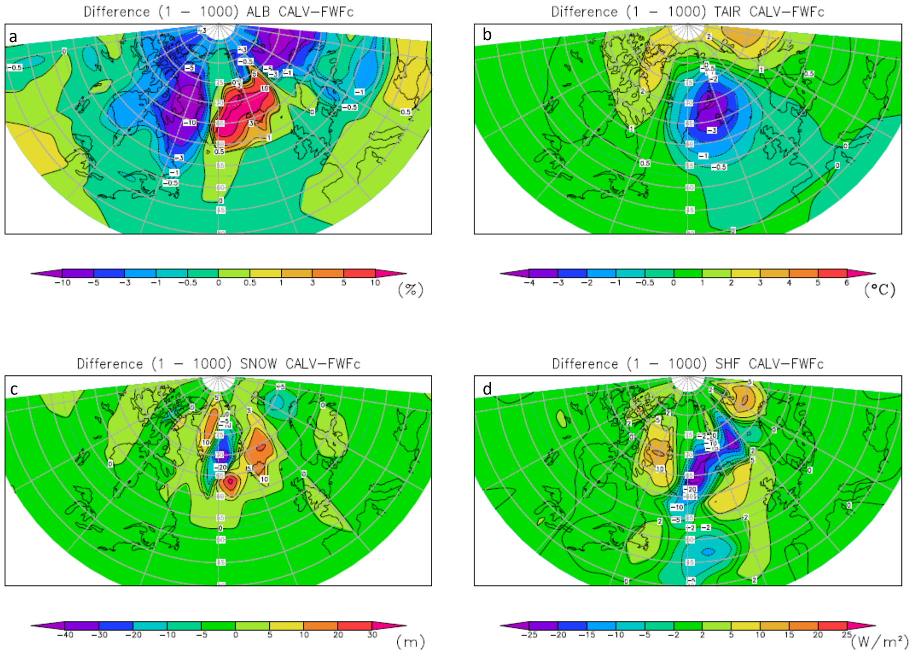

Fig. 12. CALV – FWFc differences of 1000 yr averages; top left: **(a)** Albedo ALB (%); **(b)** Air Temperature TAIR (°C); **(c)** Total Snow Fall SNOW (m); **(d)** Sensible Heat Flux SHF ($W m^{-2}$).

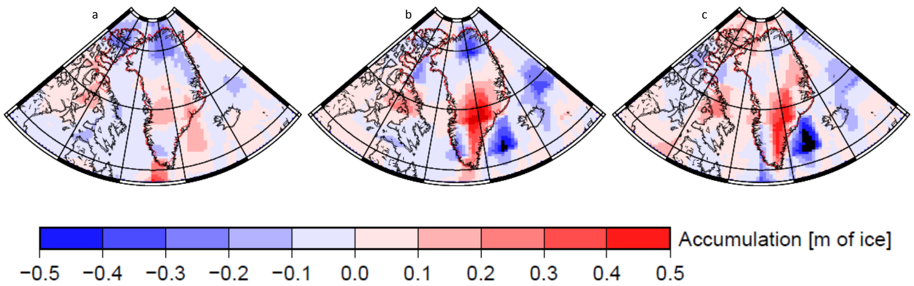

Fig. 13. The differences of 1000 yr averages in mass balance (m): **(a)** CALV-CTRL; **(b)** CALV-FWFc; **(c)** FWFc-CTRL.